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Abstract

This paper contributes to the understanding of metal demand development over time by illustrating the impacts of different aspects of technological change using historical data. We provide a direct, quantitative comparison of relative change in global primary production for 30 metals over 21 years (1993–2013), capturing the range and variation of demand development for different metals within this period. The aspects of technological change contributing to this variation are investigated in more depth for nine metals. Demand for 15 of the 30 metals increased significantly more than GDP between 1993 and 2013. For five metals, demand in 2013 was about or more than 400 % of their demand in 1993. All of these metals had a total primary production of < 100 kt in 2013. Concerning the metals under detailed investigation, comparatively high growth ($\text{demand}_{2013} > 500\ \%\ \text{demand}_{1993}$) could be attributed to emerging technologies in the case of indium and cobalt. Comparatively low growth ($\text{demand}_{2013} < 200\ \%\ \text{demand}_{1993}$) was due to substitution of a technology in case of silver and caused by improvements regarding material efficiency and recycling in case of tin, palladium and platinum.

Keywords: emerging technologies, raw materials demand, substitution

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1. Introduction

Metals are essential raw materials for both basic and advanced technologies. Consequently, ensuring a sufficient metal supply to meet demand is an economic necessity. At the same time, metal mining and processing is associated with environmental impacts [1]. For both reasons, future scenarios have become an established tool in decision guidance at national and international levels [2, 3, 4, 5, 6]. In order to focus political and industrial measures, it is necessary to estimate what developments in demand for different metals are possible and which of these developments need exceptional action. For the required future scenarios on metal demand, understanding the factors that drive demand development is crucial.

A variety of factors are known to influence metal demand, such as world population, disposable income, regulations, incentives, policy, trade regimes, etc. Concerning economic growth and changing consumer preferences [7, 8, 9, 10], the intensity of use hypothesis [11, 12] defines the intensity of use as demanded material per unit of GDP. It postulates that the expansion of manufacturing and construction by industrialization causes the intensity of metal use to rise with GDP in low-income countries. In contrast, shifting preferences towards less material-intensive goods and services are assumed to counteract this increase, finally leading to decreasing intensity of use with increasing GDP [11, 12].

However, as Crowson [10] points out, the intensity of use hypothesis alone is not sufficient to explain development in material demand, as it neglects the influence of technological change. Among the different aspects of technological change, the emergence of new technologies has gained particular attention. Especially for the so-called technology metals (e.g. indium, germanium, gallium, rhenium, selenium or rare earths), an exceptional increment in demand due to emerging technologies is considered likely [6, 5, 2, 3, 4, 13].

In addition to the emergence of new technologies (including their invention, innovation and diffusion), continual improvement of technologies is a constitutive part of technological change [9]. Continual improvement of production technologies is generally connected with a decrease in costs (e.g. for labor, energy, material), which tends to make products less expensive and more accessible to consumers, possibly leading to higher overall demand. In the case of improved material efficiency, a decrease in metal demand could be expected but this may be counteracted or even overcompensated by increased demand for the (now cheaper) products—the so-called "rebound effect" [14]. Furthermore, technological change (in the shape of emerging technologies as well as continually improved technologies) also includes enhancements of recycling and other aspects of a circular economy, which lead to a reduced primary demand for materials. Finally, new technological developments do not necessarily mean their raw material requirements are additive to that of established applications. Instead, the introduction of new technologies can also result in the substitution of an established technology, possibly shifting raw material requirements to a different set of raw materials.

Consequently, technological change can have increasing effects on demand for some materials and, at the same time, decreasing effects for others. Therefore, a better understanding of the development of metal demand over time requires a combination of aspects of GDP growth, changes in consumer preferences and gradual as well as radical technological change.

This paper aims to contribute to the understanding of metal demand development over time by illustrating the impacts of different aspects of technological change using historic data on metal demand. While it is clear that past developments cannot simply be transferred or extrapolated to future estimations, learning as much as possible from the available knowledge of historic developments is an established approach in scenario-based science on future developments [15]. In this regard, we aim to contribute to the development and interpretation of future scenarios of metal demand by improving our basic understanding of historic developments.

