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Supplementary information

Losses and lifetimes of metals in the economy

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LOSSES AND LIFETIMES OF METALS IN THE ECONOMY

Supplementary Information

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Abbreviations and Acronyms

BRGM	French geological survey *(Bureau de Recherches Géologiques et Minières)*
CCA	Chromated copper arsenide
DF	Dissipative flow (loss)
EMD	Electrolytic manganese dioxide
EMM	Electrolytic manganese metal
EOL	End-of-life
EOL-RR	End-of-life recycling rate
EV	Electric vehicles
EZC	Enriched zirconium concentrate
FCC	Fluid cracking catalysts
GSD	Geometric standard deviation
HREE	Heavy rare earth elements
HSLA	High-strength low-alloy
IMoA	International Molybdenum Association
ITIA	International Tungsten Industry Association
LCD	Liquid crystal display
LED	Light-emitting diode
LREE	Light rare earth elements
MFA	Material flow analysis
MRI	Magnetic resonance imaging
PCB	Printed circuit boards
PET	Polyethylene terephthalate
PGM	Platinum group metal
REE	Rare earth elements
REO	Rare earth oxides
SFA	Substance Flow Analysis
UNEP	United Nations Environment Programme
US	United States
USGS	United States Geological Survey
VCM	Vinyl chloride monomers

1 The anthropogenic cycle of metals

The anthropogenic cycle of metals, as represented in Fig. 1 of the article, has been extensively described in detail by other authors (Chen and Graedel, 2012; Helbig et al., 2020; Kavlak and Graedel, 2013a; Wang et al., 2007). It is illustrated as the conceptual model in in Figure S1 below. The main processes amongst each life cycle phases are described in this section.

1.1 Production (primary)

Ores are typically extracted from the ground and transformed into refined flows of metals at various degrees of purity (e.g., 3N to 7N) through successive crushing, concentrating, smelting, and refining processes. Metals obtained as by-products may be selectively extracted and refined from different steps of the carrier metal's production. In a few instances, part of the production of metals originates from industrial waste. For example, vanadium may be recovered from spent catalysts used in the petroleum industry in which it tends to accumulate. The production yield is calculated based on the recovery of metals from ores or other materials in which they are contained and from which they could be recovered, with no regard to the current technical and economic feasibility of production. In the majority of cases, only the ores that are extracted for their content of metals are considered to calculate or estimate the yield of production. However, whenever specific material flows from which metals could be recovered were identified, i.e., because they are knowingly present in such a concentration that it could represent a significant share of the production of that metal, and that such material flows were included in a published study as a potential source of that metal, these metals were also considered as resources and were accounted for. For example, this was the case for gallium in fly ash (Licht et al., 2015). In a few instances, no production yield could be found for potential by-products. In this case, the production yield is estimated based on the average ore content in comparison to the yearly extraction of such ores and the reported yearly production of the potential by-product (e.g., scandium, Table S16). The transfer coefficient for the production phase is identified as δ in Figure S1.

1.2 Fabrication and manufacturing

Fabrication and manufacturing include every step required to transform refined metal flows into final products. Refined metals may be transformed as pure substance flows (e.g., copper) or as more complex materials (e.g., copper alloy). These pure flows or materials are fabricated in semi-products (e.g., sheets, tubes, plates) and further manufactured and assembled into final products. The transfer coefficient for the fabrication and manufacturing phase is identified as λ in Figure S1.

1.3 New scrap recovery

New scraps from the fabrication and manufacturing stage may be collected for recycling. When collected new scraps enter the scrap market, they may be remelted along with virgin raw materials and old scraps. Some collected new scraps may also be recycled internally, as is the case for, e.g., some titanium metal. In such cases, the fabrication and manufacturing yield was estimated to include the potential recovery of new scraps. The transfer coefficient for new scrap recovery is identified as ξ in Figure S1.

1.4 Use and dissipation in use

The products are readily available to provide their expected functionality to users over their projected lifetimes (i.e., until they become obsolete) or provide their functionality as an expectedly dissipative use (e.g., fireworks, pesticides). Dissipation may occur during the use phase. We distinguish between three types of dissipation during the use phase, referred to as type A, B and C throughout this document.

Type A: This dissipation in use consists of a voluntary dispersion of metals in order to obtain the expected function of the product they are contained in, making it difficult or impossible to recover them. Some may theoretically be re-concentrated through natural cycles in the long-term or recuperated from the environmental media, such as lead from used ammunitions, or magnesium from ocean water. According to the terminology of Lifset et al. (2012), such dissipation in use corresponds to an intentional release of metals from the intentional use of metals.

Type B: The second type of dissipation in use is a partial dissipation of the metal over its application's lifetime. These dissipative losses are not voluntarily induced to obtain a function but are predicted to occur over the lifetime of applications due to the way metals are used. It is the case of, e.g., steel exposed to the outdoor environment that corrodes over time; of zinc used for galvanization, which is voluntarily sacrificed to improve the longevity of steel applications; of lithium used in lubricating greases that may leak from its application; of platinum group metals (PGM)s used in auto catalytic converters that may be lost due to vibrations; etc. According to the terminology of Lifset et al. (2012), such dissipation in use corresponds to an unintentional release of metals from the intentional use of metals.

Type C: The third type of so-called dissipative uses are expected losses due to the way resources are integrated into a material or product in such a way that their functional recycling is economically or technically unfeasible (e.g., some metals are present in the order of a few parts per million in products reaching EOL, making their separation and recovery inconvenient or impossible even if they are collected as part of the recycling stream). Nonetheless, these metals contribute to the function of the products they are used in over its lifetime, hence not being dissipated (yet). Therefore, it is here considered as dissipated only once the product has become obsolete and entered the waste flow, at which point the resource may be non-functionally recycled or landfilled, becoming inaccessible for future use at least temporarily (cf. discussion in Beylot et al., 2020). These are "lost by design" and correspond to "currently unrecyclable" applications according to the terminology of Ciacci et al. (2015). In this dataset, such dissipative uses are accounted for as either collection or remelting losses.

We consider dissipation of type A as a punctual dissipative use. Such applications are modeled with a lifetime of one year and a dissipation in use rate of 100%. Hence, they are no longer available for collection and recycling. Dissipation of type B are considered as partial dissipative uses, and a share of metals entering the use phase are reported to be dissipated over the lifetime of products. The remaining share of metals contained in the end-use products, i.e., which have not been dissipated in use, may be collected for recycling. Finally, the metals that are considered to undergo dissipation of type C are assumed to be functionally used throughout the lifetime of the applications. However, they are lost by default ("by design") to the collection or recycling process since they are considered to be currently unrecyclable, and a collection and sorting yield of 0% is reported for such applications. Dissipation in use is identified as ω in Figure S1.

1.5 Collection and sorting

Obsolete products are collected through waste collection schemes and either landfilled, or dismantled, cleaned, and recycled in new material streams (Chen and Graedel, 2012). Landfilling and non-functional recycling (defined below) are interpreted as dissipation, in line with the rationale of Zimmermann and Gößling-Reisemann (2013) and Helbig et al. (2020). The transfer coefficient for collection and sorting is identified as γ in Figure S1.

1.6 Recycling (secondary production)

Sorted materials enter the recycling stream and are recycled (generally, remelted) into new materials flows. Metals that enter the recycling streams may either be functionally or non-functionally recycled (Graedel et al., 2011). Non-functional recycling is accounted for as dissipative losses. Functional recycling refers to "that portion of EOL recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy" (Graedel et al., 2011). Non-functional recycling refers to "that portion of EOL recycling in which the metal is collected as old scrap and incorporated in an associated large-magnitude material stream as a 'tramp' or impurity elements" (Graedel et al., 2011). In general, the recycling of metals that can be considered to offset the demand for primary resources can be considered to be functionally recycled. By extension, we consider the recycling of metals present in complex materials into new materials voluntarily making use of primary resources (of that same metal) to also consist in functional recycling. For example, this is the case for a fraction of the recycling of magnesia refractories in cement since primary magnesia is also used for cement production (cf. Table S13). The transfer coefficient for recycling (remelting) is identified as θ in Figure S1.

2 Methods

2.1 Conceptual model

The conceptual model, as defined in the Methods section of the article, is depicted in Figure S1.

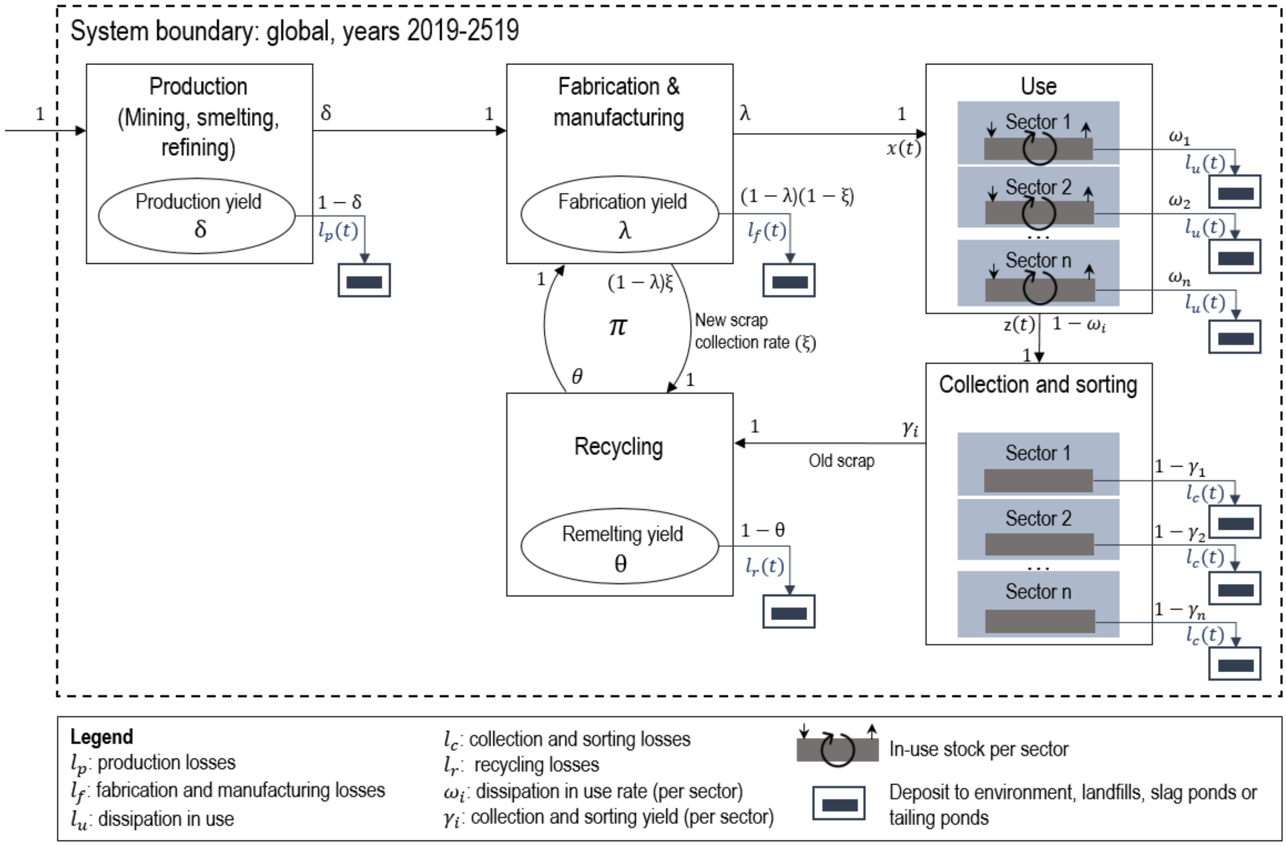

Figure S1. System definition and conceptual model (adapted from Helbig et al., 2020)

2.2 Data collection

A wide range of references was consulted to build this dataset. Peer-reviewed literature as well as studies published by governmental institutions, such as the Joint research center (JRC) of the European Commission, the US Geological Survey (USGS), and the French geological survey (BRGM), were preferred. Industrial reports were also often consulted. The main sources of data to obtain or calculate process yields, end-use distributions, and application lifetimes are presented below.

2.2.1 Process yields and dissipation in use

For 18 metals that were already included in a previous study (Helbig et al., 2020), the main process yields were calculated based on global MFA studies from 1997 to 2017. These MFA studies covered the global cycle of aluminium (Bertram et al., 2017), chromium (Johnson et al., 2006), iron (Wang et al., 2007), cobalt (Harper et al., 2012), nickel (Reck and Rotter, 2012), copper (Glöser-Chahoud, 2017), zinc (Meylan and Reck, 2017), gallium (Licht et al., 2015), germanium (Licht et al., 2015), selenium (Kavlak and Graedel, 2013b), silver (Johnson et al., 2005), indium (Licht et al., 2015), tin (Izard and Müller, 2010), tellurium (Kavlak and Graedel, 2013a), tantalum (Nassar, 2017), tungsten (Meylan et al., 2015), rhenium (Meylan et al., 2015), and lead (Mao et al., 2008a). The process yields calculated by Helbig et al. (2020) based on these MFAs were mostly re-used in the present work. However, some changes were made in order to harmonize the method across all of the studied metals (cf. section 2.4).

In addition, the Stock and Flows (STAF) and the Criticality of Metals projects of the Center for Industrial Ecology of Yale University provided insights on the life cycle of many other metals. Their criticality studies provided calculated or estimated extraction and refining (production) yields as well as end-of-life recycling rates (EOL-RR) for many metals that they used as inputs for their depletion model (Graedel et al., 2015; Harper et al., 2015; Nassar et al., 2012; Nuss et al., 2014; Panousi et al., 2016). Moreover, Du and Graedel (2011a) provided global MFAs for ten rare earth elements (REE), which allowed calculating process yields for La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Y. However, given the low resolution of the latter MFAs, additional information and data were gathered to complement this study as well as to include the five missing REEs (Er, Ho, Tm, Yb, and Lu) (cf. section 2.4.3). Moreover, Ciacci et al. (2015) provided valuable insights on the dissipation in use for most of the studied metals, which we largely relied on to establish the rates of dissipation in use across this dataset.

Finally, a short literature survey realized for each metal allowed to fill data gaps or make plausible assumptions where necessary. These surveys focused on identifying specific process yields, as well as national statistics or regional MFAs. For example, the USGS released a series of national MFAs for the year 1998, covering 13 metals (USGS, 2004a). Some technical reports or annual reports from mining companies were sometimes also considered as a complementary source of information. Estimations and assumptions are made for processes and metals for which no quantified data is found. The details on the literature underlying each data considered to calculate or report process yields are reported in Table S10-Table S70.

2.2.2 End-use distributions

The global distribution of metals into end-use applications was established based on peer-reviewed literature and governmental institutions. The data compiled for Yale University's STAF project, generally representative of the year 2008, was consulted as a starting point to establish end-use distributions for most metals (Ciacci et al., 2015; Graedel et al., 2015, 2013; Harper et al., 2015; Nassar et al., 2012; Nuss et al., 2014; Panousi et al., 2016). A literature survey was realized for each metal in order to update the end-use distributions to a more recent year whenever possible. For example, the Johnson Matthey's reports were consulted to update the end-use distributions for PGMs for the year 2019 (Johnson Matthey, 2020a, 2020b).

Moreover, the BRGM's criticality sheets (e.g., BRGM, 2018a, 2017a, 2016a) and European Commission's 2020 criticality fact sheets (European Commission, 2020a, 2020b) provided global end-use distributions for several metals, typically for some year between 2010 and 2019. In some cases, market analysis reports or technical reports from industrial sources were available, e.g., for lithium (SQM, 2019) and magnesium (Wietlisbach, 2018).

Furthermore, when additional data was available, end-uses were refined into more precise end-use categories. For example, the USGS reported 65% of lithium uses in batteries for the year 2019 (USGS, 2020). This share was further disaggregated in 44% automotive uses in electric vehicle (EV) batteries and 21% into batteries for consumer electronics based on an industrial report (SQM, 2019). The detailed description of the calculations and references considered to build the end-use distributions for each metal are listed in Table S10-Table S70.

2.2.3 Managing the diversity of end-use applications

Pragmatic decisions were made in order to keep the number of reported end-use application sectors to a manageable amount. As a rule of thumb, it was attempted not to report a sector including one single metal unless it represented a significant share of end-uses for that metal. In order to cover the wide range of applications reported as "miscellaneous" or "others" across the studied metals, four "other uses" categories were created. They were chosen to reflect the most common applications and the associated lifetimes reported in the literature for such miscellaneous applications. In order to aggregate other uses to one of these categories, we considered the most typical miscellaneous uses reported in the literature for each metal. These "other" categories are the following:

- "Other industrial, military & energy applications", including undefined industrial appliances or structural components (e.g., titanium metal used in various industrial applications, aluminum used in petrochemical piping, niobium used in heat-resistant stainless steels in chemical industries or power plants), military and medical appliances, amongst others. Various undefined applications for which relatively long lifetimes were reported in the literature were also aggregated in this category, e.g., for titanium metal (Graedel et al., 2015).

- "Other electrical & metal products" including various electrical components (e.g., switchgear, relays, etc.) and undefined metal components or products (e.g., undefined wrought products and bearings).
- "Other miscellaneous" includes a range of expectedly relatively short-lived applications or components, such as nuclear fuel rods (e.g., zirconium) and spark plugs (e.g., iridium), as well as undefined other uses for which relatively short lifetimes were suggested in the literature, such as other applications of bismuth, boron, and cobalt (Graedel et al., 2015; Panousi et al., 2016).
- "Other punctual applications" include miscellaneous uses that are inherently dissipative (type A dissipation), such as lead and bismuth used in ammunition, boron used in soaps and detergents, and thulium used as a radiation source for medical imaging. A lifetime of 1 year was reported for these applications, with a dissipation in use rate of 100%.

Moreover, it was observed that the reported end-use distributions of many metals included materials or semi-products (e.g., superalloys, glass, phosphors, rubber, and plastics). When possible, these materials and semi-products were attributed to other end-use sectors based on additional quantitative or qualitative information found in the literature, especially when they covered a large portion (i.e., >10%) of the end-use distribution for a given metal. When it was not possible to do so, they were classified into generic application sectors for materials (i.e., Glass & ceramics, Alloys & solders, and Plastics categories, described below) or into one of the four "other" categories described above.

Multiple metals are used in glass, ceramics, frits, and glazes (e.g., as pigments or to improve their characteristics for certain applications), for which the final end-use sector is seldom reported. Glass products may include, e.g., windows and window doors used in a range of contexts, e.g., construction, refrigerated sections of supermarkets, in specialty laboratory glassware and other glassware, vehicle windshields, etc. Traditional ceramic uses include home applications such as floor and roof tiles, but they can also have a range of technical applications in, e.g., industrial applications and in the aerospace sector. Similarly, the "Alloys and solders" category includes the use of several metals used in, e.g., specialty alloys, superalloys, or as micro-alloying elements, as well as solders that may be used in a variety of contexts and applications (e.g., bismuth and lead solders). Many metals were added to plastic products as fire retardants, stabilizers, and pigments; these were aggregated into one same plastics category.

Moreover, we created an englobing Metallurgy & metalworking (process) category, including multiple process uses. End-uses included in this category consist in dissipative uses of type B. Dissipative uses of type B include metallurgical additives for e.g., deoxidizing and desulfurizing purposes, typically lost to slags (e.g., manganese), and other materials that are expected to be progressively lost to a metal-making process, such as sand casting (e.g., chromite, zircon) or continuous casting (e.g., lithium). Contrastingly, some metallurgical additives are also used to improve the malleability and machinability of metals, which remain in the final product, albeit not contributing to the characteristic of the material or of the product after manufacture. For instance, the addition of tellurium to steel and copper alloys improves their machinability and remains in the final product (USGS, 2020). While Kavlak and Graedel (2013a) considered such uses to be dissipative, it is possible that metals are actually potentially recoverable during recycling, as in the case of tellurium (Ciacci et al., 2015). In this dataset, the dissipative losses due to such end-uses were considered to be type C dissipation and were reported as either collection or remelting losses.

Finally, it seemed mandatory to distinguish between different end-use sectors for industrial catalysts, batteries, and magnets, because these may have different lifetimes depending on the sector in which they are used and represent large shares of end-uses for many metals. For example, batteries represent major end-uses for e.g., lithium, cobalt, and cadmium, with around 50-70% of their respective consumptions. Different types of catalysts may have different expected lifetimes. For instance, Graedel et al. (2015) estimated the use of cobalt catalysts in petroleum refining to have an average lifetime of 2 years, and those for the production of polyester precursors, an average lifetime of 8 years. Therefore, we created two categories for catalysts to reflect such differences: Catalysts (homogenous & aggressive env.) and Catalysts (heterogeneous & stable env.). The former category generally includes catalysts that are in the same phase as reactants for a given process, as well as those used in aggressive environments such as in oxidizing conditions, leading to a need for frequent regeneration or replacement. The latter category generally includes catalysts that are not in the same phase as reactants for a given process and that are not used in particularly aggressive environments.

In the case of batteries, it was often possible to distinguish between those used in consumer electronics, lead-acid batteries, hybrid or electric vehicles, and industrial, utility or energy storage applications. Consequently, three dedicated sectors were created to reflect the variability in lifetimes in between expected lifetimes for batteries, namely batteries (consumer electronics & lead acid), batteries (electric vehicle), and batteries (utility & industrial), with average lifetimes of 4, 9.5 and 13 years, respectively. Similarly, magnet applications were also split into discrete end-use sectors. While they sometimes could be aggregated within the consumer electronics or transport (i.e., electric vehicle engines) sectors based on the available information, some magnets were reportedly used in several other uses such as magnetic resonance imaging (MRI), magnetic cooling, and wind turbines. We classified such expectedly long-lived magnet applications in a generic "Magnets (large)" category for which an average lifetime of 20 years is reported.

2.3 Application lifetime distributions

Metals are distributed into a total of 41 end-use sectors. In order to harmonize the lifetime parameters considered for each end-use sector, metals used in similar applications or in the same end-use sectors are aggregated to the same end-use sector (Helbig et al., 2020). Normal or Weibull distributions allow taking into account the variability of lifetimes between different potential applications. Both types of distributions are often reported in the literature. Normal distributions are equally distributed around the average lifetime (mean) μ with a standard deviation σ, with all probable values being included in the interval $(-\infty, \infty)$. Weibull distributions sometimes are sometimes a better fit than normal distributions. Moreover, Weibull distributions with a location parameter $y \geq 0$ allow approximating normal distributions, albeit ensuring that all probable lifetimes are greater than zero and are therefore overall well suited for application lifetime distributions. We report normal or Weibull lifetime distributions based on the consulted literature or on estimations. In the dataset, all of the normal distributions are converted into Weibull distributions in order to ensure that all probable lifetime values are non-negative. The method to do so is presented below Table S1. When Weibull distributions are reported in the literature with only an average lifetime μ and shape k values, the location (y) value is set to 0, and the scale (λ) value is calculated from the reported μ and k. When average lifetimes are estimated from sources for which no distributions are provided, we report normal distributions with a standard deviation of +/- 10% of the estimated average lifetime, following the method used in Yale's criticality studies, e.g. Graedel et al. (2015). In some cases, larger standard deviations are estimated to take into account the diversity of potential uses included in a given sector.

Table S1 provides a brief description of each end-use sector and some examples of applications that are included when relevant. For the more generic end-use sectors presented in section 2.2.3, average lifetimes are estimated based on the most common applications that they include. As an indication, metals for which the application share represents at least 20% of its end-uses are identified. Detailed aggregations into end-use sectors for each metal are presented in Table S10-Table S70.

Table S1. End-use sectors, average lifetimes and distributions

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
Agricultural & environmental applications		1	Fixed	Dissipative uses (e.g., pesticides and fertilizers); cf. section 2.2.3.
Alloys & solders	Bi, Co, Gd, Re, Se, Si, W	11	Normal σ = 3.5	These values are suggested for nickel- and cobalt-based superalloys used in blades and vanes of aircraft and land-based gas turbines (Nassar, 2017). Shi et al. (2017) report a similar lifetime of 12 years with a standard deviation of 3 years for non-ferrous copper, lead and zinc alloys. It is also estimated to be a reasonable proxy for various solder applications, for which a lifetime of 13.4 years is estimated by other authors based on the lifetime of electronics (Nassar et al., 2012; Panousi et al., 2016).
Aviation	Hf	40	Normal σ = 12	Average lifetimes of 25 to 40 years are noted as typical (Graedel et al., 2015; Liu et al., 2013). The distribution of Liu and colleagues is reported based on Helbig et al. (2020).
Batteries (consumer electronics & lead acid)	Cd, Co, Li, Pb, Sb	4	Normal σ = 0.4	Estimated lifetimes for batteries used in various consumer electronics or household products varied from about 2.5 to 7 years (Cha et al., 2013; Harper et al., 2012; Sun et al., 2019). A similar average lifetime of 4 years is reported for lead-acid batteries (Harper et al., 2015): both are here aggregated in the same category. A deviation of +/- 10% of the mean value is reported based on Graedel et al. (2015).
Batteries (electric vehicle)	As, Li	9.5	Normal σ = 0.95	Average lifetimes ranging between 8 and 11 years are typical in literature (Bobba et al., 2019; Fu et al., 2020; Richa et al., 2014; Ziemann et al., 2018).
Batteries (utility & industrial)	-	13	Normal σ = 2.6	Lifetimes between 9 and 17 years are typically reported for various utility, industrial, and energy storage batteries (Cha et al., 2013; Harper et al., 2015; Hawkins et al., 2006; Matsuno et al., 2012). Given the diversity of potential applications, we estimate a standard deviation of +/- 20% of the mean value.
Biomedical & dental	-	15	Normal σ = 1.5	Estimated lifetimes vary in function of the applications (e.g., prosthesis, dental implants, and crowns, etc.) and across different references. Given the variety of potential applications and lifetimes, we here assume an average lifetime of 15 years.
Catalysts (heterogeneous & stable env.)	Ir, Os, Ru	12	Normal σ = 1.2	Lifetimes of 8 years up to 15 years are typically reported for several catalyst applications included in this category (e.g., Graedel et al., 2015; Nassar, 2013). This category is used as a proxy for iridium-ruthenium anodes based on their expected lifetime to avoid generating additional sectors for industrial processes.
Catalysts (homogenous	Hg, Ir	2	Normal σ = 0.6	Lifetimes ranging between 0.1 and 5 years are typically reported for such catalyst applications (e.g., Graedel et al., 2015; Nassar, 2013; Sun

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
& aggressive env.)				et al., 2019); and an average lifetime of 2 years was considered in this model based on Graedel et al. (2015). This category is used as a proxy for iridium crucibles based on their expected lifetime to avoid generating additional sectors for industrial processes.
Chemicals	-	1	Normal σ = 0.3	Values based on Graedel et al. (2015). This category generally includes chemicals used for undefined processes or applications.
Construction	Al, B, Cu, Fe, Mn, Mo, Nb, V, Zn	50	Normal σ = 15	There is a range of reported lifetimes for construction applications, which may strongly depend on the region in which construction materials are used (e.g., due to earthquakes, etc.). For example, Pauliuk et al. (2013) determine probable average lifetimes for steel used in construction, which could range from 38 to 100 years in their model depending on the world region. Here, an average global lifetime of 50 years with a standard deviation of 15 years is reported based on Helbig et al., (2020), citing Liu et al. (2013). The category also includes fiberglass used for insulation. There may be some degree of overlap between the construction and infrastructure sectors.
Cutting tools	W	1	Normal σ = 0.3	Typical lifetimes reported for carbides and cutting tools included in this category (Graedel et al., 2015; Nassar, 2017).
Electronics	Ag, Dy, Er, Ga, Ge, In, Nd, Pr, Ru, Sb, Sn, Ta, Te, Tl	10	Normal σ = 3	This sector includes consumer electronics (e.g., cellphones, televisions, sound systems, and computers) and a range of other electronic appliances or components that are expected to be used mostly for consumer electronics, such as transistors, capacitors, diodes and hard disk drives, and materials such as semiconductors (e.g., gallium), sputtering targets (e.g., tantalum) and thermal interface materials (indium). Several estimates of lifetimes are available for electronic appliances included in this category, typically ranging between, e.g., 2-4 years for mobile phones, to, e.g., 7-15 years for stereos and televisions (Du and Graedel, 2011b; Graedel et al., 2015; Nassar, 2017). Given the wide range of potential applications that were reported as electronics across the consulted studies, often without further specifications, we report a normal distribution with an average lifetime of 10 years and a standard deviation +/- 30% of the mean value. There may be some degree of overlap between this category and the Other metal products and electronics categories.
Glass & ceramics	As, Er, Ho, Se, Y, Zr	30	Weibull k = 3.5	Glass and ceramics were grouped altogether, given the similarities in their wide range of potential applications. This category also includes frits and glazes. Ceramic products include, e.g., homeware, floor and roof tiles, while ceramic components may be used in a

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
				range of electronics and automotive applications, amongst many others potential end-use sectors. Glass products or components may be used in a wide variety of applications, such as cooking surfaces, windows, and cookware, lenses and screens used in electronics, amongst many others. Some estimates range between 10 years to 75 years. Given the wide variety of end-uses that are grouped in this sector, we estimate an average lifetime of 30 years, with a Weibull distribution with a shape parameter of 3.5, aligning on the estimate of Graedel et al. (2015) for lithium used in glass and ceramics.
Glass manufacturing (process)	-	2	Normal $\sigma = 0.2$	These are average lifetimes reported for platinum-rhodium used in glass manufacturing (Hagelüken, 2003; Nassar, 2013), which is also assumed to represent the lifespan of tin used for the floating glass process (cf. Table S41). The use of cerium and lanthanum as glass polishing powders is classified in other dispersive applications rather than in this category, because the former was estimated to better represent their lifetime for that application.
Household appliances	Ni	14	Normal $\sigma = 2.8$	Household appliances include refrigerators, dishwashers, air purification, and air conditioning devices. Typical average lifetimes range between 12 and 15 years (Graedel et al., 2015; Liu et al., 2013). Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. This category may overlap to some extent with the metal goods and the electronics category, for which similar lifetimes are reported.
Infrastructure	As, Fe	40	Normal $\sigma = 8$	Includes various applications such as electrical cables, construction materials used for civil engineering, and chromated copper arsenate (CCA) treated wood. There may be some degree of overlap between the construction and infrastructure sectors, and this category may also include industrial infrastructure and pipelines in some cases. The reported values are from Helbig et al. (2020), citing Graedel et al. (2015).
Jewelry & investment	Ag, Au, Pt	30	Normal $\sigma = 6$	Average lifetime for jewelry, as reported by Helbig et al. (2020) based on Nassar et al. (2012). Investment products are also included in this category when demand for such products remained positive over a 10-year period (2010-2019), considering that such products may, in theory, replace primary production for other applications. A collection yield of 100% was applied to investment products across the dataset; cf. section 2.4.2 for details.

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
Lighting	Eu, Tb, Y	2.5	Normal σ = 0.25	The lifetime of lighting applications depends much on consumer's behavior and the specific use and the environment of each lamp (see, e.g. Qu et al., 2017). We estimate an average lifespan of 2.5 years. This value may change between the types of lightbulbs, e.g. for newly commercialized OLEDs; however, the metals reported to be used in lamps in this dataset were mostly used for light-emitting diode (LED) and fluorescent lamps.
Magnets (large)	Gd	20	Normal σ = 2	Includes neodymium permanent magnets used for e.g., wind turbines, gadolinium magnets used for e.g., magnetic cooling, and holmium magnets used for e.g., magnetic flux concentrators. An average lifetime of 20 years is reported based on the lifetime of wind turbines (Du and Graedel, 2011b). Samarium-cobalt magnets are not aggregated in this category as their uses are estimated to be rather well represented by the Other industrial, military & energy applications.
Magnets (small)	Sr	8	Normal σ = 1.6	Includes ferrite magnets and other small or undefined magnets, potentially used in a variety of applications. These are assumed to have an average lifetime of 8 years. Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value.
Mechanical equipment	Cr, Mo, Ni, V	35	Normal σ = 10.5	Typical lifetimes of 25-40 years are reported for such applications (Graedel et al., 2015; Liu et al., 2013; Pauliuk et al., 2013). These lifetimes are provided with standard deviations ranging from 2.5 years to 12 years. Given the diversity of potential applications and the diversity of estimated lifetimes and distributions, we estimate an average lifetime of 35 years, with a standard deviation of +/- 30% of the mean value.
Metallurgy & metalworking (process)	Mn	1	Fixed	Dissipative use of metallurgical additives or other metallurgical processes where metals do not remain in the final product. See section 2.2.3 for details.
Other electrical & metal products	-	15	Normal σ = 3	Values of 15 years are typically reported for metal products, and 10-20 years for other electrical appliances (Liu et al., 2013; Meylan and Reck, 2017; Pauliuk et al., 2013). An average value of 15 years is reported for this category. Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. There may be some degree of overlap between this category and the electronics and household appliances category.
Other industrial, military & energy applications	Be, Ge, Ho, Sm, Ta, Tm, Yb	20	Normal σ = 6	Lifetime and distribution are based on the values for other titanium uses (Graedel et al., 2015) and other aluminum uses (Liu et al., 2013). See section 2.2.3 for details.

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
Other miscellaneous	-	5	Normal σ = 0.5	Lifetime and distribution based on Graedel et al. (2015) and Panousi et al. (2016). See section 2.2.3 for details.
Other punctual applications	Ce, Hg, La, Lu, Os, Sr, Tm, Yb	1	Fixed	Dissipative uses; Cf. section 2.2.3 for details.
Packaging	Al	1	Normal σ = 0.3	Packaging applications included in this category are expected to be mostly single uses. A lifetime of 1 year is reported based on Graedel et al. (2015).
Paint	Ti	20	Weibull k = 3.5	Values from Graedel et al. (2015)
Paper	-	5	Weibull k = 3.5	Paper whitening agents and printing inks (titanium) are classified in this category. The lifetime and distribution are from Graedel et al. (2015).
Pharmaceutics & cosmetics	-	1	Fixed	Dissipative uses; Cf. section 2.2.3 for details.
Photography	-	30	Normal σ = 6	Silver is used for photography, and a useful lifetime of 30 years is estimated by Nassar et al. (2012).
Plastics	Ti	11.5	Normal σ = 2.3	Multiple metallic compounds are added to plastic components and products, often PVCs, in the form of, e.g., pigments or chemicals as vulcanizing agents, stabilizers, and flame retardants. These may be used in a variety of applications, and an average lifetime of 11.5 years is estimated based on average lifetimes of 8-15 years reported in the literature for titanium pigments (Graedel et al., 2015) and cadmium stabilizers (Cha et al., 2013). Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value.
Protective coatings	-	9	Normal σ = 1.8	Includes galvanizing, plating and other coatings. In the dataset, the use of protective coatings is often attributed to actual end-use sectors, e.g. for zinc-galvanized steel parts used in the construction and transport sectors. The reported lifetime of 9 years is estimated to be representative of the values for metals included in this end-use sector. These include cadmium, with an estimated lifetime of 7 years (Hawkins et al., 2006), zinc galvanization, with an estimated lifetime of 10 years for its use in industrial and metal working machinery (Meylan and Reck, 2017). In comparison, the estimated average lifetime of 17 years for zinc galvanizing reported by Harper et al. (2015) also includes the use of galvanized steel in the transport and construction sectors, with longer expected lifetimes than those included in this end-use sector. Given the diversity of potential applications, we estimate a standard deviation of +/- 20% of the mean value.
Refractories	Mg	1	Normal σ = 0.1	Horckmans et al. (2019) reported a lifetime of MgO bricks in the order of weeks, while the EC reported a lifetime from weeks to several years

End-use sector	≥20% end-use	Average lifetime (years)	Distribution type & parameter	Description
				for refractory materials based on their quality (European Commission, 2020c). The reported values are from Graedel et al. (2015).
Rubber	-	7	Normal σ = 1.4	Includes vehicle tires, and undefined rubber components (e.g., for vulcanizing agents). An average lifetime of 7 years is reported with a deviation of +/- 20%, considering that average lifetimes range between 4 and 10 years (Ciacci et al., 2015)
Solar cells	Te	30	Normal σ = 9	Helbig et al. (2020), citing Marwede and Reller (2012)
Solid oxide fuel cells	Sc	7	Normal σ = 0.7	Estimate based on Cooper and Brandon (2017)
Telecommunication	-	30	Normal σ = 6	Helbig et al. (2020), citing Glöser et al. (2013)
Transport	Be, Bi, Dy, Nb, Pd, Pt, Rh, V, Zn	20	Normal σ = 6	Transport applications mostly include road vehicles, but may also include boats, trains and railways in some cases. The reported values are the same used by Helbig et al. (2020), based on the value reported for auto and light trucks in Liu et al. (2013), and also considered as the average value for the transport category in the baseline scenario for steel products in the model of Pauliuk et al. (2013). Includes auto catalysts.
Well drilling	Ba, Sr	1	Fixed	Dissipative use of barium (barytes) and strontium (celestine).

As noted above, Weibull distributions are automatically derived from normal distributions when these are reported in the dataset. Three variables (location y, scale λ, and shape parameter k) must be defined to obtain a Weibull distribution that matches the mean, the mode, and the variance of the normal distribution. By iteratively updating the estimated shape parameter and recalculating the three parameters λ, k, and y, we approximate the Weibull distribution with the same mean, mode, and variance as the original normal distribution defined by parameters μ and σ. The Weibull distribution strings with defined parameters λ, k, and y are provided in the Supplementary Data.

A system of three equations is resolved by estimating the values of the Gamma function.

1) Mean: $\mu = \lambda\Gamma\left(1+\frac{1}{k}\right)+y$
2) Mode: $\mu = \lambda\left(\frac{k-1}{k}\right)^{\frac{1}{k}}+y$
3) Variance: $\sigma^2 = \lambda^2\left(\Gamma\left(1+\frac{2}{k}\right)-\left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right)$

As noted above, Weibull distributions reported in the literature did not include location y and scale λ parameters. We assume that, in these cases, location (y) is equal to zero, and the scale is calculated as:

4) $\lambda = \frac{\mu}{\Gamma(1+1/k)}$

2.4 Additional methods for three groups of metals

Three groups of metals necessitated specific methods to either fill large data gaps or harmonize data. These methods are defined below.

2.4.1 Methods for the eitheen metals considered in the “Quantitative assessment of dissipative losses of 18 metals” article of Helbig et al. (2020)

These eighteen metals are aluminum (Table S14), chromium (Table S19), iron (Table S21), cobalt (Table S22), nickel (Table S23), copper (Table S24), zinc (Table S25), gallium (Table S26), germanium (Table S27), selenium (Table S29), silver (Table S38), indium (Table S40), tin (Table S41), tellurium (Table S43), tantalum (Table S60), tungsten (Table S61), rhenium (Table S62), and lead (Table S69).

In order to harmonize the methodologies for all metals in the present study, some changes were made to the parameters used by Helbig et al. (2020). In this dataset, collection rates and dissipation rates are application-specific in addition to being metal-specific. Therefore, additional data were collected or calculated to fill these data with updated collection and recycling rates, which are reported for each of the 18 metals in their respective tables included in section 3 of this Supplementary Information.

Moreover, Helbig et al. (2020) considered inherently dissipative uses (including some dissipation in use of type C) to be dissipated initially during the fabrication and manufacturing step, i.e., before they underwent the use phase. Instead, in the present work, such uses are modeled to be either dissipated over their lifetime (e.g., agricultural products are modeled to be dissipated over one year), either to be dissipated during the collection step for those that are currently unrecyclable as a consequence of the way they are incorporated in products, i.e., “lost by design” (Ciacci et al., 2015). Because of these methodological changes, updated product distribution, and the updated values to sector-specific collection yields, it is possible to observe some variations in the results between both studies.

2.4.2 Methods for the Platinum group metals and investment products

Most process yields are calculated based on the works of Nassar (2013). End-use distributions are obtained from Johnson Matthey’s market reports for PGMs covering the past ten years (Johnson Matthey, 2020a, 2020b, 2015), with the exception of iridium, for which more disaggregated data was available (BRGM, 2020a, based on SFA Oxford, 2020).

For each PGM, the most recent reported distribution is used to calculate the end-use distribution (2019), with the exception of financial (investment) products. The end-use demand for investment products is averaged over ten years in order to smoothen out the effects of the economic cycles on demand for such products. For the years 2010 to 2013, the Johnson Matthey’s report from 2015 is considered (Johnson Matthey, 2015), and for the years 2014 to 2019, the reports from 2020 are considered (Johnson Matthey, 2020a, 2020b). The end-use for other sectors is corrected accordingly to still reflect the most recent demand scheme. This is done by estimating the average percentage of demand for investment products over ten years and balancing the remaining uses for the most recent year accordingly. For example, if financial products represent an average of 20% of an metal’s demand over ten years, the remaining end-uses are determined for a total of 100% (excluding financial uses) and scaled down to 80% of total demand. The same method is applied for other precious metals used in investment products, i.e. silver and gold.

Moreover, in order to harmonize data for high economic value and relatively scarce metals such as PGMs and gold, the production yields were calculated using a similar approach as for gold (cf. Table S66). Nassar (2013) provide generic process yields for concentration, smelting, and refining of PGMs based on a literature review, and the reported values are used for this dataset. The average extraction yield is estimated to be 85% for all PGMs, like gold. Post-mining recovery yields for the other production processes are calculated with the data reported by Nassar (2013) for the different PGMs. While the author applied specific recovery percentages for different mines in some cases, only average values are considered in this dataset. The calculated production yields are generally consistent with values reported in the technical report for the Waterberg Project, which is part of the Bushveld Complex in South Africa (Stantec, 2019). Since the Bushveld Complex holds the largest PGM reserves and produces most of the world's PGMs (Labbé and Dupuy, 2014; USGS, 2020), the reported production yields are estimated to be reasonably accurate.

For other processes, as well as dissipation in use, the yields are also obtained or calculated from the values reported by Nassar (2013) and complemented with additional literature referenced for each PGM, presented in their respective tables: ruthenium, Table S35; rhodium, Table S36; palladium, Table S37; osmium, Table S63; iridium, Table S64; and platinum, Table S65.

2.4.3 Methods for the Rare Earth Elements

There are 15 REEs, in addition to which scandium and yttrium are sometimes classified. REEs are often grouped as either light rare earth elements (LREE) or heavy rare earth elements (HREE). We include yttrium as part of this joint REE methodology, and scandium is considered separately. Promethium is not included in this dataset because it is radioactive and extremely rare. LREEs consist of cerium (Ce), lanthanum (La), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd) and scandium (Sc). HREEs consist of terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), lutetium (Lu), ytterbium (Yb), thulium (Tm), and yttrium (Y).

Du and Graedel (2011a) traced the global anthropogenic cycles for 10 out of 15 REEs in 2007: lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, and yttrium. Based on this work, the yields of production, fabrication and manufacturing, new scrap recovery, collection, and recycling can be calculated. However, the MFAs rely on estimates for the yield of production, and the REE sector has kept developing rapidly in the past decade. Therefore, it is attempted to gather some additional information in order to complement or update the data provided in the study of Du and Graedel (2011a).

Notably, the production yield is recalculated using the methodology of Nassar et al. (2015), considering region- or site-specific compositions of REE ores and estimated processing yields for each of them. This method is detailed in section 2.4.3.1. Concerning end-use distributions, various studies report disaggregated end-use distributions for each REE separately. These are available for the years 1995-2007 (Du and Graedel, 2013), 2008 (Goonan, 2011a; Nassar et al., 2015), 2010 (Lynas Corporation Ltd., 2010; Peiró et al., 2013) and 2012 (European Commission, 2014). The European Commission (2020a) also reports global aggregated end-use statistics for all REEs for the years 2017 and 2019 and specific end-uses for, e.g., Nd-Fe-B permanent magnets in 2019. The European Commission also describes the different end-uses for all REEs qualitatively and provides quantified end-use applications in Europe in recent years based on European statistics (Eurostat) and Guyonnet et al. (2015). The demand trends for each end-use are also discussed in many of these references.

Finally, Ciacci et al. (2015) provides valuable information on the dissipation in use and the current recyclability of various REE applications. Generally, it is thought that only negligible amounts of REEs are functionally recycled (Graedel et al., 2011; Nassar et al., 2015). However, criticality studies reveal the overall reliance on China for most of the primary production of REEs, which may increasingly drive research for innovative recycling processes to recover secondary REEs. For instance, the BRGM (2016a) suggested that between 10-20% of the supply of dysprosium could result from the recycling of permanent magnets by 2020, based on the projected operation of a pilot plant in 2016. The European criticality study of 2020 also reports significant EoL-Recycling input rates (EOL-RIR) for praseodymium (10%), europium (38%), terbium (6%), and yttrium (31%) (European Commission, 2020a). Therefore, additional efforts were spent on estimating the current EoL-RRs for REEs in their different application, as presented in section 2.4.3.5.

2.4.3.1 Production yields

Du and Graedel (2011a) proposed global MFAs for 10 REEs in the year 2007, using a top-down approach. The study suggests typical losses of 20% to tailings during concentration and 10% to slag during hydrometallurgy, resulting in a production yield of about 72% for all REEs. A literature survey is undertaken in order to estimate REE-specific production yields.

REEs are mostly produced from bastnaesite, monazite, xenotime, loparite, allanite, and eudialyte ores (Davris et al., 2017). Most production occurs from bastnaesite in carbonatite-rich deposits of Bayan Obo, China, and Mountain Pass, USA, as well as from the Mount Weld mines in Western Australia (Davris et al., 2017; European Commission, 2020a; USGS, 2020). China produced over 60% of the global REEs in 2019, most of which originated from the Bayan Obo mine (USGS, 2020). The distribution of REEs in the ores differs between deposits, resulting in supply capacity, which may not align with demand. For instance, lanthanum and cerium are currently oversupplied in order to produce enough of the rarer REEs for, e.g., permanent magnets (Alves Dias et al., 2020).

Several estimates of production yields for various deposits are available in the literature. Nassar et al. (2015) mention overall recovery rates (combined yield for extraction, beneficiation, and separation) of 40-60% for bastnaesite deposits in Bayan Obo, 50% for bastnaesite deposits in Sichuan, and 75% for ion-adsorption clay deposits in Southern China, citing (Cheng and Che., 2010). Chen et al. (2017) report recovery efficiencies to concentrates as low as 10% for Bayan Obo in 2011, while recovery rates of rare earth oxides (REO) of 75% and 72.5% are reported for Sichuan and ion-absorbed deposits, respectively. Similarly, Huang et al. (2015) mention potential recovery rates of over 75% for ion-adsorbed using the in-situ leaching method. The Chinese 13th Five-Year Plan established production targets of 75% recovery from the processing of light rare earth ores and ion type rare earth ores, and smelting separation recovery rates of 90% for light rare earth ores and 94% for ion type rare earth ores in 2015 (European Commission, 2020a, table 144). For 2020, the Chinese objectives increased to 80% recovery from the processing of light rare earth ores, 85% for ion type rare earth ores, and aim for smelting recovery rates of 92% and 96% for light rare earth ores and ion type rare earth ores, respectively. These targets and other estimates suggest that the actual recovery of REEs from the Bayan Obo ores should be higher than the 10% reported for lanthanum in 2011 as reported by Chen et al. (2017), and this data was disregarded for this dataset.

In addition to this literature, some technical reports are available. The technical report for preliminary test work realized in the La Paz project in Arizona (World Industrial Minerals, 2020) suggests a combined recovery of at least 50% REEs for the concentration and hydrometallurgy processes. Roche Engineering (2014) prospected an average recovery yield of 79% for the Bull Hill Mine (Wyoming) over its projected lifetime. The project relies on REE-bearing carbonatite with particularly high REE content (some may undergo hydrometallurgy without prior concentration). SRK Consulting (2010) proposed an Alternative Technical Economic Model for the Mountain Pass Re-Start Project. They estimated an average concentration rate of 65% based on historical production at the Mountain Pass mining site. Moreover, the recovery of 99.8 lb out of 109.9 lb during the extraction/separation processes suggests a projected smelting yield of about 91% (cf. Figure 6.1 of the cited report).

In the Feasibility study for the Nechalacho Rare Earth Elements Project lead by Avalon Rare Metals (Micon International Limited, 2013), it is mentioned that the project relies on similar technologies that are used in China to produce REEs with solvent extraction. The process description for the Nechalacho project is indeed similar to that used to extract REEs from the bastnaesite deposits in the Bayan Obo mine in China (Cf. Davris et al., 2017; Xie et al., 2014). First, a concentrator produces a floatation concentrate from ores through crushing, grinding, flotation and filtration. Then, a hydrometallurgical plant separates the concentrate into a mixed RE precipitate and an enriched zirconium concentrate (EZC). The precipitate is sent to the refinery to produce pure REOs. The EZC may be sold to third parties for further processing. It is said that the client for EZC would likely be located in China. In this feasibility study, the recovery rates for the concentrator pilot plant are estimated to represent recovery yields once operating under optimal conditions (Micon International Limited, 2013). It is noted that the on-site hydrometallurgical recovery of LREEs from LREE-rich ores may be easier than for HREEs, as the latter require the caustic cracking of zircon to improve their leaching to the precipitate. Based on the values provided in table 14.4 of the report (pages 148-149), the calculated on-site production yields ranged between 20% and 47% for HREEs, while that of LREEs ranged between 51% and 70%, suggesting that there may be substantial differences between the recovery rates for different REEs within the same mining site. When considering the potential further recovery of REEs from the EZC as described above, and assuming that two-thirds of the REE content of EZC will be recovered by the third-party company purchasing the EZC, the following post-mining recovery yields for 15 REEs are calculated: cerium, 75%; lanthanum, 75%; praseodymium, 74%; neodymium, 75%; promethium, 74%; samarium, 73%; europium, 72%; gadolinium, 72%; terbium, 72%; dysprosium, 72%; holmium, 72%; erbium, 71%; lutetium, 68%: ytterbium, 69%; thulium, 70%; and yttrium, 71%.

Moreover, recovery yields for each REE may vary based on the distribution of the different REEs in various deposits as they have different mineralogy settings and different concentrations of various REEs (European Commission, 2020a; Nassar et al., 2015). For instance, Huang et al. (2015) mention that heavier rare earths are more than ten times richer in ion-adsorbed deposits than in ores such as bastnaesite and monazite. Therefore, more HREEs may originate from ion-adsorbed deposits in comparison to other ores. Nassar et al., (2015) estimate that Southern provinces produced about 29% of the Chinese REE production in 2008 (30 000 tons out of 104 000 tons of REEs), while their production accounted for 91% of the country's total HREE production, with approximately 13 000 tons out of 14 300, and for 19% of the country's total LREE production.

The currently installed production capacity remains mostly in China (Binnemans et al., 2018; Nassar et al., 2015). The Chinese REE industry has been actively aiming to increase its efficiency in the past decade (Shen et al., 2020). Meanwhile, in recent years, an increasing share of REE production has also been occurring outside of China, particularly in Mountain Pass (Molycorp operations in California) and Lynas Corporation in Mount Weld (extraction and concentration in Australia, refining in Malaysia). Important artisanal mining activities also take place in Myanmar, whose concentrates are sent to China for refining (European Commission, 2020a; USGS, 2020).

From this literature survey, it can be expected that the concentration yields are lower, and the smelting yields are similar to the estimated of Du and Graedel (2011a). Because it is not possible to extract single REEs from a mine (Binnemans et al., 2018), the ore composition at different mining sites can provide a reasonable assessment of how many REEs are currently extracted and produced. Element-specific production yields for REEs are thus computed using the methodology of Nassar et al. (2015). It is not possible to improve the method due to the lack of data regarding concentration and smelting yields for specific REEs for the current mining operations. The data required to determine the production yields are the process yields for each main mining site as well the REE-distribution in the REE-ores of each site.