For this purpose, we firstly provide a direct, quantitative comparison of relative change in global primary production for 30 metals over 21 years (1993–2013), which will show the range and variation of demand development for different metals within this period. In particular, we use the historic data to test the intuition that smaller markets and metals associated with "high-tech" applications are more prone to exhibit exceptional growth. Secondly, we analyze how demand changed for different applications between 1993 and 2013 for nine metals to investigate which aspects of technological change drive the variation in demand development for different metals. The nine metals selected show examples of the influence of a phase-out or substitution of a technology in decreasing demand for a certain metal, as well as of the effects of efforts regarding efficiency and recycling. Furthermore, the significance of change in demand due to emerging technologies in comparison to established technologies and its dependence on market size and specific demand for a metal for a certain emerging technology are illustrated. This aspect is further illustrated by a future scenario of demand for copper and lithium for electric cars.

2. Data and approach

The period 1993–2013 (21 years) has been selected as the time frame of this study because it appears long enough to allow significant changes in demand for different metals due to technological change while at the same time having comparably good data availability. For this period, data of global primary production for 30 metals was collected. These data on raw material extraction from the lithosphere provide a first approximation to raw material demand—ignoring temporary stocks and recycling. They have the advantage of being readily available for a wide variety of raw materials and usually as time series for a number of years, provided by geological services. For this paper, primary production data as published by the U.S. Geological Survey [16, 17] was used for all metals except for lithium. Since global primary production of lithium in 1993 was not published by USGS, we rely on a personal communication from the Federal Institute for Geo-Sciences and Raw Materials (BGR/DERA) for production data in 1993 as well as 2013.

Data for demand by application for the selected nine metals was collected from metal institutes (ITRI, The Silver Institute, CDI), companies (Johnson Matthey), market analysts (Roskill) and geological services (BGR/DERA, USGS) [18, 19, 20, 21, 22, 23, 24, 25, 16, 17].

To further illustrate the effect of a technological development on different raw materials markets, two scenarios for electric cars and their requirements of lithium and copper are presented in Section 4. Scenarios were taken from [26] and only the production data were updated for this manuscript.

3. Results and discussion

3.1. Primary production of selected metals in 1993 and 2013

Figure 1 shows the relative increase in global primary production of 30 metals between 1993 and 2013 as the ratio of demand$_{2013}$/demand$_{1993}$ on the y-axis versus the absolute tonnage of primary production in 2013 on the x-axis (cf. [5]). For comparison, economic growth (expressed as increase in GDP [27] in the same time period) is also shown.

Examination of Figure 1 reveals that, while primary production for none of the metals has decreased, the degree of increase is largely variable: from essentially zero (Be) to more than 500 % of the original level (In and Co) in the time period considered. The world economy grew to approximately 180 % of the level in 1993 in the same time period [27]. Half of the metals (15 of the 30 metals considered) increased to less than 200 % of their total production in 1993 by 2013. Therefore, they increased in a similar manner as GDP or less than GDP, i.e. their intensity of use is about or below 1. Note that this group comprises metals with a total primary production ranging from small (< 10 kt) over medium (< 1 Mt) to large (> 1 Mt) total size. The same is to be noticed for the 15 metals which experienced significantly stronger growth than GDP (intensity of use above 1). However, for all five metals having a ratio of demand$_{2013}$/demand$_{1993}$ of about or more than 400 % (tantalum, bismuth, niobium, cobalt and indium), the total primary production is < 100 kt.