Regarding the composition of REE ores, Nassar et al. (2015) provide the REO distribution for various Chinese mining sites as well as for Mountain Pass (US), India, Perak (Malaysia), Eastern coast (Brazil), and the Lovozero complex (Russia) based on various literature. The composition of Mount Weld ores is estimated based on the composition of the central lanthanide deposit (Jaireth et al., 2014), which is currently exploited by the Lynas Corporation (Lynas Corporation Ltd., 2010). The BRGM provides distributions for similar mining sites or regions as Nassar et al. (2015), based on Roskill Services (cf. table 14 in Bru et al., 2015). Although the values are very similar amongst the provided literature, some minor differences could be found. In the case of conflictual values, the data reported in the BRGM study are considered. Distributions are normalized to 100% when the total REO content is not equal to 100%. Given the dynamics of (often illegal and undocumented) artisanal mining operations in the Jiangxi province, and because of the lack of data on the current production, it is not possible to replicate the distribution of production shares in that province as done by Nassar et al. (2015). Therefore, the average REO distribution across the Jiangxi province is applied to all of its REO production. Moreover, while Myanmar's artisanal operations provided a significant share of the recent years' supply of REEs, no information could be found on their specific REE ores or production. Still, Adamas Intelligence (2019) reported that about 32% of the global dysprosium and terbium production, and that 13% of neodymium and praseodymium global production may have originated from Myanmar in 2018. The USGS also noted that Burma (Myanmar) produced most of the world's yttrium in 2019 along with China, from similar clay deposits as in southern China (USGS, 2020). Without further information, the average distribution of REOs in all of the clay deposits of southern China are applied to the total REO production of Myanmar as a first estimate. The average ore content across the studied deposits are presented in Table S2.

Table S2. Average ore content in REOs in different mining sites or regions (based on Bru et al., 2015 and Nassar et al., 2015). Distributions are normalized to 100% total REO content.

	China								**Brazil**	**India**	**Russia**	**United States**	**Australia**	**Myanmar**
REO	Bayan Obo	Mianning Sichuan	Weishan Shandong	Jiangxi (average)	Shanghang Fujian	Pingyuan Guang-dong	Jianghua Hunan	Guangxi	Eastern coast	monazite deposits	Lozovero complex	Mountain pass	Mount Weld	N/A*
Y_2O_3	0.50%	0.50%	0.76%	26.61%	25.93%	20.00%	47.29%	28.99%	1.40%	0.45%	0.00%	0.10%	0.00%	26.7%
La_2O_3	22.98%	29.26%	35.30%	21.54%	27.63%	30.40%	15.99%	24.06%	23.97%	22.56%	27.99%	33.25%	25.57%	22.5%
CeO_2	49.95%	50.40%	47.55%	11.48%	2.04%	1.90%	0.32%	0.60%	46.94%	48.63%	57.48%	49.17%	46.88%	9.7%
Pr_6O_{11}	6.19%	4.61%	3.93%	4.74%	5.85%	6.60%	4.39%	5.56%	4.49%	5.61%	3.80%	4.31%	5.34%	4.9%
Nd_2O_3	18.48%	13.03%	10.85%	17.12%	20.04%	24.40%	10.33%	19.80%	18.48%	18.55%	8.80%	12.02%	18.55%	17.7%
Sm_2O_3	0.80%	1.50%	0.79%	3.44%	4.24%	5.20%	2.42%	4.38%	3.00%	2.71%	1.00%	0.80%	2.28%	3.6%
Eu_2O_3	0.20%	0.20%	0.13%	0.44%	0.88%	0.70%	0.10%	0.72%	0.10%	0.02%	0.13%	0.10%	0.44%	0.5%
Gd_2O_3	0.70%	0.50%	0.53%	4.20%	4.28%	4.80%	3.95%	4.35%	1.00%	1.20%	0.20%	0.20%	0.75%	4.2%
Tb_4O_7	0.10%	0.00%	0.14%	0.80%	0.75%	0.60%	0.97%	0.62%	0.10%	0.06%	0.07%	0.02%	0.07%	0.8%
Dy_2O_3	0.10%	0.00%	0.00%	4.20%	3.81%	3.60%	6.23%	4.06%	0.40%	0.18%	0.09%	0.03%	0.12%	4.2%
Ho_2O_3	0.00%	0.00%	0.00%	0.91%	0.42%	0.00%	1.20%	0.77%	0.00%	0.02%	0.03%	0.00%	0.00%	0.8%
Er_2O_3	0.00%	0.00%	0.00%	2.61%	2.35%	1.80%	3.51%	2.59%	0.10%	0.01%	0.07%	0.00%	0.00%	2.6%
Tm_2O_3	0.00%	0.00%	0.00%	0.38%	0.39%	0.00%	0.56%	0.39%	0.00%	0.00%	0.00%	0.00%	0.00%	0.4%
Yb_2O_3	0.00%	0.00%	0.03%	1.32%	1.01%	0.00%	2.37%	2.66%	0.02%	0.00%	0.30%	0.00%	0.00%	1.3%
Lu_2O_3	0.00%	0.00%	0.00%	0.20%	0.37%	0.00%	0.38%	0.45%	0.00%	0.00%	0.05%	0.00%	0.00%	0.2%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

*The distribution of REOs in Myanmar are assumed to be represented by the average composition of clay-deposits in China due to lack of information

The share of production of REEs from the different mines is estimated using USGS statistics for the year 2019 (USGS, 2020) and the share of global production per country or Chinese province in 2019 as reported by Roskill Services statistics, reported in the Figure 337 of the European Commission (2020a). The small share of the production occurring in Vietnam, Thailand, Burundi, and other countries is disregarded from the study. The covered production represents nearly 99% of the total production in 2019 and is assumed to be representative of the global production yield for the year 2019. The estimated production for each region or mine are calculated as shown in Table S3.

Table S3. Estimated REO production per mine or region in 2019 (tons) based on annual production data and region-specific average REO content of the ores reported by the European Commission (2020a)

Country	**China**								**Brazil**	**India**	**Russia**	**Unites States**	**Australia**	**Myanmar**	**Other**	**Total prod. (ton REO)**
Mine / region	Bayan Obo	Mianning Sichuan	Weishan Shan-dong	Jiangxi	Shang-hang Fujian	Ping-yuan Guang-dong	Jiang-hua Hunan	Guangxi	East-ern coast	Monazite deposits	Lozovero complex	Mountain pass	Mount Weld	N/A*	Not covered	
production of REOs (tons)	80220	9450	3990	31446	2442	2772	1050	630	1000	3000	2700	26000	21000	22000	2300	
% of total production	38%	5%	2%	15%	1.2%	1.3%	0.5%	0.3%	0.5%	1.4%	1.3%	12.4%	10.0%	10.5%	1.1%	
Y_2O_3	401	86	30	8674	633	302	497	183	14	14	34	0	0	5904	N/A	16770
La_2O_3	18432	2975	1409	6610	675	798	168	152	240	674	672	7703	5413	4821	N/A	50742
CeO_2	40070	4506	1897	3912	50	144	3	4	469	1409	1358	14197	9914	2360	N/A	80293
Pr_6O_{11}	4969	388	157	1393	143	205	46	35	45	168	134	1019	1129	1045	N/A	10877
Nd_2O_3	14826	1224	433	5121	489	866	108	125	185	613	403	2844	3927	3850	N/A	35015
Sm_2O_3	641	139	31	1181	103	158	25	28	30	77	17	237	482	858	N/A	4008
Eu_2O_3	160	25	5	175	21	17	1	5	1	0	2	0	94	126	N/A	633
Gd_2O_3	561	62	21	1436	104	114	41	27	10	37	15	0	0	989	N/A	3418
Tb_4O_7	80	8	6	209	18	21	10	4	1	2	0	0	14	150	N/A	522
Dy_2O_3	80	21	0	1178	93	76	65	26	4	6	15	0	26	825	N/A	2414
Ho_2O_3	0	4	0	235	10	15	13	5	0	1	19	0	0	160	N/A	461
Er_2O_3	0	6	0	682	57	27	37	16	1	0	22	0	0	470	N/A	1317
Tm_2O_3	0	2	0	94	10	4	6	2	0	0	3	0	0	66	N/A	187
Yb_2O_3	0	5	1	476	25	21	25	17	0	0	5	0	0	323	N/A	898
Lu_2O_3	0	0	0	71	9	4	4	3	0	0	0	0	0	52	N/A	143

*The distribution of REOs in Myanmar are assumed to be represented by the average composition of clay-deposits in China due to lack of information

The best possible estimates based on the consulted literature are used to establish process yields. We estimate pre-concentration losses of 5% (assuming imperfect in-situ leaching of ion-adsorbed REEs and generic mining losses during open pit mining), and concentration yields of 65% for the Bayan Obo mine, 75% for the Sichuan/Shandong provinces, 80% for all of the ion-adsorbed deposits in southern China, 70% for the Mountain Pass mine and the Mount Weld mines, 75% for the deposits of Myanmar, and 65% for all other mines. A uniform smelting yield of 90% is considered for all REEs, as estimated by Du and Graedel (2011a). Considering these yields and the average share of each REOs in mined ores, it is possible to estimate REO-specific production yields. These are shown in Table S4.

Table S4. Estimated production tonnage, production yield, and total extraction tonnage for 15 REOs in 2019

REO	Estimated total production in 2019 (excluding Vietnam, Thailand, Burundi & other countries) (tons)	Estimated production yield	Estimated total extraction in 2019 (tons)
Y_2O_3	16641	66%	25059
La_2O_3	51846	60%	86397
CeO_2	78693	58%	135325
Pr_6O_{11}	11103	60%	18646
Nd_2O_3	35165	60%	58751
Sm_2O_3	3817	63%	6081
Eu_2O_3	599	62%	969
Gd_2O_3	3452	64%	5395
Tb_4O_7	586	65%	906
Dy_2O_3	2651	66%	4003
Ho_2O_3	496	67%	744
Er_2O_3	1545	67%	2315
Tm_2O_3	217	67%	325
Yb_2O_3	767	67%	1151
Lu_2O_3	123	67%	185

The average production yield is approximately 60% across the REOs, which is about 12% lower than that calculated with the generic yields utilized in the MFAs of Du and Graedel (2011a). Part of this difference is explicable by the consideration of 5% pre-concentration losses, while the remainder of the difference is due to lower estimated recovery yields from the concentration process of different mining sites in comparison to the estimates of Du and Graedel (2011a). In general, HREEs are observed to have higher production yields than LREEs since they are mostly recovered from the ion adsorbed clay deposits, for which the recovery is estimated to be higher than that from other ores. A notable limitation of the estimated production yields is that average concentration and smelting yields are applied equally to all REEs occurring in a given mining site or region, since no element-specific concentration yields for different REEs could be determined for current mining and smelting operations. It is likely that these yields do vary to some extent amongst REEs during concentration and separation processes, as previously discussed.

2.4.3.2 End-use distribution

Detailed end-use distributions for ten out of fifteen rare earths (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Y) are available in the literature. The most recent available data from various sources are considered to establish end-use distributions (European Commission, 2014; Goonan, 2011a; Peiró et al., 2013). The data from Peiró et al. (2013) are reportedly based on Lynas Corporation Ltd. (2010) and Goonan (2011a). The values reported by Peiró et al. (2013) are more disaggregated than the 2008 distribution of Goonan (2011a). The latter has also been taken up in the Yale studies (Ciacci et al., 2015; Graedel et al., 2013; Nassar et al., 2015). Peiró et al. (2013) disaggregated the use of REEs in phosphors based on the distribution of red, green, and blue phosphors in applications making use of them (liquid crystal displays [LCD]s, plasma panels, and lighting applications). The values in these various references suggest similar distributions of end-uses for REEs between the years 2008 and 2010. The three tables below show the end-use distributions based on Goonan (2011a), Peiró et al. (2013) and European Commission (2014).

Table S5. End-use applications of REOs in 2008 (based on Goonan, 2011a)

End use	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3
Auto- catalytic converters	1%	16%	2%	1%	0%	0%	0%	0%	0%	0%
Ceramics	3%	2%	5%	4%	0%	0%	0%	0%	0%	32%
FCC	46%	5%	0%	0%	0%	0%	0%	0%	0%	0%
Glass additives	7%	19%	1%	2%	0%	0%	0%	0%	0%	2%
Metallurgy except batteries	8%	14%	7%	8%	0%	0%	0%	0%	0%	0%
Nd magnets	0%	0%	70%	76%	0%	0%	69%	11%	100%	0%
Battery alloys	16%	10%	5%	5%	73%	100%	0%	0%	0%	0%
Phosphors	2%	2%	0%	0%	0%	0%	21%	89%	0%	54%
Glass polishing	13%	25%	7%	0%	0%	0%	0%	0%	0%	0%
Other	4%	7%	3%	5%	27%	0%	10%	0%	0%	12%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table S6. End-use applications of REEs in 2010 (calculated based on Peiró et al., 2013)

End-use	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y
LCD display	0%	0%	0%	0%	0%	13%	3%	17%	0%	5%
Plasma panel	0%	0%	0%	0%	0%	5%	1%	5%	0%	2%
Lighting	2%	2%	0%	0%	0%	83%	18%	67%	0%	47%
Internal combustion vehicles	1%	17%	2%	1%	0%	0%	0%	0%	0%	0%
FCC	44%	4%		0%	0%	0%	0%	0%	0%	0%
Electric vehicle (battery)	12%	7%	5%	6%	48%	0%	0%	0%	0%	0%
Electrical & electronic devices (battery)	7%	4%	0%	0%	27%	0%	0%	0%	0%	0%
Electrical & electronic devices (magnets)	0%	0%	53%	58%	0%	0%	0%	0%	69%	0%
Electric vehicles (magnets / engine)	0%	0%	13%	13%	0%	0%	0%	8%	22%	0%
Wind Turbines	0%	0%	4%	4%	0%	0%	0%	2%	6%	0%
Magnetic resonance imaging (MRI)	0%	0%	2%	2%	0%	0%	13%	1%	3%	0%
Magnetic cooling	0%	0%	0%	0%	0%	0%	56%	0%	0%	0%
Alloys	6%	11%	6%	6%	0%	0%	0%	0%	0%	0%
Glass products	8%	20%	1%	2%	0%	0%	0%	0%	0%	2%
Ceramic industry (additives)	3%	2%	5%	4%	0%	0%	0%	0%	0%	32%
Glass industry (abrasives)	13%	24%	6%	0%	0%	0%	0%	0%	0%	0%
Others	4%	7%	3%	5%	25%	0%	10%	0%	0%	12%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table S7. End-use applications of REEs in 2012 (based on European Commission, 2014)

End-use	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Er	Ho, Tm, Yb, Lu
Magnets	0%	0%	73%	89%	97%	0%	35%	24%	98%	0%	0%	0%
batteries	26%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
other metallurgy	10%	19%	4%	2%	0%	0%	28%	0%	0%	0%	0%	0%
Fluid cracking catalyst	44%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
auto catalyst (transport)	1%	13%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%
Other catalyst	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
polishing	1%	36%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
glass	5%	12%	0%	1%	0%	0%	0%	0%	0%	0%	72%	0%
phosphors	1%	4%	12%	1%	0%	96%	23%	71%	0%	79%	25%	0%
ceramics	1%	1%	7%	4%	0%	0%	0%	0%	0%	21%	0%	0%
Other	9%	8%	2%	0%	3%	4%	14%	5%	2%	0%	3%	100%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Values in Table S6 are based on those of Table S5; yet, they are more disaggregated given the additional data considered by the authors (Peiró et al., 2013). Some variation between end-uses in 2008 (Table S6) and 2012 (Table S7) can be observed. Especially, the end-use sectors reported by the European Commission (2014) diverged from that of Peiró et al. (2013) for praseodymium, neodymium, and samarium. While the European Commission reports that samarium is used mostly in magnets (cobalt-samarium), the previous studies suggested that the principal uses were in battery alloys. Moreover, the replacement of NiMH batteries with lithium-ion batteries also reduced the demand for mischmetal, typically composed of lanthanum, cerium, praseodymium, and neodymium. However, the distributions for 2012 (Table S7) show that no praseodymium and neodymium is used in NiMH batteries, contradicting the values reported for lanthanum and cerium (as the four elements constitute mischmetal). Therefore, additional steps are undertaken to calculate end-uses for these two REEs.

In order to estimate flows of praseodymium and neodymium used in NiMH batteries, we consider a typical NiMH battery composition. This composition is estimated based on the results of the ProSUM project as published on the Urban Mine Platform's web page (Huisman et al., 2017). It is estimated that mischmetal is composed of approximately 85% lanthanum, 10% cerium, 2% praseodymium, and 3% neodymium. The values suggest a lanthanum-to-cerium ratio of 89:11, slightly different than the 87:13 ratio suggested with the values reported by the European Commission (2014). It is therefore expected to be fairly representative of the generic composition of mischmetal used in batteries. Based on this information, we estimate that a total of 200 tons of praseodymium and 300 tons of neodymium were used as mischmetal in NiMH batteries in 2012. Since these values are substantially higher than those reported as "other" uses for praseodymium and neodymium in the European criticality report (110 and 75 tons, respectively), these values are treated as phantom flows and are added to the reported consumption of praseodymium and neodymium to calculate their end-use distributions in 2012.

In order to establish the final distribution for 2012, the values reported by the European Commission (2014) are disaggregated into more specific sectors when possible, using data of Peiró et al. (2013). The end-use distributions reported in batteries are disaggregated between electric vehicles batteries and electronic devices. Phosphors are disaggregated by color (green, blue, and red) and attributed to LCDs, plasma panels, and lighting applications based on their typical shares between each of these applications. Magnets are split between MRI, magnetic cooling, electrical & electronic devices, and electric vehicles (engine). Since Peiró et al. (2013) did not report the use of praseodymium and neodymium in NiMH batteries used in electronic devices, their shares are disaggregated between end-use sectors using the same ratio observed for cerium and lanthanum: 64% of batteries used in vehicles, and 36% used in electronic devices. Finally, the various end-use applications are re-aggregated into final end-use categories in order to match our end-use sectors presented in section 2.3.

Moreover, since end-uses for erbium, holmium, thulium, ytterbium, and lutetium were not precisely reported in any of these references, their end-use distributions were estimated based on various literature sources. The share of end-uses and references utilized to determine end-use sectors for each REE are specified individually in their respective tables presented in section 3.

2.4.3.3 Fabrication & manufacturing and new scrap recovery yields

Given the diversity of applications and the overall paucity of data on specific REEs processes, the fabrication and manufacturing as well as new scrap recovery yields are calculated for 10 REEs based on the MFA data of Du and Graedel (2011a). Fabrication and manufacturing yields are estimated for the five other REEs based on these MFAs. It is assumed that the fabrication and manufacturing yields remain constant, although the share of various end-uses may have evolved over time. Moreover, the recovery and recycling of new and old scrap are not expected to occur for holmium, thulium, ytterbium, and lutetium (European Commission, 2020a).

2.4.3.4 Dissipation in use

Dissipation in use is reported based on the works of Ciacci et al. (2015). Notably, the authors report 3% losses of lanthanum and cerium used in polishing powders for the glass industry due to volatilization, as well as 2% losses from the use of REEs in auto catalysts like PGMs used in that same application.

2.4.3.5 Recycling

It is challenging to recycle rare earths economically (Bru et al., 2015; Reimer et al., 2018). It is also difficult to assess the current recycling rates of REEs, as many relatively new applications such as wind turbines have not yet reached their end-of-life and as recycling projects aiming to recover REE from spent applications are still mostly in early-stage developments (Bru et al., 2015; Ciacci et al., 2019). All REEs were reported to have recycling rates below 1% around 2010 (Graedel et al., 2011). However, some recovery may occur for a few REEs currently. Notably, Binnemans et al. (2013) mention that magnets, batteries, and lamp phosphors are key applications in terms of recycling potentials. Similarly, the European Commission (2020a) notes that some technologies exist to recycle new or old scraps of magnets, batteries, and phosphors, while they may not always be economically competitive against the cost of primary production. The European Commission also notes that polishing powders may be re-used in the form of mischmetal in Japan and that ongoing research may enable to recover REOs from fluid cracking catalysts (FCC), although it remains unlikely to be economically feasible for lanthanum and cerium. The USGS reports that limited quantities of REEs are currently recovered from batteries, permanent magnets, and fluorescent lamps (USGS, 2020). REEs are seemingly not readily recyclable from other applications currently (Ciacci et al., 2015).

Binnemans et al. (2013) predicted pessimistic versus optimistic global EoL-RR for REEs used in magnets, NiMH batteries, and lamp phosphors by 2020. They anticipated EOL-RRs of 16.5%-33% for REES in magnets, 20%-35% from batteries, and 32-56% for REEs in lamp phosphors. Out of phosphors used in lighting applications, the yttrium-europium green phosphors are thought to be most readily recyclable due to the ease of the recycling process and the higher economic value of these elements (Binnemans and Jones, 2014). On the other hand, green phosphors containing lanthanum, cerium, gadolinium, terbium, and especially the blue phosphors also containing europium, are much more difficult to recycle (Binnemans and Jones, 2014). For this reason, the authors mention that some recycling processes may only target the recovery of yttrium and europium from green phosphors. Moreover, while NiMH batteries were reportedly using mischmetal in 2008, these were expected to be mostly replaced by REE-free lithium-ion batteries in the future (Goonan, 2011a; Guyonnet et al., 2015). In the end-use distribution of REEs in 2012 considered in this dataset, only lanthanum and cerium were still reportedly used in batteries, suggesting that a small share of praseodymium and neodymium was still used in mischmetal for that application. Nonetheless, we estimated shares of praseodymium and neodymium used in this application in 2012 (section 2.4.3.2), which could also be functionally recyclable.

In Europe, the most targeted REEs for recovery are praseodymium, europium, yttrium, and terbium, for which EoL-RIR of 10%, 38%, 31%, and 6% are reported, respectively (European Commission, 2020a). However, Europe processes only a small fraction of REEs in comparison to its imports of REEs in final products, partly explaining these relatively high EoL-RIRs. Moreover, the data underlying the European criticality studies suggest a global EoL-RIR of 1% for cerium, lanthanum, samarium, and gadolinium, and of 10% for praseodymium (Deloitte Sustainability et al., 2017; European Commission, 2020a). Given the paucity of data on single EOL-RRs per application and per REE, we estimated EOL-RR for different REEs and different applications based on the quantitative and qualitative information available, as detailed below. In general, it is estimated that the current EoL-RR is much below those suggested in the pessimist scenario for the year 2020, as anticipated by (Binnemans et al., 2013).

2.4.3.6 EoL Recycling of cerium and lanthanum from spent polishing powders and FCCs

Although both cerium and lanthanum could be regenerated in spent FCC and polishing powders in some cases (Goonan, 2011a; Vogt and Weckhuysen, 2015), such recovery is assumed to be accounted for in the lifetime distribution and dissipation in use modeling for these applications. Therefore, no collection and recycling is reported to occur for these applications in this dataset.

2.4.3.7 EoL Recycling of REE from mischmetal used in NiMH batteries

It is estimated that few efforts would be put to separate and recycle cerium and lanthanum since they are currently in oversupply due to the production of rarer REEs. An assumption of 5% EoL-RR from mischmetal used for NiMH batteries was considered for cerium, lanthanum, neodymium, and praseodymium.

2.4.3.8 EoL Recycling of REE from phosphors in lighting applications

There seems to be a small amount of REEs recovered from lighting applications. To the best of our knowledge, there the amounts of recycling of phosphors outside of Europe are also small, and we use values for Europe as a proxy for global EoL-RRs. The reported recycled quantities from European MSA studies (BIO by Deloitte, 2015) were used to estimate a global EoL-RR for europium, yttrium, and terbium used in lighting applications. In 2013, 33.5 tons of europium, 362 tons of yttrium, and 21.7 tons of terbium were functionally recycled in Europe (BIO by Deloitte, 2015). Comparing these values with the consumption of the same REEs for lighting applications between 2012-2016 as reported by the European Commission (2020a) and the relative share of REEs in lighting applications in 2012, we estimated EoL-RRs of 10% for yttrium and europium, and 20% for terbium. Given the discrepancy between these values and the qualitative information found in literature, as well as the high uncertainty reported for recycling in these MSA studies, an EoL-RR of 10% is reported for these 3 REEs. Finally, Ciacci et al. (2015) mention that cerium is almost exclusively recycled from phosphors, and we assume EoL-RRs of 5% for the less valuable cerium and lanthanum. It is further assumed to be representative of the EoL-RR of gadolinium. An EoL-RR of 0% is estimated for other REEs contained in lighting applications.

2.4.3.9 EoL Recycling of REE from permanent magnets

While it has been estimated that the recovery of dysprosium from spent magnets could reach 10 to 20% of supply by 2020 (BRGM, 2016a) and that 170 to 230 tons of neodymium could be recovered per annum in Europe by 2020 (Guyonnet et al., 2015), no approach has been developed beyond pilot plants and the recycling of EoL magnets remains at a standstill in Europe (European Commission, 2020a; Reimer et al., 2018). Similarly, no evidence of an installed industrial recycling capacity in the US for either new or old magnet scraps could be found.

Moreover, it was investigated whether some EoL recycling of REEs could occur in other countries processing most of the REEs, i.e., Japan and China (Du and Graedel, 2011a; Reimer et al., 2018), as they are more likely to be the ones able to recycle REEs (Ciacci et al., 2019). According to the substance flow analysis (SFA) of dysprosium in Japan in 2008 (Shi et al., 2010), about 30% of dysprosium of the EOL dysprosium was recycled in other material cycles. However, in the subsequent dynamic SFA of neodymium and dysprosium in Japan, including one of the authors of the previous study, Sekine et al. (2017) report that these REEs in motors are seldom domestically recovered, as most scrap is either exported, either non-functionally recycled as steel scrap. Thus, we assumed that recovery reported by Shi et al. (2010) referred to non-functional recycling. Similarly, no recycling of neodymium seemed to have occurred from magnets in China between 2002 and 2011, according to an SFA of Chen et al. (2018). In an SFA of neodymium in China in 2016, Geng et al. (2020) mention that a small part of neodymium inputs originate from the recycling of EoL neodymium products; however, the value is aggregated with the inputs from stockpile materials. Without further information, we assumed that the recycling of magnets was still globally negligible today, and an EoL-RR of 0% was considered for each end-use sector making use of magnets.

2.4.3.10 Recycling of other REEs and other applications

EoL-RRs of 0% are reported for other applications (e.g., ceramics, alloys), as well as for all end-uses of erbium, holmium, lutetium, ytterbium, and thulium. This is justified by the small amounts of highly dispersed REEs and the end-use applications in which they are found, as well as the current unfeasibility of their recycling (Ciacci et al., 2015). The table below presents the estimated global EoL-RR for various REEs based on their end-use application.

Table S8. Overview of estimated EoL-RR for REEs in potentially recyclable applications. N/A = not applicable (no share of end-uses attributed to that end-use sector)

End-use sector	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Other REEs
Magnets	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Phosphors (lighting application)	5%	5%	0%	0%	N/A	10%	5%	10%	N/A	10%	0%
Batteries (NiMH)	5%	5%	5%	5%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Other applications	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

2.5 Uncertainty evaluation

Uncertainty is inherent to any statistic or data point, and this dataset does not go without its share of uncertainties. We use a Monte Carlo simulation of 1000 iterations to obtain a 95% interval on the key results of the model. The uncertainty is approximated for each data point using a Pedigree-like matrix originally proposed by Weidema and Wesnæs (1996). The matrix is modified to reflect uncertainty on the end-use distributions and process yields reported in this dataset and allow to estimate variance for each data point. Five parameters are included in the rubric, as presented in Table S9. The reliability of the background data sources (U1) is evaluated, as well as its temporal correlation (U2). Since the model and data are meant to be as representative as possible of the contemporary state of the global anthropogenic cycles of metals, U2 is evaluated using the year 2019 as a reference year. The geographical and/or technological representativeness of the data is evaluated (U3) since it is attempted to provide end-use distributions and process yields representative of the global average. The corroboration of the reported data (U4) is evaluated in line with Graedel et al. (2012). Finally, an exogenous uncertainty parameter (U5) is included in the uncertainty assessment in order to take into account the uncertainty linked to the background data (e.g., potential human errors in calculations), as well as the exogenous uncertainty linked to the apparent stability or dynamics of the studied end-use distributions (i.e., market for a resource) or that of supply chains and processing technologies used over time. In the most optimal case, U5 = 1 is attributed a base GSD^2 of 1.05, which increases based on the apparent stability of processes, supply chains, and markets for each metal, allowing to further consider the likeliness of the reported data with regards to the temporal (U2) and geographical/technological (U3) representativeness. U5 may be evaluated differently between the end-use distributions and processes for one same metal.

Table S9. Data uncertainty rubric for the end-use distributions and process yields, and their associated GSD^2 (adapted from Ciroth et al., 2016 and Graedel et al., 2012)

Uncertainty level	1	2	3	4
Reliability (U1)	Verified data published in peer-reviewed manuscript or equivalent	Non-verified data reported by governmental, non-governmental agencies, scientific working groups, commercial entities, or equivalent	Non-verified and/or unpublished results, including personal communications, expert estimates, and interpolations OR calculated based on low-resolution data (one significant digit)	Rough estimate with expectedly large uncertainty
	1.00	1.10	1.20	1.40
Temporal correlation (U2)	Representative for a year between 2017 and 2019, or covering a range of years between 2014 and 2019.	Representative of a year between 2012 and 2016, or covering a range of years between 2010 and 2016.	Representative of a year between 2007 and 2011, or covering a range of years between 2006 and 2013.	Representative of a year prior to 2007, or covering a range of years before 2008.
	1.00	1.03	1.06	1.10
Geographical & technological correlation (U3)	Representative of the global scope at the time of the reported data	Extrapolated from regional data estimated to represent >75% of the global end-use or global processing technology, at the time of the reported data	Extrapolated from regional data estimated to represent 50-75% of the global end-use or global processing technology, at the time of the reported data	Extrapolated from regional data estimated to represent <50% of the global end-use or global processing technology at the time of the reported data
	1.00	1.03	1.08	1.15
Corroboration (U4)	Multiple independent sources indicating data are in strong agreement	At least two independent sources indicating data are in moderately strong agreement	Single source or independent sources indicating results are only in fair agreement	*not applicable*
	1.00	1.10	1.20	
Base & exogenous uncertainty (U5)	Stable supply chains (e.g. large magnitude flows and long-lived processes)	Moderately stable supply chains	Dynamic or unstable supply chains & rapid technological and process development	*not applicable*
	1.05	1.10	1.20	

The basic idea of estimating GSD^2 with the Pedigree matrix calculations is to get to a 95% confidence interval $[\frac{\mu_g}{GSD^2};\ GSD^2 \cdot \mu_g]$ (Muller et al. 2012). Graedel et al. (2012) does it similarly with the following calculation:

$$GSD^2 = e^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2}}$$

This way, two standard deviations, or 95% of all randomly drawn samples, are within this 95% confidence interval, assuming a log-normal distribution.

2.5.1 Uncertainty evaluation (data)

The evaluation of uncertainty for process yields is meant to represent as accurately as possible the uncertainty of the actual root source of information that was utilized to calculate a yield or that was reported as such in the dataset. For example, the production yield of 76% reported for strontium is reportedly based on an informed estimate (Panousi et al., 2016), and U1 for this data is evaluated to be 3 ($GSD^2 = 1.20$).

For the 18 metals for which global material flow analysis underlying the study of Helbig et al. (2020), uncertainty is assessed based on the background MFA studies. As only a few of these studies reported uncertainties, we estimate that each of these background documents relied on reasonably solid mass balanced models at the global scale, assuming a corroboration corresponding to a moderately strong agreement (U4 = 2). For these statistics, uncertainty may have been reported differently whenever other or more recent data was taken into account.

The evaluation of the uncertainty for the dissipation in use parameter is based on a simplified approach in comparison to that of process yields. Since dissipation in use for specific applications is not expected to evolve over time, and as the reported values are estimated to represent an average global dissipation rate, no uncertainty is reported for U2, U3, and U5 across all metals and applications. Moreover, since most values are based on the works of Ciacci et al. (2015), itself relying on other sources or informed estimates, we estimate the U1 and U4 values for each of these data based on the nature of the background information reported by the authors. The same procedure is used to estimate uncertainty when other references are considered. Moreover, the values for applications for which no dissipation in use is expected to occur due to the nature of the applications are considered reliable (U1 = 1). Finally, no uncertainty is reported for specific sectors that are inherently dissipative uses of type A or B, i.e., the agricultural & environmental applications (type A), metallurgy & metal-making (process) (type B), other punctual applications (type A or B), pharmaceutical & cosmetics (type A), and well-drilling sectors (type A).

As an example, we here briefly exemplify the evaluation of uncertainty of the end-use distribution of lithium. Lithium's end-use distribution is based on industry reports and governmental data, hence U1 = 2 ($GSD^2 = 1.10$). The distribution is representative of the global distribution for the year 2019 (U2 = 1; $GSD^2 = 1.00$ and U3 = 1; $GSD^2 = 1.00$), and it is based on multiple sources that are in strong agreement (U4 = 1; $GSD^2 = 1.00$). Since lithium supply for lithium-ion batteries increased rapidly in the past decade and is a predominant end-use for that metal, its U5 parameter is evaluated as 3 ($GSD^2 = 1.20$). Based on this evaluation, the resulting standard deviation remains relatively low ($GSD = 1.11$).

2.5.2 Uncertainty calculation – standard deviation and the beta distribution

Since process yields are inherently comprised between 0 and 100%, beta distributions are computed using the average value and estimated variance of the data point. Similarly, since the share for each end-use sector must also be included between 0 and 100%, while the sum of the distribution must be equal to 100%, multivariate beta distributions were applied for each end-use distribution depending on the estimated uncertainty for the end-use distribution for each metal (Dirichlet distribution).

2.5.3 Uncorrelated parameters with a lower and upper bound

Uncertainty of parameters with a lower bound of 0 and upper bound of 1 (e.g., fabrication yield) is considered with the beta distribution, which has two degrees of freedom: parameters α, β.

$$f(x;\alpha,\beta) = \frac{1}{\mathrm{B}(\alpha,\beta)} x^{\alpha-1}(1-x)^{\beta-1} \qquad (S1)$$

where $\mathrm{B}(\alpha,\beta)$ is the beta function with $\alpha, \beta > 0$:

$$\mathrm{B}(\alpha,\beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)} \qquad (S2)$$

Mean and variance can be calculated from α and β:

$$\mu = \mathrm{E}[X] = \frac{\alpha}{\alpha + \beta} \tag{S3}$$

$$\sigma^2 = \mathrm{Var}[X] = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)} \tag{S4}$$

Likewise, α and β can be calculated easily with the method of moments from a known expectation value and its variance if $\sigma^2 < \mu(1 - \mu)$:

$$\alpha = \left(\frac{\mu(1 - \mu)}{\sigma^2} - 1\right)\mu \tag{S5}$$

$$\beta = \left(\frac{\mu(1 - \mu)}{\sigma^2} - 1\right)(1 - \mu) \tag{S6}$$

2.5.4 Using the pedigree matrix with beta distributions

In order to generate α and β, we need to estimate the mean and the variance, or any other set of two equivalent statistical parameters. The cumulative distribution function of the beta distribution is the regularized incomplete beta function $I_x(\alpha, \beta)$.

Beta distributions following the two following properties can be defined, considering that the variance is defined by the square of the standard deviation σ, which can be approximated with the upper half of the 68% confidence interval of the log-normal distribution characterized by a mean of 0.5 and a given geometric standard deviation GSD:

1) $\mu = \mathrm{E}[X] = \frac{\alpha}{\alpha+\beta}$
2) $\left((GSD - 1) \cdot 0.5\right)^2 \approx \mathrm{Var}[X] = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$

The method of moments described above allows generating the values for α and β of beta distributions for each datapoint, with the condition $(GSD - 1)^2 < 4\mu(1 - \mu)$:

$$\alpha = \left(\frac{4\mu(1 - \mu)}{(GSD - 1)^2} - 1\right)\mu \tag{S7}$$

$$\beta = \left(\frac{4\mu(1 - \mu)}{(GSD - 1)^2} - 1\right)(1 - \mu) \tag{S8}$$

For computational reasons, alpha or beta values were required to be greater than 1 to ensure that all random variables are within the interval $(0, 1)$, but neither 0 nor 1. Whenever the resulting alpha or beta values were lower than one for a given data point, both values were normalized so that the lowest value equaled 1. The other value was augmented proportionally so that the mean value remained the same.

3 Data, references and result graphs per metal

3.1 MaTrace dataset to be used with the ODYM framework

ODYM is an open software framework for studying dynamic material systems (Pauliuk and Heeren, 2019). Online documentation is available at: https://github.com/IndEcol/ODYM.

The dataset and code underlying our work are provided in an ODYM-ready format and are publically available in a OSF repository at https://doi.org/10.17605/OSF.IO/CWU3D (Helbig and Charpentier Poncelet, 2022).

3.2 Data tables and result figures per metal

The tables included in this section present the values reported or used to calculate each data point included in the dataset and their references, and provide complementary descriptions or explanations. Result graphs from the MaTrace model for all metals are depicted under their corresponding tables (Figure S2- Figure S62). Numerical values underlying Figure S2- Figure S62 are provided in the Supplementary Data.

3.3 Lithium

Table S10. Lithium.

<table>
<tr><th>Lithium</th><th>Li, element number 3</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Recent end-use distributions for lithium are available for 2015 (BRGM, 2017b), and 2019 (SQM, 2019; USGS, 2020). The demand of lithium for batteries has followed a strong trend over the studied years, increasing from 37% to over 60% of the global demand between 2015 and 2019.

For this dataset, the distribution of end-use lithium ion batteries from the USGS (2020) is disaggregated into electric vehicle (about 67% of lithium use for batteries) and other batteries (about 33% of lithium use for batteries) based on SQM (2019). Air conditioning was reported as a household appliance. Lubricating greases were reported to have an average lifetime of 10 years and are used in a range of applications such as induced draught fans and lubricated-for-life bearings (Graedel et al., 2015). These were here classified in the Other electrical & metal products. The following estimates for end-use are thought to be representative global yearly averages for the year 2019:
<table>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>21%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>44%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>3%</td></tr>
<tr><td>Glass & ceramics</td><td>18%</td></tr>
<tr><td>Household appliances</td><td>3%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>3%</td></tr>
<tr><td>Other electrical & metal products</td><td>5%</td></tr>
<tr><td>Other miscellaneous</td><td>5%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 3</td></tr>
<tr><td>Production yield</td><td>The production of lithium occurs from both brines and ores. The production loss from brine is estimated at 33% based on Evans (2014), Foss et al. (2016), and Houston and Gunn (2011). The production losses from ores (e.g., spodumene) are estimated to be of 30% for extraction (proxy for spodumene ores), with an additional 15% refining loss (Graedel et al., 2015).

The share of lithium production from ores and brines is calculated based on each country’s share of total production for 2019 (USGS, 2020) and on their respective production method (brine or ores) as reported by Goonan (2012). Based on Chinese production in 2008, it is estimated that China produces 880t/(880t+2410t) = 78.5% lithium from brines (Goonan, 2012).

The US production is undisclosed in the USGS statistics. Although US production was historically important, it seems to have remained marginal in the recent years, since the only active mine was the Silver Peak brine mine. For instance, the BRGM estimated that lithium production at the Silver Peak site was around 2 000 tons in 2018 (BRGM, 2020b), which represented around 2% of the total production during that year. Therefore, it was considered to be negligible and not considered for the calculation of the production yield. Based on this information, we calculated a production yield of 70%.</td><td>U1: 3 U2: 4
U3: 1 U4: 3
U5: 2</td></tr>
</table>

Fabrication and manufacturing	While some MFAs of lithium and lithium-ion batteries have been published (Calisaya-Azpilcueta et al., 2020; Hao et al., 2017; Liu et al., 2021), none provide specific information on fabrication and manufacturing yields. The Clean Energy Manufacturing Analysis Center (CEMAC) estimated that yields for lithium-ion cell manufacturers range between 70-90% depending e.g. on the maturity of the processing firms (Chung et al., 2016). The relatively low yield is reportedly due to difficulties with precisely and consistently controlling the electrochemical reactions utilized in the battery manufacturing process (Chung et al., 2016). Based on the latter reference, we estimate the average fabrication and manufacturing yield for batteries to be of 80% globally, while the manufacturing of other lithium applications is assumed to be of 90%. Taking into account the respective share of lithium in battery and other applications, the resulting overall yield is calculated to be of 84%.	U1: 2 U2: 2 U3: 1 U4: 3 U5: 2
New scrap recovery	The studied MFAs of lithium suggest that there is no recycling of lithium new scraps. The recycling of new scraps, if any, is considered to be done on-site and to be included in the yield of fabrication and manufacturing.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	85% (assumption)	U1: 4 U2: 1 U3: 1 U4: 3 U5: 3
Dissipation in use	Pharmaceuticals and lubricants may be assumed to be lost during use (Ziemann et al., dissipated 2012). While pharmaceutical products can be expected to be consistently dissipated during use, Graedel et al. (2015) noted that lubricants are rather long-lived and that in some cases may even remain in the product for its entire lifetime, such as in lubricated-for-life bearings. We assume a dissipation in use of 80% of lithium lubricants (aggregated in the Other electrical & metal products). Moreover, a dissipation in use of 100% is reported for lithium used in continuous casting and catalysts. Furthermore, we estimated that no dissipation in use occurs from other applications of lithium.	Per sector; please refer to Supplementary Data
Collection and sorting	The European Commission (2020a) reported that lithium may only be recovered from batteries. Graedel et al. (2015) estimated a 10% EoL-RR for lithium in battery applications based on an MFA for cobalt (Harper et al., 2012), and 0% for other applications. Europe now has an installed recycling capacity of over 40,000 tons of LIBs per year (European Commission, 2020a); however, the recycling of lithium remains challenging. There is some evidence suggests that the global EoL-RR of lithium batteries remains lower than 10%, as the global EoL-RR of lithium is estimated remain around 1% since 2010 (BRGM, 2017b). The current collection and recycling rate of spent LIBs from consumer electronics in China and the US is reported to be likely lower than 10%, or probably even lower than 5% (Gu et al., 2017). While the global collection rate of EV batteries is higher, at around 40-60%, the recycling of lithium is low due to economic reasons (primary production is cheaper than recycling) and, generally, other elements than lithium contained in batteries are targeted by recycling processes (Bobba et al., 2019; Harper et al., 2019; Ziemann et al., 2018). Based on this evidence, we estimate a 5% EoL-RR for LIBs, which is applied to both types of batteries. The collection yield for the lithium content in batteries is	Per sector; please refer to Supplementary Data

	calculated considering the reported 85% remelting yield, resulting in a collection and sorting yield of 6% for LIBs. There are a number of on-going projects aiming to improve the installed recycling capacity for lithium batteries (Harper et al., 2019), and the recycling of batteries deserve special attention if ever it is attempted to establish prospective scenarios.	

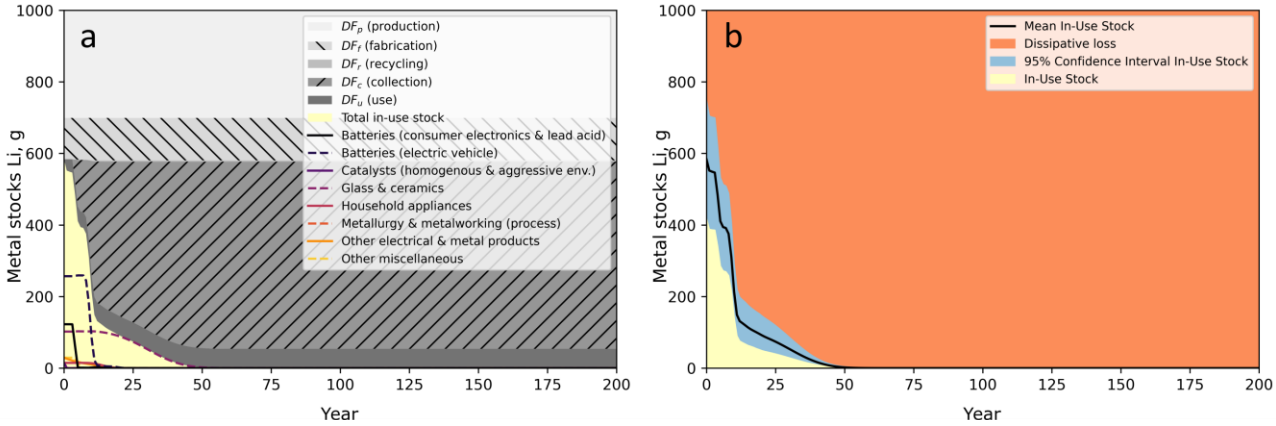

Figure S2. In-use stocks and losses of lithium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.4 Beryllium

Table S11. Beryllium.

Beryllium	Be, element number 4	Uncertainty
End-uses	It is difficult to dissociate between beryllium end-uses as there is large overlap between beryllium-containing materials and end-use sectors (Trueman and Sabey, 2014). For instance, beryllium-copper alloys represent about 80% of uses of beryllium (BeST, 2016) and are used in multiple electronic applications, in transport and aerospace for both commercial and defense applications, telecommunication, etc. Moreover, end-uses are sometimes reported as aggregated end-use sectors, e.g. aerospace and defense altogether. The global end-use values are estimated based on US values for years 2015 to 2019 (Lederer et al., 2016; USGS, 2020) and Europe values reported as averages for years 2012 to 2016 (European Commission, 2020a). Since US is the main producers worldwide (around 60% of the production in 2019) and Europe is mostly dependent on imports (European Commission, 2020a), more weight was given to US end-use statistics than to Europe's statistics when a notable mismatch was observed. The US is also a leading manufacturer of beryllium materials and products. Given that uses have been quite constant in the past years, data are also checked against 2007 end-use distribution reported by Christmann et al. (2010) for consistency. Data matching and reconciliation into end-use sectors was performed with the available information. Auto electronics and auto components were aggregated into the transport category. Industrial applications are classified into the mechanical eq. category. Defense includes some nuclear uses, missiles, ceramic and beryllium alloy components for aerospace and military jets. These were classified in Other industrial, military & energy applications. Medical applications include high-resolution medical radiography used in computerized tomography scanning and mammography (European Commission, 2020a) and were also classified as Other industrial, military & energy applications. Energy applications are various, including research for fusion reactors. If ever fusion energy becomes widely used, demand for pure beryllium metal could grow substantially in the future (Christmann et al., 2010). The distribution of beryllium end-uses are estimated to be representative of the global yearly averages from 2015 to 2019: Aviation: 10% Electronics: 15% Mechanical equipment: 15% Other industrial, military & energy applications: 22% Telecommunication: 12% Transport: 26%	U1: 2 U2: 1 U3: 2 U4: 3 U5: 1
Production yield	About 87% of the beryllium content of bertrandite and beryl ores is estimated for the recovered in the US, whose production represent over 50% of the global production (Lederer et al., 2016). US is the leading producer of beryllium, although Kazakhstan also had substantial stockpiles of beryllium concentrates as leftovers from the Soviet Union stocks accumulated during the Cold War. However, little is known on the former Soviet Union production of beryllium concentrates, and these	U1: 2 U2: 2 U3: 3 U4: 3 U5: 1

	stockpiles are thought to be nearly depleted (Lederer et al., 2016). Hence, US production is assumed to be reasonably representative of the current production.	
Fabrication and manufacturing	The major US beryllium producer, Materion (as mentioned by the USGS, 2020), has a highly integrated production chain from beryllium ores to material (ceramics & alloys) and products manufacturing (Materion, 2016). Manufacturing losses for copper alloys (the principal material use, with approximately 80% of total beryllium consumption) can be expected to be minimal (BeST, 2016). Beryllium is difficult to cut and manufacture due to its high hardness, which results in a lot of new scrap being generated in some industries like aerospace (Trueman and Sabey, 2014). However, this new scrap is mostly collected and sent back to produce new alloys, since beryllium is a valuable and its recycling provides great energy savings (European Commission, 2017a; SCRREEN, 2018). United States have historically been a major producer of beryllium bearing materials and products. The USGS static MFA for the year 2000 is used to estimate process yields for beryllium (Cunningham, 2004). It is expected to be fairly representative of global yields, as 455 tons of primary and secondary beryllium were processed within the US that year (higher volumes than global production for recent years reported by the USGS (Lederer et al., 2016; USGS, 2020)), and about 75% beryllium was used in copper alloys, similar to its current share. The calculated fabrication and manufacturing yield is of 92% (385/420 tons).	U1: 2 U2: 4 U3: 3 U4: 1 U5: 1
New scrap recovery	86%, calculated from (Cunningham, 2004). A lot of beryllium bearing scraps are generated in Europe (about 50% of Europe’s consumption) that is sent back to recyclers outside of Europe (European Commission, 2020a).	U1: 2 U2: 4 U3: 3 U4: 1 U5: 1
Remelting	It is assumed that recovered new scraps are mostly from copper alloys and remelted with a 100% yield (BeST, 2016). The same yield is assumed to apply to old scraps, which are considered to be only targeted for the beryllium content when they are collected in specific high beryllium-content waste flows. Cf. explanation for fabrication and manufacturing above.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	USGS reports some dissipative uses without specification on which of beryllium’s applications are considered as dissipated (Cunningham, 2004). Uses in defensive military applications or space have potential for dissipation in use; however, the actual use rate for these applications could not be determined. Therefore, no dissipative uses were reported for beryllium. These are considered to be indirectly taken into account in the collection and recycling rates reported for different applications.	Per sector; please refer to Supplementary Data
Collection and sorting	Bulk metal with high beryllium content could be recycled, but it is difficult to recover as it is used in small components and represent a tiny fraction of the appliances sent to recycling (European Commission, 2020a; Lederer et al., 2016; Trueman and Sabey, 2014). It is thought that beryllium contained in copper alloys is typically non functionally recycled or lost to slag (UNEP, 2011). A global EOL-RIR of 19% was reported in the 2010 criticality European study according to Christmann et al. (2010), while no EOL recycling was reported in the 2020 study (European Commission, 2020a).	Per sector; please refer to Supplementary Data

	Yet, specific recycling schemes such as those promoted by Materion might allow for the recycling of some EoL beryllium applications. Trueman and Sabey (2014) mention that pure beryllium metal applications that return to the recycling flow can easily be recycled, although this might not be the case for some space, nuclear or military applications due to contamination or their sensitive nature. In 2000, 3.8% of old scraps of beryllium were recycled in the US (Cunningham, 2004). In a recent publication, Graedel et al. (2022) provided updated informed estimates for the global EOL-RR of beryllium for different sectors. Based on this publication, we report collection yields of 30% for the aviation, mechanical equipment, telecommunication and other industrial, military & energy applications; of 10% for electronics; and of 1% for the transportation sector. The latter values seem to corroborate the EOL-RIR of 19% of Christmann et al. (2010) for the year 2010.	

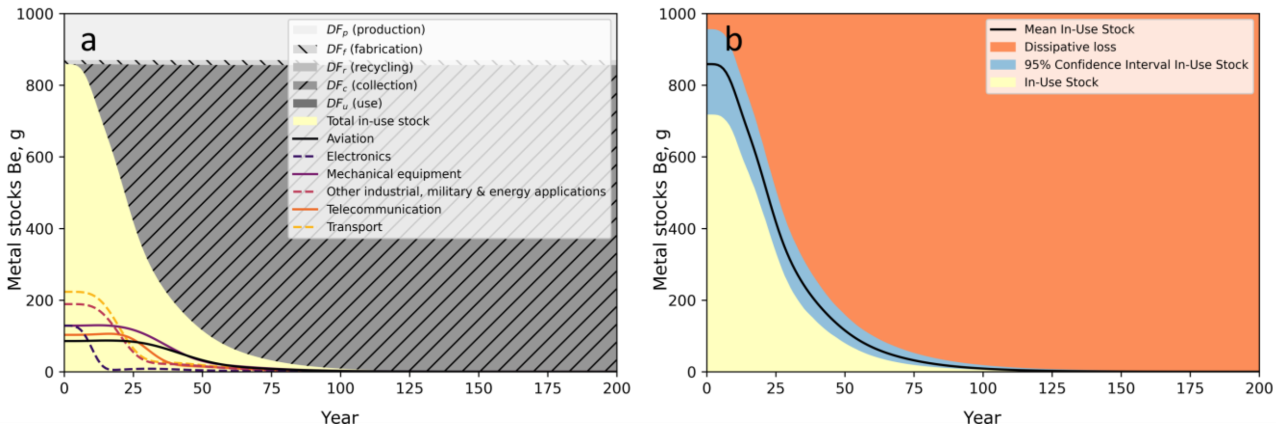

Figure S3. In-use stocks and losses of beryllium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.5 Boron

Table S12. Boron.