3.2. Demand by application for selected metals between 1993 and 2013

In order to analyze which factors connected with technological change were responsible for the large variation seen in Figure 1, we selected nine metals covering a broad range of values in relative change in demand between 1993 and 2013 and having reasonably complete data series obtainable from published sources. Figure 2 shows time series for the demand of In, Co, Li, Al, Co, Sn, Ag,

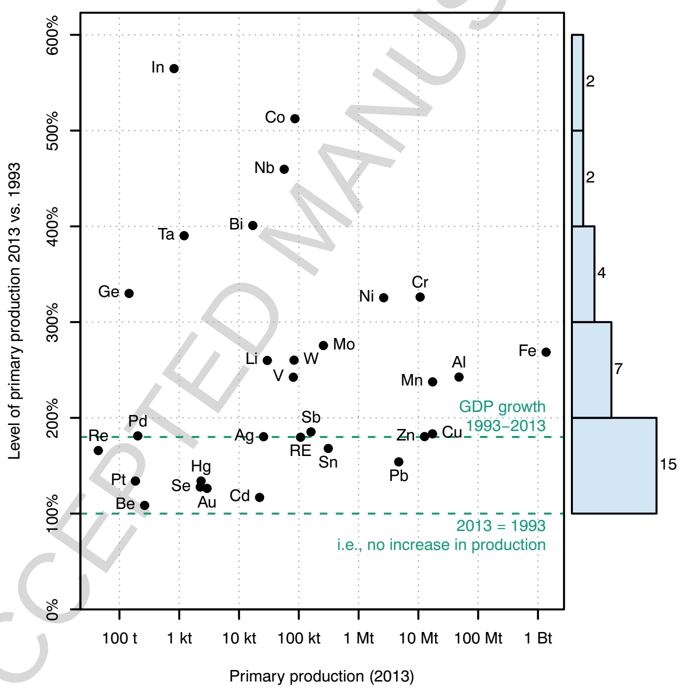

Figure 1: Relative increase in primary production of various metals. Production data taken from [5]; GDP growth (constant 2010 US$) from [27]. Units: t = metric tons, kt = thousand metric tons, Mt = million metric tons, Bt = billion metric tons.

Pt, and Pd. Note, however, that the figure is limited by data availability: While data for In, Al, Cu, Sn and Ag include demand satisfied both by primary and secondary sources (including both manufacturing and post-consumer scrap), the curves for Co, Pt, Pd correspond to demand satisfied from primary production only. Recycling of Li is negligible [28] such that it makes essentially no difference whether recycling is included or not. Furthermore, for Pt and Ag only physical demand for industrial applications is included as demand for investment is not within the focus of this work. Therefore, Figures 1 and 2 are not in all cases directly comparable with each other. The conclusions drawn on the trends for each metal remain nevertheless valid.

3.2.1. Copper and Aluminum

The overall demand for Cu and Al developed smoothly between 1993 and 2013, with the only noticeable kink in the curves being tied to the economic crisis in 2009. The ratio of $\text{demand}_{2013}/\text{demand}_{1993}$ is between 150 and 300 % for all application sectors considered, i.e. there are no application sectors showing particularly strong growth.

With the high total demand and production of these metals and their distribution over a broad range of applications, it appears plausible that demand for these metals for special and emerging applications is small in comparison to total demand and thereby not significant for the development of overall demand. For example, demand for Cu, Fe and Al for wind power plants is higher than for any other metal, yet the increase in demand of these three mass metals for wind power until 2035 is below 5 % of their present total production even in high demand scenarios [5]. The point of market size is further explored in Section 4.