<table>
<tr><th>Boron</th><th>B, element number 5</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Boron is used in over 300 applications; more than three-quarters of world consumption was estimated to be used in detergents, fertilizers, ceramics and glass in 2019 (USGS, 2020). The only global end-use distribution of boron that was found is that of Graedel et al. (2015), which provides highly aggregated end-uses for the year 2007 based on Roskill (2010). Regional end-use data are also available for Europe for years 2012-2016 (European Commission, 2020a), while historical use statistics in the US are reported until 2003 (USGS, 2015). The European data suggest that 49% of boron was used in glass products, 15% in frits and ceramics, 13% in fertilizers, 4% in chemical manufacture, 4% in metals and 11% in other uses (European Commission, 2020a). The USGS historical stats suggest that approximately 5/6th of glass uses are used for cellulosic insulation and insulation-grade glass, and the other 1/6th into other glass products in the US between 1998 to 2003 (USGS, 2015). These uses have been fairly constant from 1998 to 2003 and are assumed to be representative of the US consumption partly considered to elaborate this dataset. Based on these two regional distributions, the distribution for 2007 is slightly revised. The 64% share of boron used in glass products, as reported by Graedel et al. (2015), is further disaggregated. Insulation and insulation-grade glass are considered to be used in the construction sector, while other glass products are classified in the glass & ceramics sector. It is also assumed that metal uses for boron in Europe are representative for global end use, with 4% of its global share. The latter are aggregated in the alloys & solders category. Finally, other boron end-uses are split even between Other miscellaneous and Other industrial, military & energy applications to reflect the diversity of potential applications (cf. Graedel et al., 2015). The following estimates for the end-uses of boron are assumed to be representative global yearly averages for years circa 2005-2015:
<table>
<tr><td>Agricultural & environmental applications</td><td>6%</td></tr>
<tr><td>Alloys & solders</td><td>4%</td></tr>
<tr><td>Construction</td><td>49%</td></tr>
<tr><td>Glass & ceramics</td><td>18%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>10%</td></tr>
<tr><td>Other miscellaneous</td><td>10%</td></tr>
<tr><td>Other punctual applications</td><td>4%</td></tr>
</table></td><td>U1: 3
U2: 3
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>Graedel et al. (2015) reported a recovery rate of 80% for the combined mining and refining operations. Althaus et al. (2007) assumed a 80% extraction yield, as well as a yield of 98% for refining from sodium borates to anhydrous borax (based on US production), and of 95% for the refining of calcium borates to boric acid. Based on this information, we consider an extraction yield of 80%, and an average refining yield of 97%, resulting in a production yield of 78%. It should be noted that both references seem to refer to the extraction of boron from minerals, and not from brines.</td><td>U1: 3 U2: 3
U3: 3 U4: 2
U5: 1</td></tr>
</table>

Fabrication and manufacturing	A large diversity of different products is manufactured with borates. An assumption of 95% overall yield is used in the dataset, including the potential recovery of new scrap, if ever it occurs.	U1: 4 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	The recovery of new scraps, if any, is considered to be included in the fabrication yield, and a yield of 0% is reported.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	There is no recycling considered in this dataset, and a remelting yield of 0% is reported.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	Agricultural products, as well as other punctual application (soaps and detergents) are estimated to be completely dissipated during use (type A). Other uses are considered not to be dissipative.	Per sector; please refer to Supplementary Data
Collection and sorting	Some uses as a fertilizer could be considered as recycling (e.g., via composting of food waste). Nonetheless, we consider an EOL-RR of 0% for all applications based on European Commission (2020a) and Graedel et al. (2015).	Per sector; please refer to Supplementary Data

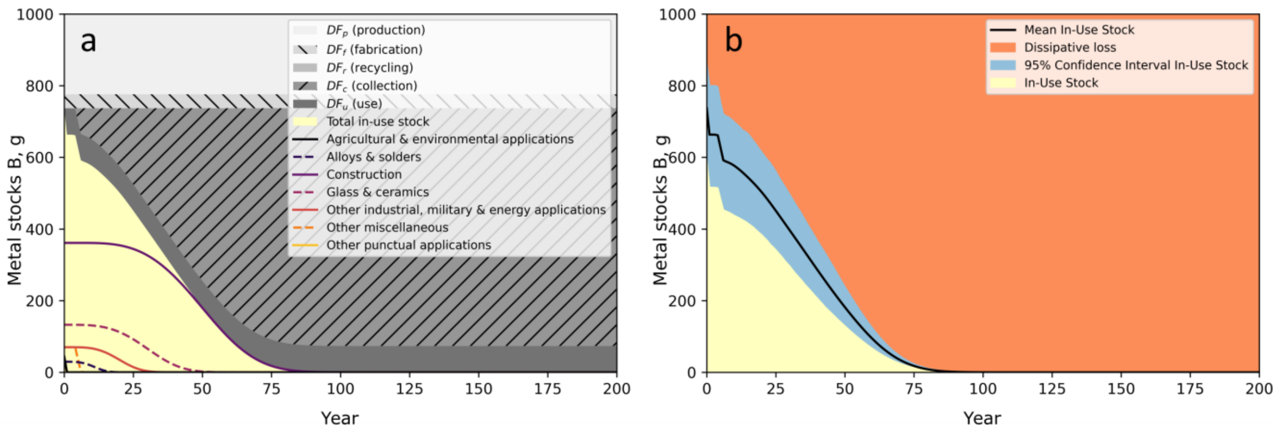

Figure S4. In-use stocks and losses of boron over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.6 Magnesium

Table S13. Magnesium.

<table>
<tr><th>Magnesium</th><th>Mg, element number 12</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Most of global magnesium uses are directly from magnesium compounds or minerals such as magnesia, especially for steel refractories, while magnesium metal only represents a small share of total uses (Kramer, 2000). Graedel et al. (2015) reports end-uses for year 2002 based on Roskill (2005). The data from Graedel et al. (2015) are updated based on global data use for magnesium compounds in 2017 (Wietlisbach, 2018) as well as global end-uses for magnesium metal for years 2012-2016 reported in European Commission’s criticality study (European Commission, 2020a). The end-use of magnesium metal was considered to represent 6% of total magnesium consumption based on reported production of 1 100 and 28 000 thousand tons of magnesium metal and magnesium compounds (MgO), respectively, in 2019 (USGS, 2020). Therefore, the distribution for Mg metal of the European Commission (2020a) is normalized to a total of 6% of global magnesium consumption, and the remaining 94% is split between magnesium compound uses based on the other cited literature.

The use of magnesium for the desulphurization of steel is considered to be dissipation in use of type B (cf. section 1.4), and added to the metallurgy & metalworking (process) category. Environmental applications and agricultural products are aggregated altogether. The use of magnesium in iron and steel foundries, as well as magnesium metal castings, are aggregated in the transport category following the works of Graedel et al. (2015), as it is considered to be the main use for the produced materials (e.g., ductile iron).

Based on the consulted literature, the remainder of other uses are thought to mostly include various industrial tools and machinery, and structural uses. Therefore, they are included in the Other industrial applications category. The following distribution for magnesium end-uses is estimated to be representative of the global yearly average for years circa 2017:
<table>
<tr><td>Agricultural & environmental applications</td><td>15%</td></tr>
<tr><td>Chemicals</td><td>6%</td></tr>
<tr><td>Construction</td><td>17%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>1%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>4%</td></tr>
<tr><td>Packaging</td><td>1%</td></tr>
<tr><td>Refractories</td><td>53%</td></tr>
<tr><td>Transport</td><td>3%</td></tr>
</table></td><td>U1: 2
U2: 2
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>Graedel et al. (2015) reported extraction losses of 28.5% and other pre-fabrication losses of 5%. However, this is reportedly for magnesia production from dolomite based on Ramakrishnan and Koltun (2004). Yet, dolomite represents only a small share of global production in comparison to other minerals such as magnesite, representing about 84% of total production (Wietlisbach, 2018). Harraz (2017) presents a yield of 0.75 ton of electrofused MgO for an input of 2.5 tons of magnesite ore mined, suggesting a production yield of about 63%.</td><td>U1: 3 U2: 2
U3: 1 U4: 3
U5: 1</td></tr>
</table>

	Based on this information, we estimate an average production yield of 65% across all potential magnesium production routes.	
Fabrication and manufacturing	Scarce information could be found on the fabrication and manufacturing yield of magnesium-containing products. The USGS statistics suggest a manufacturing yield of 92% for magnesium metal products in 1998, with a new scrap recovery rate of 86% (USGS, 2004b). However, as noted previously, this covers only 6% of the end-uses of magnesium. Therefore, it is attempted to estimate the fabrication yield for refractories, as they are by far the largest end-use for magnesium. Yet, no information on the yield of the manufacturing processes for refractories could be found. Still, the manufacturing process is well described by the US EPA (2003). Based on that reference, we assume that about 5-10% of magnesium could be emitted as particulate matter, or be lost as a residue of the crushing, grinding, calcining and milling processes. Furthermore, we assume that few efforts would be made to recycle these new scraps given the low economic value of magnesia. Based on this information, we estimate an overall fabrication and manufacturing yield of 92.5% for all of magnesium products, including the recovery of new scraps, whenever it occurs.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	The recovery of new scraps, if any, is considered to be included in the fabrication yield, and a yield of 0% is reported.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	95% (assumption)	U1: 4 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	Some sources consider magnesium use in refractories as a dissipative use (Bell et al., 2017; Wang et al., 2018), while recycling rates ranging from 15 to 90% have been reported (Muñoz et al., 2020). However, these rates include non-functional recycling in road bed aggregates or as slag former and conditioners in metallurgical processes (Horckmans et al., 2019). Here, we assume the use in refractories not to be dissipative, as for magchrome refractories (Ciacci et al., 2015). Agricultural and environmental applications are considered to be completely dissipated during use (type A). The metallurgical use of Mg compounds to desulfurize steel is considered to be dissipative (type B). Likewise, other magnesium chemicals are assumed to be dissipated during use (type B) based on their most common applications, such as magnesium hydroxide used for flue gas desulfurization and water treatment, or magnesium sulfate used as food additive and pharmaceuticals (Kramer, 2000; Wietlisbach, 2018).	Per sector; please refer to Supplementary Data
Collection and sorting	Graedel et al. (2015) reported EOL-RRs of 60% for packaging, and 75% for magnesium metal used in transport and construction, using aluminium used in similar applications as proxies. Similarly, we assume the collection rates of aluminium packaging to represent those of magnesium used in the same application, and report a collection yield of 58% for packaging. The collection yields for iron applications are used as proxies to estimate those of magnesium used in similar applications, which are also almost identical to those of aluminum for these two sectors: 93% for transport, and 87% for construction. The latter is corrected to take the share of Mg metal included in the construction sector into account (approximately 4%). Establishing the functional recycling rate of magnesium minerals used in refractories and construction sectors is not straightforward. Since	Per sector; please refer to Supplementary Data

	primary magnesite can be used to produce construction materials such as cement, we consider that some of the recycled refractories used for cement production actually offset the demand for primary magnesite, thereby potentially consisting in functional recycling. As a first estimate, an EoL-RR of 10% of refractories is considered. Moreover, some magnesium compounds are directly used in construction materials, which are thought to be mostly cement (Kramer, 2000; Wietlisbach, 2018). However, we did not consider the recycling of cement to be functional, based on the works of Gutowski et al. (2013); and a collection yield of 0% is reported for this application. As magnesium metal represents only 4% of the use of magnesium in construction applications, a collection yield of 3% is reported for that sector. Finally, EoL-RR of 0% are considered for other end-uses (Graedel et al., 2015). The collection yields are corrected accordingly with the reported remelting yield of 95%. We would like to highlight that increasing quantities of magnesium are reported to be obtained from seawater, thereby making the anthropogenic cycle of magnesium potentially include the environmental media. It was not investigated how the environmental applications of magnesium and emissions to the environment could be considered to be somewhat recyclable from brine.	

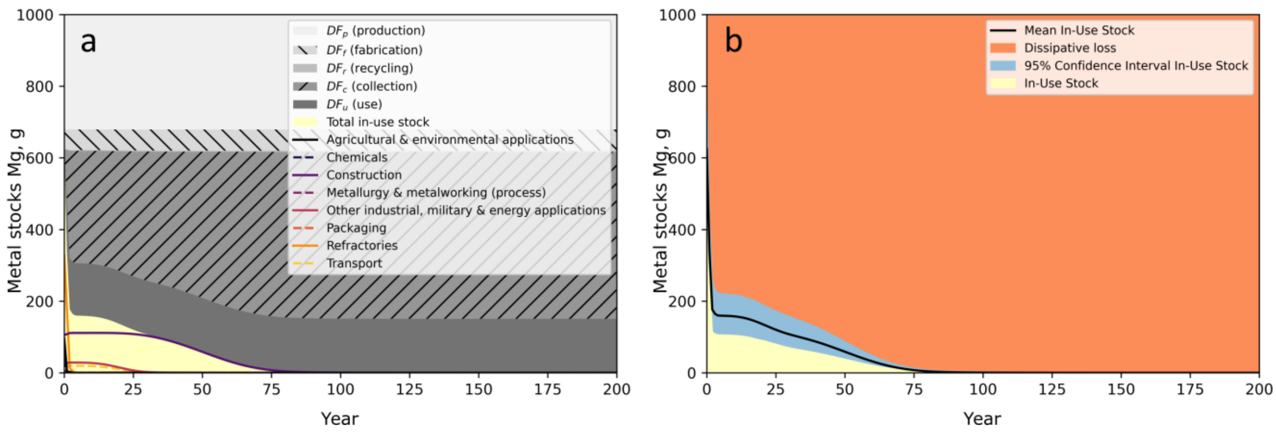

Figure S5. In-use stocks and losses of magnesium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.7 Aluminum

Table S14. Aluminum.

<table>
<tr><th>Aluminium</th><th>Al, element number 13</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distribution are available for year 2007 (Graedel et al., 2013), 2014 (Bertram et al., 2017) and 2015 (USITC, 2017). The most recent distribution of wrought aluminium products is considered (USITC, 2017). Aluminum foil was aggregated along with packaging applications. Aluminum use in electrical sector was classified in infrastructure, as major applications include medium- and high-voltage overhead power lines as well as aluminum alloy wiring in the construction of new buildings (USITC, 2017). Moreover, about 3% of aluminum is used to deoxidize steel and lost to slags (Ciacci et al., 2015), corresponding to the destructive use reported by other authors (Bertram et al., 2017; Liu et al., 2013). This percentage is assumed to remain relatively constant as both aluminium and steel are consistently and widely used. Therefore, 3% of aluminium is reported to be used for metallurgical processes, and the remaining end-uses are normalized to fit a total of 97% accordingly.

The global end-use distribution for aluminium is the following:
<table>
<tr><td>Construction</td><td>33%</td></tr>
<tr><td>Household appliances</td><td>4%</td></tr>
<tr><td>Infrastructure</td><td>17%</td></tr>
<tr><td>Mechanical equipment</td><td>9%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>3%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Packaging</td><td>20%</td></tr>
<tr><td>Transport</td><td>12%</td></tr>
</table></td><td>U1: 2
U2: 2
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>88% (Helbig et al., 2020, based on Bertram et al., 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>59% (Helbig et al., 2020, based on Bertram et al., 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>95% (Helbig et al., 2020, based on Bertram et al., 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>97% (Helbig et al., 2020, based on Bertram et al., 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>0% for all applications except metallurgy, for which 100% dissipation in use is considered (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Helbig et al., (2020) calculated an average 83% collection yield based on Bertram et al. (2017). The latter article was written in parts by authors affiliated to the International Aluminium Institute.

The worldwide market weighted recycling rates reported in the Global Material Flow model of the (International Aluminium Institute, 2018) are used to calculate application-specific collection yields. While more</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	recent estimates are reported in that reference, we considered the recycling yields of 2014 to be consistent with the reference year of the study of (Bertram et al., 2017). For the aggregated packaging and foil sectors, the weighted average is calculated based on end-use demand in 2014 established by the (International Aluminium Institute, 2018). Considering the remelting yield of 97%, the following collection yields are calculated: Construction, 87%, Infrastructure, 68%, Transport, 93%, Packaging, 58%; Mechanical equipment, 67%; Household appliances, 58%; and Other industrial, military & energy applications, 45%.	

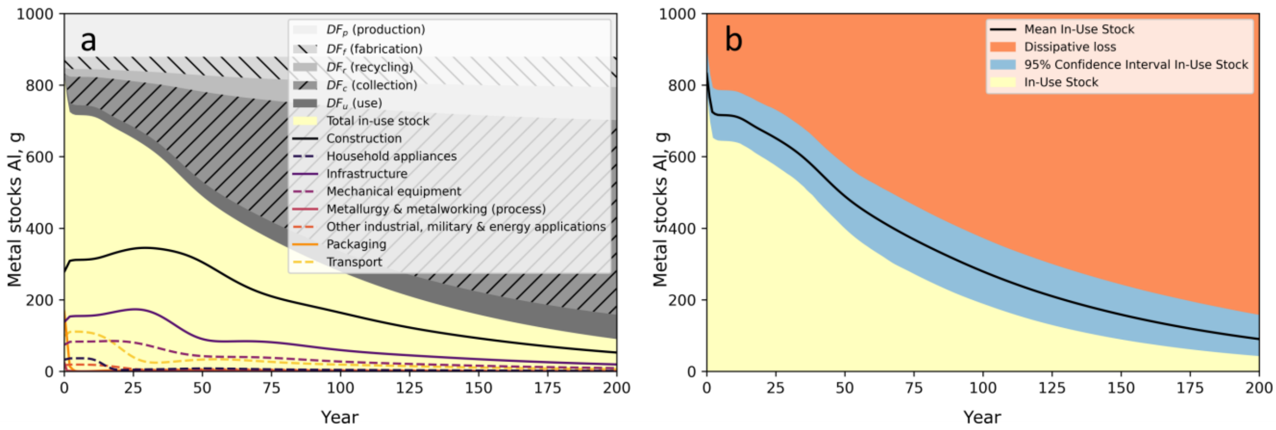

Figure S6. In-use stocks and losses of aluminium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.8 Silicon

Note: Since silicon is the second most common element in the earth's crust after oxygen, it is expected that enormous amounts of silicon are extracted from the ground yearly. It notably a constituent of quartz crystals and silica sand which are used in a range of applications (European Commission, 2020c), albeit not for the specific characteristics of silicon metal. For such reasons, it is treated separately from silica sand in criticality studies (BRGM, 2019a; European Commission, 2020c). Therefore, we only consider the production of silicon metal from high purity quartz that is used for silicon metal production. The metallurgical use of ferrosilicon or calcium silicon for e.g. the deoxidization or reduction of steel, magnesium or nickel is not covered.

Table S15. Silicon

Silicon	Si, element number 14	Uncertainty
End-uses	Global end-uses of silicon are reported for 2018 (BRGM, 2019a). Another estimate is reported by the European Commission (2020a), suggesting that around 50% of silicon metal is used in silicones, 40% in aluminium, and 10% in solar panels. Another end-use distribution could be calculated for 1998 based on Williams (2003). Finally, a partial distribution of electronic grade silicon can be calculated for solar cells and wafers in 2009 (Takiguchi, 2011). The BRGM's values are considered to build the present dataset, and some refinements are made based on other available information, as detailed below. The BRGM reports that 41% of silicon is used as an alloying element in aluminium, iron and steel product (mostly aluminium); 35%, in silicones and silanes; 18% in solar cells; and 6% in other uses (BRGM, 2019a). Between 0.4% and 1% of Si is added to almost all aluminium alloys, and high temperature applications may contain up to 13% Si (Maubert, 1989). A substantial fraction of silanes may be used as precursors for the manufacture of optical fibers and semi-conducting wafers or for the production of polysilicon, further used in the manufacture of wafers (Williams, 2003). Based on the available information, it is estimated that around 2% of global silicon (as silanes) is used to produce semiconducting wafers and fiber optic cables (both were aggregated in electronics); and the remainder 33% of the silanes and silicone category is estimated to be used for silicone applications. Given the variety of applications for aluminium-silicon alloys (mostly cast products), they are included in the alloy category. The family of silicones include oils, pastes, emulsions, resins, gums and elastomers that are used in over 200 sectors (Maubert, 1989). These applications include inherently dissipative uses such as lubricating greases, and non-dissipative uses such as silicone rubber and elastomeric seals, and resins used for isolation purposes in electronics (Maubert, 1989). Likewise, other silicon compounds uses are thought to be used in a range of applications such as food additives, cosmetics, thermocouples, crucibles, refractories, ceramics, etc., while other silicon alloys include brass used in e.g. shipbuilding and nickel-silicon alloys used in e.g. electronics and chemical industries (Maubert, 1989). Without further information, we roughly split silicone applications and "other" silicon uses evenly between Other industrial, military & energy applications, Other miscellaneous and Other punctual applications. The following end-use distribution is estimated to be representative of global end-uses of silicon metal in 2018: Alloys & solders | 41%	U1: 2 U2: 1 U3: 1 U4: 2 U5: 2

<table>
<tr><td></td><td>
<table>
<tr><td>Electronics</td><td>2%</td><td></td></tr>
<tr><td>Other industrial, military & energy applications</td><td>13%</td><td></td></tr>
<tr><td>Other miscellaneous</td><td>13%</td><td></td></tr>
<tr><td>Other punctual applications</td><td>13%</td><td></td></tr>
<tr><td>Solar cells</td><td>18%</td><td></td></tr>
</table>

Although this distribution is quite generic due to the lack of precise information available, it is estimated to represent the large diversity of lifetimes amongst the various silicon uses reasonably well. Nonetheless, it may warrant additional investigations of the silicon anthropogenic cycle.</td><td></td></tr>
<tr><td>Production yield</td><td>The production yield of silicon metal from quartz is estimated to be of around 85% in a well-operated furnace (Ali et al., 2018), and a production yield of 80% is estimated including losses to other processes and mining losses.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>The fabrication and manufacturing processes for metallurgical grade silicon are thought to have a globally high yield, since process residues (e.g., kerf loss) and off-grade silicon can still be used in solar cell manufacturing and as a cheap additive to aluminium alloys (Takiguchi, 2011; Williams, 2003). We assume the yield of fabrication and manufacturing processes for chemical grade silicon (used in the manufacture of silanes and silicones) to also be similarly efficient. A global yield of 90% is reported for silicon-containing products, including the recovery of new scraps that are used in other applications requiring primary silicon metal.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>New scrap recovery is assumed to be included in the fabrication yield, and a yield of 0% is reported.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>The remelting of new scraps is considered to be included in the fabrication and manufacturing yield. No uses of silicon are reported to be functionally recycled currently (BRGM, 2019a; CRM Alliance, n.d.; European Commission, 2020a), and a remelting yield of 0% is reported.

It should be noted that the silicon content of aluminium or iron alloys may remain in the carrier metal flow and possibly retain its functionality, but is “probably lost” (UNEP, 2013).</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Most uses of silicon are estimated not to be dissipative as they are expected to be mostly used in protected environments. Some silicone products are reported as punctual applications for which a dissipation in use of 100% is reported, including e.g. lubricating oils and food additives.</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>No uses of silicon are thought to be functionally recycled (BRGM, 2019a; CRM Alliance, n.d.; European Commission, 2020a), and a collection yield of 0% is reported. It should be noted that some losses identified as collection losses could be attributed to remelting losses instead, i.e., when silicon is lost to non-functional recycling.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

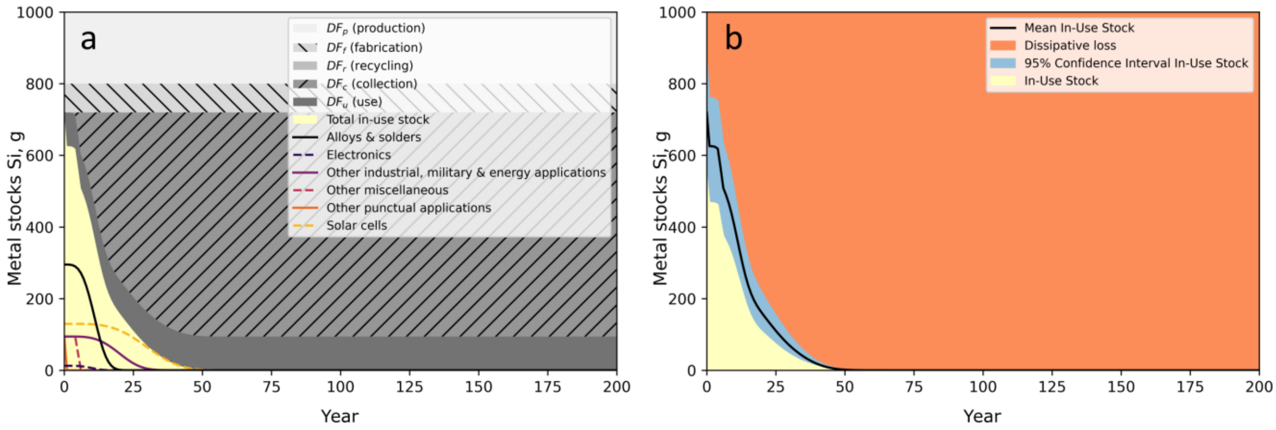

Figure S7. In-use stocks and losses of silicon over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.9 Scandium

Table S16. Scandium.

<table>
<tr><th>Scandium</th><th>Sc, element number 21</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The global distribution of scandium into end-uses is available for years 2008 (Graedel et al., 2013) and 2017 (BRGM, 2017c). In recent years, its dominant application has been in solid oxide fuel cells, followed by scandium-aluminium alloys (BRGM, 2017c). Alloys are used for high performance applications such as sporting goods and aerospace; other uses include ceramics, electronics, lasers, lighting, and radioactive isotope (USGS, 2020). We assume that half of the scandium alloys are used in aerospace applications, while the remainder is classified as other metal products. The following distribution is representative of end-uses of scandium in 2017, based on BRGM (2017c):
<table>
<tr><td>Aviation</td><td>5%</td></tr>
<tr><td>Other electrical & metal products</td><td>5%</td></tr>
<tr><td>Solid oxide fuel cells</td><td>90%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 3
U5: 3</td></tr>
<tr><td>Production yield</td><td>Only about 10-15 tons of scandium is produced annually (BRGM, 2017c; USGS, 2019). Scandium is highly dispersed in the crust due to the absence of geological processes concentrating it (Emsley, 2014). It has typically been obtained as a by-product of REE, uranium or nickel-cobalt lateritic ores, as well as from solid residues from tungsten, titanium or bauxite processing (BRGM, 2017c). The weathering of lateritic deposits developed over ultramafic–mafic rocks was found to enrich scandium concentrations by a factor of ten in Eastern Australia deposits, which could make such deposits a viable source of primary scandium (Chassé et al., 2017).

It is uneasy to estimate what portion of scandium should be considered as a resource, and therefore what is the actual production yield. Panousi et al. (2016) estimated a production yield of 85% based on the voluntary production of scandium from a few select processes or projects as described by Wang et al. (2011) and Khoo (2012). However, much more scandium that is extracted could be processed as a by-product and be considered as a resource, and therefore we expect the actual production yield, as defined in this article, to be lower.
There seems to be some degree of anticipation of an important increase in the future demand for scandium, especially for aluminium-scandium alloys for casting and additive manufacturing. There are multiple on-going projects aiming to recover scandium as a by-product of uranium, bauxite, nickel and cobalt ores (Khoo, 2012; USGS, 2019), or from past mining wastes, e.g. from red mud caustic wastes, uranium tailings, coal and coal by-products, and sulfate titanium wastes (European Commission, 2020a; USGS, 2019).

As a first estimate, we estimate the amount of scandium potentially lost to red mud waste, assuming that all of the scandium content of red mud could be considered as a resource. Indeed, Wang et al. (2011) noted that ores with a scandium content ranging between 0.002 and 0.005% can be considered as resources of scandium and deserve exploitation. An estimated 0.0078 wt.% of Sc_2O_3 has been measured to be present in red mud by Wei et al. (2020), while Khairul et al. (2019) mention values</td><td>U1: 4 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
</table>

	ranging between 60 and 120 mg of scandium per kg of red mud. These references suggest a content of 0.005 wt.% and 0.006 – 0.012 wt.% of scandium in red mud, respectively, and therefore the scandium content of red mud may potentially be considered as a resource. Considering that about 150 million tons of red mud is generated yearly (Khairul et al., 2019), it is estimated that between 8 000 and 18 000 tons of scandium are deposited as part of red mud wastes each year. Based on this, it can be estimated that the production yield of scandium from bauxite most likely ranges between 0.05 and 0.2%. An average production yield of 0.13% is proposed as a first estimate for the production yield of scandium. It may warrant further investigations, including other potential sources of scandium.	
Fabrication and manufacturing	95%, including the recovery of new scraps (assumption)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
New scrap recovery	N/A; 0% reported in this dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	N/A; 0% reported in this dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	While some minor applications of scandium may have a potential for dissipation (Ciacci et al., 2015), these were assumed to be negligible and a 0% rate is reported for all scandium applications.	Per sector; please refer to Supplementary Data
Collection and sorting	Scandium contained in EoL products is not functionally recycled (BRGM, 2017c; Panousi et al., 2016).	Per sector; please refer to Supplementary Data

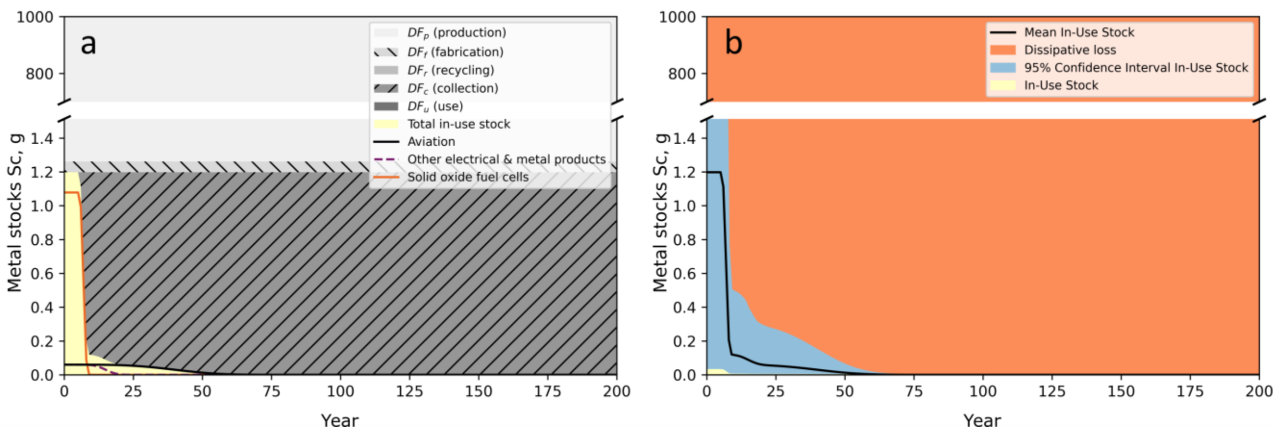

Figure S8. In-use stocks and losses of scandium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.10 Titanium

Table S17. Titanium.

<table>
<tr><th>Titanium</th><th>Ti, element number 22</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use data are reported for 2005 (Ciacci et al., 2015; Graedel et al., 2015) and 2013 (BRGM, 2017a). Titanium is mostly used as a pigment (TiO_2), with approximately 90% of global uses. These are mainly split between paint, paper, plastics & rubber, and to a lesser extent textile fibers and printing ink (BRGM, 2017a).

This end-use distribution is based on the data for 2013 (BRGM, 2017a). Various industrial applications for titanium metal are included in the Other industrial category, which includes e.g. chemical and petrochemical plants, deep-sea petroleum production, and seawater desalination (BRGM, 2017a; European Commission, 2020a; Woodruff et al., 2017). Printing ink is classified along with pigments used by the paper industry, assuming that printing ink is used on paper and therefore has the same lifetime. Moreover, parts of miscellaneous titanium applications are thought to be inherently dissipative, such as nano-scale applications in sunscreens, toothpaste, cosmetics, food additives, etc. (BRGM, 2017a; Ciacci et al., 2015; European Commission, 2020b). We assume that 1% of titanium is used in such applications, and grouped them in the pharmaceuticals & cosmetics category.

The following end-uses of titanium are estimated to be representative of 2013:
<table>
<tr><td>Aviation</td><td>2%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>8%</td></tr>
<tr><td>Other miscellaneous</td><td>2%</td></tr>
<tr><td>Paint</td><td>53%</td></tr>
<tr><td>Paper</td><td>11%</td></tr>
<tr><td>Pharmaceutics & cosmetics</td><td>1%</td></tr>
<tr><td>Plastics</td><td>23%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>86%, calculated based on the estimate for the recovery and refining of Graedel et al. (2015).</td><td>U1: 3 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>As new titanium scraps from metal applications are collected and recycled efficiently (Goonan, 2010; Takeda and Okabe, 2019), and as processes required to integrate and apply pigments in different applications are assumed to be relatively efficient, we consider an overall 95% yield covering all fabrication and manufacturing routes (including in-house new scrap recycling).</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>Only does titanium metal have a potential for recycling. The major resource for titanium recycling is in-house titanium scrap (metal) generated in smelting and fabrication processes (BRGM, 2017a; Takeda et al., 2020; Takeda and Okabe, 2019). Since cascade recycling occurs, it is difficult to precisely estimate the new scrap recovery yield. Moreover, titanium metal only covers about 5% of the end-uses of titanium. Therefore, we assumed the fabrication and manufacturing process yield to include the recovery of new scraps.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
</table>

Remelting	95%, assuming that remelting has the same yield as refining.	U1: 4 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	Ciacci et al. (2015) estimated that 10% uses in paint are dissipated in use due to corrosion (type B). Moreover, the uses of titanium included in the pharmaceutical & cosmetics category are estimated to be dissipative (type A). Dissipation in use for other titanium applications is considered to be negligible (Ciacci et al., 2015).	Per sector; please refer to Supplementary Data
Collection and sorting	Only metal uses are currently potentially recyclable (Ciacci et al., 2015). Graedel et al. (2015) report an EOL-RR of 20% for the "other" category, which includes titanium metal applications. The estimate is based on information obtained from a report for the US. In a recent publication, Graedel et al. (2022) provide revised EOL-RR for aviation (80%) and other metal uses (30%). The reported collection yields are corrected considering the remelting yield of 95%.	Per sector; please refer to Supplementary Data

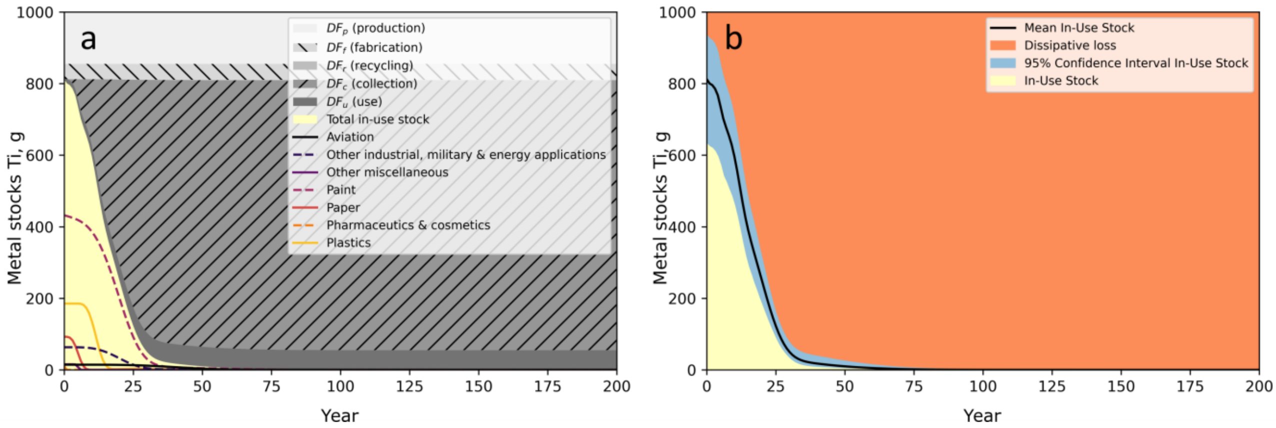

Figure S9. In-use stocks and losses of titanium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.11 Vanadium

Table S18. Vanadium.

Vanadium	V, element number 23	Uncertainty
End uses	Over 90% of vanadium is used in steel alloys (BRGM, 2018b; Nuss et al., 2014). The other uses of vanadium include titanium alloys used in aerospace industry for e.g. airframes and jet engine parts, aluminium alloys, as well as catalysts, glasses, ceramics, electronics and redox flow batteries (BRGM, 2018b; European Commission, 2020a; Kelley et al., 2017; Nuss et al., 2014). While catalysts could be used in both heterogeneous and homogenous catalysts (Ciacci et al., 2015), their typical average lifetime is estimated to be of 8-10 years (Ciacci et al., 2015; Nuss et al., 2014), and therefore they are aggregated in the Catalysts (heterogeneous & stable env.) category. Global end-uses are reported for the year 2017 (BRGM, 2018b), 2000 and 2011 (Nuss, 2014) and 2014 (Roskill, 2014). Bushveld Minerals Limited (2019) reports around 3% end-use of vanadium in redox flow batteries in 2018. Uses of vanadium are mostly reported as different types of steels in which it is alloyed (e.g., HSLA steel, full alloy steel) which are each used in different end-use sectors. Hence, classifying steels into different end-use categories is challenging. Here, it is disaggregated upon qualitative description and quantitative distribution of the principal end-uses for the different types of steels and alloys reported in a range of sources (BRGM, 2018b; Ciacci et al., 2015; European Commission, 2020a; Kelley et al., 2017; Nuss et al., 2014) as well as historical USGS stats. Based on available information, steels are considered to be used approximately 1/3 each in transport, construction (including pipelines and nuclear plants) and mechanical equipment. Although this end-use distribution would benefit from more detailed data, each of the main steel uses reported here are rather long lived, with a minimum average lifetime of 20 years. Hence, it is not expected that more precise data would have much influence on the results of this model. Based on this information, we estimated the following end-use distribution circa 2017-2018: Aviation: 4% Batteries (utility & industrial): 3% Catalysts (heterogeneous & stable env.): 2% Construction: 30% Glass & ceramics: 1% Mechanical equipment: 30% Transport: 30%	U1: 3 U2: 1 U3: 1 U4: 2 U5: 1
Production yield	Since vanadium can be produced from a wide array of materials and through specific proprietary procedures (USGS, 1994), estimating its production yield is difficult. Vanadium is mostly produced in three distinct ways: from the co-production along with iron, from primary production from ores and secondary production from e.g. spent catalysts from the petroleum industry (Moskalyk and Alfantazi, 2003; Nuss et al., 2014; Zhang et al., 2014). In 2014, co-production with iron provided about 64% of total supply of vanadium, along with 24% from	U1: 3 U2: 2 U3: 2 U4: 3 U5: 2

	primary production and 12% from other sources such as spent petroleum catalysts and vanadium-uranium ores (GE21 Consultoria Mineral, 2017). While co-production with iron is the principal source of vanadium, only do the largest steel plants recover vanadium oxides from slags (Ciacci et al., 2015). Around 2000, South Africa was the leading producer of vanadium, followed by Russia, China and to a lesser extent US and Australia (Goonan, 2011b; Moskalyk and Alfantazi, 2003). More recently, China became the main vanadium producer with around 60% of global production in 2019, followed by South Africa, Russia and Brazil covering most of the remaining production (Roskill, 2014; USGS, 2020). Nuss et al. (2014) calculated a 13.8% production loss based on USGS (1994), which seems to cover only vanadium recovery from plants that actually aim to recover vanadium as a by-product. This loss was of 10% in 2004 (Goonan, 2011b). Similarly, GE21 Consultoria Mineral (2017) report recovery yields of approximately to 90%. However, substantial quantities of vanadium may be lost in other potential sources of vanadium which are not accounted for in these yields. For instance, in 2010, around 32.2% of the available vanadium from different production routes was extracted in China, with only 25.6% of the iron ores being processed for vanadium extraction (Zhang et al., 2014). Given the paucity of available data, we estimate the global production yield based on an extrapolation of US and China's contributions to global production in 2019 based on USGS (2020) and their respective yields for the most recent years for which data was available, resulting in a production yield of 33%. As only a few countries produce vanadium in comparison to those refining petroleum or producing steel, it is likely that the actual global yield from all of the potential vanadium sources would be below this value, which may warrant additional investigations.	
Fabrication and manufacturing	A few national MFAs are available for vanadium, for the US and China (USGS, 2011, 1994; Zhang et al., 2014). The fabrication and manufacturing and new scrap recovery are extrapolated from available data for China (Zhang et al., 2014) and the US (Goonan, 2011b). Based on these two static MFAs, we assume that China is representative of 89% of the global production (approximately 31.6 kt entering fabrication), and the US, 11% (4 kt entering fabrication). However, the fabrication yield is not possible to measure from the MFA of Goonan (2011b) since vanadium used by the steel industry is reported to be dissipated by default, whereas we consider such losses as dissipation of type C. Hence, we assume the same dissipative losses to molten slags during the fabrication of steel products as in China in year 2010 in the calculation (approximately 22%). The resulting yield is 68%.	U1: 2 U2: 3 U3: 2 U4: 3 U5: 2
New scrap recovery	1%, using the same method as for fabrication and manufacturing, based on Goonan (2011b) and Zhang et al. (2014).	U1: 2 U2: 3 U3: 2 U4: 3 U5: 2
Remelting	We assume that collected new scraps are remelted with a yield of 95%. While a lower yield could be expected for the recycling of old scraps, these losses are taken into account in the reported collection yield (see the Collection and sorting box below).	U1: 4 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	Negligible for most applications; we consider that 10% of the vanadium content of catalysts is dissipated in use, based on Ciacci et al. (2015).	Per sector; please refer to Supplementary Data

Collection and sorting	The functional recycling of old vanadium scraps is mostly from high speed steels and superalloys (BRGM, 2018b). Most of the vanadium used in steel is not readily recovered, with the global EoL-RR for vanadium reported as below 1% circa 2010 (Graedel et al., 2011). While the USGS reported that around 40% of vanadium in catalysts originates from recycled vanadium from spent chemical process catalysts in the US in 2019 (USGS, 2020), these seem to refer to vanadium that accumulated on catalysts during petroleum refining rather than from actual vanadium catalysts (Nuss et al., 2014). Moreover, it is reported that China (which is a leading consumer of vanadium) virtually did not recycle any vanadium in 2010 (Zhang et al., 2014). Graedel et al. (2022) provide informed estimates for the global EOL-RR of vanadium, based on Petranikova et al. (2020): 5% for steel applications, and 15% for superalloys, and 0% for other applications. Without further information, we assume that the same EOL-RR of 5% apply to the construction, mechanical equipment and transport sectors. An EOL-RR of 15% is considered for the aviation sector (superalloys). These losses are corrected with an assumed remelting yield of 95%. While these are accounted for as collection losses, it should be noted that parts of these losses could be reported as remelting losses instead.	Per sector; please refer to Supplementary Data

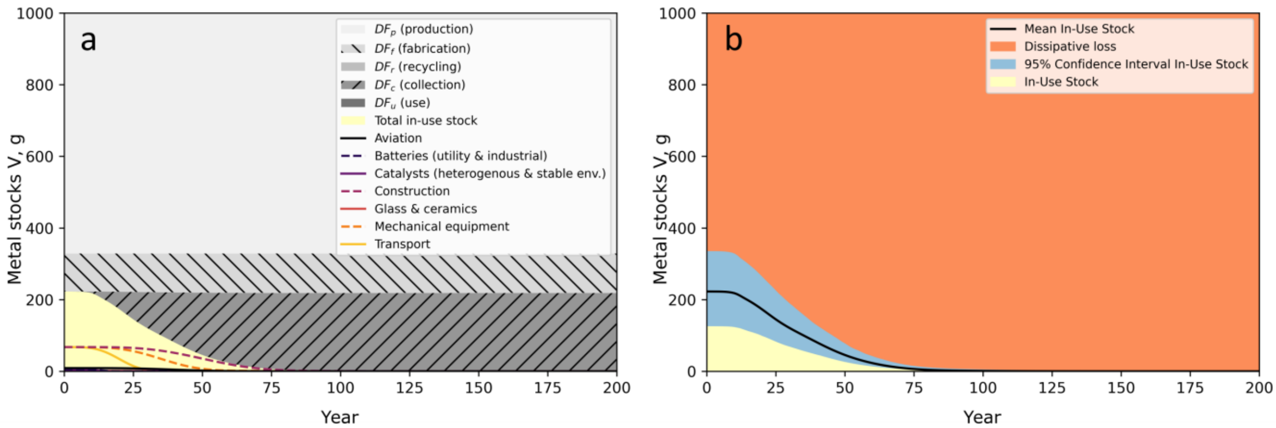

Figure S10. In-use stocks and losses of vanadium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.12 Chromium

Table S19. Chromium.

<table>
<tr><th>Chromium</th><th>Cr, element number 24</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distribution of chrome are available for 2000 (Ciacci et al., 2015 based on Johnson et al., 2006) and 2015 (BRGM, 2017d). The end-use distribution for chromium is calculated based on the data of 2015 (BRGM, 2017d). Since most of the end-uses for chromium are reported as materials (e.g., 23% chromium steels) or aggregated in multiple industries (e.g., 48% of stainless steel used in food industry, medical & domestic utensils), the BRGM’s distribution is partially matched with end-use sectors using the information of Ciacci et al. (2015) as an indication. Chromite directly used as foundry sand is accounted for in the Metallurgy & metalworking (process) category; part of chromium steels is aggregated in the mechanical equipment category along with industrial equipment. Half of the chemicals are assumed to be used in CCA used for wood treatment and aggregated in the infrastructure sector. The other half is aggregated in the Other industrial, military & energy applications category due to the variety of applications it includes (pigments for paint, leather tanning, chromium metal for e.g. aerospace, and chrome plating). The following end-use distribution is estimated to be representative of the year 2015:
<table>
<tr><td>Alloys & solders</td><td>4%</td></tr>
<tr><td>Construction</td><td>12%</td></tr>
<tr><td>Household appliances</td><td>5%</td></tr>
<tr><td>Infrastructure</td><td>14%</td></tr>
<tr><td>Mechanical equipment</td><td>31%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>2%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>14%</td></tr>
<tr><td>Refractories</td><td>0.2%</td></tr>
<tr><td>Transport</td><td>18%</td></tr>
</table>
</td><td>U1: 2
U2: 2
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>75% (Helbig et al., 2020, based on Johnson et al., 2006)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>73% (Helbig et al., 2020, based on Johnson et al., 2006).</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>A new scrap recovery of 44% can be calculated based on the global chromium MFA of 2000 (Helbig et al., 2020, based on Johnson et al., 2006). This yield is lower than that of other steel alloying elements, as downgraded new scraps were accounted for as fabrication losses in the MFA of Johnson et al. (2006).

Recycling losses of new scraps were here re-allocated to remelting, and a new scrap recovery of 68% was calculated. In comparison to the new scrap recovery previously reported, this new scrap recovery yield is closer to that of nickel (84%; cf. Table S23). Nickel is used in stainless steels in similar proportions as chromium. This difference may partly be explained by the lower value of ferritic stainless steel in comparison to nickel-containing austenitic stainless steel, and because the former are harder to separate from mixed steel scrap flows than the latter (cf. collection and sorting box).</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
</table>

Remelting	A remelting yield of 54% can be calculated based on the global chromium MFA of 2000 (Helbig et al., 2020, based on Johnson et al., 2006). The EOL-RR of chromium was estimated to be as high as 87-93% circa 2010 (UNEP, 2011). Most chromium is thought to be collected as part of steel products (Graedel et al., 2011); between 70 and 80% of stainless steels, accounting for over 70% of chromium end uses, get recycled (BRGM, 2017d). Considering our end-use distribution with the reported remelting yields of stainless steel uses per sector of Reck et al. (2010), an average remelting yield of chromium of approximately 90% can be calculated. However, non-functional recycling of chromium often occurs when chromium unintentionally enters old steel scrap flows (Helbig et al., 2022; Nakajima et al., 2013; Ohno et al., 2014), and this issue seems to lead to non-functional recycling in a larger proportion than it was estimated in the UNEP report of 2011 and in previous Reck et al.'s work. Recently, Reck provided an updated estimate of the EOL-RR of 42% for chromium across all of its applications (B.K Reck, personal communication, 01-27-2022). This estimate builds on the "Comprehensive Multilevel Cycle of Stainless Steel in 2015" study led by B. K. Reck (Team Stainless, 2021). Considering our reported collection yields and an EOL-RR of 42%, we report an average remelting yield of 52% for chromium. It is assumed that this remelting yield is also valid for new scraps. It should be noted that remelting losses could be attributed to sorting instead of remelting when chromium steels are unintentionally recycled in the wrong steel flow.	U1: 3 U2: 2 U3: 1 U4: 2 U5: 1
Dissipation in use	While negligible dissipation in use can be expected from metal applications of chromium, approximately 2.5% of chromium may leach from treated wood products over their lifetimes (Ciacci et al., 2015). The rate is corrected to 0.2% dissipation in use for the construction category when considering the share of chromium used in wood products aggregated in that sector. Moreover, some of the other uses of chromium may be dissipated in use. Ciacci et al. (2015) estimated that about 16% of chromium used in yellow paint is inherently dissipated in road paint. Leather tanning can also be considered to be dissipated in use (BRGM, 2017d). The exact share of chromium used in these applications is uncertain, but it was estimated to represent less than 1% of the global distribution of chromium uses. The resulting dissipation in use for these applications is taken into account in an estimated dissipation in use of 1% applied to the Other industrial, military & energy applications sector. Finally, the use of chromite as foundry sand for mold casting is considered to be totally dissipated in use over a lifetime of 1 year.	Per sector; please refer to Supplementary Data

Collection and sorting	The collection and recycling/remelting steps are aggregated in the global MFA of chromium of Johnson et al. (2006) underlying the works of Helbig et al. (2020). An EoL-RR of 54% was calculated based on that MFA. It was also reported by Nuss et al. (2014) using the same MFA reference, which they applied to all of chromium end-use applications. However, the latter also lacks a distinction between collection and remelting yields, and includes unrecyclable applications as part of the global EoL-RR. Hence, additional information is gathered in order to obtain application specific collection rates. Austenitic steels are easier to separate from old scrap steel flows in comparison to ferritic stainless steel; and the alloying content of ferritic steel is diffused in carbon steel recycling flows (Nakajima et al., 2013). Reck et al. (2010) estimated that, in 2005, 79% of steel products were collected for recycling, out of which 70% were recycled in stainless steel and 9% were downcycled in carbon steel flows (Reck et al., 2010). We use the estimates of Reck et al. (2010) to calculate the collection yields of chromium used in various applications made out of stainless steel. Values for other chrome steels and alloys are calculated using the lower range of values reported for stainless steel values as proxies (cf. Remelting box). Moreover, chromium contained in chemicals and refractory (“chrome-mag”) applications are considered not to be recyclable (Ciacci et al., 2015). We attributed a collection yield of 0% to these applications. The end-use of chemicals reported as CCA preservative is considered in order to adjust the collection rate applied to construction products. The following collection yields are reported, based on Reck et al. (2010): Alloys & solders, 60%; Construction, 82%; Household appliances, 70%; Infrastructure, 92%; Mechanical equipment, 92%; Other industrial, military & energy applications, 60%; Transport, 87%; and others, 0%.	Per sector; please refer to Supplementary Data

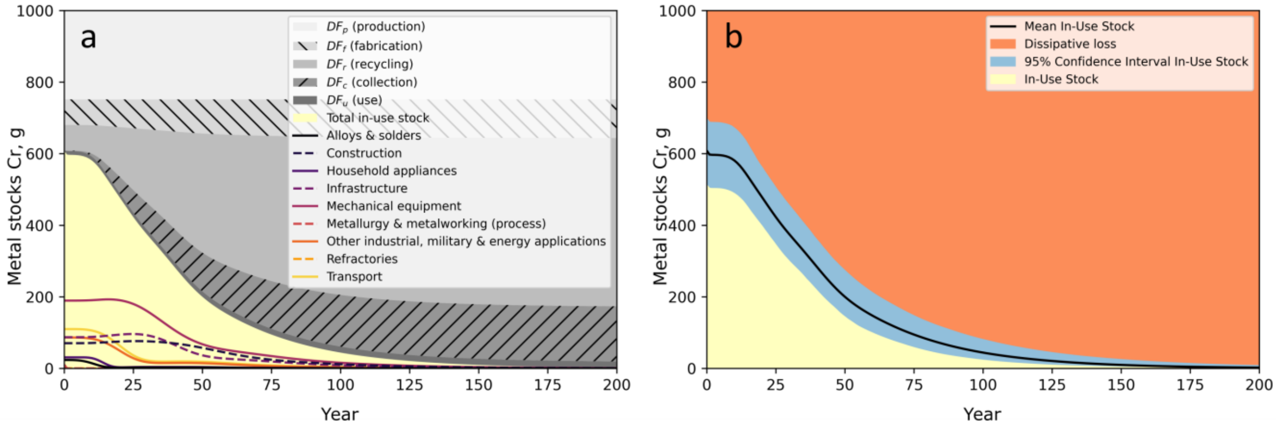

Figure S11. In-use stocks and losses of chromium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5^{th} percentile); the blue area represents the 2.5^{th}-97.5^{th} confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.13 Manganese

Table S20. Manganese.