3.2.2. Indium

The growth of more than 500 % in production of In between 1993 and 2013 was driven by applications of ITO—a mixed oxide of tin and indium used for transparent electrodes—in displays and thin film solar cells. The requirement of a material which is both transparent and conductive makes ITO difficult to

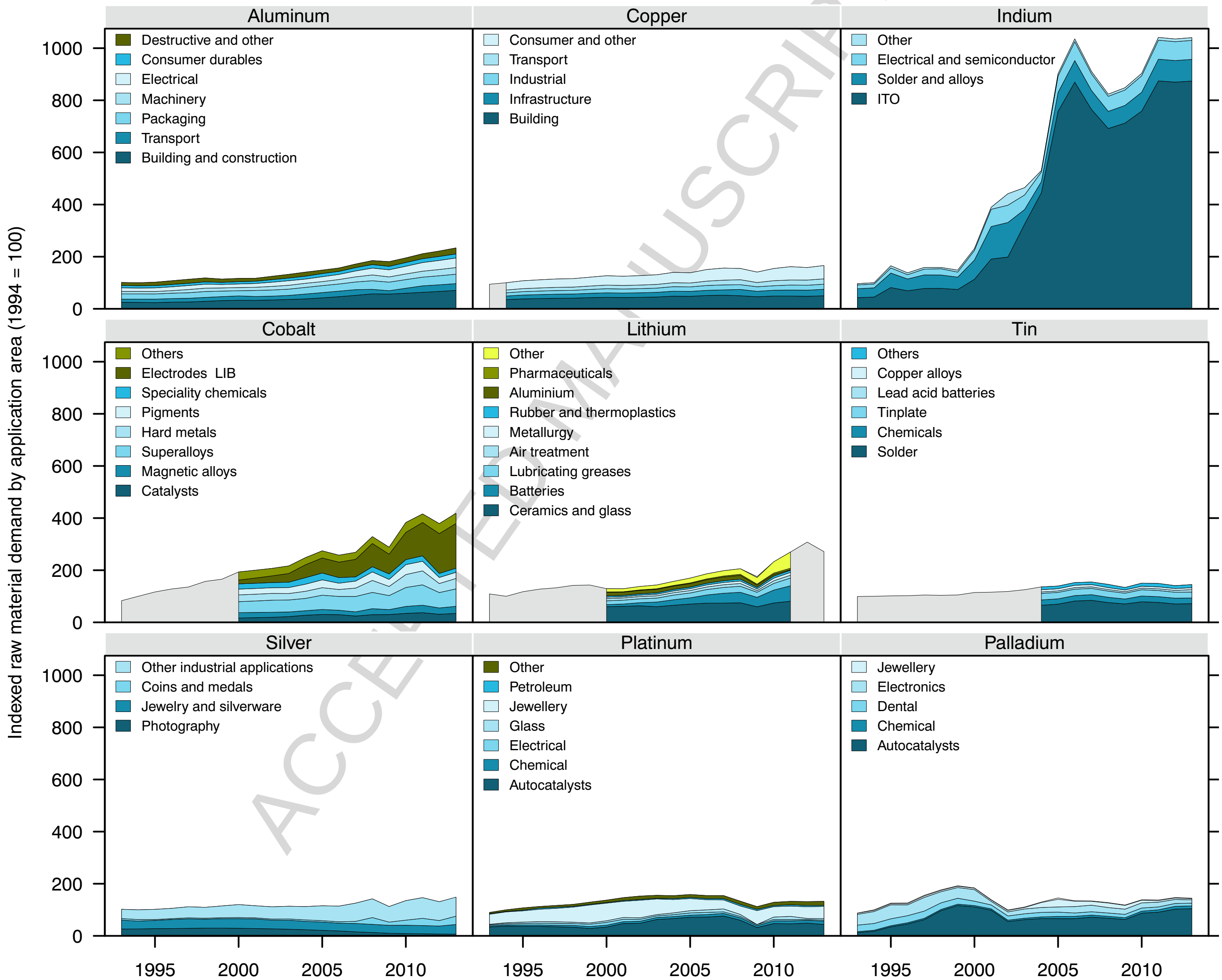

Figure 2: Demand trends for selected raw materials (cf. Figure 1). Note that the figures for aluminum, copper, indium, tin and silver include demand for both primary and secondary material (i.e. including recycling of old and new scrap) whereas the figures for cobalt, lithium, platinum and palladium are for primary material only [18, 19, 20, 21, 22, 23, 24, 25, 16, 17].

substitute in these applications, and the rapid spread of flat screen TVs and portable electronic devices has been enough to fundamentally change the In market in a very short period of time.