<table>
<tr><th>Manganese</th><th>Mn, element number 25</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>
Manganese is a basic constituent of steel. Around 90% of the global manganese production is consumed by the steel industry, in which it is used to deoxidize and desulfurize iron, and as an alloying agent decreasing steel’s brittleness and increasing its strength (6 to 9 kg of manganese is used per ton on steel) (USGS, 2014). Other manganese uses include chemicals (animal feed, pesticides, water treatment), batteries, and non-ferrous alloys (aluminium and copper alloys) (Jones, 1994).
Nuss et al (2014) report the global end-uses of manganese in 2008. The European Commission reports global end-use of manganese for the year 2014 (European Commission, 2017b). In 2014, steel and aluminium alloys accounted for 87% and 6% of the global demand of manganese, respectively. Moreover, 5% of the global demand was used in chemicals, and 2% was used in the cathodes of batteries. We disaggregate end-uses of manganese in steel and other alloys based on Europe data for the years 2012-2016 (European Commission, 2020c), average USGS data for the years 2015-2019 (retrieved from USGS Mineral Commodity Statistics for these years), as well as global end-uses of steel reported by the World Steel Association (World Steel Association, 2020a, 2019). Asia uses a large proportion of the total steel products, with China alone consuming nearly half of the world total (World Steel Association, 2019). Similarly, Sun and colleagues (2020) reported that China accounted for 48% of the global apparent consumption of manganese, highlighting the correlation between steel and manganese consumption. Of the 6% reported to be used in non-ferrous alloys, one third is assumed to be used in aluminium cans given the important volume produced (Clarke and Upson, 2017). Chemicals are used in a wide variety of applications, most of which are estimated to be dissipative uses such as animal feed, fertilizers, maneb (fungicide), as well as potassium permanganate used for water purification, waste water treatment and odor control (International Manganese Institute, 2021).
Moreover, around 30% of manganese used in steelmaking is used for deoxidization and desulfurization, while the remaining 70% is used in the alloy as part of the final product (USGS, 2014). Therefore, we report that 30% of the manganese used in steelmaking is for deoxidization and desulfurization purposes (about 26% of the total end-use of manganese); and the remainder of the end-uses are normalized to 70% of the end-use applications of steel products.
Based on this information, data matching and reconciliation into end-use sectors is performed, providing the following estimates considered to be representative of the global yearly averages circa 2015-2019:
<table>
<tr><td>Alloys & solders</td><td>4%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>2%</td></tr>
<tr><td>Chemicals</td><td>5%</td></tr>
<tr><td>Construction</td><td>32%</td></tr>
</table>
</td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
</table>

	<table><tr><td>Household appliances</td><td>3%</td></tr><tr><td>Mechanical equipment</td><td>9%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>26%</td></tr><tr><td>Other electrical & metal products</td><td>7%</td></tr><tr><td>Packaging</td><td>2%</td></tr><tr><td>Transport</td><td>11%</td></tr></table>	
Production yield	A historical study of manganese flows in the US is available (Jones, 1994), along with national MFAs for manganese in the US in 1998 (USGS, 2004b), South Korean steel industry in 2005 (Jeong et al., 2009) and Japanese steel industry, also in 2005 (Nakajima et al., 2008). In 2019, manganese was mostly produced as silicomanganese (1.73 billion mt), followed by manganese ores (20.3 million dry mt) and high carbon ferromanganese (4 million mt) (International Manganese Institute, 2019). To a lesser extent, low and medium carbon ferromanganese are also produced along with electrolytic manganese metal (EMM) and electrolytic manganese dioxide (EMD) (Elliott et al., 2018a; International Manganese Institute, 2019). In 2019, 1.52 million mt of EMM was produced from manganese ores, most of which in China with 97% of global EMM production (International Manganese Institute, 2019). On top of the manganese content in iron ores, manganese is often directly extracted as an alloying agent through the additions of steel scraps, manganese ores and manganese alloys at different stages of the steelmaking process, making it difficult to determine specific yields for the production and fabrication processes separately. EMM is also used for the production of copper and aluminium alloys. Elliott et al. (2018a) provide a detailed review of the major production processes of manganese alloying materials used in steelmaking. The production yield is here estimated to cover the share of manganese that remains in the EMM, EMD, ferromanganese or silicomanganese before these are used in steelmaking or in other alloys and products. Westfall et al. (2015) report a 68.8% recovery rate for the production of ferromanganese from manganese ores. A yield of 65% is calculated from the data in the ES for manganese compounds and metal in the US in 1998 (USGS, 2004b). South Korean data indicate a similar yield of 69% for the production of crude steel (Jeong et al., 2009). Dashevskiy et al. (2013) report 45 to 40% losses of manganese to slags in the production of manganese ferroalloys with the silicothermal process. Elliott et al. (2018b) estimated 40% loss of MnO to the slag phase during carbothermic reduction of manganese oxides from manganese ores in the conventional FeMn process. Elliott et al. (2018a) reported a global average of 85% recovery from all production routes for alloying materials; however, this yield does not seem to cover the operations occurring prior to the smelting (for manganese alloys) or electrowinning processes (for EMM and EMD production). When considering the yields of ore processing & beneficiation and sinter production of FeMn (Westfall et al., 2015), the production yield falls back to 71%. Based on these references, we consider an average production yield of 70%. While it is attempted to provide the best possible estimate for the production yield of manganese, there may some losses included in the	U1: 3 U2: 1 U3: 1 U4: 2 U5: 1

	reported yield that are also accounted for in the use of manganese for deoxidization and desulfurization purposes. This may deserve some attention if a dedicated study of manganese flows is performed.	
Fabrication and manufacturing	We approximate the steelmaking (and other alloy/chemicals) yields altogether based on the previously cited literature (Jeong et al., 2009; Nakajima et al., 2008; USGS, 2004b) and the 70% yield that is reported for production. For example, the steelmaking efficiency in the US is measured by dividing 65% reported efficiency from manganese extraction to manganese-bearing metal and compounds with 70% production rate, resulting in a yield of 91% for steelmaking (i.e. alloying manganese content of FeMn, SiMn and EMM into steel). In addition to these yields, additional manufacturing and fabrication losses can be expected to be similar to the fabrication yield of steel products. We assume the latter to correspond to the 87% fabrication yield calculated from US data, which closely matches the yield of fabrication for iron products considered in this dataset (i.e. 89%, cf. Table S21). Combining these yields results in an average yield of 73% for the fabrication and manufacturing processes.	U1: 3 U2: 4 U3: 2 U4: 2 U5: 1
New scrap recovery	We consider a new scrap recovery yield of 95% calculated on statistics for the US in 1998 (USGS, 2004b), which is adjusted to include the unrecovered losses of manganese to slags during steelmaking (approximately 8%), resulting in a new scrap recovery yield of 88%.	U1: 3 U2: 4 U3: 2 U4: 2 U5: 1
Remelting	Based on the consulted literature, we estimate a functional remelting yield of 80%, the rest being lost to slags. There may be some discrepancies between what is considered to be functional recycling between references: cf. the Collection and sorting box below.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	Some steel applications may have minor in-use dissipation, such as the abrasion of railways, though these may be considered to be negligible (Ciacci et al., 2015). Moreover, we estimate that 80% of manganese chemicals are dissipated during use based on a qualitative description of its most common applications (International Manganese Institute, 2021).	Per sector; please refer to Supplementary Data
Collection and sorting	Manganese uses as chemicals are thought to be unrecyclable, while uses in steel and non-steel alloys as well as batteries could be recycled (Ciacci et al., 2015). The UNEP reported EoL-RR of over 50% for manganese (Graedel et al., 2011) based on USGS (2004a), while the EC mentions actual functional recovery rates of 10% (European Commission, 2020a). US stats for 1998 suggest a recycling rate of 53% for old scraps of aluminium, iron & steel products containing manganese (USGS, 2004a). The rates reported by the USGS seem to represent old scraps entering the recycling flow rather than actual functional recycling, although they have been considered as functional recycling rates in the Yale's criticality study (Nuss et al., 2014). Such discrepancies may result from the consideration of different definitions of functional recycling, provided that manganese can potentially be considered to be functionally recycled when it is used as a deoxidization and desulfurization of steel even when it ends up in slags. In this dataset, we assume the actual EOL-RR to be halfway between that reported by the US and that by the EC, with a global EOL-RR of 32%. This value is corrected accordingly with the remelting yield of 80%, resulting in an estimated collection rate of 39% for manganese contained in steel-containing applications and other alloys. Finally, a collection rate of 58% is reported for packaging applications based on	Per sector; please refer to Supplementary Data

	aluminum's collection yield (cf. Table S14), and an EOL-RR of 0% is considered for batteries and chemicals based on Nuss et al. (2014).	

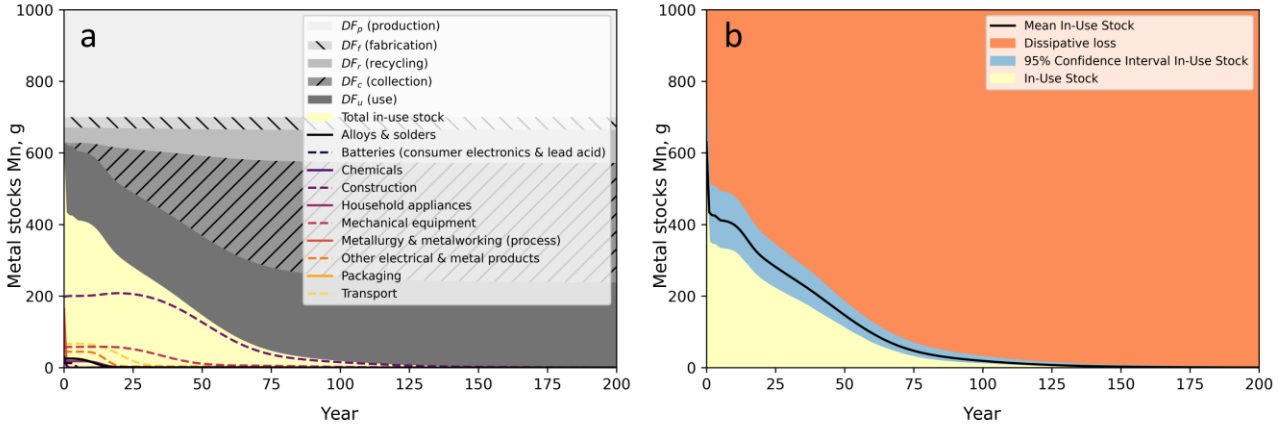

Figure S12. In-use stocks and losses of manganese over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.14 Iron

Table S21. Iron.

Iron	Fe, element number 26	Uncertainty
End-uses	End-uses of iron largely consist of steel applications, which have been used in the Yale studies to establish end-use distributions in 2008 (Graedel et al., 2013). Other end-use distributions of steel are available for the year 2008 (Cullen et al., 2012) and 2019 (World Steel Association, 2020b). The latter end-use distribution is considered to build the current dataset, using the values of 2008 (Cullen et al., 2012) to further disaggregate the construction and metal products categories. The 10% metal products are considered to be split between packaging (0.5%), home appliances (2%) and other metal products (8%). Similarly, the 52% end-use in the construction sector is estimated to be split between construction (31%) and infrastructure (21%). The following end-use distribution is estimated to be representative of 2019: Construction: 31% Electronics: 3% Household appliances: 4% Infrastructure: 21% Mechanical equipment: 16% Other electrical & metal products: 8% Packaging: 0.5% Transport: 17%	U1: 2 U2: 1 U3: 1 U4: 1 U5: 1
Production yield	87% (Helbig et al., 2020, based on Wang et al., 2007). Other data for 2004 (Price, 2009) and a more recent global steel MFA for 2008 (Cullen et al., 2012) suggest the 87% yield to be reasonnable. Thus, although the MFA is representative of year 2000, we estimate that the production yield remains sensibly the same in recent years given the long history of ironmaking and steelmaking processes. Uncertainty is reported accordingly.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Fabrication and manufacturing	89% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009): uncertainty is reported accordingly.	U1: 1 U2: 4 U3: 1 U4: 1 U5: 1
New scrap recovery	100% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009): uncertainty is reported accordingly.	U1: 1 U2: 4 U3: 1 U4: 1 U5: 1
Remelting	94% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009); uncertainty is reported accordingly.	U1: 1 U2: 4 U3: 1 U4: 1 U5: 1
Dissipation in use	Helbig et al. (2020) calculated an average dissipation rate of 1% for all steel products based on Wang et al. (2007). This dissipation in use is seemingly due to atmospheric corrosion of steel used in building and construction as well as friction and corrosion of steel products used in transportation. Ciacci et al. (2015) estimated that about 0.5% of steel is expected to be lost over a lifetime of 50 years in construction (including infrastructure), and 0.4% in the transport sector. These dissipation rates are reported for the corresponding sectors.	Per sector; please refer to Supplementary Data
Collection and sorting	Helbig et al. (2020) calculated an average collection yield of 74% for all steel products based on Wang et al. (2007). In this dataset, the EoL-RR are disaggregated per sector. The values reported by Nuss et al.	Per sector; please refer to Supplementary Data

	(2014), citing Pauliuk et al. (2013), are considered: construction, 87% (attributed to construction and infrastructure), machinery, 82% (attributed to mechanical equipment); transport, 82%; and 58% for other products (attributed to all of the other categories). Considering a remelting yield of 94%, collection rates of 93% are calculated for construction and infrastructure; 87% for transportation and mechanical equipment; and 62% for all other applications. We consider these values to remain representative of recent years, and uncertainty is reported accordingly.	

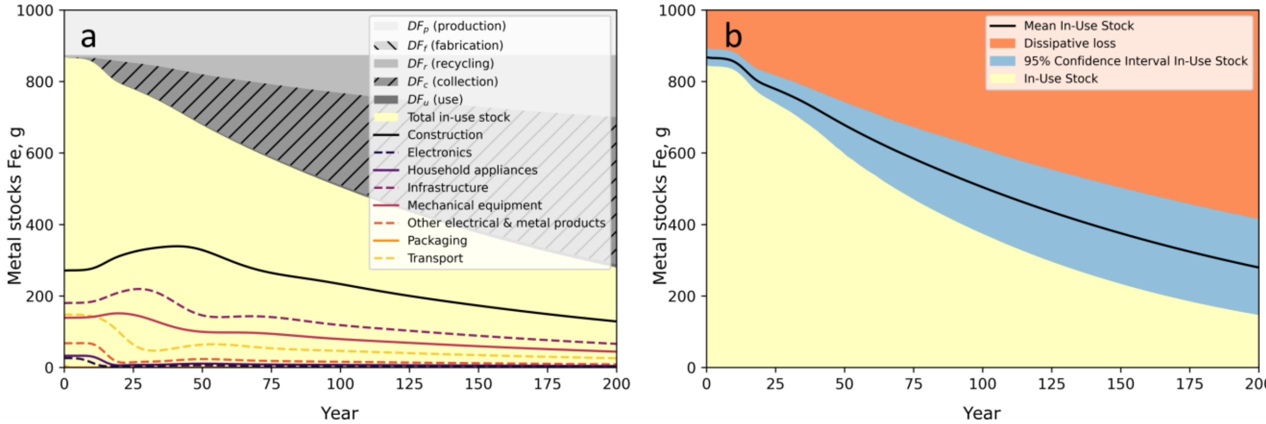

Figure S13. In-use stocks and losses of iron over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.15 Cobalt

Table S22. Cobalt.

Cobalt	Co, element number 27	Uncertainty
End-uses	Cobalt end-use distributions are available for the year 2006 (Graedel et al., 2015), 2011 (Roberts and Gunn, 2014), 2016 (BRGM, 2017e) and 2017 (Fu et al., 2020). The principal use of cobalt is in rechargeable batteries, with 53% of the consumption of cobalt in 2017 (up from 22% in 2006, and 30% in 2011), followed by superalloys (16%). The reported distribution is representative of the year 2017, based on Fu et al. (2020) and matching data to end-use sectors using other complementary information provided for 2016, for which the distribution is similar (BRGM, 2017e). The share of catalysts is split in 2/3 as petroleum refining catalysts (lifetime of 2 years) and 1/3 as polyester precursor and hydroformylation (oxo-process) catalysts (lifetime of 8 years) based on Ciacci et al. (2015) and Harper et al. (2012). Cobalt compounds used as pneumatic and drying agents are classified as Other miscellaneous uses, along with other undefined applications. Superalloys and hardfacing alloys are aggregated in the alloys sector. Pigments are estimated to be used mostly for ceramics and glazes (BRGM, 2017e) and are aggregated in the glass & ceramics sector. Samarium-cobalt magnets are added to the other industrial sector based on typical applications for these magnets (cf. Table S49). Since batteries represented a large share of end-uses of cobalt, its share across different types of applications was further detailed. Fu et al. (2020) reported that, in 2017, 40% out of 53% of cobalt used in batteries was for consumer electronics, the other two main uses being EVs and advanced battery energy storage systems. Given the importance of Chinese consumption of cobalt especially for the rechargeable battery industry (USGS, 2020), we also analyzed the cobalt use in the battery industry in China in recent years (Chen et al., 2020; Liu et al., 2021). According to the distribution of cobalt consumption in several battery applications in China in 2015 (Chen et al., 2020), approximately 35 kt of cobalt was consumed for batteries in total. These include lithium ion, NiMH and NiCd batteries, which were used for about 83% in consumer electronics products (for this analysis, we included electric bicycles and other special vehicles in this category), 6% for energy storage systems and 11% for electric vehicles (including electric and hybrid cars and buses). Moreover, in 2018, cobalt used in lithium ion batteries was estimated to be shared half and half between consumer electronics and electric vehicles, with approximately 10 kt each (Liu et al., 2021). These values suggest a rapid transition of the use of cobalt towards electric vehicles especially in the past 5 years. It is apparent from the studied literature that cobalt has been increasingly used in lithium ion batteries for electric vehicles, while consumer electronics seem to have beneficiated from an increase of the efficiency of cobalt use in lithium ion batteries (cf. Roberts and Gunn, 2014), reducing the relative share of cobalt in these batteries. Based on this information, we estimate that globally, in 2017, about 20% of cobalt used in batteries was used in EVs, 75% was used in consumer electronics, and 5% was used in energy storage systems. The latter is reported as industrial batteries. Given the sharp trends that are	U1: 2 U2: 1 U3: 1 U4: 1 U5: 3

<table>
<tr><td></td><td>observed, special attention should be paid to the evolution of cobalt uses in batteries if ever it is attempted to update these data. The following distribution is estimated to be representative of the year 2017:
<table>
<tr><td>Alloys & solders</td><td>20%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>40%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>11%</td></tr>
<tr><td>Batteries (utility & industrial)</td><td>3%</td></tr>
<tr><td>Catalysts (heterogeneous & stable env.)</td><td>2%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>4%</td></tr>
<tr><td>Cutting tools</td><td>7%</td></tr>
<tr><td>Glass & ceramics</td><td>5%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>3%</td></tr>
<tr><td>Other miscellaneous</td><td>6%</td></tr>
</table></td><td></td></tr>
<tr><td>Production yield</td><td>44% (Helbig et al., 2020, based on Harper et al., 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>94% (Helbig et al., 2020, based on Harper et al., 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>5% (Helbig et al., 2020, based on Harper et al., 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>While the MFA of cobalt for 2005 allowed to calculate a remelting yield of 31% (Harper et al., 2012), the value is updated given the new values of EOL-RR considered in this dataset (cf. the collection and sorting box). While multiple recycling industries may recycle different cobalt products (Roberts and Gunn, 2014), we assume an average remelting yield of 95%, and the remainder of losses are here attributed to the collection and sorting step.</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Ciacci et al. (2015) estimated losses of cobalt of 5% in cemented carbides, as well as 9% in catalysts used in the oxo-process (hydroformylation) and 5% in heterogeneous catalysts. Based on this information, we report 5% dissipation in use for catalysts used in petroleum refining, and an average 7% for long lived catalysts (including catalysts used in the oxo process). Other cobalt applications are not considered to be dissipated during use.</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Helbig et al. (2020) calculated an average collection yield of 22% in 2005, based on Harper et al., 2012). The EoL-RR has seemingly increased rapidly in the following years due to the rapidly increasing use of cobalt in batteries, reaching an estimated EoL-RR of 68% around 2010 (UNEP, 2011).

We consider that chemicals (classified in the Other industrial, military & energy applications), short lived petroleum catalysts, glass products and other miscellaneous uses of cobalt are not collected for recycling (Ciacci et al., 2015; Graedel et al., 2015; Roberts and Gunn, 2014). An estimated EoL-RR of 50% is considered for carbides (cutting tools) based on Graedel et al. (2015), 80% for superalloys and 89% for long lived catalysts (Graedel et al., 2015), 90% for electric vehicle batteries and 10% for magnets (Harper et al., 2012). The same 90% value is assumed to apply to energy storage applications (industrial batteries). Furthermore, while it is particularly difficult to track the recycling of</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	cobalt in consumer electronics batteries (see e.g., Chancerel et al., 2016), an estimated EoL-RR of 35% is reported based on the consulted literature. The reported collection yields are calculated considering a remelting yield of 95%.	

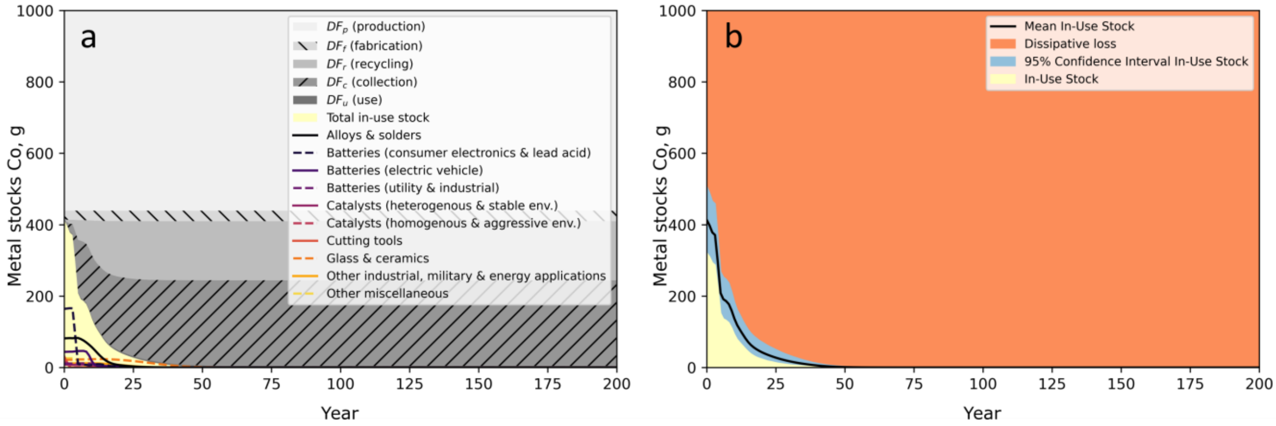

Figure S14. In-use stocks and losses of cobalt over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.16 Nickel

Table S23. Nickel.

<table>
<tr><th>Nickel</th><th>Ni, element number 28</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distributions of nickel are available for several years, e.g. 2008 (Ciacci et al., 2015; Graedel et al., 2015), 2015 (BRGM, 2016b) and for a recent unspecified year (Nickel Institute, 2021a), based on Roskill. The Nickel Institute also provides the distribution of nickel is different materials or semi-products (Nickel Institute, 2021b). The shares of nickel in its end-use applications seem to have remained rather stable over the studied years. Around 65-70% of nickel is used for stainless steel for various applications. Other uses include batteries, other steel alloys and non-ferrous Cu- and Ni- based alloys. The distribution of the Nickel Institute (2021a) is used to establish the end-use distribution of nickel, using the other references to disaggregate some of the reported values. The 10% share reported for electronics is assumed to combine batteries (5% of use of nickel) along with other electronic applications which are disaggregated in two separated categories. Batteries are reported as consumer batteries, considering that electric vehicles and hybrid vehicles mostly replaced NiMH batteries with Li-ion batteries in recent years. The use of nickel in engineering applications is reported as mechanical equipment. Metal goods may include a range of appliances such as dishwashers, washing machines, tools, cutlery, pots and pans (Graedel et al., 2015); these are all classified as household appliances. Finally, nickel compounds used in various applications are also considered as an end-use sector and reported as chemicals, representing 1% of total nickel consumption (Ciacci et al., 2015; Nickel Institute, 2021b). The following end-use distribution is estimated to be representative of years circa 2015-2019:
<table>
<tr><td>Aviation</td><td>3%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>5%</td></tr>
<tr><td>Chemicals</td><td>1%</td></tr>
<tr><td>Construction</td><td>16%</td></tr>
<tr><td>Electronics</td><td>5%</td></tr>
<tr><td>Household appliances</td><td>22%</td></tr>
<tr><td>Mechanical equipment</td><td>31%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>4%</td></tr>
<tr><td>Transport</td><td>12%</td></tr>
</table>
</td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>79% (Helbig et al., 2020, based on Reck and Rotter, 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>86% (Helbig et al., 2020, based on Reck and Rotter, 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>84% (Helbig et al., 2020, based on Reck and Rotter, 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Reck and Rotter, 2012)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Dissipation may occur from various chemicals used as e.g. fertilizers, and a dissipation rate of 50% is reported for that sector based on Ciacci</td><td>Per sector; please refer to</td></tr>
</table>

	et al., (2015). Dissipation in use from other nickel applications is estimated to be negligible (Ciacci et al., 2015), and 0% is reported for all other applications.	Supplementary Data
Collection and sorting	Helbig et al., (2020) calculated an average collection rate of 63% based on (Reck and Rotter (2012). The BRGM estimates that between 80 and 90% of stainless steels get recycled (BRGM, 2016b). The global EoL-RR of nickel was estimated to be between 57 and 63% by the UNEP's report on recycling rates (UNEP, 2011), and as high as 68% in 2010 by the Nickel Institute (2016). The latter also reported that, out of the 32% that is not functionally recycled, around 17% of nickel contained in EoL products is lost to landfills (mainly metal goods and electrical and electronic equipment), while 15% is non functionally recycled in the carbon steel loop (Nickel Institute, 2021c). Given the calculated remelting yield of 100%, we consider losses to the carbon steel flows as collection losses, unlike in the case on chromium, where the calculated remelting yield is around 90% and includes losses to carbon steel (Table S21). These slight differences between chromium and nickel do not have much influence on the results of the model; however, some attention could be spent on harmonizing these in future research. The following collection rates are reported in this dataset based on Graedel et al. (2015), which are estimated to be representative of the current recycling situation based on the other consulted literature. It is assumed that the collection yield for household appliances is the average collection yield reported for household appliances and metal goods: aviation, 74%; batteries, 29%; chemicals, 0%; construction, 87%; electronics, 29%; household appliances, 39%; mechanical equipment, 87%; and others, 29%. Assuming a constant distribution of nickel between end-use applications over time, these collection rates result in an EOL-RR of 65% across all nickel applications. These data are similar to those underlying the collection and sorting yield of chromium that is also largely used in stainless steel products (Table S19), suggesting some degree of consistency between these two steel-alloying elements.	Per sector; please refer to Supplementary Data

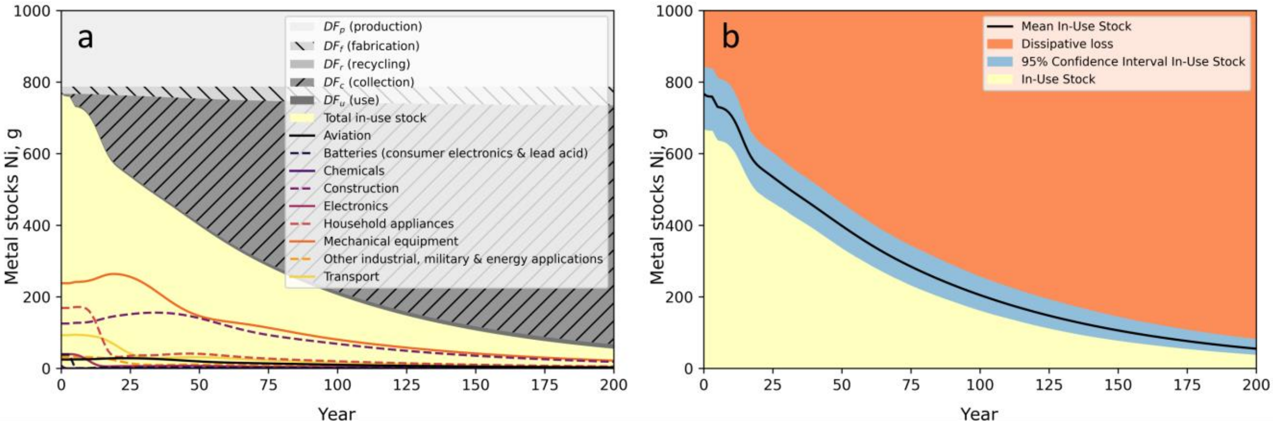

Figure S15. In-use stocks and losses of nickel over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.17 Copper

Table S24. Copper.

<table>
<tr><th>Copper</th><th>Cu, element number 29</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Multiple global end-use distributions are available for copper. Some recent distributions include that of 2016 (BRGM, 2018c) and 2019 (International Copper Study Group, 2020). The latest distribution of 2019 is considered, while the distribution of Ciacci et al. (2015) is used to disaggregate the “equipment” category, representing 31% of end-uses in 2019. Of these, 11% is considered to be used in electronics, 5% in telecommunication, and 14% in a range of other miscellaneous applications. Moreover, 0.5% of end-uses of copper are classified as chemicals, which are thought to be dissipated in use in appications such as fireworks, pesticides and animal feed (Ciacci et al., 2015). Industrial equipment is classified as mechanical equipment. The following distribution is estimated to be representative of the year 2019:
<table>
<tr><td>Chemicals</td><td>1%</td></tr>
<tr><td>Construction</td><td>28%</td></tr>
<tr><td>Electronics</td><td>11%</td></tr>
<tr><td>Infrastructure</td><td>16%</td></tr>
<tr><td>Mechanical equipment</td><td>12%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>14%</td></tr>
<tr><td>Telecommunication</td><td>5%</td></tr>
<tr><td>Transport</td><td>13%</td></tr>
</table>
</td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>83% (Helbig et al., 2020, based on Glöser-Chahoud, 2017). The works of Glöser-Chahoud were published in a scientific article (Glöser et al., 2013) and we considered this value to be as relevant for the uncertainty assessment.</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>82% (Helbig et al., 2020, based on Glöser-Chahoud, 2017)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>92% (Helbig et al., 2020, based on Glöser-Chahoud, 2017)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Glöser-Chahoud, 2017)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Some uses of copper imply dissipation in use. Ciacci et al. (2015) report that about 0.4% of copper used in transport, 0.6% of copper used in plumbing, and 0.7% of copper used in architectural applications may be dissipated during use. The latter two are weighted to represent their share of the construction sector (approximately 2% for architectural uses, and 6% for pipes, out of 28% of copper used in construction). This results in approximately 0.2% of the copper used in construction to be dissipated in use over its lifetime. Furthermore, chemicals are considered to be used in dissipative applications and are attributed a dissipation in use rate of 100%.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

Collection and sorting	All of the losses of copper during EOL waste management are attributed to collection, considering the remelting yield of 100%. Helbig et al. (2020) calculated an average collection yield of 47% based on Glöser-Chahoud (2017). In contrast, a slightly lower overall EoL-RR of 40% (International Copper Study Group, 2020) is used as a guideline to establish collection rates per sector. The estimates of Glöser et al. (2013, table 1) are used as a starting point to estimate the following collection yields: construction & infrastructure, 55%; electronics & telecommunication, 25%; mechanical equipment; 40%; transport, 40%; and other uses, 30%. As a general indication, these yields follow similar trends to alloying elements for stainless steel used in similar end-use sectors (nickel and chromium), albeit being lower for copper across its applications.	Per sector; please refer to Supplementary Data

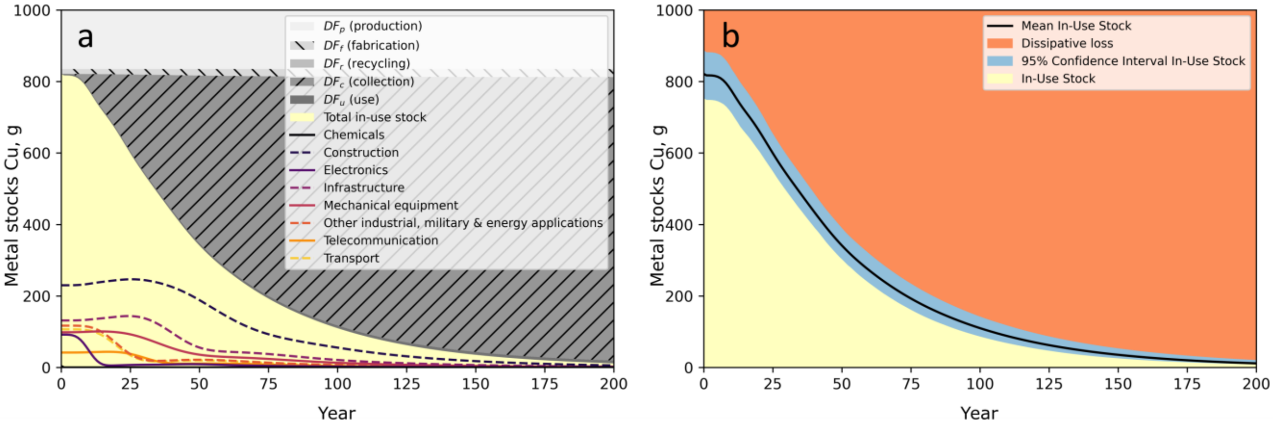

Figure S16. In-use stocks and losses of copper over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.18 Zinc

Table S25. Zinc.

Zinc	Zn, element number 30	Uncertainty
End-uses	Global end-use distribution of zinc are available for the years 2008 (Harper et al., 2015), 2010 (Meylan and Reck, 2017), 2011 (Ciacci et al., 2015) and 2018 (International Lead and Zinc Study Group, 2021a). The end-uses seem to have remained mostly the same over the 2008-2018 period. Hence, the distribution of Meylan and Reck (2017) is selected to establish the current end-use distribution, because it links first uses of zinc to actual end-use sectors. The principal first use of zinc is for galvanizing steel and iron products (52%), followed by zinc alloying (25%), chemicals (10%), brass (9%) and others (4%) (Meylan and Reck, 2017). Galvanized steel, brass and alloys may each be used for construction, transport, electrical and electronic and miscellaneous applications (Ciacci et al., 2015; Meylan and Reck, 2017). The authors have attributed these first uses to end-use applications. However, it is not possible to replicate the allocation procedure with the data provided by the authors, and some estimations are necessary to establish the end-use distribution for this dataset. It is estimated that about 5% out of the 25% reported in transport applications is for the vulcanization of rubber and improvement of performance of tires, based on Ciacci et al. (2015) as well as the dissipation share attributed to transport in the MFA of Meylan and Reck (2017). Moreover, 20% of miscellaneous uses are reported as other miscellaneous applications, and 80% as protective coatings. Finally, half of the end-uses reported as electrical and electronic products are reported as electronics, and the other half as Other metal and electronic products, to reflect the variety of potential applications. The following distribution is estimated to be representative of 2010, and to be fairly representative of years 2008-2018 given the apparent stability of zinc end-uses over time: Agricultural & environmental applications: 1% Construction: 33% Electronics: 10% Mechanical equipment: 7% Other electrical & metal products: 10% Other miscellaneous: 3% Protective coatings: 12% Rubber: 5% Transport: 20% This distribution could benefit from more precise data than those available in the consulted literate to establish the distribution of end-uses of zinc between electronics, home appliances, electrical products and other miscellaneous applications. Nonetheless, most of these applications of zinc are estimated to have lifetimes between 10 and 15 years according to (Meylan and Reck, 2017), similarly to the lifetimes reported in this dataset. Therefore, the uncertainty of this end-use distribution is expected to have a small influence on the results of the model for zinc.	U1: 1 U2: 2 U3: 1 U4: 2 U5: 1

Agricultural & environmental applications	1%
Construction	33%
Electronics	10%
Mechanical equipment	7%
Other electrical & metal products	10%
Other miscellaneous	3%
Protective coatings	12%
Rubber	5%
Transport	20%

Production yield	84% (Helbig et al., 2020, based on Meylan and Reck, 2017)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
Fabrication and manufacturing	78% (Helbig et al., 2020, based on Meylan and Reck, 2017)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
New scrap recovery	91% (Helbig et al., 2020, based on Meylan and Reck, 2017)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
Remelting	64% (Helbig et al., 2020, based on Meylan and Reck, 2017)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
Dissipation in use	About 0.4% of zinc coatings used in construction is dissipated yearly, resulting in 20% zinc being dissipated over a building's lifetime of 50 years (Ciacci et al., 2015). Moreover, the dissipation in use rates are estimated for other applications based on Ciacci et al. (2015) and Meylan and Reck (2017): 100% for agricultural applications; 5% for the protective coatings category (including some uses for industrial and metal working machinery); 5% for other miscellaneous applications (taking into account losses from e.g. sacrificial anodes, paint and lubricants); and 40% for rubber (tires). The dissipation from other applications is estimated to be negligible.	Per sector; please refer to Supplementary Data
Collection and sorting	Helbig et al. (2020) calculated an average collection yield of 65% based on Meylan and Reck (2017). The latter reference is used to report collection rates per application category, that are recalculated taking into account the different aggregation into end-use sectors that is used in this dataset. For instance, the collection yield for transport category is corrected to take into account the share of tires included in that category in the works of Meylan and Reck (2017). The following collection rates are calculated: construction, 52%; electronics, 40%; mechanical equipment, 82%; other electrical & metal products, other miscellaneous and protective coatings, 29%; and transport, 61%. Some estimations and end-use aggregations different than that of Helbig et al. (2020) and Meylan and Reck (2017) are made in this dataset. The reported collection yields, combined with the remelting yield of 64%, suggest a global EoL-RR of approximately 30% for zinc if a constant end-use distribution is assumed, similar to that of 33% that was calculated by Meylan and Reck (2017) for 2010.	Per sector; please refer to Supplementary Data

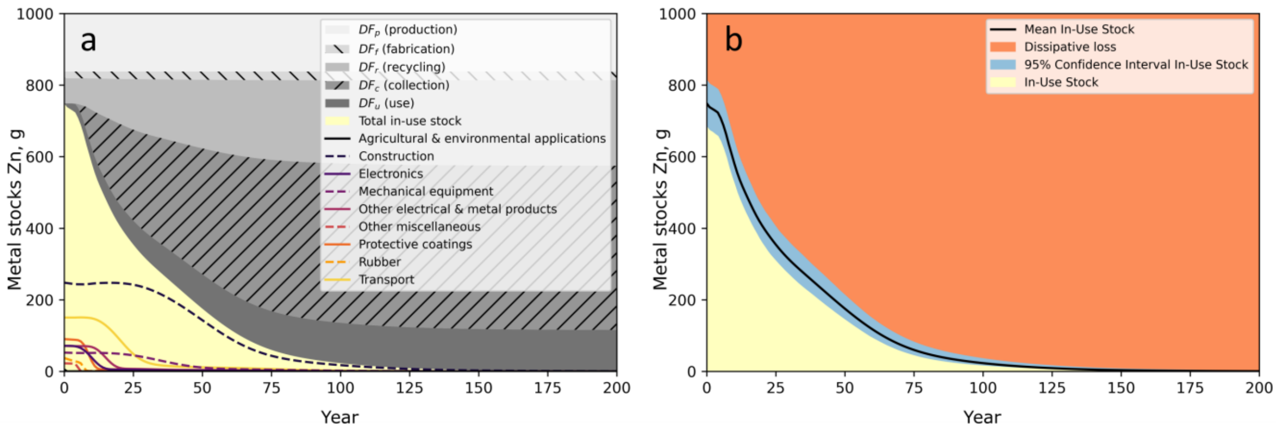

Figure S17. In-use stocks and losses of zinc over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.19 Gallium

Table S26. Gallium.

<table>
<tr><th>Gallium</th><th>Ga, element number 31</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distributions are available for 2010 (Butcher and Brown, 2014 and Peiró et al., 2013), 2011 (Licht et al., 2015) and 2013 (BRGM, 2016c). The USGS also provide qualitative and quantitative indications of the major global markets for gallium (GaAs wafers used in e.g. smartphones, GaN used in opto and power semi-conductors, LEDs and radiofrequency devices, and copper-indium-gallium-selenide solar cells) in the Mineral Yearbooks (Jaskula, 2020) and Mineral Commodity Summaries (USGS, 2020). For this dataset, the most disaggregated distribution of Butcher and Brown (2014), also considered in the works of Ciacci et al. (2015), is used as a starting point, and is updated based on other available information (BRGM, 2016c; Jaskula, 2020; Licht et al., 2015; USGS, 2020).

Given the variety of uses of semi-conductors and integrated circuits, we estimate that about 70% of gallium is used in various electronics applications, regrouping LEDs used in e.g. computer screens and tablets, as well as integrated circuit boards used for e.g. smartphones, and radiofrequency devices. It is also estimated that 10% of gallium is used in used in various telecommunication and defense applications such as military radars, wireless telecommunication infrastructure and cable television transmission, which are all aggregated in telecommunications. The following distribution is estimated to be representative of years circa 2013-2019:
<table>
<tr><td>Alloys & solders</td><td>5%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>1%</td></tr>
<tr><td>Electronics</td><td>60%</td></tr>
<tr><td>Lighting</td><td>10%</td></tr>
<tr><td>Magnets (small)</td><td>4%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>5%</td></tr>
<tr><td>Solar cells</td><td>5%</td></tr>
<tr><td>Telecommunication</td><td>10%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>2% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Fabrication and manufacturing</td><td>28% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>80% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Remelting</td><td>71% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Dissipation in use</td><td>Out of all gallium end uses, only is the use as a catalyst thought to be inherently dissipative (Ciacci et al., 2015; Licht et al., 2015). While no actual amount of gallium is reported to be lost during the use phase of catalysts, these are here reported to be totally dissipated over a lifetime of 2 years.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

Collection and sorting	0% (Helbig et al., 2020, based on Licht et al., 2015). While small quantities of gallium may be recovered, the EOL recycling of gallium is thought to still be globally negligible today (BRGM, 2016c; Ciacci et al., 2015; European Commission, 2020a).	Per sector; please refer to Supplementary Data

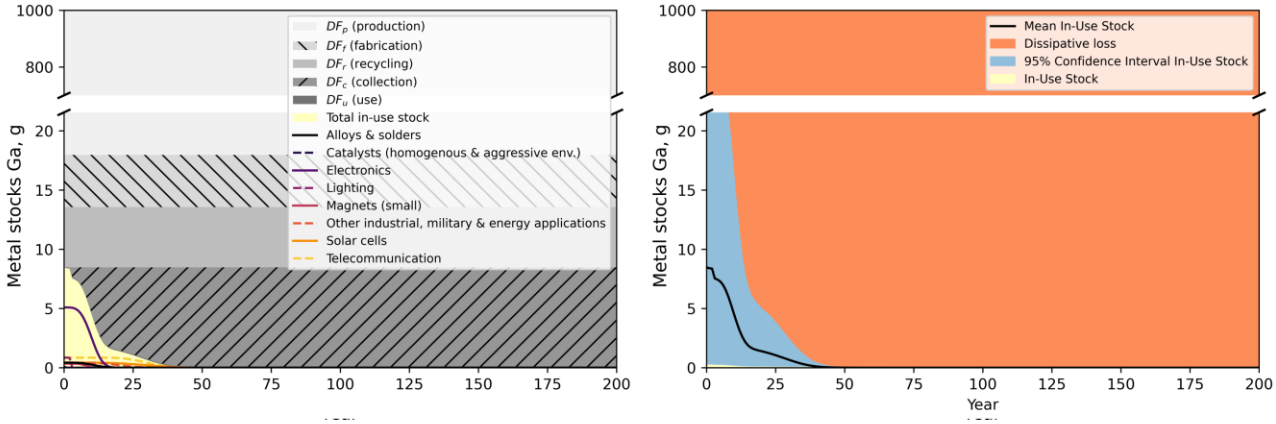

Figure S18. In-use stocks and losses of gallium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.20 Germanium

Table S27. Germanium.

<table>
<tr><th>Germanium</th><th>Ge, element number 32</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>End-use distributions of germanium are reported for 2008 (Harper et al., 2015), 2010 (Peiró et al., 2013), 2011 (Licht et al., 2015), 2013 (BRGM, 2015a), and 2015 (Guberman, 2016). End-uses remain fairly constant over the studied years, with similar shares of germanium being used in fiber optic cables, infrared optic devices and polyethylene terephthalate (PET) catalysts (25-35% each). One study estimated a higher share of germanium used in PET catalysts, with around 40% of its total use (Licht et al., 2015). Infrared applications are mostly used in military applications (Guberman, 2016). Other uses include solar cells, semi-conductors used in electronic appliances and phosphors used in lighting applications.

We consider the most recent distribution of 2015 (Guberman, 2016). The values for the electronics and solar cells applications are disaggregated using the data of (Peiró et al., 2013). Similarly, the ‘other’ category is further refined into lighting applications and other industrial categories. Infrared optics are aggregated within the Other industrial, military & energy applications. Finally, electronics and fiber optic appliances are both aggregated in the electronics category, and PET catalysts are classified in the packaging sector as they typically remain in the bottle, contributing to its brightness and transparency (Ciacci et al., 2015). The following end-use distribution is estimated to be representative of the year 2015:
<table>
<tr><td>Electronics</td><td>39%</td></tr>
<tr><td>Lighting</td><td>9%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>26%</td></tr>
<tr><td>Packaging</td><td>20%</td></tr>
<tr><td>Solar cells</td><td>6%</td></tr>
</table></td><td>U1: 2
U2: 2
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>1% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Fabrication and manufacturing</td><td>42% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>100% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Remelting</td><td>51% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Dissipation in use</td><td>Helbig et al. (2020) reported that 52% of germanium is dissipated in use, based on Licht et al. (2015). In the latter study, most dissipative losses result from the use of germanium as a catalyst used to produce PET for bottles. As discussed above, the share of germanium in this application is quite higher than in other end-use distributions reported in the literature. Instead, it is here considered that 100% of germanium ending up in PET bottles is non-functionally recycled (type C dissipation).</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	While some minor uses of germanium may be dissipative, such as chemotherapy, these were assumed to be a negligible share of total germanium consumption. Other uses can also be assumed to undergo negligible amounts of dissipation during the use phase (Ciacci et al., 2015).	
Collection and sorting	Helbig et al. (2020) reported 0% recycling of end-of-life products, based on Licht et al. (2015). While about 12% of EoL germanium is reported to be functionally recycled in Europe, it is mentioned that only a small share of germanium may be collected for recycling from IR optics, while it is unrecoverable from other applications (European Commission, 2020a). This coincides with the EOL-RR estimate of 7.5% for infrared optics reported by Harper et al. (2015). An EoL-RR of 0% is considered for other applications (European Commission, 2020a; Harper et al., 2015). In order to implement this value for IR optics, we extrapolated a collection rate of about 15% for old scraps of IR product (considering the remelting yield of 51%), and adjusted the resulting yield to represent the share of IR optics aggregated in Other industrial, military & energy applications (77%). The resulting collection yield is of 11% for that sector. A collection yield of 0% is reported for other applications.	Per sector; please refer to Supplementary Data

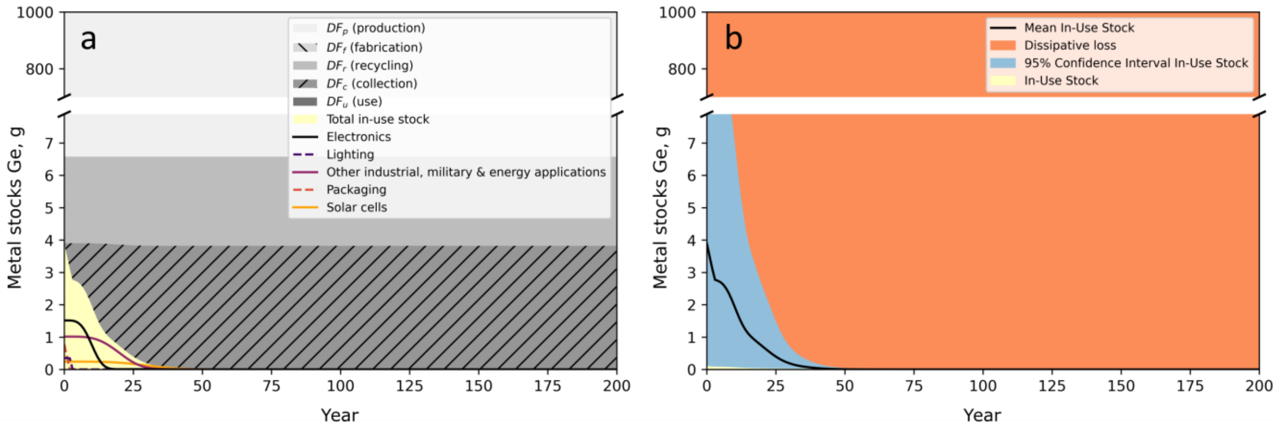

Figure S19. In-use stocks and losses of germanium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.21 Arsenic

Table S28. Arsenic.

<table>
<tr><th>Arsenic</th><th>As, element number 33</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Common uses of arsenic include CCA treatment for wood products, herbicides and insecticides, grids of lead-acid batteries, gallium-arsenide semiconductor and specialty glass products including optical products (European Commission, 2020c; Shi et al., 2017; USGS, 2020). In Europe, the main use of diarsenic trioxide is to remove impurities from zinc during the electro-winning process for zinc production (European Commission, 2020c).

A global end-use distribution for arsenic is reported for the year 2008, however it is based on estimates for the US (Ciacci et al., 2015; Nassar et al., 2012). In addition, end-uses in Europe are reported for years around 2009-2010 (European Commission, 2020c). SFAs of antimony for mainland China in 1990, 2000 and 2010 (Shi et al., 2017), as well as for Taiwan in 2008 (Chen et al., 2013), provide additional information on end-uses of arsenic.

For this dataset, we construct an approximate global end-use distribution based on the available data for these four regions or countries circa 2008-2010. Considering production data for 2008-2010 reported by the USGS, as well as consumption data in the literature cited above, we estimate that the consumption of arsenic by China, US, Europe and Taiwan represented about 60%, 10%, 3% and 0.3% of global consumption during these years, respectively, covering approximately 75% of the total consumption. The consumption of arsenic reported as zinc alloys in China is assumed to be in a metallurgical process similar to that in Europe. Chemicals use in Europe (total 7%) is assumed to be split between wood treatment (94%), agricultural products (5%) and electronics (1%). Wood and pesticide category for the US is assumed to split between wood products (95%) and agricultural products (5%) based on historical US end-use statistics (USGS, 2017). Other uses reported in the US are assumed to be split evenly between glass, lead alloys (e.g., for ammunition) and lead batteries.

Moreover, we assume that half of arsenic used for alloys is added to lead alloys for shot and bullet production (Ciacci et al., 2015); these are accounted for in the Other punctual applications. Finally, wood products are categorized in infrastructure, and copper and lead alloys in alloys. Semi-conductors are aggregated in electronics, which also includes photovoltaic panels. Fertilizers, pesticides and herbicides are categorized in agricultural & environmental applications. The following distribution is estimated to represent the global end-uses of arsenic circa 2008-2010:
<table>
<tr><td>Agricultural & environmental applications</td><td>2%</td></tr>
<tr><td>Alloys & solders</td><td>2%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>29%</td></tr>
<tr><td>Electronics</td><td>4%</td></tr>
<tr><td>Glass & ceramics</td><td>28%</td></tr>
<tr><td>Infrastructure</td><td>27%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 2
U4: 3
U5: 2</td></tr>
</table>

	Metallurgy & metalworking (process) 5% Other punctual applications 2%	
Production yield	The process yields for arsenic are calculated based on a SFA for China in 2010 (Shi et al., 2017). This is estimated to provide a reasonable depiction of global yields, since China produces and transforms more arsenic than any other country. The values were compared with the SFA of arsenic in Taiwan (Chen et al., 2013) to ensure some degree of consistency. Taking into account arsenic contents of arsenic, lead, zinc, copper and tin ores, the calculated production yield is of 8%. Similarly, most arsenic extracted and processed in Taiwan is not used in products for its specific functionalities, as most extracted arsenic ends up in various aggregates used in construction (Chen et al., 2013).	U1: 1 U2: 3 U3: 2 U4: 2 U5: 2
Fabrication and manufacturing	98% is reported in this dataset, based on Shi et al. (2017). The yield is close to 100% in Taiwan (Chen et al., 2013).	U1: 1 U2: 3 U3: 2 U4: 2 U5: 2
New scrap recovery	The recycling of arsenic from new scraps may occur in the manufacture of GaAs semiconductors (Ciacci et al., 2015). However, given that no new scrap recovery was noted in the SFA of arsenic, it is assumed that the reported manufacturing yield of 98% includes new scrap recovery and remelting when it occurs, and 0% is reported in this dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	0% (cf. new scrap recovery, and 0% EOL-RR is considered)	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	100% of agricultural products and of metallurgical use (desulfurization) of arsenic are estimated to be used dissipatively (Ciacci et al., 2015). The authors mentions that some dissipation may result from the use of arsenic in CCA preservatives, although no percentage is explicitly reported in the study. We assume a dissipation in use rate of 5% due to the lixiviation of treated wood products. While other minor end-uses of arsenic may be dissipative, such as the use in cancer treatment and fireworks (Ciacci et al., 2015), these are not considered in the end-use distribution and thus are not reported in this dataset. Other applications are not considered to be dissipated during use.	Per sector; please refer to Supplementary Data
Collection and sorting	Arsenic is unrecyclable in most of its applications, and is not targeted for recycling currently (Ciacci et al., 2015; Graedel et al., 2011; USGS, 2020).	Per sector; please refer to Supplementary Data

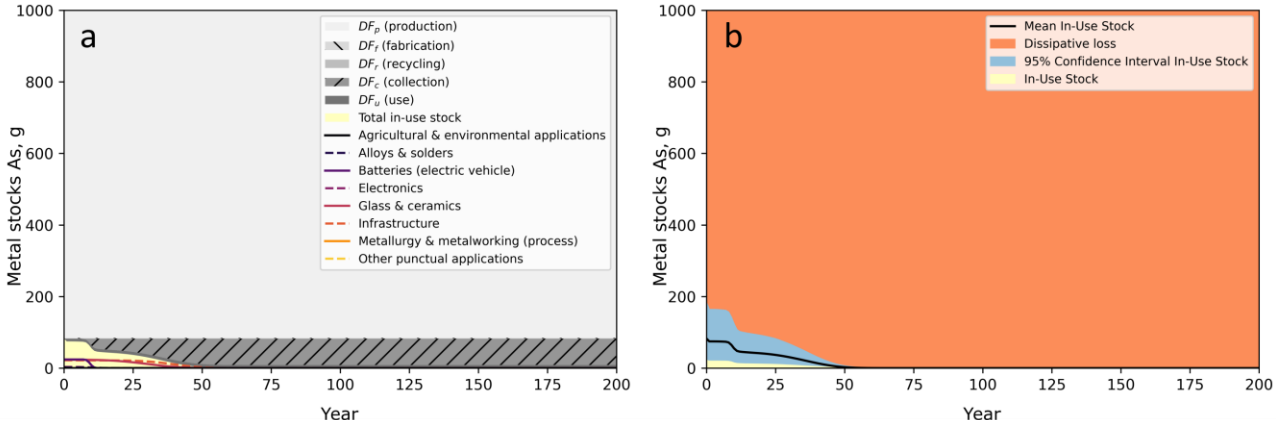

Figure S20. In-use stocks and losses of arsenic over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.22 Selenium

Table S29. Selenium.

<table>
<tr><th>Selenium</th><th>Se, element number 34</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>The USGS reported global estimates of selenium consumption in its Mineral Commodity Summaries for several past years. The end-use distribution for the year 2019 (USGS, 2020) is used to build this dataset. It is slightly refined with additional information provided by Kavlak and Graedel (2013b) and Ciacci et al. (2015). The electronics sector is divided between solar cells and photoreceptors, used in e.g. photocopy machines, using a 4:6 ratio (cf. data for 2010, provided by Kavlak and Graedel, 2013b, table A.3 of the Supporting information). Photoreceptors are aggregated in the electronics category, while solar cells are reported in their dedicated sector.

The principal uses of selenium are in glassmaking and metallurgical processes. Kavlak and Graedel (2013b) considered these two uses to be dissipative. Yet, selenium in fact mostly remain in the manufactured products, possibly contributing to its functions, and could in theory be recycled (Ciacci et al., 2015). As noted in section 1.4, we consider such uses as dissipation of type C. Moreover, about 20% of the selenium used in glassmaking is here considered to be a punctual use of selenium to reflect dissipation is use losses, while the remaining 80% is considered to be part of the glass product (Ciacci et al., 2015) and is reported as such. Regarding metallurgical processes, selenium is either used as an alloying element for steel, copper, lead alloys, or added to the electrolytic manganese production process to increase its efficiency (Kavlak and Graedel, 2013b). We estimate that 10% out of its 40% share reported in metallurgy are dissipative process uses of selenium where it may volatilize or is lost to slags; and the remaining share of 30% is reported in the alloys category.

Finally, due to the range of applications for selenium chemicals (catalysts, pigments for paint and plastics, heat stabilizing agent for rubber production), half were reported as chemicals, and the other half as other miscellaneous applications to reflect the variability of lifetime across their different potential applications. The following distribution is estimated to be representative of the global end-uses of selenium in 2019:
<table>
<tr><td>Agricultural & environmental applications</td><td>10%</td></tr>
<tr><td>Alloys & solders</td><td>30%</td></tr>
<tr><td>Chemicals</td><td>5%</td></tr>
<tr><td>Electronics</td><td>4%</td></tr>
<tr><td>Glass & ceramics</td><td>20%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>10%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>5%</td></tr>
<tr><td>Other miscellaneous</td><td>5%</td></tr>
<tr><td>Other punctual applications</td><td>5%</td></tr>
<tr><td>Solar cells</td><td>6%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>4% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
</table>

Fabrication and manufacturing	85% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
New scrap recovery	24% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
Remelting	100% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 1
Dissipation in use	The uses of selenium in glass production (reported as other punctual application) and agricultural applications are considered to be wholly dissipated during use (Ciacci et al., 2015). Moreover, its use reported in the metallurgical processes is considered to be dissipated in use (Ciacci et al., 2015). Selenium used in other applications is not considered to be dissipated in use.	Per sector; please refer to Supplementary Data
Collection and sorting	Helbig et al. (2020) calculated an average collection rate of 50% based on Kavlak and Graedel (2013b). However, this yield covered only a few categories summing up to 13% of the total uses, while the remaining 87% of end-uses were considered to be dissipative uses. Moreover, while selenium was historically recovered from rectifiers and photocopiers, it is nowadays seldom used in these applications, and the selenium contained in most of its current applications being put on the market is not readily recyclable (European Commission, 2020c; Kavlak and Graedel, 2013b). The BRGM estimates that the EOL-RR of selenium is below 5% (BRGM, 2018d). Selenium contained in old alloy scraps is not considered to be targeted during waste management and recycling. Based on this information, a conservative collection yield of 10% is reported for electronics, and 0% is reported for all other uses.	Per sector; please refer to Supplementary Data

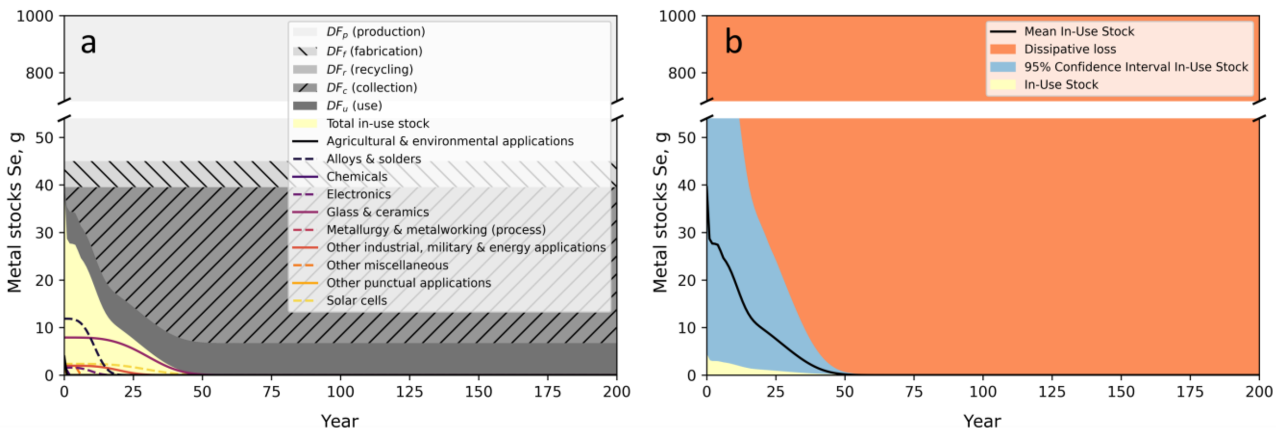

Figure S21. In-use stocks and losses of selenium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.23 Strontium

Table S30. Strontium.

<table>
<tr><th>Strontium</th><th>Sr, element number 38</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Strontium can be directly used as a drilling fluid for oil and gas production (as part of the celestine mineral), and in a range of applications such as the electrolytic production of zinc, pyrotechnics and signals, magnets, pigments and fillers, master alloys, glass and for cancer treatment (European Commission, 2020a; USGS, 2020). Celestine is isostructural with barytes, that are also used for well drilling (cf. Table S44). USGS statistics report a substantial use of celestine in drilling fluids since 2006.

The Yale criticality studies and the EC report values based on US statistics (European Commission, 2020a; Graedel et al., 2013; Panousi et al., 2016). The 2020 EC criticality study report that no data is available beyond those of the USGS for recent years (European Commission, 2020a), though it is estimated that European uses are more similar to the use of strontium compounds than those of celestine since few oil and gas projects occur in Europe compared to the US.

In this dataset, global end-use values are estimated from the US statistics for 2019 (USGS, 2020). In 2019, the US consumed around 7% of the global production of strontium, with 17 000 of the 220 000 tons of strontium produced worldwide. This corresponds to the average of approximately 4-10% consumed annually from years 2015-2019. Since the US produces around 20% of the total oil and natural gas production worldwide, we roughly estimate the actual average global strontium end-use as a drilling fluid to be one half of 64% (32%). The remaining share of strontium uses are corrected to 100% proportionally to their original distribution. Based on qualitative descriptions of major end-uses in (European Commission, 2020a), strontium pigments are assumed to be used mostly in ceramic glazes, and master alloys are assumed to be split half and half between the transport and aviation sectors. Moreover, half of the “other” category is assumed to be used in various glass products. Pyrotechnics and signals are added to Other punctual applications. The final distribution considered in this dataset is estimated to be representative of 2019:
<table>
<tr><td>Aviation</td><td>3%</td></tr>
<tr><td>Glass & ceramics</td><td>9%</td></tr>
<tr><td>Magnets (small)</td><td>23%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>6%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>3%</td></tr>
<tr><td>Other punctual applications</td><td>23%</td></tr>
<tr><td>Transport</td><td>3%</td></tr>
<tr><td>Well drilling</td><td>32%</td></tr>
</table>
This distribution is very different than that reported by other authors earlier years, which included 55% used in television tubes. Flat screens no longer make use of strontium. Another difference that may explain discrepancies is that other studies may not have considered celestine used for well drilling as a strontium use, which is here the case.</td><td>U1: 2
U2: 1
U3: 4
U4: 3
U5: 3</td></tr>
</table>

Production yield	Panousi et al. (2016) reported a yield of 76% based on an informed estimate. Considering that the production of celestine requires less processing than that of pure strontium, we estimate a slightly higher average yield of 80%.	U1: 3 U2: 3 U3: 1 U4: 3 U5: 1
Fabrication and manufacturing	Assumption of a yield of 90%.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	0% (assumed to be accounted for in fabrication and manufacturing losses)	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	Assumed to be accounted for in fabrication and manufacturing losses, and a collection yield of 0% is reported for all applications (no EoL recycling is considered to occur).	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	Uses of strontium for well-drilling, zinc production and pyrotechnics & signals (included in other punctual applications) are considered to be dissipative. Other uses are not expected to be dissipated in use given the nature of the applications.	Per sector; please refer to Supplementary Data
Collection and sorting	Local recycling of drilling fluids may occur (cf. barium, Table S44); we consider that these are included in the reported lifetime of 1 year. Negligible (<1%) recycling rates are reported for all other strontium uses (European Commission, 2020a; Panousi et al., 2016). We consider an EoL-RR of 0% for all strontium uses in this dataset.	Per sector; please refer to Supplementary Data

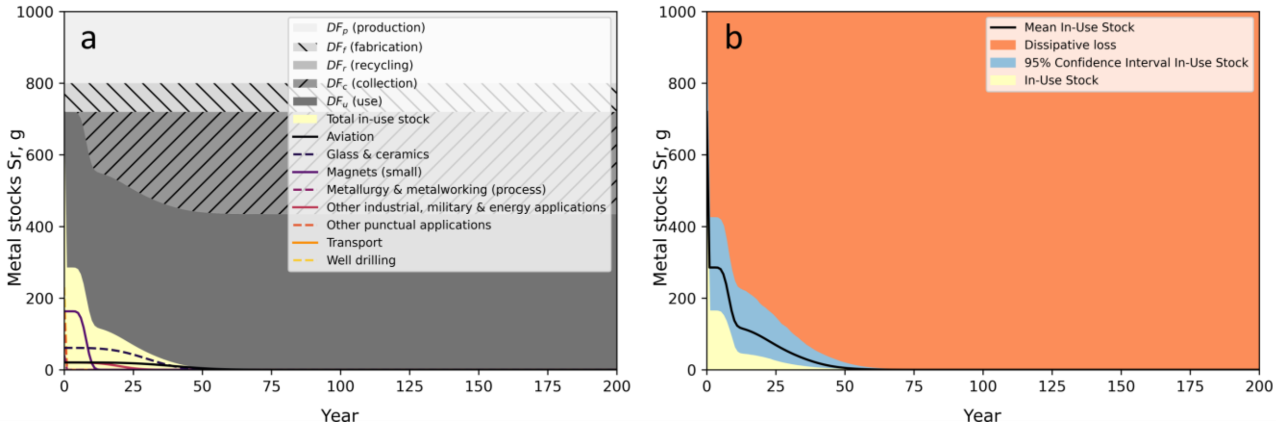

Figure S22. In-use stocks and losses of strontium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.24 Yttrium

Table S31. Yttrium.

<table>
<tr><th>Yttrium</th><th>Y, element number 39</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>End-uses reported in the 2014 European criticality report (European Commission, 2014) were matched and disaggregated with end-use data from Peiró et al. (2013). The general methodology for REEs is described in section 2.4.3.2. The following distribution is estimated to be representative of the global end-uses of yttrium in 2012:
<table>
<tr><td>Electronics</td><td>10%</td></tr>
<tr><td>Glass & ceramics</td><td>21%</td></tr>
<tr><td>Lighting</td><td>69%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>0.4%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 3</td></tr>
<tr><td>Production yield</td><td>66% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>85% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>0% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>Remelting</td><td>100% (assumption)</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>0% (Ciacci et al., 2015)</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Based on section 2.4.3.5, an EOL-RR of 10% is reported for yttrium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

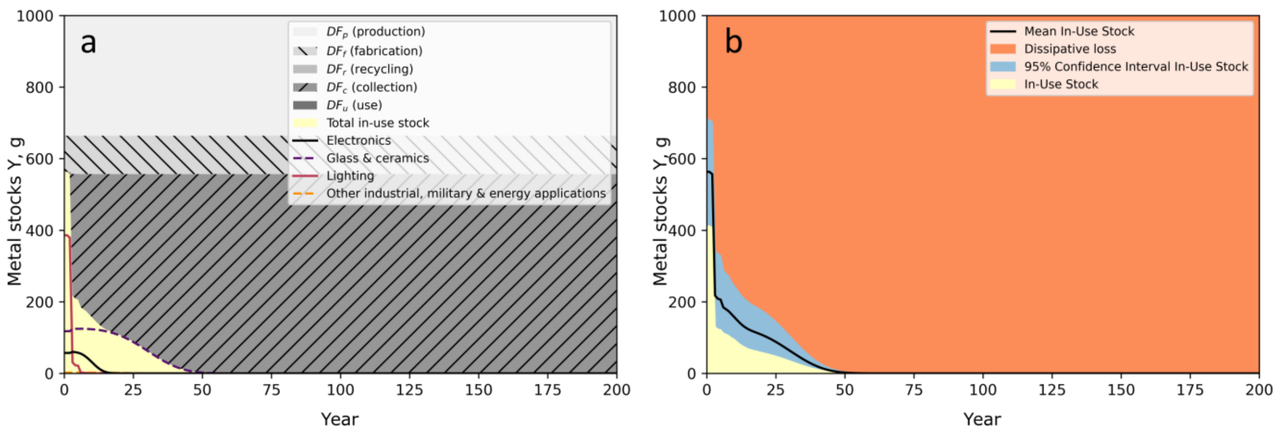

Figure S23. In-use stocks and losses of yttrium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.25 Zirconium

Table S32. Zirconium.

<table>
<tr><th>Zirconium</th><th>Zr, element number 40</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>A majority of zirconium is used directly as minerals, i.e., zirconium silicate (ZrSiO4) and baddeleyite (ZrO2), with around 75% of its uses, while the remainder 25% is transformed in zirconium oxide and other chemicals including zirconium metal (European Commission, 2020c). Zirconium metal sponge represents only about 3% of zirconium uses, used mostly in the chemical process and nuclear energy industries (BRGM, 2018e; USGS, 2020). Major uses of zirconium include ceramics, foundry sand, opacifiers, and refractories (BRGM, 2018e; USGS, 2020).

Several end-use distributions are available for zirconium: for 2008 (Graedel et al., 2013), 2011 (Zircon Industry Association, 2019a), 2012 (Iluka, 2014), 2015 (BRGM, 2018e; European Commission, 2020c) and 2019 (Zircon Industry Association, 2019b). Overall, the ceramics sector consumes around 50-60% of zirconium over the studied years. The latest distribution available is quite generic, and only values for ceramics (54%), foundries (14%) and refractories (11-14%) are provided. Therefore, we estimate the distribution based on other information available for prior years. Notably, the report of the Zircon Industry Association (2019a) provides the most disaggregated values out of the consulted studies.

The use of zirconium metal for nuclear fuel cladding used in nuclear rods is aggregated in the Other miscellaneous category. ‘Chemicals’ are split between technical ceramics and gemstones (both aggregated in glass & ceramics category). ‘Other chemicals’, representing around 10% of end uses, are split even between the chemicals and Other miscellaneous categories to reflect the wide diversity of end-uses for such chemicals (cf. Zircon Industry Association, 2019a). Foundry sandcasting is aggregated to the metallurgical process sector. The following distribution is estimated to be representative of years 2015-2019:
<table>
<tr><td>Alloys & solders</td><td>1%</td></tr>
<tr><td>Chemicals</td><td>5%</td></tr>
<tr><td>Glass & ceramics</td><td>56%</td></tr>
<tr><td>Metallurgy & metalworking (process)</td><td>15%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Other miscellaneous</td><td>7%</td></tr>
<tr><td>Refractories</td><td>14%</td></tr>
</table>
</td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>Zirconium is most commonly produced from heavy minerals enriched sand, with around 97% of its production (Zircon Industry Association, 2019a). Althaus et al. (2007) reported a combined concentration and beneficiation yield of 95%. Iluka, an important actor in the global production of zirconium, rather suggests losses of around 10% during the processing stage (Iluka, 2020), and of between 85-94% for their Hamilton and Narngulu mineral separation plants depending on the mineral concentrate source feed and product stream characteristics</td><td>U1: 2 U2: 1
U3: 2 U4: 2
U5: 1</td></tr>
</table>

	(Iluka, 2019). Therefore, we consider an average concentration and refining yield of 90%, and further assume extraction losses of 5%. The resulting production yield is estimated to be of 86%. There may be some cases where zirconium is extracted along, but not further processed, from other heavy mineral ores such as baddeleyite. These are not considered in this dataset. In some other cases, the zircon-enriched concentrate may be exported to processing plants in China for further processing (Zircon Industry Association, 2019a), alike for zirconium-bearing REE ores (see e.g. the case of the Nechalacho Rare Earth Elements Project discussed in section 2.4.3.1). We assume such processes to have a similar yield to those reported above.	
Fabrication and manufacturing	95% (assumption)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	Although some new scraps of zirconium metal may be recycled (BRGM, 2018e), we estimate the global recovery of zirconium new scraps to be overall negligible (European Commission, 2020c). Thus, we assume possible losses to be included in the fabrication yield, and 0% is reported in this dataset.	U1: 2 U2: 1 U3: 1 U4: 3 U5: 1
Remelting	We assume a remelting rate of 100% for zirconium metal and zircon; and all EOL losses are reported as collection losses.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	Although zircon used for sandcasting may be recycled (Ciacci et al., 2015), we consider that it needs to be continuously replenished over time, and a dissipation in use rate of 100% is reported over an application lifetime of 1 year (cf. section 2.2.3). A dissipation in use rate of 0% is reported for other applications, based on Ciacci et al. (2015).	Per sector; please refer to Supplementary Data
Collection and sorting	Zirconium may be recycled from some steel alloys or refractory material (Ciacci et al., 2015; European Commission, 2020c; USGS, 2020). The USGS mentions that “spent or rejected zirconia refractories are often recycled”, and the European Commission (2020c) estimated that about 70% of refractory materials and alloys may be recycled. However, this rate likely includes a wide share of downcycling, especially in the case of refractories, as it is estimated to be the case for magnesia refractories (cf. Table S13). Without further available information, we assume a functional EOL-RR of 10% for zirconium refractories. Contrastingly, alloys are expected to be more easily recyclable into new metal products with similar functionality since it is mostly used in specialized applications, and we assume a collection rate of 50% for alloys and Other industrial applications. While there seems to be some potential for the recycling of zirconium alloys used for nuclear fuel cladding in the future (OECD Nuclear Energy Agency, 2018), it is estimated not to be recyclable currently.	Per sector; please refer to Supplementary Data

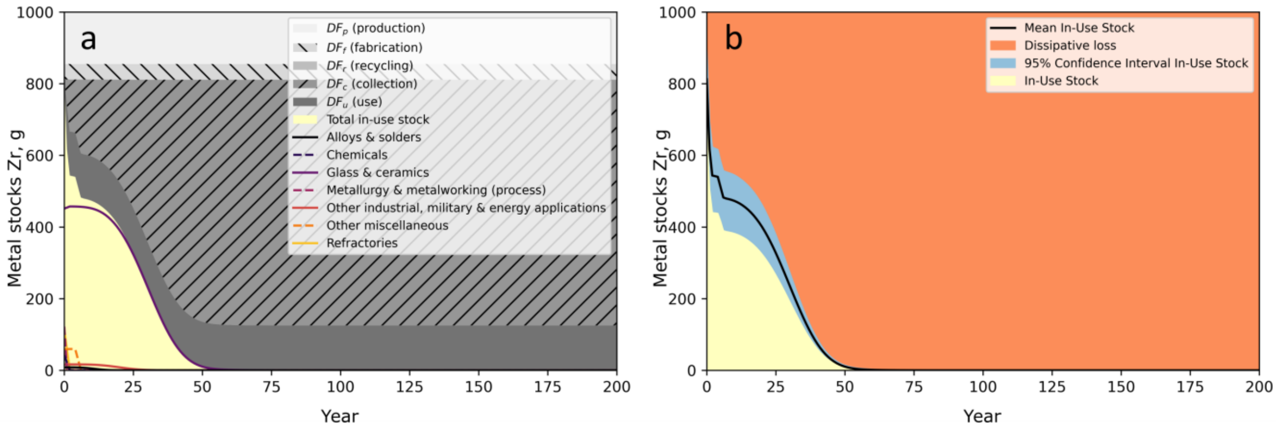

Figure S24. In-use stocks and losses of zirconium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.26 Niobium

Table S33. Niobium.

<table>
<tr><th>Niobium</th><th>Nb, element number 41</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Several global end-uses of niobium are reported, e.g. for years 2004 and 2010 (Schwela, 2011), 2008, 2009 and 2010 (Nuss et al., 2014), 2014 (BRGM, 2016d), and 2017 (European Commission, 2020a). The latter is based on the sales of the largest niobium producer (CBMM) for that year; and a distribution is also available for 2018 (CBMM, 2018a).

Around 90% niobium was consistently used in steels and alloys between 2004 and 2018. About 75% of niobium is used in steel production for a variety of microalloy and low-alloy steels to improve corrosion resistance, strength and toughness, amongst other properties. These steels are used mostly in pipelines, transportation, and structural applications (Schulz et al., 2017). Other niobium alloys are used in nickel-, cobalt-, and iron-base superalloys for high-temperature applications such as jet engine components, in superconducting magnets used in MRI, nuclear magnetic resonance instruments and particle accelerators (Schulz et al., 2017). It has recently started to be used as solid niobic acid that acts as a catalyst in the conversion of palm oil to biodiesel (Schulz et al., 2017).
The following end-use distribution is based on end-use data for 2018 (CBMM, 2018a), and is further refined with other available information. Other uses, representing 9% of niobium’s end-uses in 2018, are estimated to be split between catalysts (1%), cutting tools (carbides, 2%), large magnets (1%), superalloys (3%) and electronics, including magnets (2%), based on qualitative and quantitative information (BGS, 2011; BRGM, 2016d; European Commission, 2020a; Nuss et al., 2014). Pipelines are categorized as infrastructure. Heat-resistant steels are classified in Other industrial, military & energy applications, given that their final distribution in end-uses is not precisely known. These could include e.g. uses for the petrochemical industry and power plants (Nuss et al., 2014). The following distribution is estimated to reflect global end-uses of niobium in 2018:
<table>
<tr><td>Alloys & solders</td><td>3%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>1%</td></tr>
<tr><td>Construction</td><td>40%</td></tr>
<tr><td>Cutting tools</td><td>2%</td></tr>
<tr><td>Electronics</td><td>2%</td></tr>
<tr><td>Infrastructure</td><td>16%</td></tr>
<tr><td>Magnets (large)</td><td>1%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>11%</td></tr>
<tr><td>Transport</td><td>24%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>Extraction losses of 13% and processing losses of 16% are reported in Nuss et al. (2014), resulting in a production yield of 71%.</td><td>U1: 2 U2: 4
U3: 1 U4: 3
U5: 1</td></tr>
</table>

Fabrication and manufacturing	A CBMM's technical document for the addition of ferroniobium during steelmaking suggests that in optimal conditions, the recovery of niobium to the alloy should be above 95% (CBMM, 2018b). The remainder of niobium is expected to be lost to slags. Other losses from the fabrication and manufacturing of steel into end-use products is expected to follow similar trends to that of iron, for which a fabrication and manufacturing yield of 89% has been calculated, with a new scrap recovery of 100% (cf. Table S21). The MFA of niobium in the US in 1998 also suggests a fabrication yield of 89%, with a new scrap recovery of 94% (USGS, 2004b). Based on this information, we estimate that, in average, about 5% of primary niobium is lost to slags during steelmaking, and that an additional 5% of niobium is lost during other fabrication and manufacturing processes without further functional recovery. Given the potential discrepancies between the remelting rates of new and old scraps, the recycling of new scraps is estimated to be included in the fabrication and manufacturing yield (cf. Remelting box). The overall fabrication yield is estimated to be of 90%.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	New scrap recovery is integrated in the estimate of the fabrication yield.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	EOL-RR of 50% and 56% have been reported for the US and globally, respectively circa 2010 (UNEP, 2011). Yet, while a large fraction of niobium may be collected and enter the recycling flow along with old steel scraps, the European Commission (2020a) estimated that only about 0.3% of niobium was functionally recycled. Indeed, the composition of old steel scraps is often not precisely known (UNEP, 2013). Similarly, Andersson et al. (2017) considered that the niobium content of EOL vehicle scraps that get recycled were non-functionally recycled, and that niobium was either lost to the carrier metal or to other materials. In a more recent publication, Graedel et al. (2022) reported updated EOL-RR of 5% for steel alloys and 65% for superalloys based on Tkaczyk et al. (2018). Considering the latter recycling rates and the collection yields reported below, we estimate an average remelting yield of 13% for niobium.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	The dissipation in use rates from the main niobium uses are thought to be negligible (Ciacci et al., 2015). Parts of niobium uses as catalysts and cutting tools (carbides) may be dissipated during use. For the latter, we report a dissipation in use of 5%, using the estimate reported for cobalt as a proxy, as done for e.g. tungsten (Ciacci et al., 2015). For catalysts, the latter authors report a dissipation in use rate of 2% using palladium catalyst losses as a proxy, which is also reported here.	Per sector; please refer to Supplementary Data
Collection and sorting	Collection rates of niobium-alloyed steel are assumed to be globally similar to iron, with a collection yield of 74% (cf. Table S21), and those of carbides, similar to that of tungsten (41%, cf. Table S61). The former yield of 74% is considered for the construction, infrastructure, We assume that superalloys are collected at a rate of 85% based on Graedel et al. (2022). Other uses are estimated not to be collected and separated for their niobium content based on the literature review.	Per sector; please refer to Supplementary Data

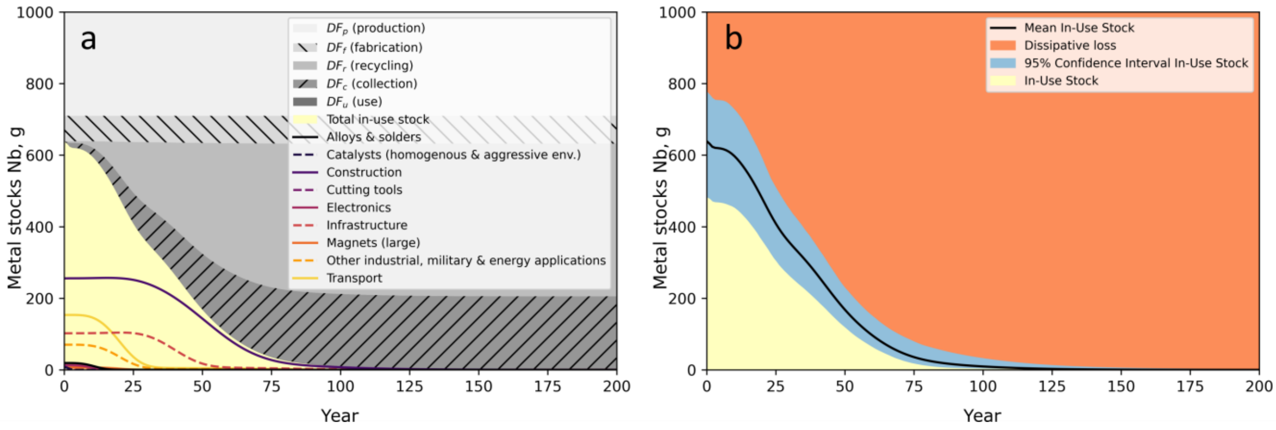

Figure S25. In-use stocks and losses of niobium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.27 Molybdenum

Table S34. Molybdenum.

Molybdenum	Mo, element number 42	Uncertainty
End uses	Global end-uses of molybdenum are reported for years 2008 (Graedel et al., 2015), 2012 (Henckens et al., 2018, based on the International Molybdenum Association [IMoA]), and 2018 (IMoA, 2020). The main uses of molybdenum are in engineering steels (42% of molybdenum use) and stainless steels (23%), both of which are used extensively in heavy machinery and infrastructure for the oil and gas industry (including pipelines) as well as other industries, large-scale transport (trains, ships) and construction (Graedel et al., 2015). Molybdenum is also used in cast iron (7%) for transportation, machinery and metal processing, as well as tool steels (7%), including high speed tool steels. Molybdenum metal and alloys (5%) are used in many specialty applications, many of which are heat resistant industrial components for high temperature processing (e.g., glass melting furnace electrodes, high temperature furnaces and heat exchangers) and heat resistant transport components (e.g., coatings for piston rings, molybdenum-rhenium alloys for rocket engines) (IMoA, 2020). Molybdenum superalloys (Ni alloys, with 3% of global molybdenum use) are highly corrosion-resistant and find extensive use in the chemical processing, pharmaceutical, oil & gas, petrochemical and pollution control industries (IMoA, 2020). Other notable uses of molybdenum metal and alloys include lighting and various electronic devices (e.g., in power transistors, thin films and sputter targets) (IMoA, 2013). Molybdenum chemicals are also used in a range of non-metal applications such as catalysts, agricultural products and pigments (13% of total uses). In this dataset, end-uses reported by the IMoA (2020) are disaggregated based on quantitative and qualitative description of each end-use sectors provided by Ciacci et al., (2015), European Commission (2020c), Graedel et al. (2015), and IMoA (2013). Pipelines are included in the construction sector. Heat resistant materials are split into the mechanical equipment and transport sectors. Stainless steels are split between construction and industrial components. Various industrial components are categorized as mechanical equipment. Tools are split between cutting tools and mechanical equipment. Half of pigments & flame retardants category are attributed to plastic uses, and the remaining share of pigments are split into paint and ceramics. Moreover, it is estimated that about 4% of chemicals are used in inherently dissipative uses of type A or B (mostly agricultural products). The following end-use distribution for molybdenum is estimated to be representative of year 2018: Agricultural & environmental applications: 4% Catalysts (homogenous & aggressive env.): 5% Construction: 41% Cutting tools: 2% Electronics: 1% Glass & ceramics: 1% Lighting: 1% Mechanical equipment: 31%	U1: 2 U2: 1 U3: 1 U4: 2 U5: 1

<table>
<tr><td></td><td><table><tr><td>Paint</td><td>1%</td></tr><tr><td>Plastics</td><td>2%</td></tr><tr><td>Transport</td><td>12%</td></tr></table></td><td></td></tr>
<tr><td>Production yield</td><td>Henckens et al. (2018) assumed a recovery of 80% from Mo ores and 40-45% recovery as a by-product from porphyry ores used for copper production, resulting in a production yield of 60%. These values are corroborated by other reported values reported in literature, for instance 47% recovery from porphyry ores (Ayres and Peiró, 2013) and 75–90% recovery from molybdenum ores (Roskill, 2020). Similarly, Graedel et al. (2015) reported 29% extraction losses and 13% other prefabrication losses for molybdenum.</td><td>U1: 3 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>Scarce information is available for the yield of fabrication and manufacturing processes of molybdenum containing products. The USGS report aggregated losses for both steelmaking and fabrication processes (USGS, 2004b). Moreover, Nakajima et al. (2013) studied the flows of molybdenum in alloyed steels along with other alloying elements (Ni, Cr) in the Japanese economy in 2000. The reported yields for fabrication and manufacturing, new scrap recovery and remelting yields are estimated from these two references based on the following calculations and assumptions.

Nakajima et al. (2013) mention that almost all of the scraps generated in the steel industry are recycled during the steel-making process, while scraps generated from the manufacturing of parts and accessories are relatively difficult to recycle. 7.4% losses of molybdenum are reported for the manufacturing of parts and accessories, suggesting that these new scraps are either not recovered, either that their molybdenum content is not functionally recycled. We here assume that these losses are mostly due to non-functional recycling given the 100% new scrap recovery rate reported in (USGS, 2004b).

Both steelmaking and subsequent steps are covered in the fabrication and manufacturing process. However, melting losses from primary inputs to the steel melt are not easily identifiable, alike for other alloying elements such as niobium. We assume that downgraded steel as reported in (USGS, 2004b) results only from the remelting of new and old scraps, while new scrap generated originate from all of the material inputs to the fabrication process. Following this assumption, a yield of 83% is calculated from US statistics for 1998 (USGS, 2004b).</td><td>U1: 2 U2: 4
U3: 2 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>100%, according to US statistics for molybdenum in 1998 (USGS, 2004b). This is consistent with the data for iron, for which a 100% rate has also been calculated (Helbig et al., 2020). However, it may be slightly overestimated given molybdenum uses in non-steel products.</td><td>U1: 2 U2: 4
U3: 2 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>A global EoL-RR of 20% is reported by Henckens et al. (2018), based on UNEP (2011) and USGS (2004b), while Graedel et al. (2015) reported an EoL-RR of 30% for all applications based on UNEP (2011). We here consider an average EoL-RR of 25% across all molybdenum applications in order to estimate the collection and remelting yields.

Since molybdenum consistently remains in the metal phase during recycling, it often becomes a contaminant rather than an alloying agent due to its involuntary addition to the melt (Ohno et al., 2014).</td><td>U1: 4 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
</table>

	USGS statistics suggest a melting yield of 89% from a mix of virgin materials, new scraps and old scraps during steelmaking, provided that downgraded steel is accounted for as non-functional recycling (USGS, 2004b). Assuming that losses from the melting process are mostly due to the share of new and old scraps in the melt (12 000 out of 25 300 mt), a remelting yield of 77% can be calculated. Moreover, Nakajima et al. (2013) reported 7.4% losses of molybdenum for the manufacturing of parts and accessories. Assuming a collection rate of 100% for new scraps, their data suggest functional remelting yield of 44% for these new scraps. This value is similar to the reported 69% of molybdenum unintentionally fed into the electric arc furnace during the EoL recycling of vehicles in Japan (Ohno et al., 2014). Based on this information, we roughly estimate a global functional remelting yield of 50%.	
Dissipation in use	Based on Ciacci et al. (2015), we attributed the following dissipation in use rates to molybdenum end-use sectors: Agricultural & environmental applications (type A) and lubricants (type B), 100%; Catalysts, 5% (type B); Cutting tools, 5% (type B); Pigments (paint), 10% (using titanium as a proxy for paint use); and Other applications, 0%.	Per sector; please refer to Supplementary Data
Collection and sorting	The collection yields are extrapolated accordingly with the following observations and assumptions. Plastic additives (pigments & smoke suppressants) are not readily recyclable, along with pigments used in paints and ceramics and dissipative uses of chemicals (Ciacci et al., 2015). These are attributed a collection rate of 0%. Moreover, the content of molybdenum in catalysts, lighting and electronics are less likely to be economically recyclable due to the overall low volumes and concentrations of molybdenum in final products, and are attributed a 0% collection yield as well. Thus, given the estimated remelting yield of 50% and global EoL-RR of 25%, an average collection yield of 55% is calculated for all of the other sectors. This yield is much lower than those reported for iron and its principal alloying elements, suggesting that the actual collection yields may be higher, and the remelting yield may be lower, than those reported in this dataset. This may warrant additional investigations of the global molybdenum flows, as also suggested by Henckens et al. (2018).	Per sector; please refer to Supplementary Data

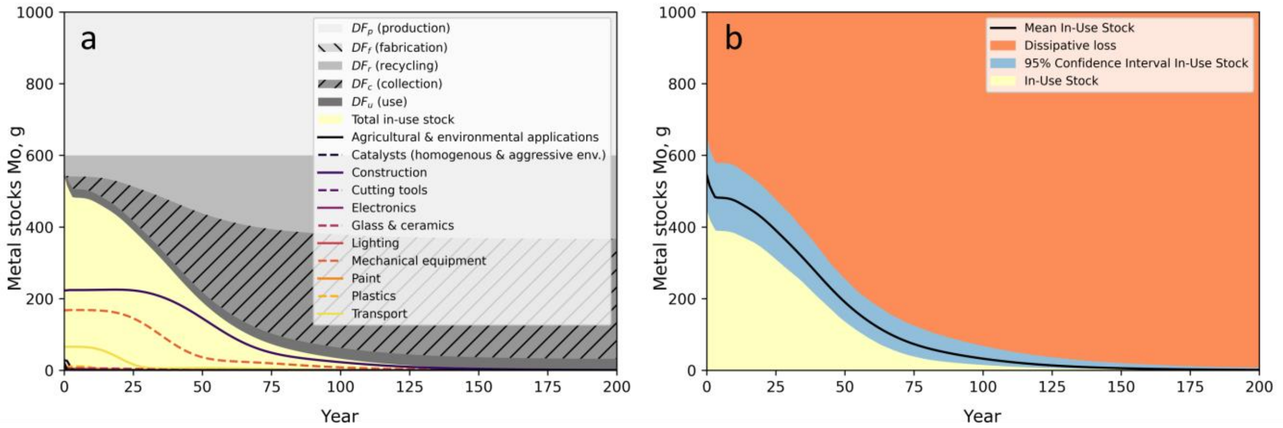

Figure S26. In-use stocks and losses of molybdenum over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.28 Ruthenium

Note: We used the catalysts category as a proxy for ruthenium-iridium anodes based on the reported lifetimes for this application to avoid generating additional single use sectors for industrial processes. The uses of ruthenium in the electrochemical industry (anodes coating) is reported in the Catalysts (heterogeneous & stable env.) sector, alike for iridium (cf. Table S64).

Table S35. Ruthenium.

<table>
<tr><th>Ruthenium</th><th>Ru, element number 44</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Ruthenium is used as a process catalyst for a number of chemical processes such as ammonia production, for the coating of dimensionally stable anodes used by the chlor-alkali industry, in various electrical devices such as computer’s hard disks and as an alloying agent for various other applications such as aeronautics and dental crowns (BRGM, 2020c; Cowley, 2013; Graedel et al., 2013). Ruthenium’s end-uses are determined based on the average gross demand statistics for the year 2019 (Johnson Matthey, 2020b). For simplification purposes, the use of ruthenium anodes and catalyst applications are both classified as Catalysts (heterogeneous & stable env.). Those in the electrical industry are reported in electronics, and those reported as “other” are classified in the alloys category. The distribution, representative of year 2019, is the following:
<table>
<tr><td>Alloys & solders</td><td>16%</td></tr>
<tr><td>Catalysts (heterogeneous & stable env.)</td><td>50%</td></tr>
<tr><td>Electronics</td><td>34%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 3
U5: 2</td></tr>
<tr><td>Production yield</td><td>The mining yield is estimated to be 85% for all PGMs. The average concentration, smelting and refining yields for ruthenium correspond to the average values reported by Nassar (2013) and are of 77.5%, 96% and 99%, respectively. The resulting production yield is of 63%.</td><td>U1: 2 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for ruthenium.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>A remelting yield of 99% is assumed (same as refining).</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Based on Ciacci et al. (2015), it is considered that 5% of ruthenium used in the chemical industry is dissipated over its lifetime, and that 20% is dissipated in electrochemical applications over their lifetimes, resulting in a weighted average of 11% dissipation in use for the catalysts sector. Other uses are not considered to be dissipative.</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>While UNEP (2011) estimated that between 5 and 15% of ruthenium was functionally recycled at its end-of-life, the BRGM more recently estimated a recycling rate of over 50% (BRGM, 2020c). Notably, the ruthenium content of catalysts and some uses in electronics (e.g., printed circuit boards, hard drives) is thought to be well recycled (BRGM, 2020c).
Assuming constant end-uses over time, the average of the EoL-RR values reported by Nassar (2013) suggest an average recycling yield of about 35% for ruthenium, which is largely below the 50% suggested by the BRGM. The values suggested by the author are therefore updated,</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	assuming that 35% of ruthenium in electronics is recycled rather than the reported 0 to 5%. The following collection yields are estimated: alloys, 15%; catalysts, 85%; and electronics, 15%.	

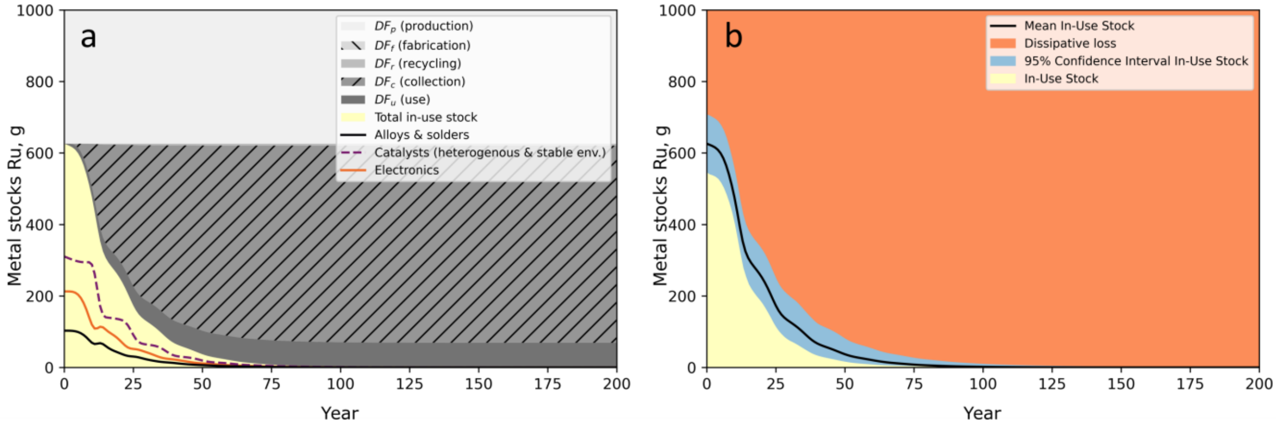

Figure S27. In-use stocks and losses of ruthenium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.29 Rhodium

Table S36. Rhodium.

<table>
<tr><th>Rhodium</th><th>Rh, element number 45</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Rhodium is largely used as a catalyst in car exhaust pipes to control NOx emissions (BRGM, 2018f; Graedel et al., 2013). It is also used by the chemicals and glass manufacturing industries, in electronic devices and motors, and in various other uses (BRGM, 2018f; Graedel et al., 2013). Rhodium’s end-uses are calculated based on the average gross demand statistics for the year 2019 (Johnson Matthey, 2020b). The following distribution is representative of the year 2019:
<table>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>6%</td></tr>
<tr><td>Electronics</td><td>1%</td></tr>
<tr><td>Glass manufacturing</td><td>5%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Transport</td><td>87%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 3
U5: 1</td></tr>
<tr><td>Production yield</td><td>The mining yield is estimated to be 85% for all PGMs.
The average concentration, smelting and refining yields for rhodium correspond to the average values reported by Nassar (2013) and are of 77.5%, 96% and 98%, respectively. The resulting production yield is of 62%.</td><td>U1: 2 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for rhodium.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>A remelting yield of 98% is assumed (same as refining).</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>About 2% of rhodium is estimated to be lost during use in exhaust pipes, 17.5% in its use as a catalyst for chemical production, and <1% in the glass manufacturing industry (Hagelüken, 2003; Nassar, 2013). The two former values are reported as such. However, Ciacci et al. (2015) estimated the loss to the glass production process to be of about 0.6% out of 8% used in that sector over a lifetime of 2 years, suggesting a dissipation in use rate of 8%. Based on this information, we assume an average dissipation in use rate of of 5% for to the glassmaking process over 2 years.</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Around 50-60% of the EoL rhodium scraps are recycled (BRGM, 2018f). The collection yields are calculated based on Nassar (2013) and UNEP (2011). For the rhodium content of auto catalysts, an average global EOL-RR of 50% is considered (UNEP, 2011). For the other yields, the average values of Nassar (2013) are considered and mostly match the estimated EOL-RR of UNEP (2011). Considering a remelting yield of 98%, the following collection yields are calculated: catalysts (homogenous & aggressive env.), 98%; electronics, 8%; glass manufacturing, 100%; other industrial, military & energy applications, 41%; and transport, 51%.

Assuming a constant distribution of end-uses over time, these yields suggest a global EOL-RR of rhodium of approximately 55%, within the</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	range recently reported by the BRGM, and are therefore estimated to be fairly representative of the current collection yields.	

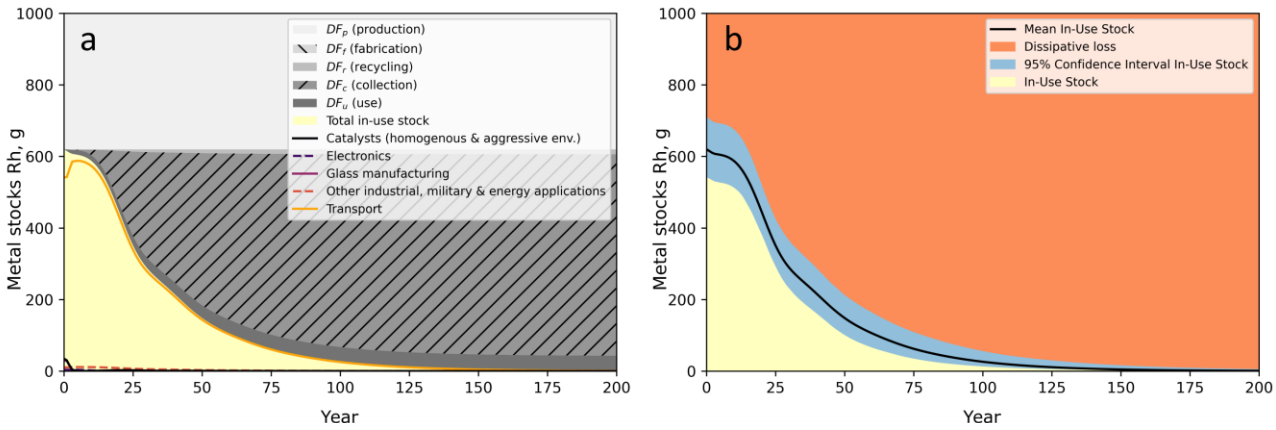

Figure S28. In-use stocks and losses of rhodium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.30 Palladium

Table S37. Palladium.

Palladium	Pd, element number 46	Uncertainty
End uses	Palladium is used in a range of applications, the main one being auto catalysts. Other applications include dentistry, jewelry, catalysts for the chemical and petroleum industries, as well as electronics (BRGM, 2017f; Graedel et al., 2013). The end-use distribution for palladium is calculated based on gross demand statistics published in Johnson Matthey's reports (Johnson Matthey, 2020a, 2015). On average, palladium has been de-invested by approximately 1.3 ton per year over the past 10 years. A possible explanation for such phenomena is the substantial increase of palladium demand for car exhausts over the same period due to e.g. more demanding air quality regulation. Therefore, the investment category is neglected for palladium, and other end-uses arere normalized to obtain a total distribution of 100%. The end uses, representative of 2019, are the following: Biomedical & dental: 3% Catalysts (homogenous & aggressive env.): 5% Electronics: 6% Jewelry & investment: 1% Other industrial, military & energy applications: 2% Transport: 84%	U1: 2 U2: 1 U3: 1 U4: 3 U5: 1
Production yield	The mining yield is estimated to be 85% for all PGMs. The average concentration, smelting and refining yields for palladium correspond to the average values reported by Nassar (2013) and are of 84.2%, 96% and 98.9%, respectively. The resulting production yield is 68%.	U1: 2 U2: 3 U3: 1 U4: 2 U5: 1
Fabrication and manufacturing	It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). Minor losses are reported for jewelry (4%) and dental applications (3%) (Nassar, 2013). A yield of 100% is considered for other applications, resulting in an average yield of 99.9% for palladium.	U1: 2 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	The recovery of new scrap is considered to be included in the fabrication and manufacturing yield, and a new scrap recovery yield of 0 % is reported in this dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	A remelting yield of 98.9% is assumed (same as refining).	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	About 2% of palladium is estimated to be lost during use in exhaust pipes, and 24% from catalyst used in the chemical industry (Nassar, 2013).	Per sector; please refer to Supplementary Data
Collection and sorting	The EoL-RR of palladium is estimated to be between 60 and 70%, about 80% of which results from the recycling of catalysts contained in car exhausts, and the remainder mostly from electronic waste (BRGM, 2017f). We estimate average collection yields based on Nassar (2013) and UNEP (2011). Considering the large shares of EOL recycling from auto catalysts and electronic wastes, the current global EOL-RR are estimated to be of 60% and 20%, respectively. These estimates are both slightly higher than the estimates of UNEP (2011) around 2010.	Per sector; please refer to Supplementary Data

	The following collection yields are calculated considering a remelting yield of 98.9%: Catalysts, 98%; Electronics, 22%; Jewelry & investment, 96%, Transport, 81%; Biomedical & dental, 18%; and Other industrial, military & energy applications, 18%. Assuming a constant distribution of end-uses over time, these values suggest a global EOL-RR of approximately 60%, and are estimated to be representative of the current recycling yields.	