Notice that the increase in In demand depicted in Figure 2 is almost about twice the increase in primary production shown in Figure 1. This difference is due to the extensive recycling of the ITO sputtering targets, of which only around 30 % are sputtered onto the glass while the remaining 70 % are amenable to recycling ("used" ITO targets, grinding sludge or on shields of the sputtering chambers) [29]. In 2011, this so-called "reclaim" In contributed an estimated 3/4 of the indium used for ITO applications [30]. In contrast, recycling of In from post-consumer scrap is currently negligible [28].

3.2.3. Cobalt

Similar to indium demand, the rise in cobalt demand ($\text{demand}_{2013}/\text{demand}_{1993} > 500$ %) was due to a specific emerging technology. In this case, lithium-ion batteries (LIB) enabled the breakthrough of portable consumer electronics like mobile phones and laptops. $LiCoO_2$ was the electrode material used in the first lithium-ion batteries commercially available in the early 1990s and is still the most widespread electrode material in lithium-ion batteries for consumer electronics. The cobalt demand for this technology increased to > 1100 % of its level in 2000 by 2013. (Note the different time frame for comparison due to limited data availability.) All other Co-applications have a ratio of $\text{demand}_{2013}/\text{demand}_{2000}$ of 80–200 % .

3.2.4. Lithium

It appears initially surprising that overall Li demand "only" doubled between 1993 an 2013 (cf. Figure 1), while Co demand increased much more driven by growth in Li-ion batteries (cf. Section 3.2.3). This impression is strengthened by the availability of alternative materials for LIB-cathodes, so the demand of Co for LIB also depends on the market share of $LiCoO_2$.

However, despite the plurality of electrode alternatives, $LiCoO_2$ cathodes have dominated the market for LIB for portable electronic devices and this market in turn dominated the LIB market in the time period 2000-2011 (for which there are data for both Co and Li). Moreover, the mass of Co required per LIB is higher than that of Li (in average, a LIB for a portable device contains ≈ 11 wt% Co and ≈ 4 wt% Li [31]). Since the primary production of both metals is comparable (see Figure 1; the data behind Figure 2 for both Li and Co excludes recycling), the larger mass requirements of Co per unit should translate into a stronger demand increase for Co than for Li. Between 2000 and 2011, the demand for Li in LIB increased by a factor of $\gtrapprox 7$, which is significant though smaller than the increase for Co.

Furthermore, not all end-use applications of Li grew in a similar manner in the period under consideration. Noteworthy is the almost 5-fold increase in the "other" category, which unfortunately cannot be elucidated further. The use of Li in pharmaceuticals also increased significantly ($\text{demand}_{2011}/\text{demand}_{2000} > 4.5$), but this end-use only accounts for ≈ 1 % of Li use and is therefore insignificant for overall demand. The remaining end-use categories grew in an average manner ($1.3 \lessapprox \text{demand}_{2011}/\text{demand}_{2000} \lessapprox 2$) in the period 2000-2011, with the exception of aluminum which shrunk to $\approx 1/5$ of the original level.

3.2.5. Tin

The major application of tin with about 50 % market share is soldering, which includes solders for general applications as well as solders for microelectronics. Soldering of printed circuit boards is essential for all electronic applications from white goods (washing machines, fridges etc.) to entertainment and communication electronics (PCs, TVs, phones), which are applications with global growth rates from average to above average [5]. In addition, with the prohibition of lead in solders in the EU RoHS 2002, weight-percentage of tin in solders for European applications increased from about 60 % to 97 %. Yet, Sn demand for solders remained about constant in the time period under consideration: $\text{demand}_{2013}/\text{demand}_{1993} \approx 1.1$.