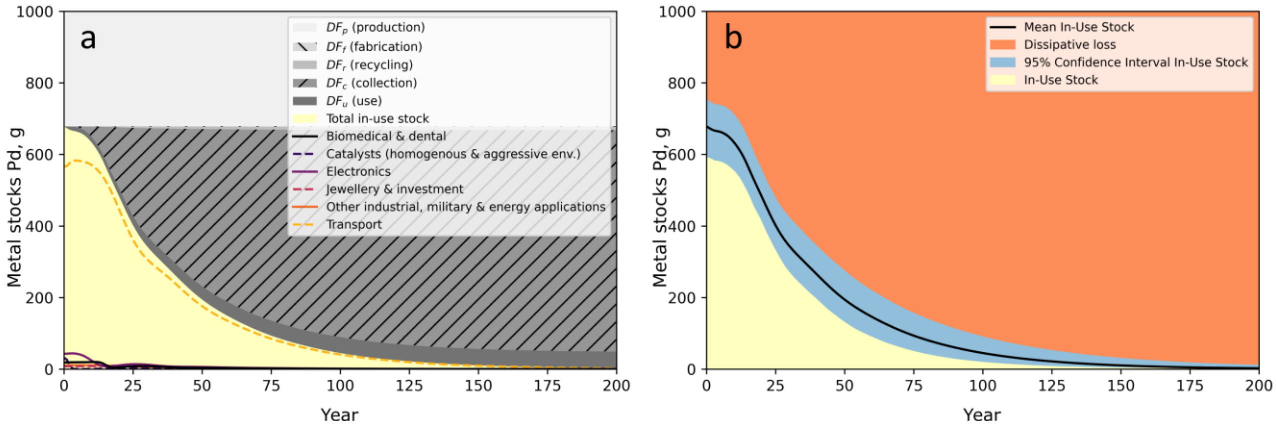

Figure S29. In-use stocks and losses of palladium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.31 Silver

Table S38. Silver.

<table>
<tr><th>Silver</th><th>Ag, element number 47</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>The Silver Institute provides yearly demand data for silver since 1991 in their yearly surveys. Demand data for the year 2018 is considered (The Silver Institute, 2019). It is chosen over the 2019 distribution since industrial applications of silver were disaggregated in a more transparent display. Alike for other investment products, the relative share of silver used in this end-use category is adjusted using a 10-years average to reflect the changes in demand due to the economic conjuncture (cf. method for other precious metals, section 2.4.2).
Silver catalysts for the production of ethylene oxide are classified as catalysts (homogenous & aggressive env.), considering that these catalysts are estimated to have a lifetime of between 18 and 36 months before they need to be regenerated (The Silver Institute, 2019). Brazing alloys and solders are categorized as alloys. Coins and bars, silverware as well as jewelry are aggregated in jewelry & investment. Finally, 1% out of the other “other” category reported by the Silver Institute is considered to be used as chemicals used in dispersive applications (food hygiene, detox chemicals, etc.), based on Ciacci et al. (2015). The following distribution is estimated to be representative of the year 2018:
<table>
<tr><td>Alloys & solders</td><td>6%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>1%</td></tr>
<tr><td>Chemicals</td><td>1%</td></tr>
<tr><td>Electronics</td><td>24%</td></tr>
<tr><td>Jewelry & investment</td><td>43%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>13%</td></tr>
<tr><td>Photography</td><td>4%</td></tr>
<tr><td>Solar cells</td><td>8%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>84% (Helbig et al., 2020, based on Johnson et al., 2005)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>91% (Helbig et al., 2020, based on Johnson et al., 2005)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>100% (Helbig et al., 2020, based on Johnson et al., 2005)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Johnson et al., 2005)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Dissipation rates of 100% are reported for chemicals , and 0% for other applications (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Helbig et al. (2020) calculated an average collection yield of 57% based on Johnson et al. (2005). We here consider the sector-specific EOL-RR for five out of seven categories representing the main silver uses reported by Nassar et al. (2012), based on Graedel et al. (2011). The following EOL-RR are estimated to represent collection yields, considering the reported remelting yield of 100%: alloys, 50%;</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	electronics, 12.5%; jewelry & investment, 95%; photography, 50%; Other industrial, military & energy applications, 50%. The silver catalysts used for ethylene oxide production are thought to be well recycled and represented half of the recycled silver from industrial applications in 2014 (BRGM, 2017g). The Silver Institute (2019) reported that approximately 2% of the silver content of catalysts is lost during the recovery process. Based on this information, we estimate a collection yield of 95% for catalysts, aligning on the higher estimates for other silver applications. Silver used in solar cells is a recent application, and the in-use stock of solar panels is growing rapidly while few solar panels have reached end-of-life (Latunussa et al., 2016). While this dataset is by no means prospective, we assume that 10% of the silver content would be readily functionally recycled currently given the technical and economic feasibility of recovering silver from panels (see e.g. Fangeat et al., 2020; Latunussa et al., 2016; Markert et al., 2020; and Suzy et al., 2020). Considering the remelting yield of 100%, a collection yield of 10% is reported for this application.	

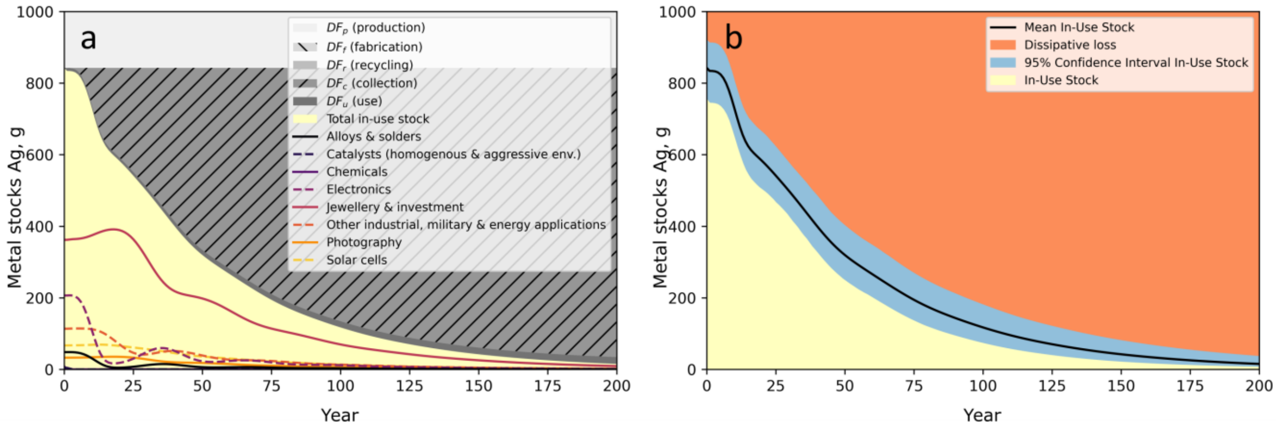

Figure S30. In-use stocks and losses of silver over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.32 Cadmium

Table S39. Cadmium.

<table>
<tr><th>Cadmium</th><th>Cd, element number 48</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Global end-uses of cadmium are reported for years 2003 (Harper et al., 2015), 2008 (USGS, 2009) and 2018 (BRGM, 2019b). These distributions are similar to the Europe end-uses in between 2012 and 2016 (European Commission, 2020c). Although cadmium is used increasingly in solar cells, their share remains small in comparison to total cadmium uses (BRGM, 2019b).

Values reported for 2018 (BRGM, 2019b) are disaggregated based on reported values for previous years. It is assumed that 20% of batteries are used in industrial applications, and the rest in user batteries (Graedel et al., 2013; Harper et al., 2015). Given the multiple potential uses for pigments (ceramics, plastics, paints, inks, etc.) for which lifetimes ranging from approximately 8 to 22 years are reported (Cha et al., 2013; Hawkins et al., 2006; Matsuno et al., 2012), these are split half and half between the plastics and the glass and ceramics sectors to reflect the diversity of potential applications. The plastics sector also includes stabilizers. The following distribution for global end-uses is estimated to be representative for years circa 2018:
<table>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>64%</td></tr>
<tr><td>Batteries (utility & industrial)</td><td>16%</td></tr>
<tr><td>Glass & ceramics</td><td>5%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>1%</td></tr>
<tr><td>Plastics</td><td>6%</td></tr>
<tr><td>Protective coatings</td><td>8%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>Cadmium is naturally present as a trace element in multiple raw materials such as gypsum, phosphates, iron, copper and lead ores, and coal, though primary cadmium is most typically produced as a by-product of zinc (BRGM, 2019b; Hawkins et al., 2006; Kwonpongsagoon et al., 2007). We here consider only that part of cadmium that originates from zinc/lead ores as potential cadmium resources.

Harper et al. (2015) report 6% mining losses and 5% refining losses based on US values in 1989 (Llewellyn, 1994). A mining and beneficiation yield of 77%, and refining yield of 83% can be calculated for Australia in the fiscal year of 1998-1999 (Kwonpongsagoon et al., 2007). Wang et al. (2018) report a 77.8% mining yield based on Cha et al. (2013); however, we could not replicate the calculation and the value is not considered in the dataset. A production yield of 76% is estimated from the average yields for Australia and the US.</td><td>U1: 2 U2: 4
U3: 3 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>Fabrication yields are reported to be of nearly 100% (Cha et al., 2013; Plachy, 2003), which seems likely given the high toxicity of cadmium and the associated regulations. Based on these references, the fabrication rate is estimated to be of 99.8% in this dataset, including the potential recovery of new scraps.

It can be observed that Hawkins et al. (2006) report cadmium emissions to air, water and “other releases” from smelting, manufacturing and recycling operations in the US, that suggest that some industries such</td><td>U1: 3 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
</table>

	as those producing plastics and coatings could have lower fabrication yields than these. However, it is not specified whether emissions result from a voluntary use of cadmium (i.e. cadmium resources) or not, nor how “other releases” are handled (cf. Hawkins et al., 2006, table 2). Therefore, these data are disregarded, but could warrant additional investigations.	
New scrap recovery	The recovery of new scraps is assumed to be covered in the fabrication and manufacturing yield.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	The recycling yield of collected scraps is believed to be nearly 100% based on values reported for the US (Plachy, 2003), Japan (Matsuno et al., 2012), and Korea (Cha et al., 2013). Up to 95% for cadmium telluride semiconductors used in photovoltaic cells is thought to be recyclable (BRGM, 2019b; Cha et al., 2013). Given that batteries are the main source of secondary cadmium, which is reported as “almost 100% recyclable” when collected (European Commission, 2020c), and that photovoltaics represent a small share of total cadmium end-use (< 1%), a remelting yield of 100% is estimated.	U1: 2 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	Around 20% of cadmium is estimated to be emitted from coatings during use (Ciacci et al., 2015). While small amounts of cadmium could also be emitted from solar panels (Cha et al., 2013), they are assumed to be negligible, and 0% dissipation in use is reported for all other applications.	Per sector; please refer to Supplementary Data
Collection and sorting	A large majority of the functional recycling of cadmium occurs from batteries (Ciacci et al., 2015; European Commission, 2020c). Collection yields are reported accordingly with the estimates for the 2001-2008 period of Harper et al. (2015). The EoL-RR is estimated to correspond to the collection yield, given that a remelting yield of 100% is reported for cadmium. These yields are of 20% for consumer batteries, 90% for industrial batteries, and of 0% for all other applications.	Per sector; please refer to Supplementary Data

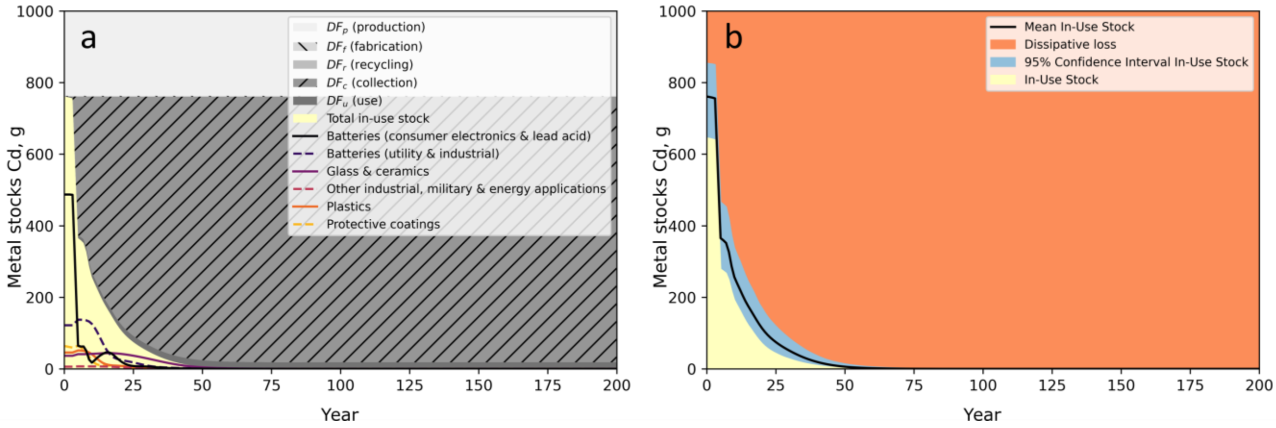

Figure S31. In-use stocks and losses of cadmium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.33 Indium

Table S40. Indium.

<table>
<tr><th>Indium</th><th>In, element number 49</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distributions of indium are available for the years 2008 (Harper et al., 2015), 2010 (Peiró et al., 2013), 2011 (Licht et al., 2015) and 2012 (BRGM, 2017h; Lokanc et al., 2015). The main end-use of indium is as a transparent conducting oxide in the form of indium-tin oxide (ITO), mostly used for flat panel displays. Thin-film coatings may also be used for various glass products (e.g., architectural glass, EMI glass, etc.). Another important emerging use of indium is in copper-indium-gallium-diselenide (CIGS) solar panels (Lokanc et al., 2015).
In this dataset, we consider the 2012 distribution of indium (BRGM, 2017h; Lokanc et al., 2015). A few refinements are made based on the end-use distribution of indium into semi-products and final products reported by Peiró et al. (2013) as well as Licht et al. (2015). First, alloys are disaggregated in dental, printed circuit boards (PCB)s and other alloys based on Licht et al. (2015). Dental uses and other alloys are reported as such, and PCBs are aggregated in the electronics category. Moreover, it is estimated that 2% of the global consumption of indium is for lighting applications based on the 2010 end-uses of indium (Peiró et al., 2013), and another 2% is considered to be used in various glass products. Thermal interface materials, representing 6% of the uses of indium, are assumed to be split equally between electronics and "Other miscellaneous" categories in order to reflect the diversity of applications for these materials. The following distribution is estimated to be representative of indium end-uses circa 2010-2012:
<table>
<tr><td>Alloys & solders</td><td>13%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>5%</td></tr>
<tr><td>Biomedical & dental</td><td>0%</td></tr>
<tr><td>Electronics</td><td>59%</td></tr>
<tr><td>Glass & ceramics</td><td>2%</td></tr>
<tr><td>Lighting</td><td>2%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>8%</td></tr>
<tr><td>Other miscellaneous</td><td>3%</td></tr>
<tr><td>Solar cells</td><td>8%</td></tr>
</table>
</td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>While the MFA of Licht et al. (2015) suggest a production yield of 54% (Helbig et al., 2020), it includes the reprocessing of zinc ore tailings in China. Other sources suggested that the actual recovery of primary indium may be lower. The Indium Corporation estimates that, in recent years, "no more than 50% of the indium mined every year is being extracted and refined as indium metal" (Mikolajczak and Peng, 2018). Similarly, citing a 2009 study by Mikolajczak, the National Renewable Energy Laboratory reported that approximately 30% of indium mined annually became refined indium metal, while their own in-depth investigation suggested that the recovery rate may be as low as 15-20% (Lokanc et al., 2015). Based on this information, we estimate the production yield of indium to be of approximately 30%.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>Fabrication and manufacturing</td><td>13% (Helbig et al., 2020, based on Licht et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 2</td></tr>
</table>

New scrap recovery	78% (Helbig et al., 2020, based on Licht et al., 2015)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 2
Remelting	96% (Helbig et al., 2020, based on Licht et al., 2015)	U1: 1 U2: 3 U3: 1 U4: 2 U5: 2
Dissipation in use	Dissipative uses reported by Licht et al. (2015) consist in type C dissipation (i.e. indium alloys and PCBs); as such, they are considered to be unrecyclable rather than dissipated during use. Moreover, while Ciacci et al. (2015) estimate an in-use dissipation rate of 5% for indium tin oxides used in thin film coatings, these are reported to be process losses and are assumed to be taken into account in the fabrication and manufacturing and new scrap recovery yields. Dissipation in use from other indium applications are expected to be negligible, and a rate of 0% is reported for all applications.	Per sector; please refer to Supplementary Data
Collection and sorting	Until recently, the EoL-RR of indium was reported to be null or negligible for all applications (BRGM, 2017h; Harper et al., 2015; Lokanc et al., 2015). A recent estimate suggests a global EOL-RR of 5% for indium (Graedel et al., 2022). Unlike for silver, the EOL recycling of indium from solar cells is estimated not to be feasible currently (Lokanc et al., 2015). Thus, a 0% collection rate is reported for all indium applications. We assume that the recovery of indium from old scraps results from electronic waste (LCD displays) (de la Torre et al., 2018; Song et al., 2021), and we extrapolate a collection and sorting yield of 9% for that end-use sector, considering a remelting yield of 96%.	Per sector; please refer to Supplementary Data

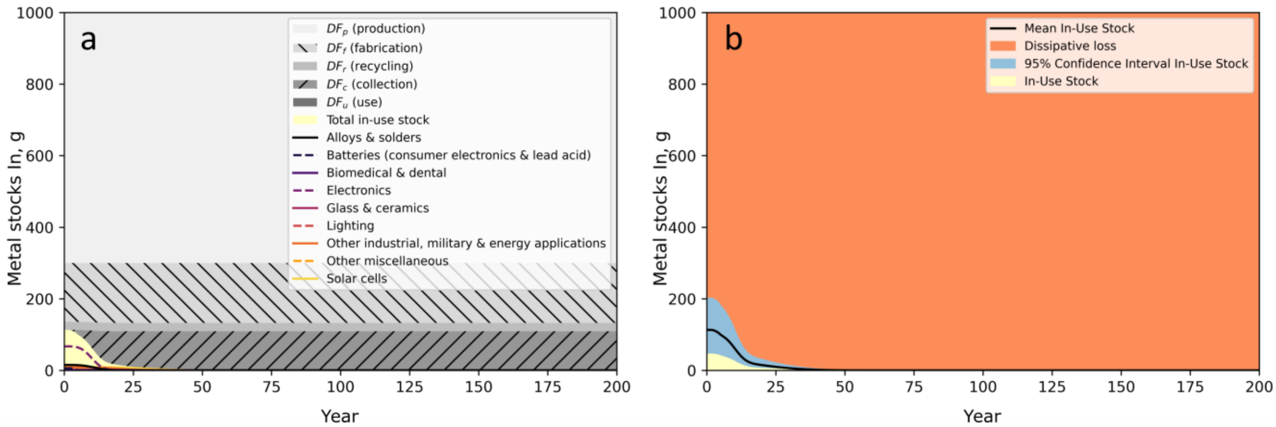

Figure S32. In-use stocks and losses of indium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.34 Tin

Table S41. Tin.

Tin	**Sn, element number 50**	**Uncertainty**
End-uses	Many end-use distributions of tin are reported in the literature, often based on the International Tin Research Institute. For example, end-use distributions are available for the years 2008 (Harper et al., 2015), 2007, 2010 and 2014 (Yang et al., 2017) and 2017 (European Commission, 2020c). The leading demand for tin remained for solders over the studied years, with approximately half of its consumption. Other notable uses include chemicals, lead acid batteries and as tinplate for packaging. It is also alloyed with copper to produce brass and bronze. For this dataset, we consider the most recent distribution for the year 2017 (European Commission, 2020c), which is refined using other available information. About 85% of tin solders are used in electronic appliances, and the rest in various industrial applications (European Commission, 2020c). Hence, 85% of the 47% reported use in solder applications are categorized in electronics, and the remaining 15% is reported in Other industrial, military & energy applications. Tinplate is disaggregated between packaging and tinning applications using a 15:2 ratio (Ciacci et al., 2015). Moreover, 2% out of the 10% others are reported as glassmaking process (floating glass process) (BRGM, 2017i). Brass and bronze are used mostly in transport and construction applications (Ciacci et al., 2015): these are assumed to be split half and half between the two sectors. The following distribution is estimated to be representative of the year 2017: Batteries (electric vehicle): 6% Chemicals: 6% Construction: 3% Electronics: 40% Glass manufacturing: 2% Other industrial, military & energy applications: 15% Packaging: 11% Plastics: 12% Protective coatings: 2% Transport: 3%	U1: 2 U2: 1 U3: 1 U4: 2 U5: 1
Production yield	88% (Helbig et al., 2020, based on Izard and Müller, 2010)	U1: 1 U2: 4 U3: 1 U4: 2 U5: 2
Fabrication and manufacturing	99% (Helbig et al., 2020, based on Izard and Müller, 2010)	U1: 1 U2: 4 U3: 1 U4: 2 U5: 2
New scrap recovery	26% (Helbig et al., 2020, based on Izard and Müller, 2010)	U1: 1 U2: 4 U3: 1 U4: 2 U5: 2
Remelting	100% (Helbig et al., 2020, based on Izard and Müller, 2010)	U1: 1 U2: 4 U3: 1 U4: 2 U5: 2
Dissipation in use	The use of tin in glass manufacturing is thought to be partly dissipative, with about 3200 tons out of 7100 tons of tin consumption	Per sector; please refer to

	for this application being reported as a consequence of losses during the production process (International Tin Association, 2017). Thus, we estimate an approximate 40% yearly dissipation rate for tin in this application, which results in about 64% of tin being lost over an average lifetime of 2 years. Some tin chemicals are used as biocides which are assumed to be used dissipatively (Ciacci et al., 2015): a dissipation rate of 100% is reported for chemicals. Other tin applications are not considered to be dissipative (Ciacci et al., 2015).	Supplementary Data
Collection and sorting	Helbig et al. (2020) reported an average collection yield of 20% based on Izard and Müller (2010). This yield seemingly results mostly from the recycling of brass and bronze used in transport and construction, for which EoL-RR of 70% is reported by Harper et al. (2015), also based on Izard and Müller (2010). Contrastingly, UNEP (2011) reported a global EoL-RR of tin above 50%, referring to the recycling rate of tin in the US in 1998 (USGS, 2004a), i.e. before tin solders started to be widely used as solder in electronics (PCBs). When collected, tin used in packaging or plating is expected to be mostly lost to steel flows (Ciacci et al., 2015; Izard and Müller, 2010). We here report such losses with a collection yield of 0% for these applications, although it should be acknowledged that the same losses could potentially be considered as remelting losses. Moreover, Izard and Müller (2010) mention that it is difficult to track the fate of post-consumer electronic waste. Some tin solders used in electronics are effectively collected as part of electronics waste collection schemes and can theoretically be recycled, as many processes exist to do so (Yang et al., 2017). We estimate that 20% of tin contained in electronics is effectively collected and recycled. In order to approximate the life cycle of tin used in the floating glass process, we report a 100% collection yield for that application. While it is not an ideal modelling choice, it allows to prevent creating an additional end-use sector, and is expected to have a minor influence on the results of the model given its small application share. Collection yields of 0% are reported for all other tin applications.	Per sector; please refer to Supplementary Data

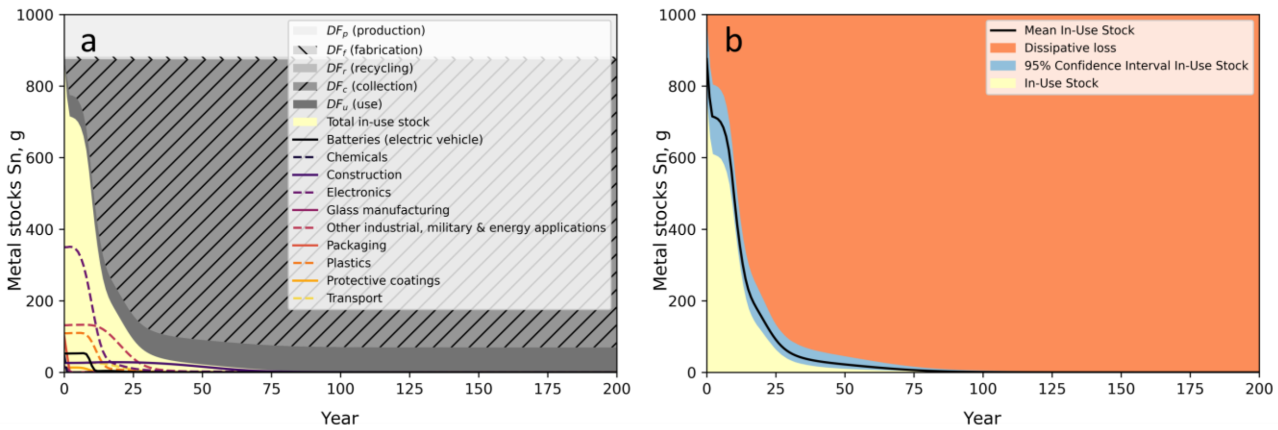

Figure S33. In-use stocks and losses of tin over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.35 Antimony

Table S42. Antimony.

<table>
<tr><th>Antimony</th><th>Sb, element number 51</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Antimony is mostly used as a flame retardant (around 50%) and in lead acid batteries (around 25%). Another leading use of antimony (approximately 6%) is as a catalyst in the production of PET polymers. Global end-uses are reported for the years 2008 (Panousi et al., 2016), 2010 (Dupont et al., 2016) and 2011 (BRGM, 2015b; Haarman, 2015). Although they are aggregated differently across references, the reported values are almost identical across these references, with the exception of a notable decrease of antimony use in glass products between 2008 and 2010-2011 values. This matches the yearly -20% end-use trend observed for this application between 2000 and 2010, as measured by Dupont et al. (2016).

Out of the 52% end-use of antimony as a flame retardant, around 70% are thought to be used for electronic appliances (Dupont et al., 2016). The remaining 30% of flame retardants are seemingly used mostly in automotive (including aircrafts) components, rubber, PVC products used in construction, and textiles (Carling, 2006; Dupont et al., 2016; Haarman, 2015; Mathys et al., 2007; USGS, 2020). These 30% are thus disaggregated in 40% automotive, 40% construction and 20% “others” sectors following the works of Haarman (2015), p. 49-50. Finally, 2% of antimony used in alloys is assumed to be used for bullets and is classified in the other punctual applications. The following distribution is estimated to be representative of years circa 2011, based on BRGM (2015b), Dupont et al. (2016), and Haarman (2015):
<table>
<tr><td>Alloys & solders</td><td>10%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>26%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>6%</td></tr>
<tr><td>Construction</td><td>6%</td></tr>
<tr><td>Electronics</td><td>37%</td></tr>
<tr><td>Glass & ceramics</td><td>2%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>4%</td></tr>
<tr><td>Other punctual applications</td><td>2%</td></tr>
<tr><td>Plastics</td><td>1%</td></tr>
<tr><td>Transport</td><td>6%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 1
U5: 2</td></tr>
<tr><td>Production yield</td><td>National MFAs of antimony are available for the US in 2000 (Carling, 2006), Switzerland in 2001 (Mathys et al., 2007) and China in 2013 (Chu et al., 2019). Some information on the SFA of antimony for Japan between 1970 and 2015 (including prospective estimates) is also available (Tsunemi and Wada, 2008). Moreover, a well-documented master’s thesis investigating the global anthropogenic cycle of antimony is available (Haarman, 2015).

Antimony can be produced as the main product from antimony ores, or as a by-product from gold, lead or zinc (BRGM, 2015b; Dupont et al., 2016). While copper ores are not used to produce antimony, they contain traces of antimony which could be recovered (Dupont et al., 2016). In this dataset, we consider only the voluntary recovery of</td><td>U1: 3 U2: 1
U3: 1 U4: 2
U5: 1</td></tr>
</table>

	antimony from antimony-bearing ores. This value could be revised if the recovery yields from gold, lead and zinc production (and eventually, copper) are considered. However, these are disregarded due to the lack of data, and the toxicity of antimony which limits its potential applications. China is the leading antimony producer with over 50% of the production in the recent years (USGS, 2020). Based on an SFA of antimony in China in 2013 (Chu et al., 2019), a production rate of 78.8% can be calculated. Panousi et al. (2016) consider an extraction efficiency of 90% and a refining of 90% as well, resulting in a 81% estimated yield for production. The data reported in Haarman (2015) suggest a primary production yield of 89% for the year 2011. An average yield of 83% is considered in this dataset.	
Fabrication and manufacturing	A global yield of 96% can be calculated with the data of Haarman (2015). For metal products, Haarman estimated fabrication and manufacturing emissions and waste values based on a study for the lead anthropogenic cycle (Mao et al., 2008b), and for non-metallic products, based on European risk report for antimony trioxide (EU RAR, 2008). A similar yield of 95% is reported for the US for year 2000 (Carling, 2006). Contrastingly, the Chinese SFA for the year 2013 suggest a yield of roughly 60%, out of which most losses are considered as unrecovered waste or emissions (Chu et al., 2019). However, this value is extrapolated from the quantity of antimony used in manufactured products in China from other literature, and it suggests net manufacturing yields (including new scrap recovery) that are well below those of e.g. lead products used in the same manufacturing processes (Mao et al., 2008b). We could not find a reasonable explanation or additional evidence for such a low yield in the literature, and the value is disregarded in the dataset. Therefore, it is considered that 96% was the best available global estimate for the fabrication and manufacturing yield, based on Haarman (2015). The values from this same reference are considered to be most representative of global yields for other post-production processes as well given the exhaustively collected underlying data.	U1: 2 U2: 3 U3: 1 U4: 2 U5: 1
New scrap recovery	29%, calculated based on Haarman (2015)	U1: 2 U2: 3 U3: 1 U4: 2 U5: 1
Remelting	83%, calculated based on Haarman (2015)	U1: 2 U2: 3 U3: 1 U4: 2 U5: 1
Dissipation in use	Some uses of antimony such as in ammunitions, and lubricating agents used in brake pads, can be dissipative (type B) (Ciacci et al., 2015). Ammunitions are reported to be used dissipatively. Other potentially dissipative applications are assumed to represent a negligible share of end use, and consequently of dissipation in use of antimony. Moreover, some antimony contained in catalysts for PET production is known to be lost to the PET. We roughly estimate that 66% of antimony is dissipation in use (type B) in PET catalysts over their lifetime, based on Ciacci et al. (2015).	Per sector; please refer to Supplementary Data

Collection and sorting	Based on our literature survey for antimony, secondary antimony is thought to provide about 15-20% of total antimony supply, approximately 80% of which originates from old scraps. Of old scraps containing antimony, only lead acid batteries are considered to be functionally recyclable (Ciacci et al., 2015). Antimony contained in recycled batteries is thought to be mostly functionally recycled in new antimonial lead (Dupont et al., 2016). Therefore, we only consider the recovery of lead acid batteries for the calculation of functional recycling. In 2011, about 90% of lead acid batteries were recycled in Europe, and approximately 70% were thought to be recycled worldwide (Haarman, 2015). Based on this information and on the collection yield reported for lead used in these same batteries (i.e. 85%; cf. Table S69), a collection yield of 85% is estimated for antimony used in lead acid batteries. While this yield is much higher than the 20% EoL-RR reported by Panousi et al. (2016), it can be explained by the sharp trend noted for the recycling of antimonial lead over the past two decades (cf. Table S69).	Per sector; please refer to Supplementary Data

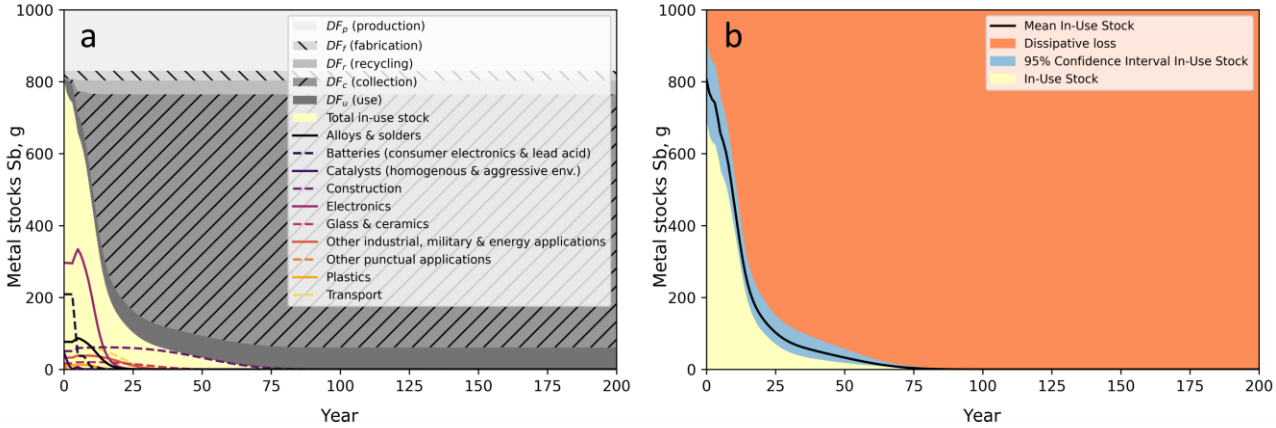

Figure S34. In-use stocks and losses of antimony over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.36 Tellurium

Table S43. Tellurium.

<table>
<tr><th>Tellurium</th><th>Te, element number 52</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Several estimates of the global end-use distributions of tellurium are available from the USGS Mineral Commodity Summaries, including years from 2014 to 2019. The latest distribution for 2019 is used (USGS, 2020). The reported end-use distribution is the same as those for the years 2015-2018 and that of 2010 published by Ciacci et al. (2015), also based on the USGS. Tellurium’s principal uses are for cadmium-tellurium solar cells and thermoelectric devices. The latter are aggregated in the electronics category. Metallurgical uses include stainless steel and copper alloys, used for e.g. power cables and automotive bearings (Ciacci et al., 2015). While tellurium is used as a metallurgical additive to improve the machinability of the alloys, it may contribute to the characteristics of the metal product, such as the resistance to vibration and fatigue of lead alloys (Kavlak and Graedel, 2013a). The latter authors considered the metallurgical use of tellurium to be dissipative, and seemingly did not account for it as part of the in-use stocks. In this dataset, we consider such use of tellurium to be dissipation of type C, since tellurium remains in the metal product over its lifetime and is in theory recyclable from its alloys (Ciacci et al., 2015). Therefore, the metallurgical uses of tellurium are here aggregated in the alloys sector.

Other uses of tellurium are diverse and include catalysts, chemicals, pigments, germicide and fungicide, lubricants, many of which are inherently dissipative (Ciacci et al., 2015; Kavlak and Graedel, 2013a). To reflect this, half of other uses are classified as other punctual applications and attributed a 100% dissipation rate, while the remainder share is classified in Other miscellaneous. The following end-use distribution is estimated to be representative of 2010-2019:
<table>
<tr><td>Alloys & solders</td><td>15%</td></tr>
<tr><td>Electronics</td><td>30%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>5%</td></tr>
<tr><td>Other punctual applications</td><td>5%</td></tr>
<tr><td>Rubber</td><td>5%</td></tr>
<tr><td>Solar cells</td><td>40%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>5% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>62% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>54% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Tellurium used in other punctual applications is estimated to cover dissipative uses of tellurium as mentioned by Ciacci et al. (2015), and a dissipation in use rate of 100% is reported for that sector. Other uses</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	are estimated not to be dissipated in use, although the metallurgical use of tellurium as well as its use in rubber are considered as dissipative uses of type C, highlighting that tellurium is currently unrecyclable from these applications (Ciacci et al., 2015).	
Collection and sorting	Some tellurium may be recovered from thermoelectric devices and solar panels, especially from copper converters (Ciacci et al., 2015). Although this amount is considered negligible by some authors (European Commission, 2020c; Nassar et al., 2012), the BRGM report that the global EOL-RR of tellurium may range between 1 and 7% (BRGM, 2018g), citing the International Copper Study Group. Based on this information and considering a remelting yield of 100%, we report a collection yield of 5% for electronics and 1% for solar cells.	Per sector; please refer to Supplementary Data

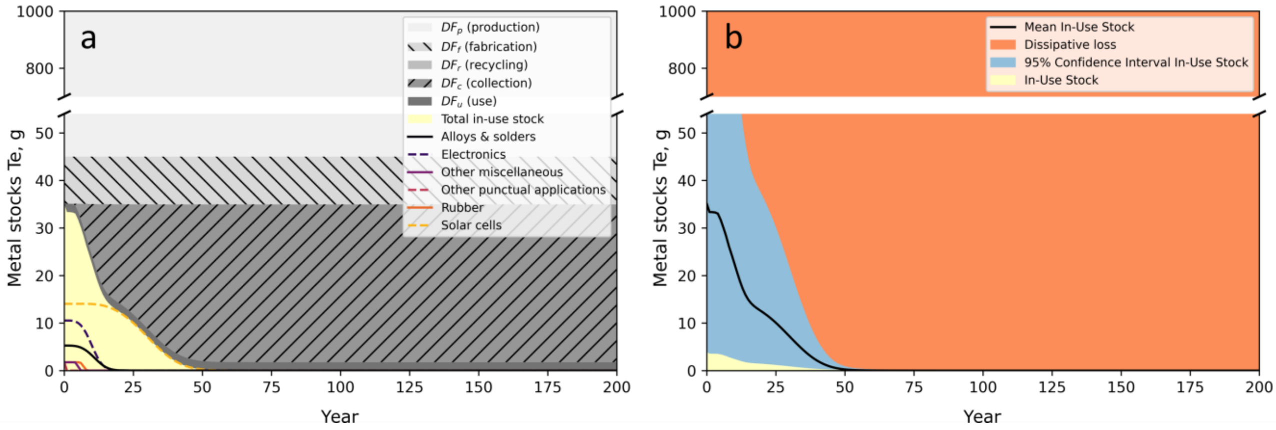

Figure S35. In-use stocks and losses of tellurium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.37 Barium

Table S44. Barium.

<table>
<tr><th>Barium</th><th>Ba, element number 56</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Barium is mostly used as part of barites used in drilling fluids for the oil and gas industry (European Commission, 2020a; Johnson et al., 2017). Recent reports indicate that between 69% and 90% of barium is used by for drilling fluids globally (Johnson et al., 2017; The Barytes Association, 2020). The variation may be explained by unpredictable changes in demand for barites linked to the oil and gas industry. An average of 80% is assumed to be representative of the end-use of barium in drilling fluids based on UNEP (2011), which appear to be fairly constant with earlier data, e.g. 78% in 1993 (Albouy and Rousseau, 1993) and 84% in 2008/2009 (Panousi et al., 2016).

Other uses include chemicals used for electronics, television screens, glass and ceramics, and medical applications (barium meals), as well as fillers used in the car, rubber and paint industries as well as various radiation shielding applications (The Barytes Association, 2020; USGS, 2020). Although it may be estimated that chemicals and fillers each represent about half of the remaining other uses (The Barytes Association, 2020), it is not possible to precisely disaggregate these in actual end-uses with the available information. Hence, 10% of barium end-uses are reported as other industrial applications, and 10% in other miscellaneous applications, to reflect its various potential end-use applications. The following distribution is estimated to be representative of recent years, i.e. 2015-2019:

<table><tr><td>Other industrial, military & energy applications</td><td>10%</td></tr><tr><td>Other miscellaneous</td><td>10%</td></tr><tr><td>Well drilling</td><td>80%</td></tr></table></td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 2</td></tr>
<tr><td>Production yield</td><td>Panousi et al. (2016) provide an informed estimate of the mining yield of 80%. As barites are mostly used as a raw mineral in various applications (cement, drilling fluids, etc.), it is assumed that the additional processing of barites in other pure barium compounds represents a negligible share of production losses.</td><td>U1: 3 U2: 2
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is estimated that small losses may incur from various processes along the fabrication and manufacturing chains, and a yield of 95% is assumed.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; and 0% is reported</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>N/A; and 0% is reported</td><td>U1: 3 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Is some situations, drilling fluids may be considered to be recycled (or reused) to a certain extent (Johnson et al., 2017). Either way, most drilling fluids will end up as dissipated due to the way they are used directly in the environment. In this dataset, it is considered that such dissipation is covered in the EoL-RR of 0% reported for this application. Some medical applications (barium meals) may also be considered to be dissipative, although these were estimated to cover a negligible</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	fraction of other uses reported above and were not considered in this dataset.	
Collection and sorting	According to Johnson et al. (2017), barium is not readily recovered from applications other than drilling fluids (cf. dissipation in use box). The European Commission indicate that some barium used in glass may be considered to be functionally recycled, and indicate a recycling input rate of 1% for barites (European Commission, 2020a). Graedel et al. (2011) report a recycling rate below 1% for barium. We here assume the functional recycling of barium to be globally negligible, like Panousi et al. (2016).	Per sector; please refer to Supplementary Data

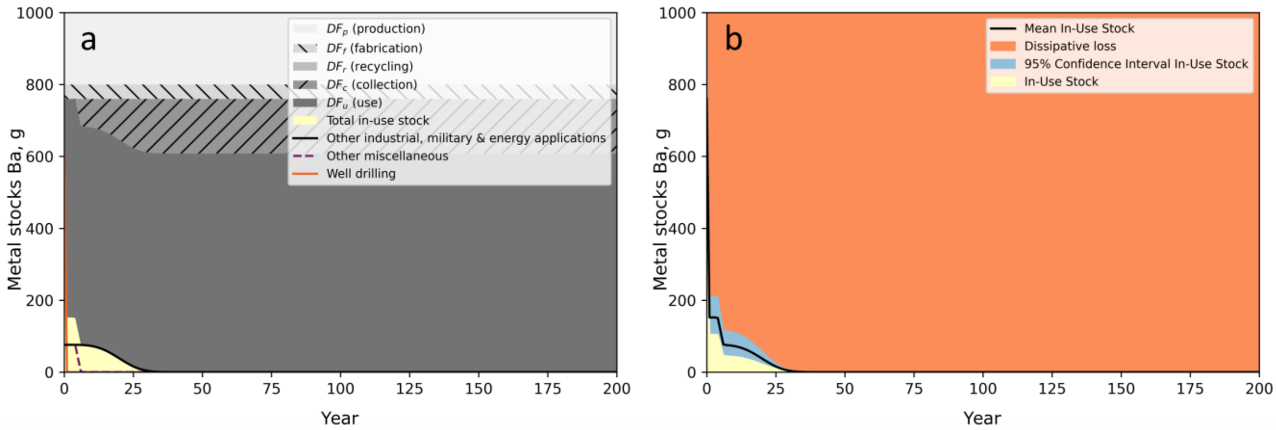

Figure S36. In-use stocks and losses of barium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.38 Lanthanum

Table S45. Lanthanum.

Lanthanum	**La, element number 57**	**Uncertainty**
End uses	The general method for REE distribution into end-use categories is described in section 2.4.3.2. End-uses for 2010 reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from (Peiró et al., 2013). End-uses are then re-aggregated in order to fit within the harmonized end-use distributions of this dataset. For example, the 3.7% end-use of lanthanum as green phosphors is disaggregated into LCD screens, plasma panels and lighting applications; then, plasma panels and LCD screens are aggregated in the electronics category, and lighting applications in their designated category. The leading use of lanthanum is in FCCs. FCCs undergo particularly harsh reaction conditions and deactivate quickly, and hence need to be constantly regenerated with fresh catalysts (Vogt and Weckhuysen, 2015). The authors estimate that their lifetime is of about 1 month before they become deactivated. We aggregated FCCs into the chemicals category, for which a dissipation in use rate of 100% is reported. The use of lanthanum for glass polishing is comprised in the other punctual applications category. The following end-uses for lanthanum are estimated to be representative of the global end-uses of lanthanum in 2012: Alloys & solders: 10% Batteries (consumer electronics & lead acid): 9% Batteries (electric vehicle): 17% Electronics: 0.4% Glass & ceramics: 6% Lighting: 1% Other industrial, military & energy applications: 9% Other punctual applications: 1% Transport: 1%	U1: 2 U2: 3 U3: 1 U4: 2 U5: 2
Production yield	60% (cf. section 2.4.3.1)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	86% (Du and Graedel, 2011a)	U1: 1 U2: 3 U3: 1 U4: 3 U5: 2
New scrap recovery	0% (Du and Graedel, 2011a)	U1: 1 U2: 3 U3: 1 U4: 3 U5: 2
Remelting	100% (assumption)	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	About 3% of lanthanum can be assumed to be lost to volatilization during glass polishing (Ciacci et al., 2015). We also note a dissipation in use rate of 2% considering the rate reported by Ciacci and colleagues for other elements used in autocatalysts (classified in the transport sector). Furthermore, given the rapid deactivation of FCCs, we approximate FCC losses with a dissipation in use rate of 100%.	Per sector; please refer to Supplementary Data

	Dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015).	
Collection and sorting	Based on section 2.4.3.5, an EOL-RR of 5% is reported for lanthanum used in batteries, 5% in lighting applications, and 0% for other applications. It is assumed that the one-year lifetime reported for glass polishing covers internal recycling of polishing powders, if ever it occurs. All of the losses due to waste management and recycling are reported as collection losses.	Per sector; please refer to Supplementary Data

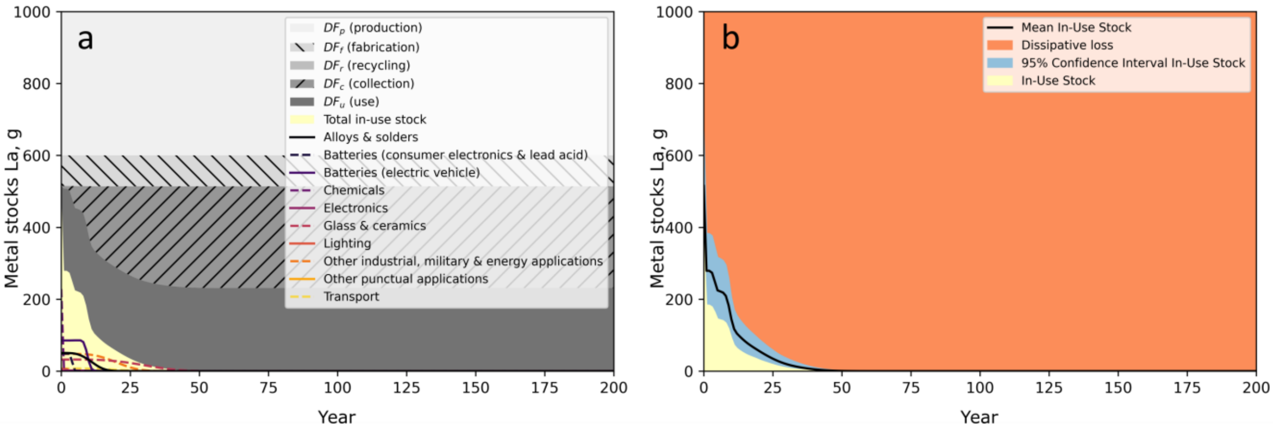

Figure S37. In-use stocks and losses of lanthanum over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.39 Cerium

Table S46. Cerium.

<table>
<tr><th>Cerium</th><th>Ce, element number 58</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). Then, end-uses are re-aggregated in order to fit within the harmonized end-use distributions of this dataset. Alike lanthanum, FCCs are categorized as chemicals and modelled with a dissipation in use rate of 100% to approximate deactivation losses. Glass polishing is categorized under other punctual applications. The following end-uses for cerium are estimated to be representative of the global end-uses of cerium in 2012:
<table>
<tr><td>Alloys & solders</td><td>19%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>1%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>2%</td></tr>
<tr><td>Chemicals</td><td>5%</td></tr>
<tr><td>Electronics</td><td>1%</td></tr>
<tr><td>Glass & ceramics</td><td>13%</td></tr>
<tr><td>Lighting</td><td>3%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>8%</td></tr>
<tr><td>Other punctual applications</td><td>36%</td></tr>
<tr><td>Transport</td><td>13%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>58% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>85% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>0% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>Remelting</td><td>100% (assumption)</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>All of cerium chemicals, including FCCs, are assumed to be wholly dissipated in use. Moreover, about 3% of cerium can be assumed to be lost to volatilization during glass polishing, and 2% from the use in automotive catalytic converters, while dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Based on section 2.4.3.5, an EOL-RR of 5% is reported for cerium used in batteries, 5% in lighting applications, and 0% for other applications. It is assumed that the one-year lifetime reported for glass polishing covers internal recycling of polishing powders, if ever it occurs. All of the losses due to waste management and recycling are reported as collection losses.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

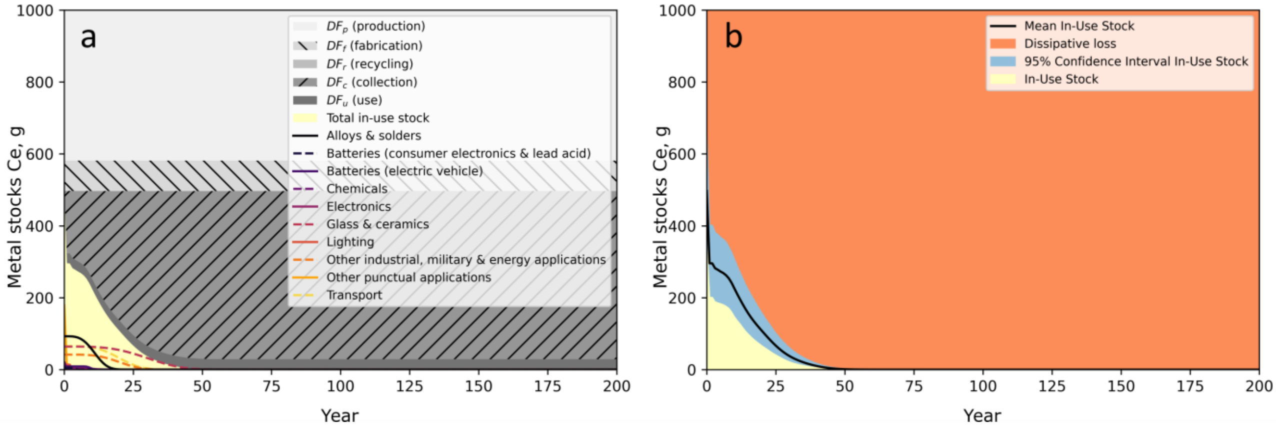

Figure S38. In-use stocks and losses of cerium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.40 Praseodymium

Table S47. Praseodymium.

<table>
<tr><th>Praseodymium</th><th>Pr, element number 59</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. A small tweak to the general method was required to establish end-uses of praseodymium, since it was not reported to be used as phosphors in the works of Peiró et al. (2013). Jayachandiran and Kennedy (2020) report most common uses of praseodymium phosphors to be optical displays, pressure sensors, lighting, dosimetry and thermal sensors. Praseodymium can also replace a share of neodymium in Nd–Fe–B magnets, and is also used in laser crystals and pigments for glass and ceramics (Binnemans et al., 2018). Magnets are split between electronics, EVs (aggregated in the transport category) and large magnet applications (e.g., wind turbines). No quantified information could be found for praseodymium used in phosphors, and we assume an average distribution of praseodymium based on average REE use of 16% in electronic appliances (LCDs and plasma displays) and 84% in lighting applications, calculated from the data of Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of praseodymium in 2012:
<table>
<tr><td>Alloys & solders</td><td>4%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>1%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>3%</td></tr>
<tr><td>Electronics</td><td>54%</td></tr>
<tr><td>Glass & ceramics</td><td>7%</td></tr>
<tr><td>Lighting</td><td>9%</td></tr>
<tr><td>Magnets (large)</td><td>6%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Other punctual applications</td><td>2%</td></tr>
<tr><td>Transport</td><td>12%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 3</td></tr>
<tr><td>Production yield</td><td>60% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>68% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>New scrap recovery</td><td>59% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Remelting</td><td>100%; assumption, based on Du and Graedel (2011a). The remelting yield may be included in the new scrap recovery yield reported in the MFA of Du and Graedel.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>About 3% of praseodymium can be assumed to be lost to volatilization during glass polishing (Ciacci et al., 2015). While the authors mention that some dissipation may occur from the use of praseodymium in auto catalysts, praseodymium is not considered to be used in this application (the share of praseodymium included in transport sector represents its</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	use in magnets for EV motors). Other dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015).	
Collection and sorting	5% for battery applications, and 0% for other applications (cf. section 2.4.3.5)	Per sector; please refer to Supplementary Data

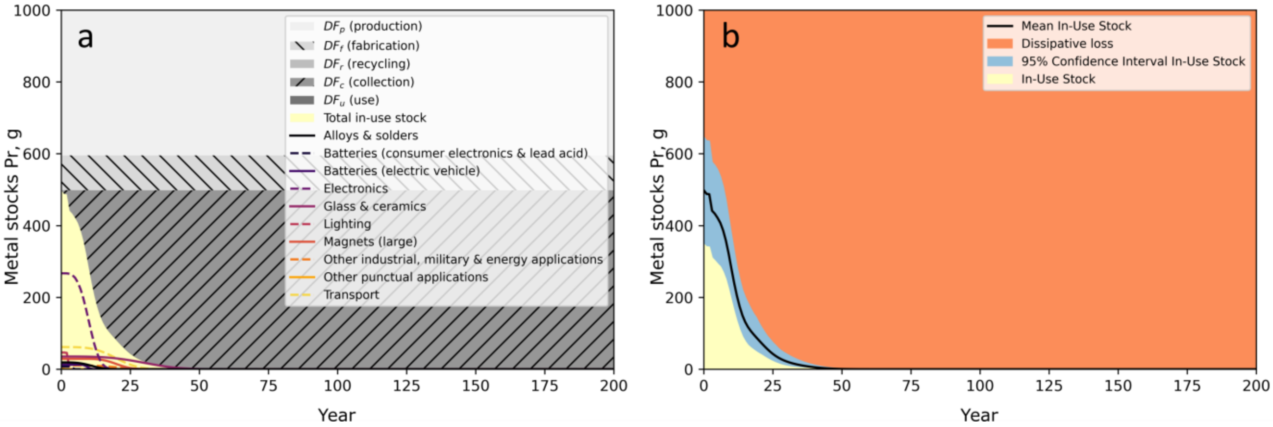

Figure S39. In-use stocks and losses of praseodymium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.41 Neodymium

Table S48. Neodymium.

<table>
<tr><th>Neodymium</th><th>Nd, element number 60</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. The same tweak as for praseodymium is required to establish the end-use distribution of neodymium’s phosphors (cf. Table S48). The following distribution is estimated to be representative of the global end-uses of neodymium in 2012:
<table>
<tr><td>Alloys & solders</td><td>2%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>1%</td></tr>
<tr><td>Batteries (electric vehicle)</td><td>1%</td></tr>
<tr><td>Electronics</td><td>65%</td></tr>
<tr><td>Glass & ceramics</td><td>6%</td></tr>
<tr><td>Lighting</td><td>1%</td></tr>
<tr><td>Magnets (large)</td><td>7%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>0.4%</td></tr>
<tr><td>Other punctual applications</td><td>0.3%</td></tr>
<tr><td>Transport</td><td>17%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>60% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>85% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>65% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>Remelting</td><td>100%; assumption, based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>2% of neodymium is estimated to be lost to corrosion over the lifetime of neodymium magnets (Ciacci et al., 2015). While the authors mention potential dissipation from the use of neodymium in auto catalytic converters, it was not considered to be used in this application in 2012 (the share of neodymium included in transport represents its use in magnets for EV motors). Dissipation in use from other applications are believed to be negligible (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>5% for battery applications, and 0% for other applications (cf. section 2.4.3.5)</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

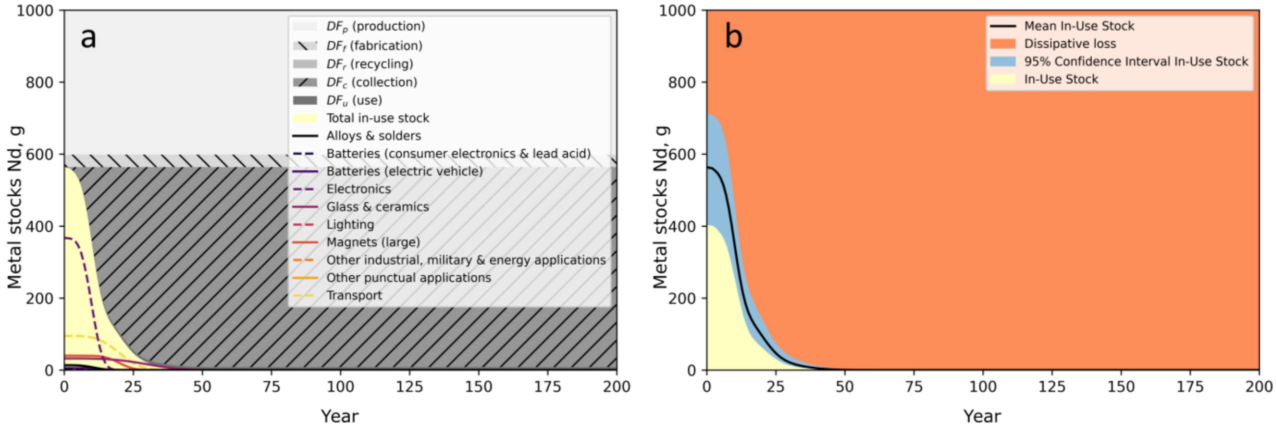

Figure S40. In-use stocks and losses of neodymium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.42 Samarium

Table S49. Samarium.

Samarium	**Sm, element number 62**	**Uncertainty**
End uses	While samarium was reported to be mostly used in NiMH batteries around 2008 (Graedel et al., 2013; Peiró et al., 2013), these had been mostly replaced by lithium-ion batteries by 2014, and samarium's principal use became permanent samarium-cobalt magnets, representing about 97% of its uses (Bru et al., 2015; European Commission, 2020a). Considering the wide range of applications for such magnets, including e.g. aerospace, microwave communications, instrumentation, electrical engineering, and magnetic machinery (Yi, 2014), they are added to the other industrial sector rather than the large magnets category. Other samarium uses are added to the other miscellaneous category. The following end-uses are reported for samarium for the year 2012, and are estimated to have remained stable in recent years: Other industrial, military & energy applications: 97% Other miscellaneous: 3%	U1: 2 U2: 1 U3: 1 U4: 3 U5: 3
Production yield	63% (cf. section 2.4.3.1)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	86% (Du and Graedel, 2011a)	U1: 3 U2: 3 U3: 1 U4: 3 U5: 2
New scrap recovery	0% (Du and Graedel, 2011a)	U1: 1 U2: 3 U3: 1 U4: 3 U5: 2
Remelting	N/A, 0% reported in this dataset.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
Dissipation in use	While some minor end-uses of samarium may be dissipative, we report a rate of 0% for all applications, based on Ciacci et al. (2015).	Per sector; please refer to Supplementary Data
Collection and sorting	0% (cf. section 2.4.3.5)	Per sector; please refer to Supplementary Data

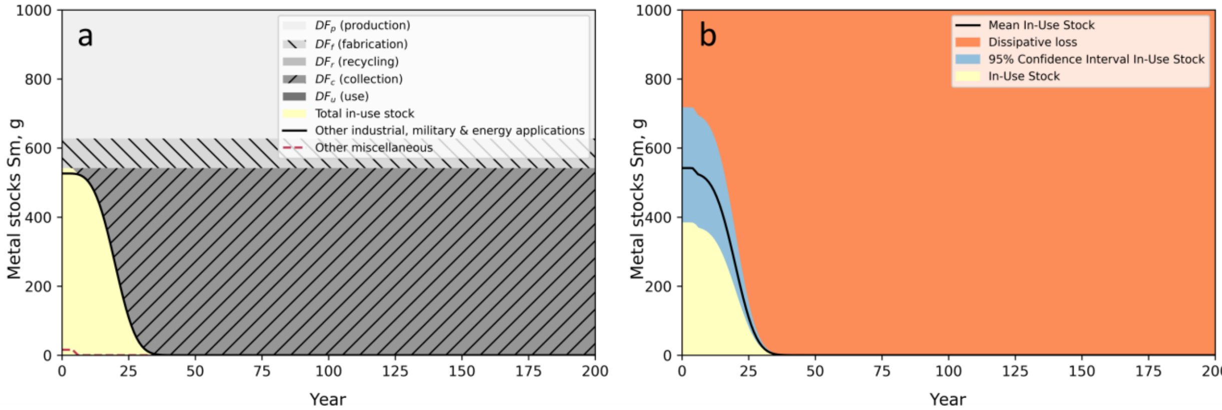

Figure S41. In-use stocks and losses of samarium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.43 Europium

Table S50. Europium.

Europium	**Eu, element number 63**	**Uncertainty**
End uses	Few applications make use of europium aside from phosphors used in lamps (Binnemans et al., 2018). The general method for REE distribution into end-use categories is described in section 2.4.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of europium in 2012: Electronics: 17% Lighting: 80% Other industrial, military & energy applications: 4%	U1: 2 U2: 3 U3: 1 U4: 2 U5: 2
Production yield	62% (cf. section 2.4.3.1)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	80%, with the assumption that both >0.1t losses reported for fabrication and manufacturing are equal to 0.03t each (Du and Graedel, 2011a)	U1: 3 U2: 3 U3: 1 U4: 3 U5: 2
New scrap recovery	0% (Du and Graedel, 2011a)	U1: 1 U2: 3 U3: 1 U4: 3 U5: 2
Remelting	100% (assumption)	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	0% (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	Based on section 2.4.3.5, an EOL-RR of 10% is reported for europium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses.	Per sector; please refer to Supplementary Data

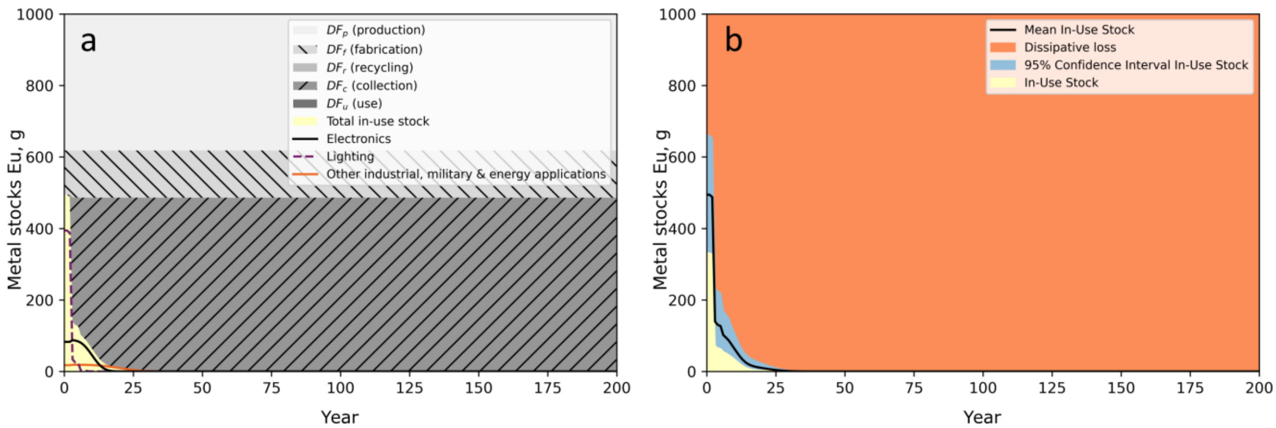

Figure S42. In-use stocks and losses of europium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.44 Gadolinium

Table S51. Gadolinium.

<table>
<tr><th>Gadolinium</th><th>Gd, element number 64</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). Moreover, 10% out of the 14% reported as other uses are assumed to be a punctual use as a tracer in medical imaging (Binnemans et al., 2018; Ciacci et al., 2015). The following distribution is estimated to be representative of the global end-uses of gadolinium in 2012:
<table><tr><td>Alloys & solders</td><td>28%</td></tr><tr><td>Electronics</td><td>4%</td></tr><tr><td>Lighting</td><td>19%</td></tr><tr><td>Magnets (large)</td><td>35%</td></tr><tr><td>Other industrial, military & energy applications</td><td>4%</td></tr><tr><td>Other punctual applications</td><td>10%</td></tr></table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 3</td></tr>
<tr><td>Production yield</td><td>64% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>70% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>New scrap recovery</td><td>20% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Remelting</td><td>100%; assumption based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>The dissipation in use from contrasting agents for MRI could be considered to be of type B or C, depending on if it is considered to be lost once discarded with wastewater. Ciacci et al. (2015) assumed that roughly 20% is dissipated during use (dissipation in use of type B), while the remainder share is currently unrecyclable (dissipation in use of type C). These same values are reported in the dataset, and dissipation in use rates of 0% are reported for other applications (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Based on section 2.4.3.5, an EOL-RR of 5% is reported for gadolinium used in lighting applications, and 0% for other applications. In order to avoid a conflictual remelting rate with that considered for new scrap recovery, all of the losses due to waste management and recycling are reported as collection losses.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

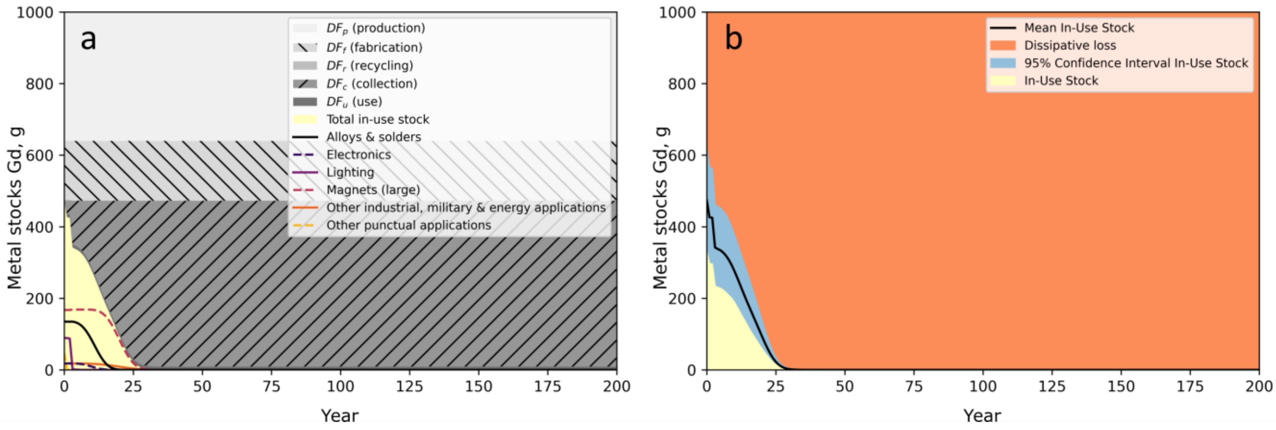

Figure S43. In-use stocks and losses of gadolinium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.45 Terbium

Table S52. Terbium.

Terbium	**Tb, element number 65**	**Uncertainty**
End uses	The general method for REE distribution into end-use categories is described in section 2.4.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of terbium in 2012: Electronics — 18% Lighting — 53% Magnets (large) — 7% Other industrial, military & energy applications — 5% Transport — 16%	U1: 2 U2: 3 U3: 1 U4: 2 U5: 2
Production yield	65% (cf. section 2.4.3.1)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	80%, with the assumption that both >0.1t losses reported for fabrication and manufacturing are equal to 0.03t each (Du and Graedel, 2011a)	U1: 3 U2: 3 U3: 1 U4: 3 U5: 2
New scrap recovery	0% (Du and Graedel, 2011a)	U1: 1 U2: 3 U3: 1 U4: 3 U5: 2
Remelting	100% (assumption)	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	0% (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	Based on section 2.4.3.5, an EOL-RR of 10% is reported for terbium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses.	Per sector; please refer to Supplementary Data

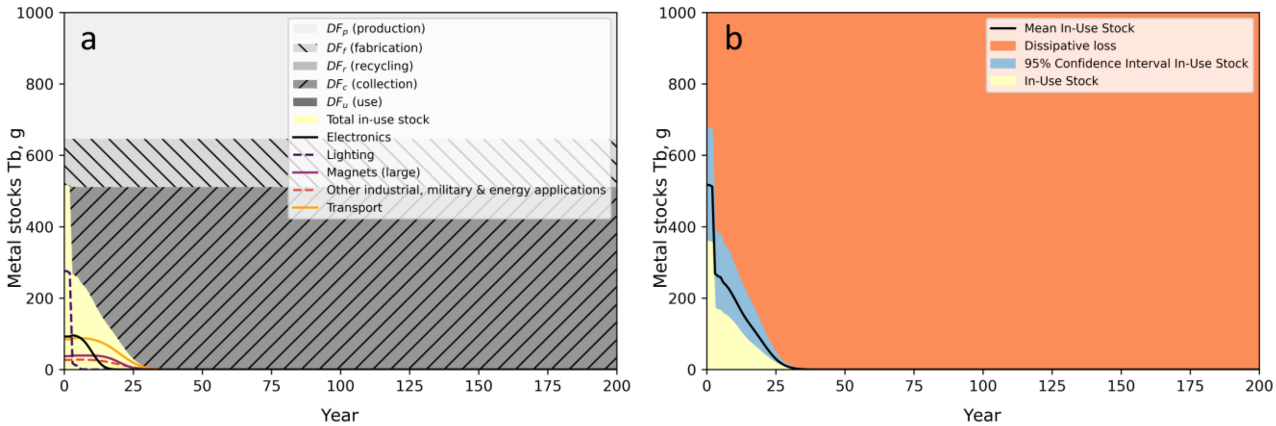

Figure S44. In-use stocks and losses of terbium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.46 Dysprosium

Table S53. Dysprosium.

<table>
<tr><th>Dysprosium</th><th>Dy, element number 66</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. Dysprosium is nearly exclusively used in permanent neodymium magnets (BRGM, 2016a). End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of dysprosium in 2012:
<table>
<tr><td>Electronics</td><td>68%</td></tr>
<tr><td>Magnets (large)</td><td>9%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Transport</td><td>22%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>66% (cf. section 2.4.3.1)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>56% (Du and Graedel, 2011a)</td><td>U1: 1 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>57% (Du and Graedel, 2011a)</td><td>U1: 3 U2: 3
U3: 1 U4: 3
U5: 2</td></tr>
<tr><td>Remelting</td><td>100%; assumption, based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>0% (Ciacci et al., 2015)</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>0% (cf. section 2.4.3.5)</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

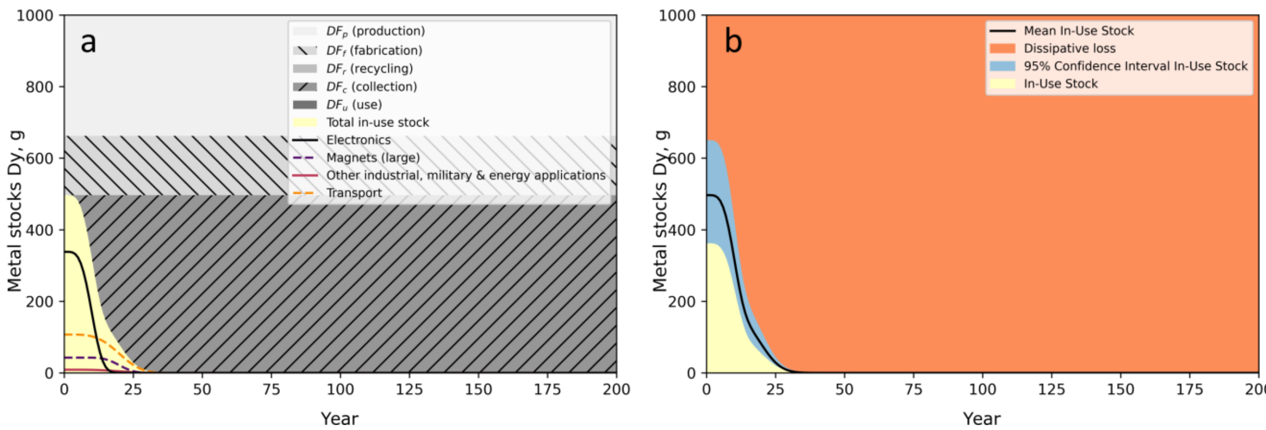

Figure S45. In-use stocks and losses of dysprosium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.47 Holmium

Table S54. Holmium.

<table>
<tr><th>Holmium</th><th>Ho, element number 67</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>It is difficult to define holmium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No global end-use distribution specific of holmium could be found. The BRGM lists four main potential applications for holmium: YAG lasers, the coloration of glass products, metal halide lamps and strong magnets used e.g. in magnetic flux concentrators (Bru et al., 2015). Holmium is thought to be used mostly for such magnets in the US (Graedel et al., 2013), while glass products are thought to be the only use for holmium in Europe (European Commission, 2020a; Guyonnet et al., 2015). Without further information, we assume a distribution of 1/3 each in magnets, glass products, and other industrial, military & energy applications. The following distribution is estimated to be representative of holmium end-uses in recent years:
<table>
<tr><td>Glass & ceramics</td><td>33%</td></tr>
<tr><td>Magnets (large)</td><td>33%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>33%</td></tr>
</table></td><td>U1: 4
U2: 1
U3: 1
U4: 3
U5: 3</td></tr>
<tr><td>Production yield</td><td>67% (cf. section 2.4.3.1)</td><td>U1: 4 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs.</td><td>U1: 3 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>New scrap recovery</td><td>No recovery of new scraps is expected to occur (European Commission, 2020a).</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>N/A, 0% reported in this dataset</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>The use in magnets is not considered to be dissipated in use (Ciacci et al., 2015). Based on dissipation reported for other REEs, the other main uses for holmium are unlikely to be dissipative and are also reported as 0%.</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>0% (cf. section 2.4.3.5)</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

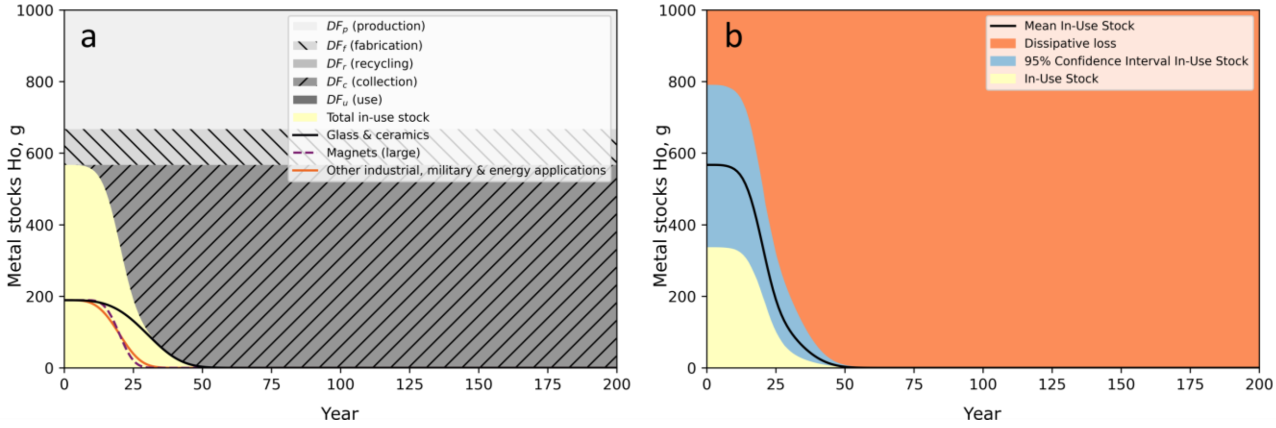

Figure S46. In-use stocks and losses of holmium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.48 Erbium

Table S55. Erbium.

<table>
<tr><th>Erbium</th><th>Er, element number 68</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The general method for REE distribution into end-use categories is described in section 2.4.3.2. In 2012, about 72% of erbium was used as a pink colorant in glass products and in EDFA amplifiers for optical communication, 25% as a dopant in phosphors, and 3% in various uses such as YAG lasers, alloys (especially for the machining of vanadium alloys) and nuclear reactor control rods (Bru et al., 2015; European Commission, 2014). Without specific quantifications of the share of erbium used for optical communications, and considering that the telecommunication sector is attributed the same average lifetime of 30 years as the glass & ceramics sector, both end-uses are aggregated altogether in the glass category. The following distribution is estimated to be representative of erbium end-uses in 2012:
<table>
<tr><td>Electronics</td><td>25%</td></tr>
<tr><td>Glass & ceramics</td><td>72%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>3%</td></tr>
</table></td><td>U1: 2
U2: 3
U3: 1
U4: 2
U5: 3</td></tr>
<tr><td>Production yield</td><td>67% (cf. section 2.4.3.1)</td><td>U1: 4 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. The yield is assumed to account for new scrap recycling if ever it occurs.</td><td>U1: 3 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>New scrap recovery</td><td>N/A, 0% reported in this dataset.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Remelting</td><td>N/A, 0% reported in this dataset.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Dissipation in use</td><td>0% (Ciacci et al., 2015)</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>0% (cf. section 2.4.3.5)</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

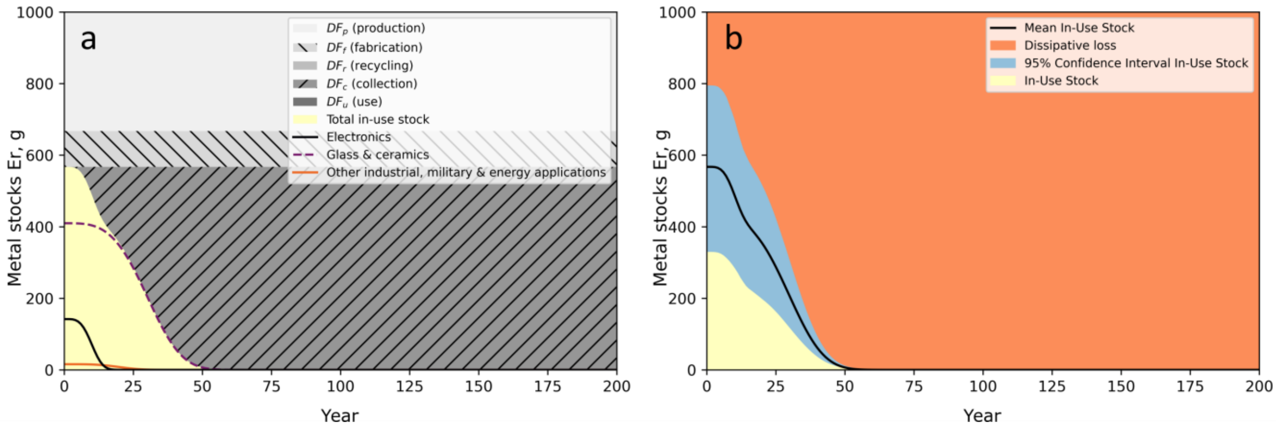

Figure S47. In-use stocks and losses of erbium over 200 years. Panel a: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". Panel b: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.49 Thulium

Table S56. Thulium.

Thulium	**Tm, element number 69**	**Uncertainty**
End uses	It is difficult to define thulium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No precise global end-use distribution specific of thulium could be found. Thulium may be used as a dopant in fiber lasers and phosphors, in magnetic ceramics, as a fluorescent agent in anti-fraud Euro banknotes, and in portable x-ray devices (Bru et al., 2015). It is estimated that 45% of thulium is used as a radiation source (e.g., in portable x-ray devices) (Ciacci et al., 2015). Given the variety of uses and lack of precise distribution, the remaining 55% is classified in other industrial, military & energy applications. The following distribution is assumed to be representative of thulium end-uses in recent years: Other industrial, military & energy applications: 55% Other punctual applications: 45%	U1: 4 U2: 1 U3: 1 U4: 3 U5: 3
Production yield	67% (cf. section 2.4.3.1)	U1: 4 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs.	U1: 3 U2: 3 U3: 1 U4: 3 U5: 3
New scrap recovery	No recovery of new scraps is expected to occur (European Commission, 2020a).	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	N/A, 0% reported in this dataset	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	100% for thulium used as a radiation source in punctual applications, and 0% for other uses (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	0% (cf. section 2.4.3.5)	Per sector; please refer to Supplementary Data

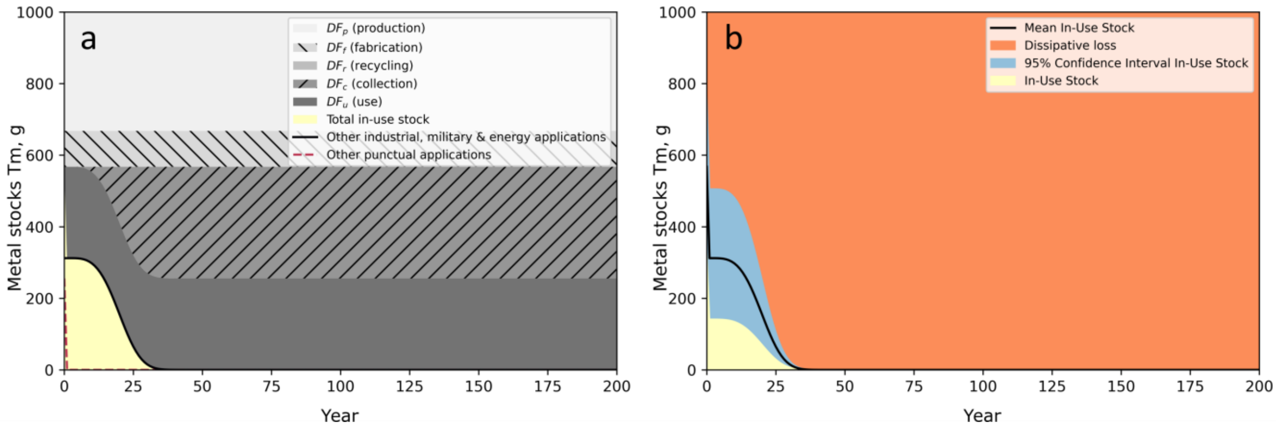

Figure S48. In-use stocks and losses of thulium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.50 Ytterbium

Table S57. Ytterbium.

Ytterbium	Yb, element number 70	Uncertainty
End uses	It is difficult to define ytterbium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). Ytterbium may be used in a variety of applications such as glass-optical devices including YAG lasers, portable x-ray devices and stress gauges for seismic measurements (Bru et al., 2015; Ciacci et al., 2015; European Commission, 2020a). Alike thulium, it is estimated that 45% of ytterbium is used as a radiation source (e.g., in portable x-ray devices) based on (Ciacci et al., 2015), which is classified in other punctual applications. The remaining share is reported as other industrial, military & energy applications. The following distribution is assumed to be representative of ytterbium end-uses in recent years: Other industrial, military & energy applications: 55% Other punctual applications: 45%	U1: 4 U2: 1 U3: 1 U4: 3 U5: 3
Production yield	67% (cf. section 2.4.3.1)	U1: 4 U2: 1 U3: 1 U4: 3 U5: 3
Fabrication and manufacturing	An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. The yield is assumed to account for new scrap recycling if ever it occurs.	U1: 3 U2: 3 U3: 1 U4: 3 U5: 3
New scrap recovery	N/A, 0% reported in this dataset	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	N/A, 0% reported in this dataset	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	100% for ytterbium used as a radiation source (classified in other punctual applications), and 0% for other uses (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	0% (cf. section 2.4.3.5)	Per sector; please refer to Supplementary Data

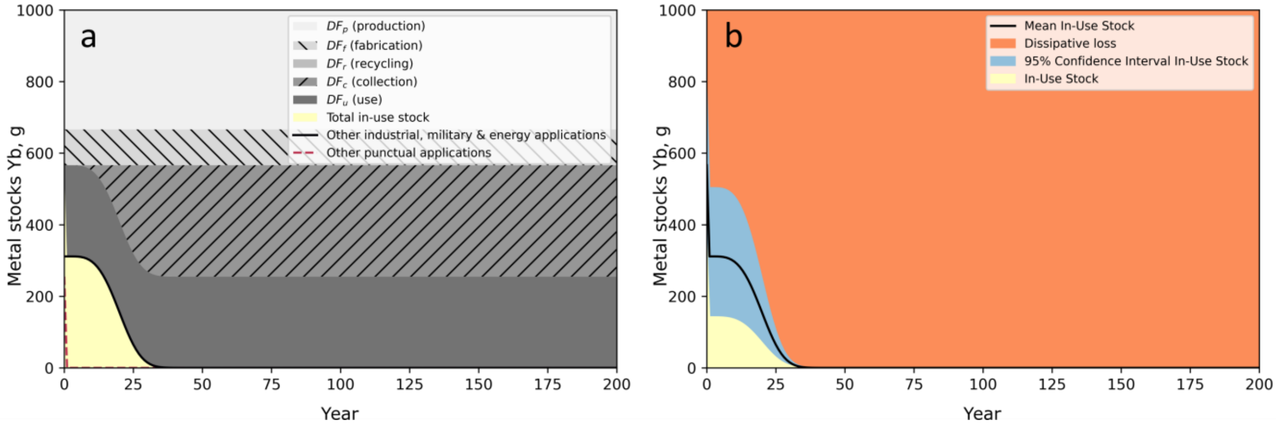

Figure S49. In-use stocks and losses of ytterbium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.51 Lutetium

Table S58. Lutetium.

<table>
<tr><th>Lutetium</th><th>Lu, element number 71</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>It is difficult to define lutetium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No global end-use distribution specific of lutetium could be found. It is believed to be used mostly in positron emission tomography, and to a lesser extent in nuclear medicine, specialty optics products and as catalysts for e.g. petroleum cracking and refining (Bru et al., 2015; Ciacci et al., 2015). It is estimated that 45% of lutetium undergoes inherently dissipative uses, based on Ciacci et al. (2015); the remaining shared is assumed to be split equally between glass products, catalysts and other industrial, military & energy applications . The following distribution is assumed to be representative of ytterbium end-uses in recent years, i.e. around 2010-2019:
<table>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>18%</td></tr>
<tr><td>Glass & ceramics</td><td>18%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>18%</td></tr>
<tr><td>Other punctual applications</td><td>45%</td></tr>
</table></td><td>U1: 4
U2: 1
U3: 1
U4: 3
U5: 3</td></tr>
<tr><td>Production yield</td><td>67% (cf. section 2.4.3.1)</td><td>U1: 4 U2: 1
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>Fabrication and manufacturing</td><td>An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs.</td><td>U1: 3 U2: 3
U3: 1 U4: 3
U5: 3</td></tr>
<tr><td>New scrap recovery</td><td>No recovery of new scraps is expected to occur (European Commission, 2020a).</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>N/A, 0% reported in this dataset</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>100% for lutetium used as a radiation source in punctual applications, and 0% for other uses (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>0% (cf. section 2.4.3.5)</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

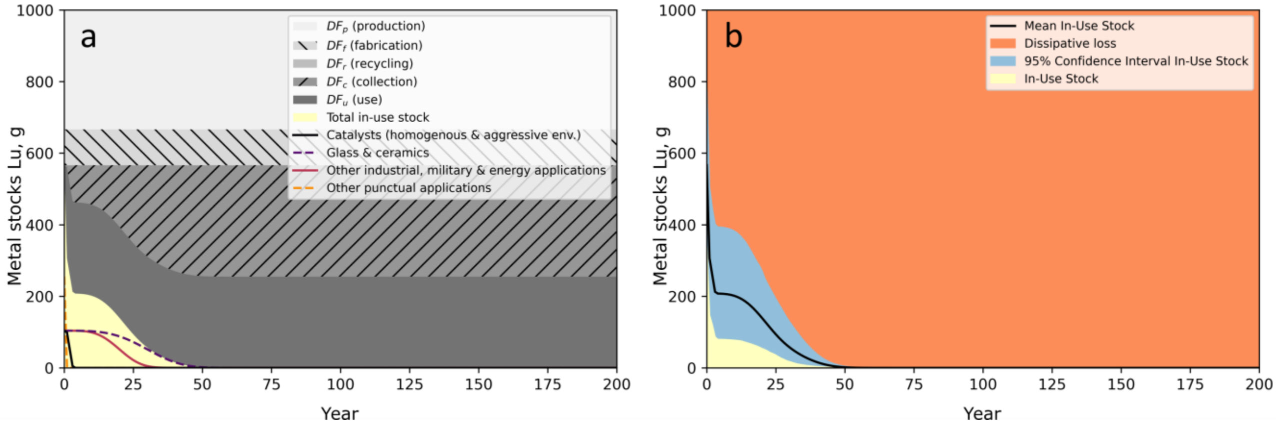

Figure S50. In-use stocks and losses of lutetium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.52 Hafnium

Table S59. Hafnium.

<table>
<tr><th>Hafnium</th><th>Hf, element number 72</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The end-uses distribution for hafnium are reported for years 2008 (Graedel et al., 2013), 2010-2014 (BRGM, 2018a) and 2016 (European Commission, 2020a). The main use of hafnium is in superalloys used in aerospace and nuclear fuel reprocessing plants (Graedel et al., 2013). The most recent distribution for 2016 is disaggregated with other available data. It is estimated that 45% out of 61% end-use of hafnium in superalloys is for aerospace, and the remaining 16% is used in reprocessing plants. End-uses in processing plants are categorized as infrastructure, and plasma cutting tips as cutting tools. Furthermore, the end-use as catalyst precursor is categorized in catalysts, and semi-conductors as well as optical applications, in electronics. The following distribution is considered to be representative of the year 2016:
<table>
<tr><td>Aviation</td><td>45%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>7%</td></tr>
<tr><td>Cutting tools</td><td>15%</td></tr>
<tr><td>Electronics</td><td>6%</td></tr>
<tr><td>Infrastructure</td><td>16%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>11%</td></tr>
</table></td><td>U1: 3
U2: 2
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>Hafnium naturally occurs in zirconium minerals (zircon and baddeleyite) (BRGM, 2018a). It is produced exclusively as by-product of zirconium metal, i.e. from residues of zirconium tetrachloride purification. Hafnium production is “nearly forced” because zirconium used for nuclear fuel rod cladding must be free of hafnium (BRGM, 2018a). The main producers of hafnium are France, the US, China and Ukraine, which all have an important nuclear power sector (BRGM, 2018a).
We estimate the production yield of hafnium by comparing its reported yearly production with the theoretical quantity that is extracted along with zircon. There is a 50:1 Zr to Hf ratio in zircon minerals, and a ratio of about 73:1 Zr to Hf ratio in baddeleyite (BRGM, 2018a; Jones et al., 2017). As most of the production originates from zircon, we consider an average ratio of 50:1 Zr to Hf ratio in the extracted ores. For the production of 1.38 million tons of zirconium concentrate in 2016, about 75 tons of hafnium was produced (BRGM, 2018a). Considering that a theoretical 28 000 tons of hafnium was extracted with zirconium concentrates (50:1 Zr to Hf ratio), a production yield of 0.27% can be calculated.

It is reported that hafnium may also have accumulated in the tailings of primary igneous deposits from which zircon and hafnium have not been historically targeted (Jones et al., 2017). These are not included in this calculation.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>95%, including the recovery of new scraps (assumption)</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
</table>

Remelting	N/A; 0% reported in this dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	0% (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	No EOL recycling of hafnium occurs (BRGM, 2018a; Ciacci et al., 2015).	Per sector; please refer to Supplementary Data

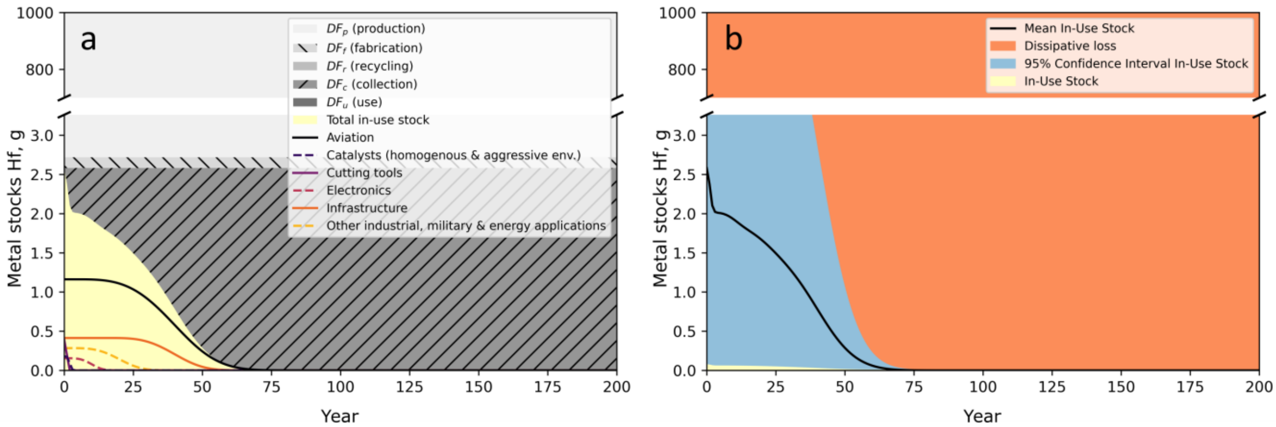

Figure S51. In-use stocks and losses of hafnium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.53 Tantalum

Table S60. Tantalum.

<table>
<tr><th>Ta</th><th>Tantalum, element number 73</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global end-use distributions are available for 2008 (Graedel et al., 2015), 1975-2015 (Nassar, 2017) and 2018 (BRGM, 2020d). The principal end-use of tantalum is in capacitators, with 48% and 34% of the share of global end-uses in 2008 and 2018, respectively. Other uses include superalloys, chemicals, sputtering targets and cutting tools (BRGM, 2020d). The latest distribution of 2018 is reported in this dataset. It is not possible to further disaggregate metallurgical uses and chemicals uses with the available information, and both are classified as other industrial, military & energy applications given the variety of potential end-uses for both of these (e.g., heat exchangers, crucibles, prosthesis, and military applications for mill products; galvanizing, anodes and ceramics for tantalum chemicals) (Nassar, 2017). Tantalum used as a sputter target is used mostly for electronic devices such as magnetic storage media, inkjet printer heads, electronic circuitry and flat panel displays (European Commission, 2020a; Nassar, 2017), and are therefore aggregated in the electronics sector, along with capacitators. The following distribution is representative of the year 2018:
<table>
<tr><td>Alloys & solders</td><td>18%</td></tr>
<tr><td>Cutting tools</td><td>5%</td></tr>
<tr><td>Electronics</td><td>48%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>29%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>65% (Helbig et al., 2020, based on Nassar, 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>76% (Helbig et al., 2020, based on Nassar, 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>54% (Helbig et al., 2020, based on Nassar, 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Nassar, 2017)</td><td>U1: 1 U2: 2
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>1.6% for cutting tools (Nassar, 2017), 0% for other applications (Ciacci et al., 2015; Nassar, 2017)</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Helbig et al. (2020) calculated a collection yield of 21% based on Nassar (2017). The EOL-RR of tantalum results mainly from the recycling of carbides used for cutting tools, mill products and superalloys, while small amounts may also be recovered from capacitators (Nassar, 2017). Collection yields of 70 to 90%, 60% and 50% are reported for superalloys, mill products and carbides (Graedel et al., 2015; Nassar, 2017). Other applications are not considered to be functionally recycled. The collection yield for the other category is calculated to be 19% based on the share of mill products in that category. Moreover, the EOL-RR of capacitators is estimated to be below 0.5% and considered to be negligible. The reported collection yields are the following: alloys, 80%; electronics, 0%; cutting tools, 50%; and other industrial applications, 19%.</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

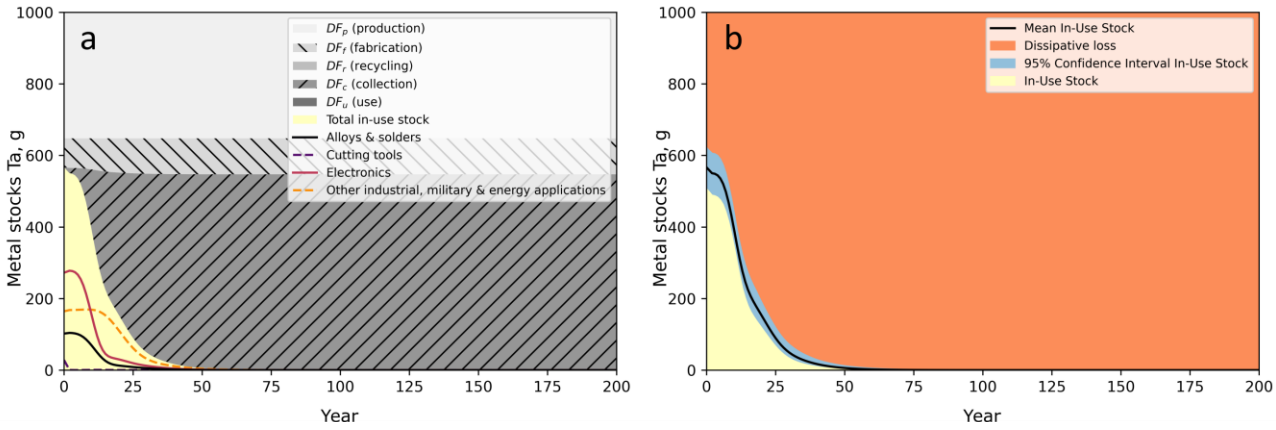

Figure S52. In-use stocks and losses of tantalum over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.54 Tungsten

Table S61. Tungsten.

<table>
<tr><th>Tungsten</th><th>W, element number 74</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Multiple global end-use distribution of tungsten are available, albeit generally including only first use sectors. Some recent distributions include 2008 (Graedel et al., 2015), some year between 2010 and 2012 (Ciacci et al., 2015), 2012-2016 (European Commission, 2020a), 2015 (BRGM, 2017j) and 2016 (ITIA, 2018). The principal use of tungsten in the studied years remained cemented carbides, with over 50% of its end uses. Other uses include steel alloys, tungsten metal used in lighting, electronics and ammunition, as well as a range of other uses (e.g., catalysts, chemicals). The end-use distribution of 2015 (BRGM, 2017j) is considered. It is refined with other information available in the cited literature in order to provide a more disaggregated distribution of tungsten uses.

Notably, the 7% reported as others is considered to be used as chemicals (3%), and 2% each in catalysts and superalloys, based on Ciacci et al. (2015). Chemicals are classified as others (short lived) based on their suggested applications (pigments, absorbent gels). Superalloys are aggregated within alloys along with steel. The 17% share of tungsten metal is assumed to be split between mill products (8%), lighting (2%) and electronics (7%) (Ciacci et al., 2015; Graedel et al., 2015). Mill products are aggregated in the Other miscellaneous category based on the expected average lifetime for these products (Graedel et al., 2015). The alloys category includes steels and alloys used in a range of applications including wear and high speed steel applications, construction tools, energy and aeronautics applications (BRGM, 2017j; European Commission, 2020a). The following distribution is estimated to be representative of the year 2015:
<table>
<tr><td>Alloys & solders</td><td>23%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>2%</td></tr>
<tr><td>Cutting tools</td><td>55%</td></tr>
<tr><td>Electronics</td><td>7%</td></tr>
<tr><td>Lighting</td><td>2%</td></tr>
<tr><td>Other miscellaneous</td><td>11%</td></tr>
</table></td><td>U1: 2
U2: 2
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>89% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 2 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>90% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>100% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Some dissipation may occur from the use of tungsten in carbide cutting tools and catalysts. The dissipation rates are estimated to be 5% for the former, and 2% for the latter (Ciacci et al., 2015). Other applications are considered not to be dissipated during use (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

Collection and sorting	Helbig et al. (2020) calculated an overall collection rate of 32%, based on Meylan et al. (2015). This yield suggests that the EoL-RR of tungsten is in the higher bound of the EOL-RR range of 10 and 25% (BRGM, 2017j; UNEP, 2011). The latest EoL-RR per application proposed by Graedel et al. (2015) are considered for this dataset (year 2008) along with estimates reported by the International Tungsten Industry Association (ITIA, 2018). A remelting rate of 100% is taken into account. The yield for carbides is weighted based on the distribution of cutting tools, dies, and mining and construction tools included in that category. Estimated shares of 40%, 20% and 40% of cemented carbides are attributed for each of these applications based on the consulted literature. The resulting collection rate is of 41% for cemented carbides, slightly below the global estimate of 46% reported by ITIA (2018). This may be explicable by the inclusion of new scrap in the latter recycling rate. Similarly, the collection yield for alloys can be calculated by weighting the share of superalloys (2%) and steel products (21%) aggregated in that category, for which recycling rates of 80% and 50% are reported by Graedel et al. (2015), respectively. The resulting collection yield for the alloys category is of 52%. However, the ITIA estimates much lower recycling yields for tungsten contained in steel and alloys, with only around 15%. This is due to the low recycling rate of stellited steel parts (stellites) and of low-tungsten containing steels which may be mostly downcycled in ordinary steel (ITIA, 2018). Nonetheless, the ITIA acknowledges that the recycling rate of superalloys may be quite high. Based on this information, a collection yield of 15% is reported for the alloys category, instead of 52% suggested by (Graedel et al., 2015). Moreover, an EOL-RR of 0% for mill products is reported by Graedel et al. (2015), while the ITIA estimates a recycling rate of 22%, albeit acknowledging this rate to include a majority of powder metallurgical new scraps (ITIA, 2018). Without further information, we assume that the EoL-RR of tungsten for these applications is close to 0%, and a collection yield of 0% is reported. Based on these same two data sources, the collection yields for other applications are estimated to be negligible, and collection yields of 0% are reported.	Per sector; please refer to Supplementary Data

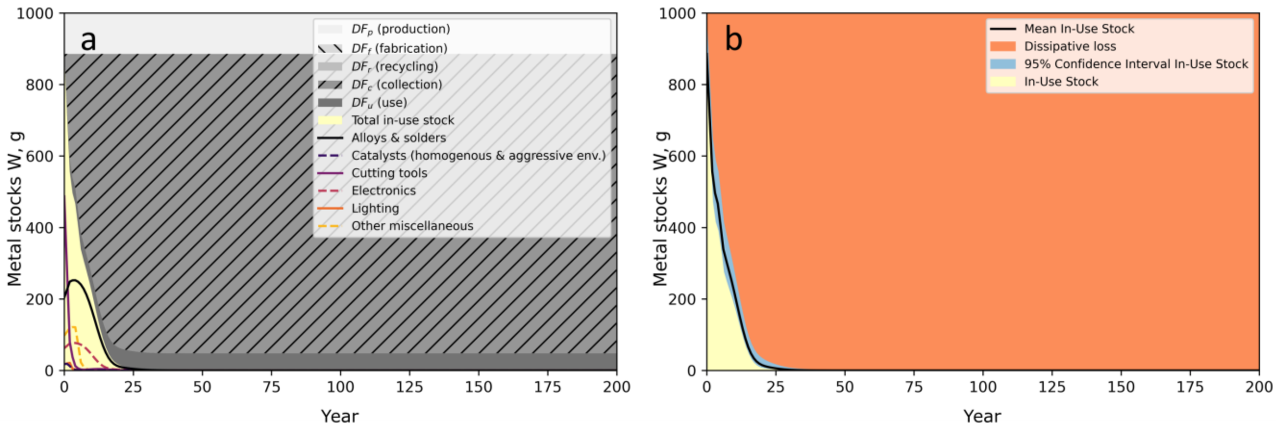

Figure S53. In-use stocks and losses of tungsten over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.55 Rhenium

Table S62. Rhenium.