There are two plausible reasons for this: miniaturization in electronics and material efficiency increase in soldering techniques. Miniaturization in electronics is an effect that cannot be transferred to other applications and can be empirically described by Moore's law: the number of components on an integrated circuit, and thereby the performance of microelectronics, grew exponentially during the past decades, reducing the demand for solders. Material efficiency benefits in soldering are mainly due to an increasing market share of surface mounted technology (SMT) versus through-hole technology (THT) [5]. Consequently, the development of tin demand between 1993 and 2013 shows the potential of efficiency improvements in production technologies as part of technological change. The overall tin demand increased little, although applications like consumer electronics had growth rates above average.

In contrast to the overall In demand (cf. Section 3.2.2), total Sn demand is not significantly influenced by growth in ITO applications. The reason for this becomes clear when examining the weight ratios of In and Sn in ITO. The mixed oxide ITO usually comprises about 90 weight-% of indium(III)oxide and only 10 % of tin(IV)oxide. In addition, total Sn demand is close to 1×10^6 tonnes, whereas total In demand is well below 1×10^4 tonnes (we revisit the issue of market size in Section 4). The demand from other tin applications remained approximately constant.

3.2.6. Silver

The demand for Ag for industrial applications increased by about 45 % from 1993 to 2013. This comparably low growth can be attributed to the fading use of Ag-ions in photography due to digitalization. Silver use in photography had a share of ≈ 25 % in all industrial silver applications in 1993 but declined to ≈ 5 % by 2013 as the absolute amounts of silver decreased to approximately 1/4 of their value in 1993. Hence, the development of silver demand for photography is a good example for decreasing demand due to substitution of a technology as part of technological change.

A comparatively strong growth in coins and medals ($\text{demand}_{2013}/\text{demand}_{1993} > 5$, market share grew from ≈ 5 % to $\gtrapprox 20$ %) partly compensated for the decline of silver use in photography. Combined growth in these two sectors, however, was only ≈ 20 % in the period 1993-2013. All other applications grew about or less than overall economic growth (jewelry and silverware, by < 10 %, other applications by ≈ 100 % in the 21-year period).

3.2.7. Platinum and palladium

Physical demand for industrial applications for Pt and Pd increased by ≈ 50 and 70 %, respectively, between 1993 and 2013. There are at least two important factors to consider when examining the demand of Pt and Pd. First, Pd can substitute for Pt in different applications, though generally at the expense of performance. Since Pt is more expensive, there have been extensive attempts to reduce the demand for Pt by usage of the less expensive Pd in various ways and with different success in the main applications jewelry and autocatalysts for decades. Second, the high price of Pt (and Pd) is a strong incentive for efficiency increases [32], the use of alternative materials and recycling.

As a result, growth in most applications both for Pt and Pd ranges from contracting (decrease by a factor of 2–3 of Pd demand for—the formerly dominating—dental and electronic uses) over essentially stagnating (no change in Pd use in jewelry and < 10 % increase for Pt demand for electrical uses). Only demand for Pt and Pd for catalysts increased more than overall economic growth. The single most significant driver of demand increase for Pt and Pd in the period under consideration was, therefore, autocatalysts. While growth for Pt demand was only modest ($\lessapprox 30$ % over 21 years), the demand for the cheaper Pd increased by a factor of $\gtrapprox 8$ in the same time period.

The impact of recycling becomes clear when comparing the development of demand with and without the demand for secondary supplies [23]. When considering the demand for primary production only, the demand of Pt and Pd for catalysts in 2013 appears to be 340 % of the demand in 1993. Including demand for recycled supplies, however, leads to a ratio of $\text{demand}_{2013}/\text{demand}_{1993} = 420$ %, i.e. recycling significantly mitigated the increase in demand for primary material.

4. Technological change: Specific demand and market size

Examination of the data in Section 3 indicates that technological change can increase (e.g. Pd demand for autocatalysts, In demand for displays, Co and Li demand for LIB) and decrease (e.g. Ag demand for photography, efficiency gains in Sn solders and Pt/Pd autocatalysts) raw material demand for certain applications. Furthermore, growth in demand for a particular technology may affect different raw material markets to different extents, as seen for Li and Co in LIB, and In and Sn in ITO. This difference is due to two main factors: the specific demand for a certain metal for a technology (demand by application unit) and (raw material) market size.

In the case of Li and Co in LIB, the specific demand is higher for Co than for Li. Since the markets are of similar size, the demand increase for Co in LIB is higher than that for Li such that the specific demand factor dominated comparative demand increase in the period under consideration despite variability in the Co and Li content of different competing battery chemistries. In the case of In and Sn in ITO, both raw material intensity per unit and market size make ITO dominate In demand but be marginal for Sn demand.

Market size alone can also determine the extent to which a particular emerging technology changes a particular market. This is illustrated in Figure 3 for Cu and Li, two raw materials associated with the "technology" electric vehicles. Though the raw material demand per vehicle is lower for Li than for Cu (up to 3 kg Li per plug-in hybrid or fully electric vehicle with a 20 kWh LIB [33] vs. $\approx$ 40–75 kg Cu for different degrees of electrification, from mild hybrid to fully electric vehicles [34]) the Cu market is three orders or magnitude larger than the Li market (10^7 vs. 10^4 tonnes per year). As a consequence, regardless of the market penetration scenario for electric cars and assuming LIB will remain the preferred battery technology in the foreseeable future, the widespread adoption of electric vehicles will more markedly define the Li market (up to 80 % share in Li demand) than the Cu market (at most 20 % share in Cu demand), despite requiring much less Li than Cu (difference on the order of 100 times in absolute amounts). Therefore, it becomes evident that smaller markets are more prone to disruption by the (rapid and) widespread introduction of new technologies.

From the observation that technological change can lead to both increase and decrease in demand for raw materials, it becomes clear that—insofar as a single application does not dominate demand—all applications of a raw material under examination must be taken into account when attempting to anticipate supply bottlenecks. Furthermore, an increase in demand alone does not necessarily lead to a supply bottleneck (or marked price increases). Conversely, even if demand increases slowly, prices and shortages can still arise if supply increases even more slowly or decreases, e.g. for political, environmental or geological reasons. It is therefore necessary to consider both supply and demand (trends) in their entirety.

Finally, even if a metal market is not strongly influenced by demand of this metal for an emerging technology, this metal can nonetheless be important or even essential for this technology. For instance, the industrial metal Cu is the material used for electrical wires and therefore important for any electric or electronic technology. Also, Sn will probably not be replaced as the fundamental element of microelectronic soldering in the foreseeable future.

5. Conclusion

The goal of this paper was twofold: (1) to establish a quantitative frame of reference for assessing scenarios for future demand based on historical data; and (2) to examine the role that technological change plays in changing demand for raw materials. For the first point, we examined the increase in primary production (as a proxy for demand) of 30 metals in the period 1993-2013 (21 years). For the second point, we studied the demand per end-use for nine metals in the same period.

For 15 of the 30 metals considered in this paper, the primary production in 2013 was between 100 % and 200 % of the primary production in 1993. Therefore, while primary production increased for all metals examined, the observed