<table>
<tr><th>Rhenium</th><th>Re, element number 75</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Rhenium is mostly used in superalloys used in the manufacture of gas turbine engines for e.g. aircrafts and energy production (BRGM, 2020e; European Commission, 2020c). Its other principal use is as a catalysts used by the petroleum and petrochemistry industries (BRGM, 2020e; Ciacci et al., 2015). Other uses are various and include e.g. electric furnace resistances, filaments of incandescent lamps and anodes for X-ray tubes used in medical radiography (BRGM, 2020e). Global end-use distributions are available for 2008 (Ciacci et al., 2015; Graedel et al., 2015) and 2018 (BRGM, 2020e). The latter is based on USGS Mineral Commodity Summaries of 2019 and is considered to establish the end-use distribution for rhenium. Catalysts are split half and half between short and long lived catalysts to reflect the average lifetime of 5 years reported by Graedel et al. (2015). This is consistent with the lifetime considered for platinum-rhenium catalysts used in the petroleum industry (cf. Table S65). The following distribution is estimated to be representative of 2018:
<table>
<tr><td>Alloys & solders</td><td>80%</td></tr>
<tr><td>Catalysts (heterogeneous & stable env.)</td><td>8%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>8%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>5%</td></tr>
</table>
</td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>50% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 2 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>100% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>100% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Meylan et al., 2015)</td><td>U1: 1 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>About 2% of the rhenium content of catalysts is estimated to be dissipated during use, while it is not dissipated in use in other applications (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

Collection and sorting	Helbig et al. (2020) calculated a global collection yield of 56% based on Meylan et al. (2015). This rate is in line with the EoL-RR estimated by UNEP (2011). It is slightly higher than that suggest by the BRGM, which estimated the global recycling rate to be between 35 and 40% (BRGM, 2020e). This is explicable by the shutdown of the hydrometallurgical production of secondary rhenium in three recycling plants between 2014 and 2020 (BRGM, 2020e), resulting in a reduced recycling potential for superalloys. Unlike superalloys, the recycling of catalysts is supported by the high value of platinum along which rhenium is recycled. In this dataset, we estimate the collection yields taking into account the remelting yield of 100%. The closed-loop recycling rate of catalysts is estimated to be of about 80% (European Commission, 2020c). This yield is slightly lower than the 90% estimate reported in Graedel et al. (2015), and matches the approximated 20% unrecyclable catalysts reported by Ciacci et al. (2015). Concerning superalloys, Reck and Graedel (2012) estimated the EOL-RR to be of 68% circa 2010. We estimate the current collection yield to be of 40%, down from 68% a decade ago. Other applications are estimated not to be collected for recycling (Graedel et al., 2015). The following collection yields are reported in the dataset: alloys & solders, 40%; catalysts, 80%; and other industrial, military & energy applications, 0%.	Per sector; please refer to Supplementary Data

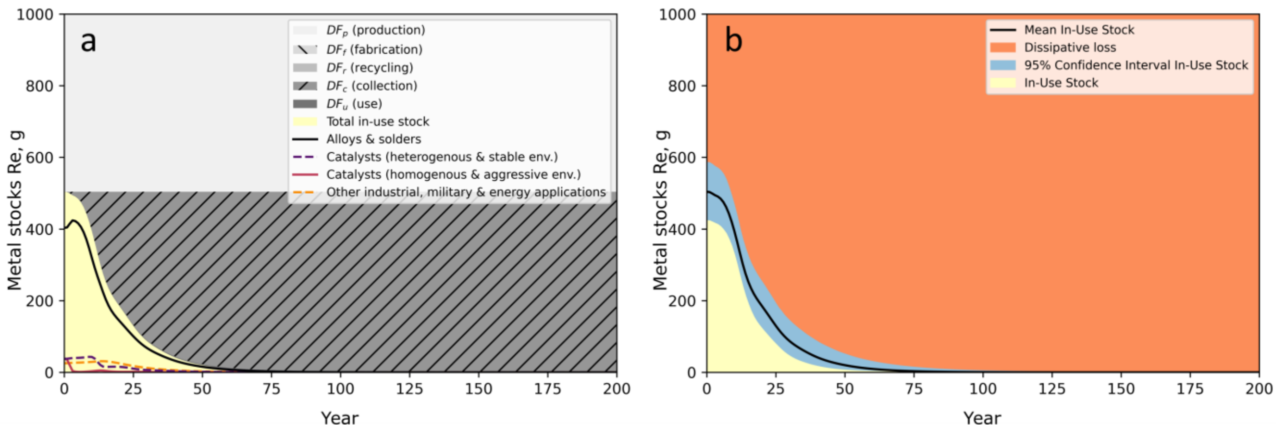

Figure S54. In-use stocks and losses of rhenium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.56 Osmium

Table S63. Osmium.

<table>
<tr><th>Osmium</th><th>Os, element number 76</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>There is scarce information available for osmium. It is used in very small quantities globally (less than 1 ton per year) (Ciacci et al., 2015; Labbé and Dupuy, 2014). Its main uses are in electron microscopy, as a process catalyst in the chemical and pharmaceutical industries, as well as an alloying agent with other PGMs for various specialty applications such as medical implants (Ciacci et al., 2015). Johnson Matthey does not report statistics for osmium, and the end-use distribution of Ciacci et al. (2015) is reported in this dataset. Applications in electron microscopy are considered as a punctual application that is not recyclable currently (Ciacci et al., 2015). The end-uses of osmium, assumed to be representative of osmium uses in recent years, are the following:
<table>
<tr><td>Alloys & solders</td><td>10%</td></tr>
<tr><td>Catalysts (heterogenous & stable env.)</td><td>45%</td></tr>
<tr><td>Other punctual applications</td><td>45%</td></tr>
</table></td><td>U1: 3
U2: 3
U3: 1
U4: 3
U5: 3</td></tr>
<tr><td>Production yield</td><td>The mining yield is estimated to be 85% for all PGMs.
The average concentration, smelting and refining yields for osmium are estimated to be the average values for PGMs reported by Nassar (2013) and are of 83.5%, 96% and 95%, respectively. The resulting production yield is 58%.</td><td>U1: 3 U2: 3
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for osmium.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Dissipation in use</td><td>Based on Ciacci et al. (2015), it is estimated that 33% dissipation in use occurs from the use of osmium in catalysts (type B), and 100% dissipation in use occurs from the use of osmium in electron microscopy (type C).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Osmium is not expected to be collected for recycling currently (Ciacci et al., 2015; UNEP, 2011).</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

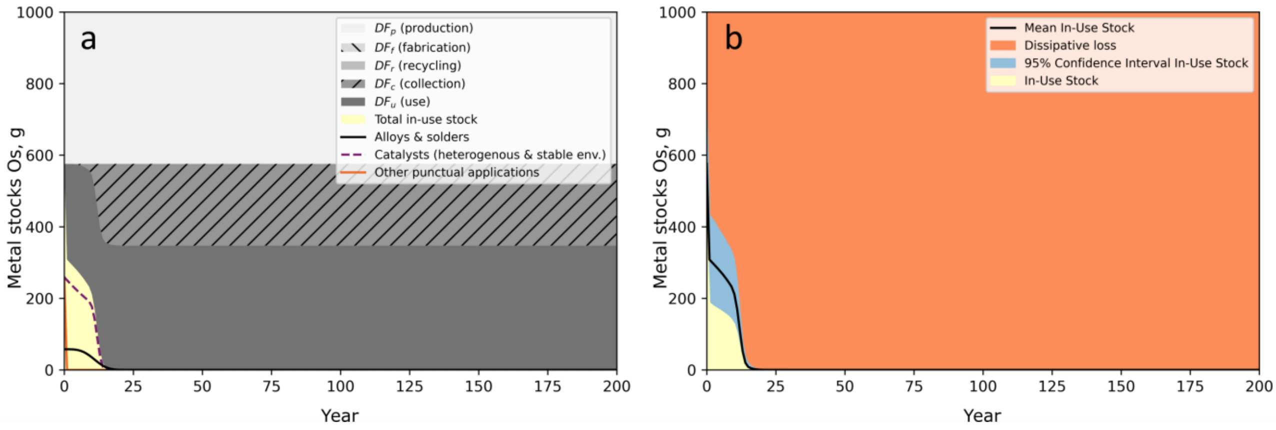

Figure S55. In-use stocks and losses of osmium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.57 Iridium

Note: We use the catalysts categories as proxies for ruthenium-iridium anodes and iridium crucibles based on the reported lifetimes for these applications to avoid generating additional single use sectors for industrial processes. The uses of iridium in crucibles is aggregated in the Catalysts (homogenous & aggressive env.) along with catalysts used by the chemical industry, and its uses in the electrochemical industry (anodes coating) was reported in the Catalysts (heterogeneous & stable env.) sector.

Table S64. Iridium.

<table>
<tr><th>Iridium</th><th>Ir, element number 77</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Iridium is mostly used in electrical, electrochemical, and chemical industries, as well as in jewelry, medical applications, automotive industry (especially for spark plugs), and a range of miscellaneous applications (BRGM, 2020a; Ciacci et al., 2015). Johnson Matthey reports demand statistics for iridium for the year 2019 (Johnson Matthey, 2020b). The BRGM also provides a more disaggregated distribution in end-use sectors for the same year (BRGM, 2020a), based on a report of SFA Oxford (2020). Both sets of data cover a total of 8.2 tons of iridium (as demand for the former, and as consumed for the latter), and present similar distributions. The data reported by BRGM (2020a) is used to establish the end-use distribution of iridium.
The use of iridium by the electrical industries is considered to be mostly in crucibles used to grow high purity crystals (Ciacci et al., 2015). Iridium is also used as a catalyst in the chemical industry, for which an estimated lifetime of 0.1 to 5 years is reported (Nassar, 2013), and as a coating for dimensionally stable anodes in the electrochemical industry along with ruthenium, for which a lifetime of 5 to 8 years is reported (Nassar, 2013).

The contemporary use of iridium in the automotive industry seems to be mostly for high-end spark plugs, which are classified as Other miscellaneous applications considering that they must be replaced a few times over the lifetime of vehicles. Other applications include alloys and superalloys used in a variety of applications; these are aggregated in the Other industrial, military & energy applications. The following end-use distribution is representative of end-uses of iridium in 2019:
<table>
<tr><td>Biomedical & dental</td><td>9%</td></tr>
<tr><td>Catalysts (heterogeneous & stable env.)</td><td>26%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>39%</td></tr>
<tr><td>Jewelry & investment</td><td>4%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>16%</td></tr>
<tr><td>Other miscellaneous</td><td>6%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>The mining yield is estimated to be 85% for all PGMs.
The average concentration, smelting and refining yields for iridium correspond to the average values reported by Nassar (2013) and are of 73.5%, 96% and 96%, respectively. The resulting production yield is 58%.</td><td>U1: 2 U2: 3
U3: 1 U4: 2
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for iridium.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
</table>

Remelting	A remelting yield of 96% is assumed (same as refining).	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	The dissipation rates for iridium are calculated based on Ciacci et al. (2015). The dissipation in use rate for catalysts in calculated considering the share of electronic and chemical industries included in the sector, for which dissipation in use rates of 33% and 5% are estimated. The resulting dissipation rates for iridium end-use sectors are the following: catalysts (homogenous & aggressive env.) (including iridium crucibles), 26%; catalysts (heterogeneous & stable env.) (proxy for ruthenium-iridium anodes), 8%; other miscellaneous (spark plugs), 5%. Other uses are considered not to be dissipated during use.	Per sector; please refer to Supplementary Data
Collection and sorting	An EoL-RR is 20-30% was estimated for iridium circa 2010 (UNEP, 2011). Assuming a constant distribution of end-uses over time, the data reported by Nassar (2013) fall quite below this value, and the estimates are updated with additional information. Notably, an EoL-RR of 95% is assumed by Ciacci et al. (2015) for the closed loop recycling of iridium crucibles that have not been dissipated during use. An EoL-RR of 5% is considered for medical applications based on the lowest bound of estimated French statistics (BRGM, 2020a). Finally, an EoL-RR of 0% for spark plugs, 7.5% for other industrial applications, and 45% for iridium uses in the chemical and electrochemical industry is considered (Nassar, 2013; UNEP, 2011). The latter is the same as that of ruthenium used in the same application. Similarly, we assume an EoL-RR of 90% for jewelry, based on the lower bound of EOL-RRs reported for other PGMs used in that application. The EOL-RR for electronic and chemical industrial uses are corrected based on their respective shares of the sector to provide the aggregated value for catalysts sectors. Finally, the collection yields are extrapolated considering a remelting yield of 96%, and are the following: Catalysts (homogenous & aggressive env.), 87%; Catalysts (homogenous & aggressive env.), 47%; Jewelry & investment, 94%; Other miscellaneous (spark plugs), 0%; Biomedical & dental, 5%; and Other industrial, military & energy applications, 7.5%. Assuming a constant distribution of end-uses over time, these collection yields suggest a global EOL-RR for iridium higher than the 30% reported in the UNEP report, which may warrant additional investigations.	Per sector; please refer to Supplementary Data

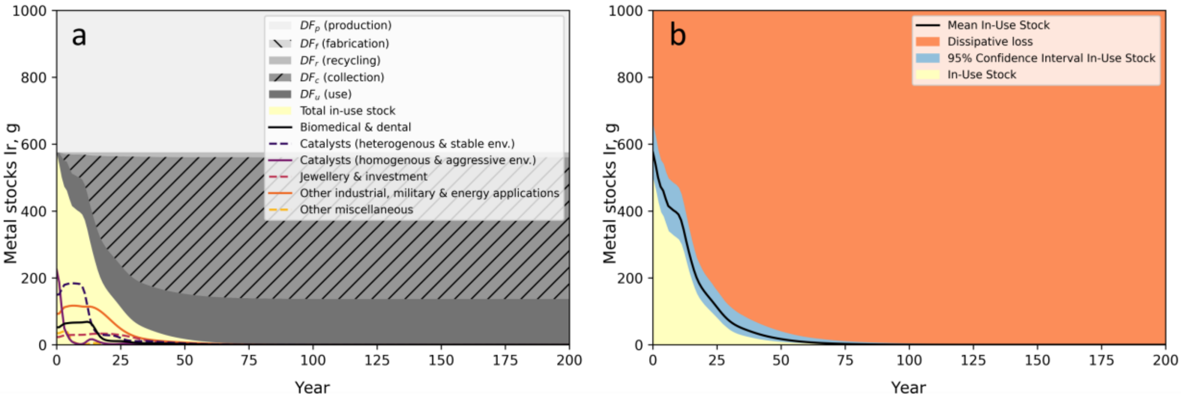

Figure S56. In-use stocks and losses of iridium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.58 Platinum

Table S65. Platinum.

<table>
<tr><th>Platinum</th><th>Pt, element number 78</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>Platinum is primarily used as a catalytic converter in exhaust pipes of vehicles, in jewelry and in investment products. Other uses include catalysts used in the chemical industry, medical and dental applications and in the glass manufacturing industry (Ciacci et al., 2015; Graedel et al., 2013).

The end-use distribution for platinum is based on Matthey Johnson's reports (Johnson Matthey, 2020a, 2015). It is assumed that 10% of the demand for medical applications are for anti-cancer drugs based on Ciacci et al. (2015), and these are classified as pharmaceutics. Moreover, the other uses of platinum are split half and half between other miscellaneous and other industrial, military & energy applications categories based on qualitative and quantitative information provided by Ciacci et al. (2015) in order to represent the different lifetimes of potential applications such as spark plugs, turbine blade coatings and oxygen sensors. Finally, catalysts used in the petroleum industries are split between the two categories of catalysts to reflect the variability of their potential lifetimes, i.e. 1 to 12 years (Nassar, 2013).

Given that platinum has been continuously used in investment products over a 10-year period, investment was considered in the end-use distribution accordingly with the methodology presented in section 2.4.2. The following distribution is estimated to be representative of 2019:
<table>
<tr><td>Biomedical & dental</td><td>3%</td></tr>
<tr><td>Catalysts (heterogeneous & stable env.)</td><td>2%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>10%</td></tr>
<tr><td>Electronics</td><td>3%</td></tr>
<tr><td>Glass manufacturing</td><td>5%</td></tr>
<tr><td>Jewelry & investment</td><td>33%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>4%</td></tr>
<tr><td>Other miscellaneous</td><td>4%</td></tr>
<tr><td>Pharmaceutics & cosmetics</td><td>0.3%</td></tr>
<tr><td>Transport</td><td>37%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 3
U5: 1</td></tr>
<tr><td>Production yield</td><td>The mining yield is estimated to be 85% for all PGMs.
The average concentration, smelting and refining yields for platinum correspond to the average values reported by Nassar (2013) and are of 84.2%, 96% and 99.25%, respectively. The resulting production yield is of 68%.</td><td>U1: 2 U2: 3
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Fabrication and manufacturing</td><td>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for platinum.</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
<tr><td>New scrap recovery</td><td>N/A; 0% reported in this dataset.</td><td>U1: 1 U2: 1
U3: 1 U4: 1
U5: 1</td></tr>
<tr><td>Remelting</td><td>A remelting yield of 99.25% is assumed (same as refining).</td><td>U1: 3 U2: 1
U3: 1 U4: 3
U5: 1</td></tr>
</table>

Dissipation in use	The dissipation in use for platinum are estimated based on Nassar (2013) and Ciacci et al. (2015). The dissipation in use rate for catalysts is determined considering the relative share of catalysts used in the chemical and petroleum industries that are aggregated in the two distinct catalysts sectors. The estimated dissipation in use rates are the following: Catalysts (heterogeneous & stable env.), 11%; Catalysts (homogenous & aggressive env.), 36%; Glass manufacturing, 1%; Other industrial, military & energy applications, 10%; Other miscellaneous, 17%; Pharmaceutics & cosmetics, 100%; and Transport, 2%. No dissipation in use is reported for other sectors.	Per sector; please refer to Supplementary Data
Collection and sorting	Between 60 and 70% of EOL platinum scraps are estimated to be recycled (BRGM, 2017k). The EOL-RR ranges reported by Nassar, (2013) and UNEP (2011) are considered to establish collection yields, considering the remelting yield of 99.25%. For the platinum content of auto catalysts, an average global EOL-RR of 60% is considered (as for palladium), slightly higher than the estimated range of 50-55% circa 2010 (UNEP, 2011). The EoL-RR for the investment and jewelry category is calculated considering an EoL-RR of 100% for the former, and 95% for the latter, and considering their respective shares for that sector. The following collection yields are reported in the dataset: Biomedical & dental, 18%; Catalysts (heterogeneous & stable env.), 99%; Catalysts (homogenous & aggressive env.), 97%; Electronics, 19%; Glass manufacturing, 99%; Jewelry & investment, 97%; Other industrial, military & energy applications, 15%; Other miscellaneous, 15%; Pharmaceutics & cosmetics, 0%; and Transport, 60%. Assuming a constant distribution of end-uses over time, the reported yields suggest a global EoL-RR of approximately 65%, and are thus estimated to be reasonably representative of the current yields.	Per sector; please refer to Supplementary Data

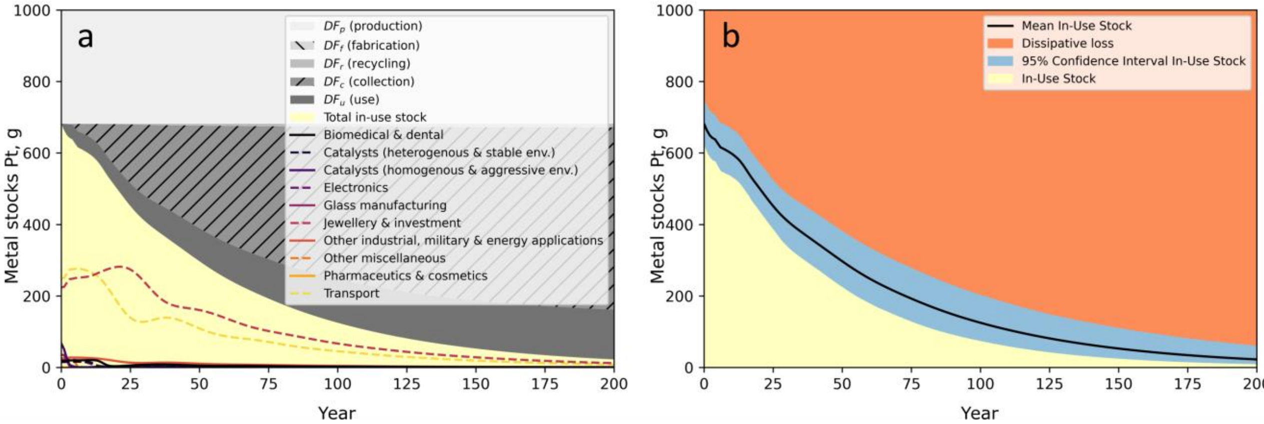

Figure S57. In-use stocks and losses of platinum over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.59 Gold

Table S66. Gold.

<table>
<tr><th>Gold</th><th>Au, element number 79</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The World Gold Council provides global end-use statistics for gold (World Gold Council, 2020). In this dataset, investment products are considered as a functional end-use of gold. Given the importance of the use of gold as a financial product, demand for gold may be influenced by the economic conjuncture. While demand for the jewelry and financial products fluctuated over the analyzed period, a notable decline of the use of gold in dentistry applications (about 70%) and in other industrial applications (about 45%) can be observed over between 2010 to 2019, which could be attributed to e.g. substitution or an increase in efficiency. The demand for gold in the electronics sector has steadily decreased over the years, for a total of about 20% decrease between 2010 to 2019. At the same time, the total demand for gold remained quite stable over the years, with an average of approximately 4 450 tons per year.

In order to flatten out the effects of economic conjuncture on the demand for financial products, the 10-years average values from 2010 to 2019 are used to measure its average share of end uses. The other end-uses for the year 2019 are balanced to account for the remaining share of end uses. This method is also used for other precious metals used in investment (cf. section 2.4.2). The following distribution is representative of the year 2019 based on demand statistics (World Gold Council, 2021):
<table>
<tr><td>Biomedical & dental</td><td>0.3%</td></tr>
<tr><td>Electronics</td><td>6%</td></tr>
<tr><td>Jewelry & investment</td><td>92%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>1%</td></tr>
</table>
Out of the 92% reported for the jewelry and financial products, about 49% is for jewelry, and about 42% for financial products (including private investment products, gold-backed exchange traded funds and demand by central banks).</td><td>U1: 2
U2: 1
U3: 1
U4: 2
U5: 1</td></tr>
<tr><td>Production yield</td><td>There is scarce information on primary gold production efficiency in the scientific literature. Nassar et al. (2012) assumes processing losses of 5% after recovery. The US statistics in 1998 suggest an efficiency of refining of 98.2% (USGS, 2004b), which seems to correspond to the refining of doré bars.

A small online survey revealed that there are many technical reports available for gold producing companies, which could be ideally consulted for an exhaustive assessment of the gold production yield. In order to obtain a more solid estimation of the production yield, several technical reports for various gold mining sites were consulted for this dataset (Base Met Labs, 2017; BBA, 2020; InnovExplo, 2013; Mannard and Ng, 2016; Snowden, 2016; Zandonai, 2017). Some of these reports cover multiple mining sites. Moreover, the annual reports from Freeport-McMoRan provide yearly recovery yields for their mining operations in Indonesia (Freeport-McMoRan, 2019, 2016).</td><td>U1: 3 U2: 1
U3: 1 U4: 2
U5: 1</td></tr>
</table>

	Alike for PGMs, some resources are expected to never reach the mill due to various factors (e.g., pillar losses in underground mining, mining losses), in addition to the mine-call-factors (Nassar, 2013). The reported ore recovery from the different drilling holes at the various mining sites range between 80% and 100% (excluding the most superficial layers, for which lower recoveries are sometimes reported). An estimated 85% mining yield is considered for this dataset, which is assumed to cover all extraction losses across both open pit and underground mining operations. Moreover, the reported post-mining recovery yields range between 75 and 100%. The total gold recovery yields for gold production in various reports range between 52% and 97%, which are generally observed to be lower for lower grade ores across the studied mining projects. For example, the Selinsing Gold Mine had its recovery rate decline from 92.9% to 67.4% while its average ore head grade declined from 4.31 to 0.88 g Au/t between 2011 and 2016 (Snowden, 2016). The lowest reported yield (52%) is from the Don Mario mine in Bolivia where gold is co-produced along with copper and silver (Zandonai, 2017). The lower yields generally seem to correspond to lower grade ores that are being processed at different plants. An average beneficiation and concentration (from ores to doré bars) yield of 87.5% is considered, which is lower than the 95% estimate of Nassar et al. (2012). Finally, a refining yield of 98.5% from doré bars to pure gold is considered, similar to those reported for the valuable PGMs, and similar to that of 98.2% reported for the US in year 1998. Based on this information, it is estimated that the global production yield of gold is of 73%.	
Fabrication and manufacturing	The processing yields for fabrication and manufacturing, new scrap recovery, collection and remelting are calculated using the US statistics of 1998 (USGS, 2004a). These are assumed to be reasonably representative of the global processing yields given the long history of gold use in the US. The fabrication rate was calculated taking into account investment and refined bullions, which are fabricated with a yield of 100%. The yields for investment products and for other products were normalized using the end-uses distribution reported in this dataset. A yield of 100% was considered for investment products, representing 44% of total demand; and a yield of 82% was calculated for other applications, with a new scrap recovery of 90%. The resulting fabrication and manufacturing yield is of 90%.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	90%, calculated from US statistics of 1998 (USGS, 2004a).	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Remelting	98%, calculated from US statistics of 1998 (USGS, 2004a).	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	No dissipative uses of gold were considered, although there might be minor losses attributed to uses in decorative applications and as flake and dust in food or drinks (Ciacci et al., 2015).	Per sector; please refer to Supplementary Data
Collection and sorting	The EoL-RR reported by Nassar et al. (2012) were considered to extrapolate collection yields given a remelting yield of 98%. The EOL-RR of the jewelry and investment category was corrected assuming a	Per sector; please refer to Supplementary Data

	collection rate of 100% for financial products along with 95% jewelry EoL-RR reported by Nassar et al. (2012). The resulting collection rates are the following: Biomedical & dental, 18%; Electronics, 13%, Jewelry & investment, 99%, and Other industrial, military & energy applications, 82%.	

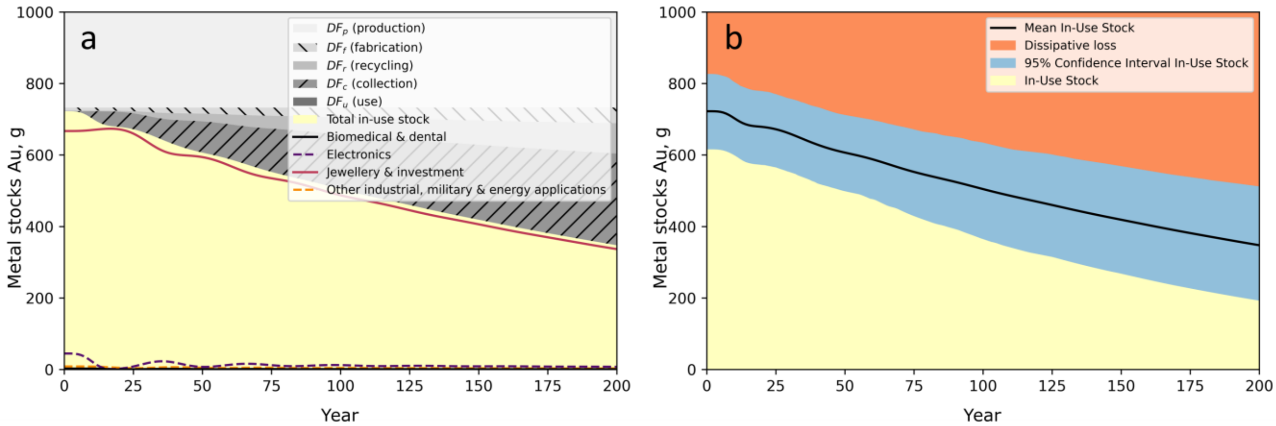

Figure S58. In-use stocks and losses of gold over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.60 Mercury

Table S67. Mercury.

Note: Given the multiple applications specific to mercury, these are aggregated in existing end-use categories used as proxies (as described above), considering the expected lifetimes for each of these applications.

<table>
<tr><th>Mercury</th><th>Hg, element number 80</th><th>Uncertainty</th></tr>
<tr><td>End uses</td><td>The latest UN Environment's report on global mercury supply, trade and demand include a detailed end-use distribution for the year 2015 (UN Environment, 2017). The mean global consumption values as published in table 17 of the UN Environment report are used to obtain the end-use distribution for mercury. The main uses are in artisanal gold mining operations and in industrial applications. Part of the chlor-alkali production is done using liquid mercury in electrolytic cells to act as a cathode, and mercuric chloride on carbon pellets is used as a catalyst to produce vinyl chloride monomers (VCM) (Maxson, 2006; UN Environment, 2017). Other uses include batteries, dental applications, measuring and control devices such as thermometers, lamps, electrical and electronic devices, and mercury compounds used in various applications (UN Environment, 2017).

Measuring and control devices, estimated to have a lifetime of 20 years (Panousi et al., 2016), are classified as Other industrial applications. Moreover, 75% of Hg compounds are assumed to be used in dissipative applications (type A and B) based on the consulted literature, including agricultural, pharmaceutical and cosmetic applications: these are aggregated into the agricultural & environmental applications. Mercury use for VCM production is classified as a Catalysts (homogenous & aggressive env.), and that for chlor-alkali production, as a chemical (based on the expected lifetime for that end use). Small scale artisanal gold mining is classified as a punctual dissipative application. The following distribution is estimated to be representative of 2015:
<table>
<tr><td>Agricultural & environmental applications</td><td>4%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>5%</td></tr>
<tr><td>Biomedical & dental</td><td>6%</td></tr>
<tr><td>Catalysts (homogenous & aggressive env.)</td><td>26%</td></tr>
<tr><td>Chemicals</td><td>6%</td></tr>
<tr><td>Electronics</td><td>3%</td></tr>
<tr><td>Lighting</td><td>3%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>7%</td></tr>
<tr><td>Other miscellaneous</td><td>4%</td></tr>
<tr><td>Other punctual applications</td><td>37%</td></tr>
</table></td><td>U1: 2
U2: 2
U3: 1
U4: 2
U5: 2</td></tr>
<tr><td>Production yield</td><td>Estimating the yield of primary production is uneasy as mercury can be obtained from various sources and is not always marketed due to its toxicity. For instance, mercury can be obtained from the de-contamination of fossil fuels, which is widespread since it is highly volatile and hazardous for human health and the environment (UN Environment, 2018, 2017). In an effort to decrease Hg emissions to the environment, severe regulations limit the use and exports of mercury in many developed countries such as those in Europe and the US (UN Environment, 2017; USGS, 2020). For such reason, mercury captured by e.g. air decontamination or as a contaminant from various non-</td><td>U1: 3 U2: 4
U3: 1 U4: 3
U5: 1</td></tr>
</table>

	ferrous ores may be stored or landfilled as a hazardous waste instead of being put on the market (UN Environment, 2017). Such potential mercury production routes are often considered as a contaminant rather than as a resource. We here consider only primary mercury production from ore mining targeting mercury. There is scarce information on the mining and concentrating processes (cf. UN Environment, 2018, box A3.6.11, p. 3-74). Up to 20-25% of mercury is lost in artisanal mining operations in Mexico (UN Environment, 2017). Still, it is assumed that artisanal mercury mining covers only a fraction of total mercury production (including within Mexico), and China produced about 25 times more mercury than Mexico in 2019 according to (USGS, 2020). Wilburn (2013) reports a recovery of 95% from mined ores based on Nowak and Singer (1995). The statistics for the US production of mercury for the year 1990 suggest a production yield of 86.2% (Sznopek and Goonan, 2000). Given the disparate and scarce available information, the values of 10% mining and 5% refining losses reported by Panousi et al. (2016) are considered as the best estimates available for global mercury production, suggesting a yield of 86%.	
Fabrication and manufacturing	Many uses of mercury do not necessitate an industrial fabrication and manufacturing phase. US stats for 2010 suggest a yield of 96% for products containing mercury (i.e. without industrial and artisanal gold mining), with a recovery of new scraps of 100% (Wilburn, 2013). A global yield of 95% is assumed, assuming that 5% mercury is lost to e.g. vaporization between the production and use phase, e.g. due to the large quantity used in the informal sector, or during the maintenance operations to renew mercury in industrial applications. It should be noted that, in such cases, the losses do not necessarily result from a fabrication process per se. The yield is assumed to include new scrap recovery and remelting, if ever it occurs.	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	0% is reported in the dataset (it is assumed to be included in the fabrication and manufacturing yield). Some recovery of new scraps does occur, e.g. in the US (Wilburn, 2013).	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	95 % (assumption)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
Dissipation in use	All of mercury used for artisanal and small-scale gold mining is expected to be dissipated during use (type B dissipation), and a rate of 100% is reported (Ciacci et al., 2015; UN Environment, 2017). We also consider that all of the mercury used in agricultural, environmental, pharmaceutical or cosmetic products is lost during use. Moreover, about 2% of mercury is thought to be dissipated during its use for the production of VCM (dissipation in use of type B), 31% during the production of chlorine caustic soda, and 0% for other uses (Ciacci et al., 2015).	Per sector; please refer to Supplementary Data
Collection and sorting	About 50% of the mercury used in industrial processes is recycled (UN Environment, 2017). The EOL-RR for non-dissipative applications were reported to be 15% by Maxson (2006), which were also considered by Panousi et al. (2016). Recently, Graedel et al. (2022) estimated EOL-RR of 70% for relays/sensors/switches/valves (included in the electronics and Other industrial, military & energy applications); of 40% for dental amalgams; and of 10% for batteries and lighting applications.	Per sector; please refer to Supplementary Data

	Considering a remelting yield of 95%, the collection yields for the different applications are estimated to be the following: Biomedical & dental, 42%; Catalysts (homogenous & aggressive env.) (proxy for VCM production), 53%; Chemicals (proxy for chlorine caustic soda manufacturing), 53%; Electronics, 74%; Other industrial applications, military & energy applications, 74%; Other miscellaneous, 16%; and 0% for all of the dissipative uses including environmental & agricultural applications as well as artisanal gold mining.	

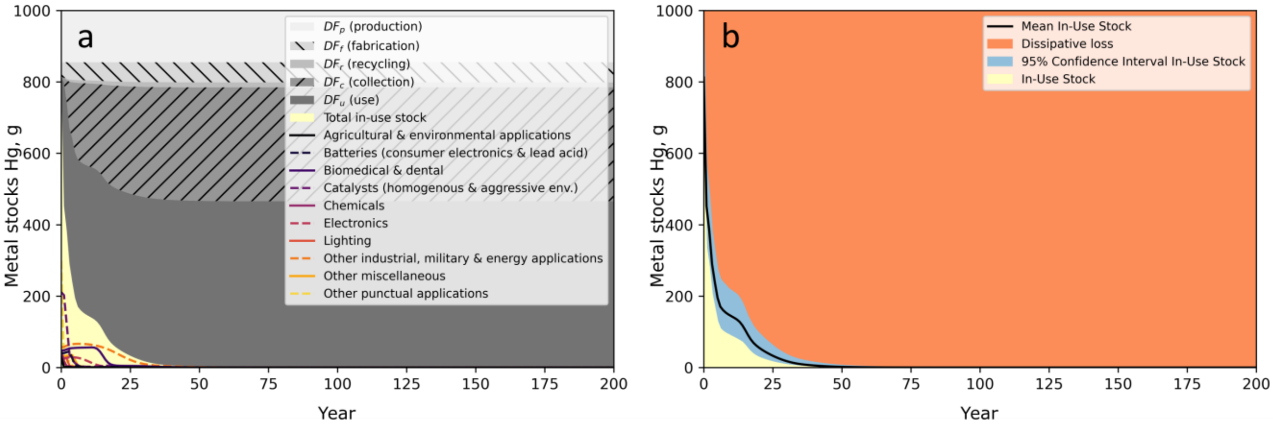

Figure S59. In-use stocks and losses of mercury over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.61 Thallium

Table S68. Thallium.

Thallium	**Tl, element number 81**	**Uncertainty**
End uses	Scarce quantitative information is available for thallium, and it was not included in the latest European Commission's criticality studies (European Commission, 2020c, 2020a). Thallium is a highly toxic metal and its uses are heavily regulated (USGS, 2020). Its principal uses are limited to photoelectric cells, infrared optical materials, and low melting glasses (USGS, 2020). Is this dataset, the end-use distribution suggested by Panousi et al. (2016) based on an informed estimate, is reported: Electronics: 90% Other miscellaneous: 10%	U1: 3 U2: 4 U3: 1 U4: 3 U5: 2
Production yield	Thallium is present in trace amounts in copper, lead, zinc other sulfide ores from which it is seldom extracted as a by-product (USGS, 2020). Alike mercury, much thallium is mined out, but is considered to be a contaminant rather than a resource in most cases, given its toxicity and the paucity of end uses. Global production was estimated to be below 8000 kg in 2019, while several million of kilograms are present in the reserves of the different ores (e.g., zinc) in which it is found (USGS, 2020). Without further information, it is assumed that only the thallium targeted for extraction is to be considered as a resource, alike for mercury, and an informed estimate of 70% is considered for the production yield (Panousi et al., 2016).	U1: 3 U2: 4 U3: 1 U4: 3 U5: 1
Fabrication and manufacturing	100% (assumption)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	N/A, 0% in the dataset	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	N/A, 0% in the dataset	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	0% for both application sectors (Ciacci et al., 2015)	Per sector; please refer to Supplementary Data
Collection and sorting	0% (Ciacci et al., 2015; Panousi et al., 2016).	Per sector; please refer to Supplementary Data

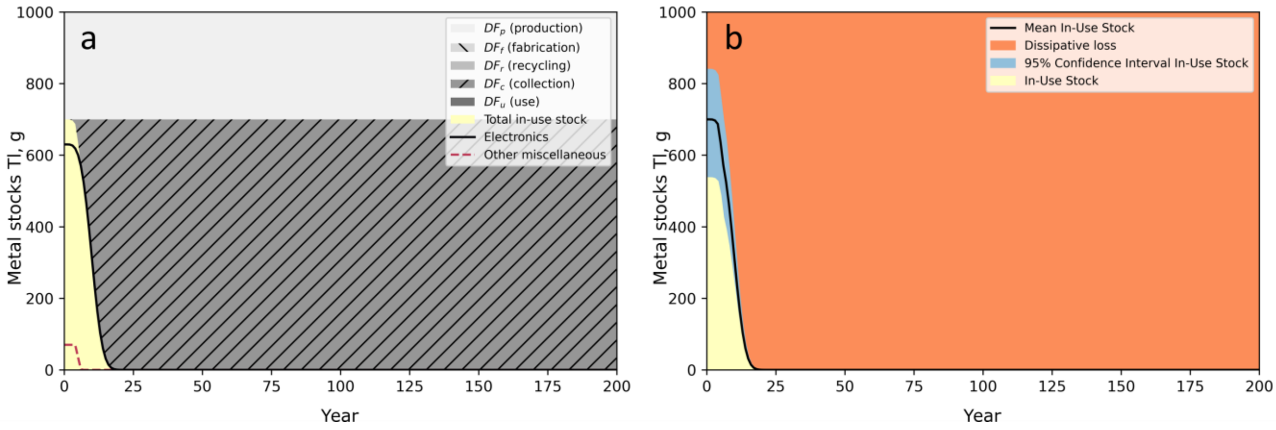

Figure S60. In-use stocks and losses of thallium over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.62 Lead

Table S69. Lead.

<table>
<tr><th>Lead</th><th>Pb, element number 82</th><th>Uncertainty</th></tr>
<tr><td>End-uses</td><td>Global lead end-use distributions are available for several years, often based on the International Lead and Zinc Study Group (ILZSG). For example, end-use distributions are available for 2014 (Ciacci et al., 2015), 2016-2020 (average) (International Lead and Zinc Study Group, 2021b). Another single year distribution is reported by the International Lead Association for the year 2017 (Wilson, 2019). The principal end-use of lead is in batteries, with over 80% of its use. Based on the consulted literature, the 5% other end-uses reported by Wilson (2019) is partitioned between alloys (including solders) (2%), cable sheathing (1%), gasoline additive (0.3%), and others (1.7%). Pigments and paint are added to the paint category. Cable sheathing are aggregated in the infrastructure category, and gasoline additives are aggregated in other punctual uses along with ammunitions. Rolled and sheet products are thought to be used mostly in construction or industrial installations (Ciacci et al., 2015; European Commission, 2020c) and are added to the construction sector. The following distribution is estimated to be representative of years 2017-2019:
<table>
<tr><td>Alloys & solders</td><td>2%</td></tr>
<tr><td>Batteries (consumer electronics & lead acid)</td><td>86%</td></tr>
<tr><td>Construction</td><td>4%</td></tr>
<tr><td>Infrastructure</td><td>1%</td></tr>
<tr><td>Other industrial, military & energy applications</td><td>2%</td></tr>
<tr><td>Other punctual applications</td><td>2%</td></tr>
<tr><td>Paint</td><td>3%</td></tr>
</table></td><td>U1: 2
U2: 1
U3: 1
U4: 1
U5: 1</td></tr>
<tr><td>Production yield</td><td>89% (Helbig et al., 2020, based on Mao et al., 2008a)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Fabrication and manufacturing</td><td>94% (Helbig et al., 2020, based on Mao et al., 2008a)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>New scrap recovery</td><td>80% (Helbig et al., 2020, based on Mao et al., 2008a)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Remelting</td><td>100% (Helbig et al., 2020, based on Mao et al., 2008a)</td><td>U1: 1 U2: 4
U3: 1 U4: 2
U5: 2</td></tr>
<tr><td>Dissipation in use</td><td>Some lead uses are considered to be dissipative. Yellow paint used in road marking and rolled products are considered to be partly dissipated in use (type B dissipation), while gasoline additives and ammunitions are completely lost to the environment when they are used (dissipation type A) (Ciacci et al., 2015). Based on the latter authors, we estimate dissipation in use rates of 20% for pigments and paint (road paint), 5% for the construction sector, and 100% for other punctual applications. Other uses are not considered to be dissipative (Ciacci et al., 2015).</td><td>Per sector; please refer to Supplementary Data</td></tr>
<tr><td>Collection and sorting</td><td>Lead is one of the most recycled metal, with nearly 60% of the supply originating from secondary sources according to the International Lead Association (Wilson, 2019). Helbig et al. (2020) calculated a global collection yield of 66% in year 2000 based on Mao et al. (2008a). Due to</td><td>Per sector; please refer to Supplementary Data</td></tr>
</table>

	the severe regulations surrounding the uses of lead and the progressive elimination of dissipative uses of lead, the EOL-RR has seemingly increased in the past two decades in comparison to that in 2000. We estimate that currently, 85% of lead batteries are collected and functionally recycled based on Harper et al. (2015) and Wilson (2019), and that 10% of cable sheating (included in infrastructure) and 60% of construction and alloys & solders applications are currently collected for recycling based on Ciacci et al. (2015) and Harper et al. (2015).	

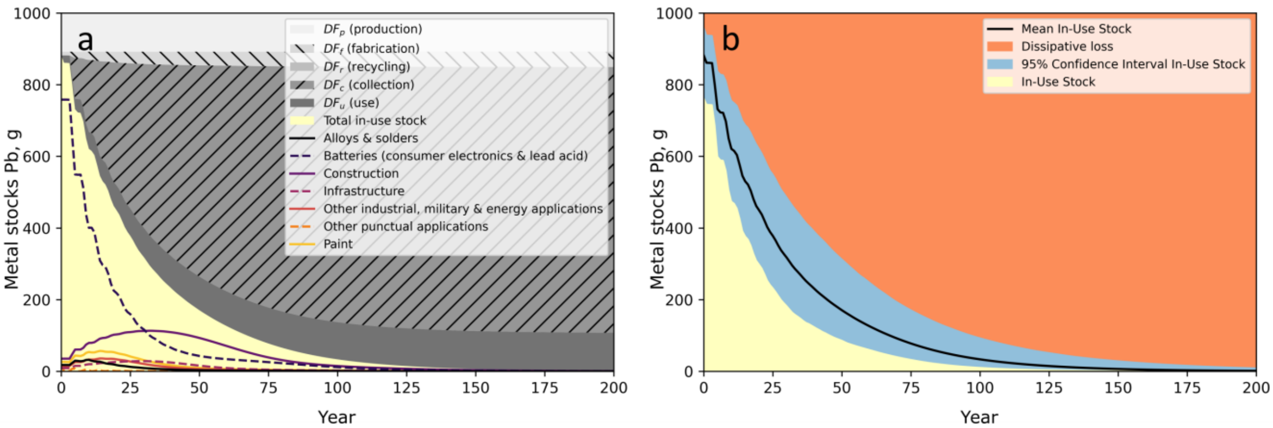

Figure S61. In-use stocks and losses of lead over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to “Total in-use stock”. *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

3.63 Bismuth

Table S70. Bismuth.

Bismuth	**Bi, element number 83**	**Uncertainty**
End uses	Bismuth is mostly used in various chemicals (approximately 50-60% of its uses) in a wide variety of products such as pharmaceutical and cosmetic products, X-Ray shielding in medical applications, pigments in paints, ceramics and plastics, electronic ceramics and flame retardants for plastic products, amongst others (Burgess et al., 2014; European Commission, 2020a; Raja, 2009; USGS, 2020). It is also used as a metallurgical additive in a variety of alloys and solders as well as a component of frit material in ceramic glass enamels. Other uses include extreme pressure greases and lubricants, brake linings, clutch pads, fluorescent lamps and fireworks (Burgess et al., 2014; Raja, 2009; USGS, 2020). Global bismuth end-uses are available for the fiscal year 2006-2007 (Graedel et al., 2013; Panousi et al., 2016) and 2008 (Raja, 2009), and the demand for metallurgical and chemical bismuth compounds is available for year 2014 (Burgess et al., 2014). The end-uses reported in this dataset are based on the end-uses reported by Raja (2009) and Panousi et al. (2016), which are updated with quantitative and qualitative information (Burgess et al., 2014; Ciacci et al., 2015; European Commission, 2020a; Fortune Minerals, 2020; USGS, 2020). Special attention is spent on attributing chemicals to actual end-use categories given their large share of the reported bismuth uses. Notably, 25% bismuth uses are attributed to the automotive industry, as windshield frits alone could represent approximately 3000 to 5 000 tons of bismuth used annually considering that about 50 grams are used "for most of the 95 million cars produced annually" (Fortune Minerals, 2020). Moreover, parts of chemicals are expected to be used in dissipative applications such as animal feed, cosmetics and pharmaceutical products. Ciacci et al. (2015) assumed that one third of chemical uses were dissipated in use. Based on that information, we assumed that 10% out of chemical uses of bismuth, including subsalicylates (7% of total bismuth use according to Burgess et al., 2014), are used in pharmaceutical and cosmetics products, as well 5% in agricultural & environmental applications. Another 2% of bismuth is estimated to be used in a range of Other punctual applications, including e.g. lubricants and fireworks. The remainder of bismuth chemicals is considered to be used in plastics (as pigments and flame retardant), ceramics and electronic ceramic materials, and catalysts (Raja, 2009). We assume that 5% of bismuth is used as catalysts, and the remainder share of chemicals is split half and half between Other industrial, military & energy applications and Other miscellaneous applications to reflect the diversity of potential uses. Finally, we estimate that 5% out of the 33% considered to be used as alloys are used for bullets, based on Ciacci et al. (2015). These are also aggregated in the Other punctual applications category. Based on this information, the following distribution is estimated to be representative of the global end-uses of bismuth around 2010-2019:	U1: 3 U2: 1 U3: 1 U4: 2 U5: 2

	Agricultural & environmental applications: 5% Alloys & solders: 28% Catalysts (homogenous & aggressive env.): 5% Other industrial, military & energy applications: 10% Other miscellaneous: 10% Other punctual applications: 7% Pharmaceutics & cosmetics: 10% Transport: 25%	
Production yield	Most bismuth is obtained as a by-product of lead, while the remainder is obtained as a by-product from various non-ferrous ores, and as a primary product from bismuth-bearing sulfide ores in two mines (one in Bolivia and one in China) (Raja, 2009; Singerling, 2020). According to Panousi et al. (2016), the Molybdenite Corporation of Canada reports that 70% to 80% of bismuth is recovered, based on which the authors estimated a recovery yield of 75%. The technical report for the NICO Gold-Cobalt-Bismuth-Copper Project in the Northwest Territories, Canada, estimates the production of 73 656 thousand pounds of refined bismuth for 102 082 thousand pounds extracted, suggesting a production yield of 72% (Burgess et al., 2014). Given the similarity between this value and the estimate from Panousi et al. (2016) and without further available data, the latter is considered as a reasonnable estimate for the global production yield.	U1: 3 U2: 2 U3: 2 U4: 2 U5: 1
Fabrication and manufacturing	95% (assumption)	U1: 3 U2: 1 U3: 1 U4: 3 U5: 1
New scrap recovery	0%; new scrap recycling is considered to be included in the fabrication and manufacturing yield as home scrap recycling, if ever it occurs.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Remelting	N/A; 0% is reported in the dataset.	U1: 1 U2: 1 U3: 1 U4: 1 U5: 1
Dissipation in use	Many bismuth uses are voluntarily dissipative as there are dissipated in use as a condition to obtain their function (type A dissipation), e.g. the use of bismuth subsalicylates as pharmaceuticals or animal feed, or dissipated during use due to the way they are used (type B dissipation), e.g. ammunition and fireworks. The end-use sectors that are considered to be 100% dissipative are pharmaceuticals & cosmetics, agricultural & environmental applications, and other punctual applications. No dissipation in use is reported for other sectors.	Per sector; please refer to Supplementary Data
Collection and sorting	Bismuth is not considered to be functionally recycled currently (European Commission, 2020a; Panousi et al., 2016).	Per sector; please refer to Supplementary Data

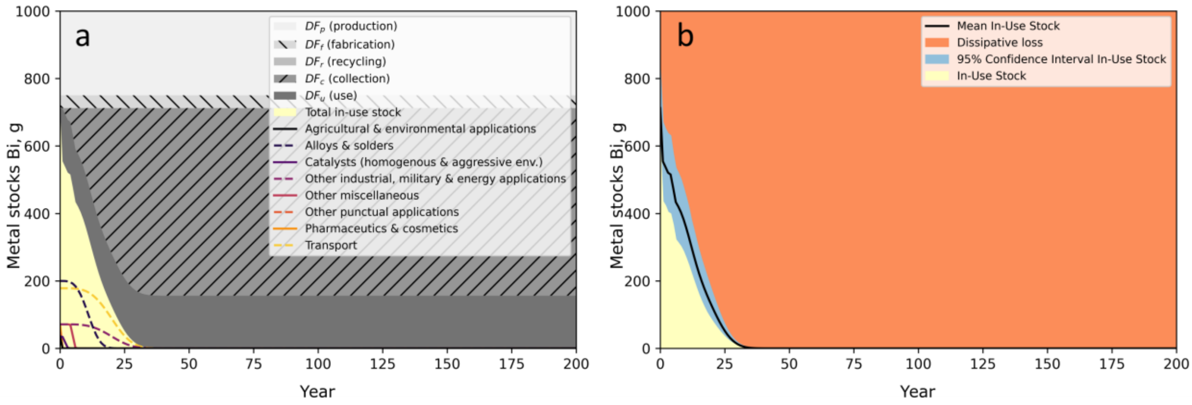

Figure S62. In-use stocks and losses of bismuth over 200 years. *Panel a*: the stacked area plot shows the total remaining in-use stock and the different cumulative losses for 1 000 g extracted. Line plots depict the shares of the total in-use stock into end-use sectors. All lines add up to "Total in-use stock". *Panel b*: Monte Carlo Simulation. The yellow area represents the minimum remaining in-use stock (2.5th percentile); the blue area represents the 2.5th-97.5th confidence interval for the in-use stock; and the orange area represents maximum remaining in-use stock (97.5th percentile). Data underlying this figure are available in the Supplementary Data.

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