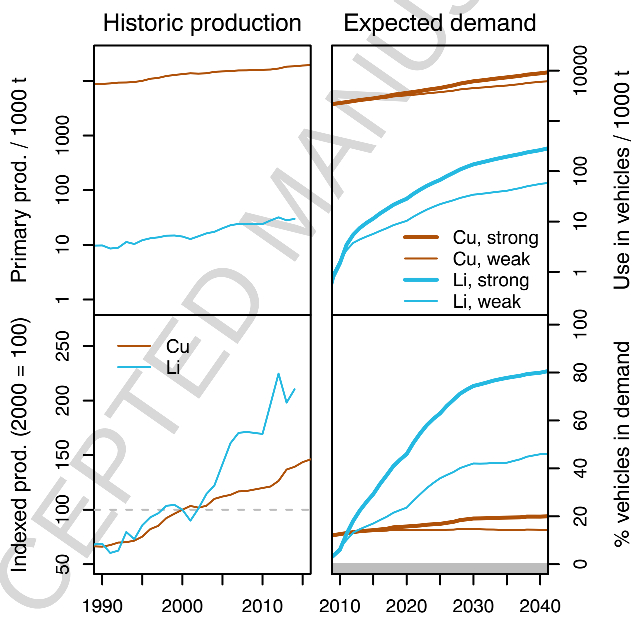

Figure 3: Historic primary supply and expected demand for copper and lithium for (electric) vehicles. Two scenarios for the market penetration of electric vehicles are considered: "strong" and "weak". Figure updated from [26] using production data from [35] (demand scenarios not changed from [26, 33, 34]).

increase was about or lower than economic growth as measured by GDP for these 15 metals (cf. Fig. 1). Primary production for the other 15 metals showed stronger growth than GDP. The analyzed data indicates that a relative change of about or more than 400 % in 21 years is exceptional, as it occurred for only five (Ta, Bi, Nb, Co and In) of the 30 analyzed metals. Furthermore, this level of increase was observed only for small to medium-sized markets (less than 100,000 t). Therefore, the results substantiate the intuition that in general, a small or medium size makes a metal market more prone to exhibit exceptional growth due to emerging technologies, while larger metal markets (more than 1 Mt) can buffer demand peaks due to emerging technologies more easily.

Conversely, nine metals (Pd, Ag, Re, Hg, Pt, Se, Au, Cd and Be) with market sizes < 100 kt grew to less than 200 % of their 1993 levels by 2013. Therefore, a small to medium size and association with nascent and emerging technologies (e.g. Pt and Pd with autocatalysts and fuel cells) are not sufficient to display outstanding demand growth.

It is important to add that also the specific demand for a metal for a technology (i.e. demand by product or service unit) has a high impact on the relative change in demand. This paper showed the example of lithium-ion batteries, which had a stronger impact on the cobalt than on the lithium market, partly due to the higher specific demand for cobalt for $LiCoO_2$-based batteries (cf. Fig. 2). It is also important to remember that a metal, which is not significantly increasing in demand due to an emerging technology, can nonetheless be essential for this technology. A good example for this relation is copper, which is important for all electric and electronic technologies, though this is not directly visible in its continually, moderately increasing demand (cf. Fig. 2).

A detailed examination of the development of demand by application for nine of the considered metals (Al, Cu, In, Co, Li, Sn, Ag, Pt, Pd) highlighted the different aspects of technological change that lead to the observed high variation of metal demand development. A single emerging technology determined the two largest relative changes observed in demand: indium-tin-oxide for displays in the case of In, and lithium-ion batteries in case of Co. This finding strongly supports the perceived outstanding importance of the emergence of new technologies within the aspects of technological change for unusual demand increases.

The effects of efficiency increases, substitution and recycling become evident when examining changes in demand for Sn, Ag, Pd and Pt, all of which showed growth to less than 200 % of their 1993 levels by 2013. The substitution of one technology by another can strongly reduce the respective metal demand for the substituted technology and thereby diminish the overall increase in demand, as shown by the results for photography and silver. Progress in production technologies leading to higher efficiency can sustain metal demand on a constant value even when applications are growing above average, as was seen in the case of tin and solders. Moreover, high metal prices can be a powerful incentive for efforts concerning efficiency, recycling and substitution to mitigate demand increases, as seen in the example of platinum and palladium for catalysts. Although the success of efforts geared towards substitution, recycling and increased efficiency is to a certain extent determined by intrinsic technological factors and cannot be simply transferred from one metal to another, it appears reasonable that incentives in these areas are conducive to securing metal supplies as well as to reducing ecological impacts connected with mining in the future.

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