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Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium

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ABSTRACT

There are considerable concerns about the supply security of certain high-tech elements produced as by-products. To determine in how far these concerns are justified by the actual availability of these elements, we compare the supply potentials for three particularly relevant examples – gallium, germanium and indium – to current and historic production volumes. Our assessment is based on detailed estimates of the amounts extractable from various raw materials given contemporary market prices and technologies. While the estimate for gallium is taken from a previous publication, the estimate for germanium is recalculated from an earlier estimate of recoverable germanium in reserves and resources, and the estimate for indium is compiled as part of this article.

We find that the supply potentials of all three elements significantly exceed current primary production. However, the degree to which this is the case varies from element to element. While both the supply potentials of gallium and germanium are ~10 times higher than primary production, the supply potential of indium is ~3 times higher.

Differences also exist in historic growth trends, with indium showing the fastest growth rate of the utilised supply potential. This makes it the most likely of the three to reach its maximum production level in the future. Based on these considerations we propose a new quantitative indicator for the future availability of by-products, time-to-maximum extraction as a by-product (TMEB), and show its utility in discriminating between the different supply situations of the three by-product elements.

1. Introduction

Many technological innovations at the heart of modern society were enabled by the unique properties of certain rare elements and their compounds (Graedel et al., 2015b). Consequently, the consumption of these elements has increased rapidly in recent years (Kelly and Matos, 2014). Many have been classified as 'critical', i.e. as being of high economic importance, while simultaneously subject to high supply risks (Erdmann and Graedel, 2011; EU Commission, 2014). A large number are produced exclusively as by-products from the ores of other metals (Wellmer et al., 1990; Nassar et al., 2015). This means their production is in principle strictly limited by the production of the 'host' materials to which they are associated (Campbell, 1985; Wellmer et al., 1990).

Gallium (Ga), germanium (Ge) and indium (In) are three such elements (Nassar et al., 2015). Their major uses are in the renewable energy, telecommunications and electronics sectors (Guberman, 2015; Jaskula, 2015; Tolcin, 2015). Fig. 1 shows the relative growth in their primary production from 1973 to 2013, compared to the growth in the production of their corresponding host materials. It is clear that both primary Ga and In production grew much faster than the production of their host materials, while primary Ge production grew at a similar, if not smaller, rate. Some authors predict this trend to continue into the foreseeable future (Angerer et al., 2009; Viebahn et al., 2015). Therefore, a major question in the assessment of supply risk is how long the faster growth rates of certain by-products compared to their source materials will be sustainable before supply becomes limited by raw material availability, possibly resulting in major disruptions of dependent markets. Such disruptions could jeopardise the deployment of new technologies, and therefore pose a risk to technological progress (Graedel et al., 2015b).

So far, this important aspect of by-product supply is not adequately incorporated into any criticality assessment (e.g. DOE, 2011; EU Commission, 2014; Graedel et al., 2015a; NSTC, 2016). While

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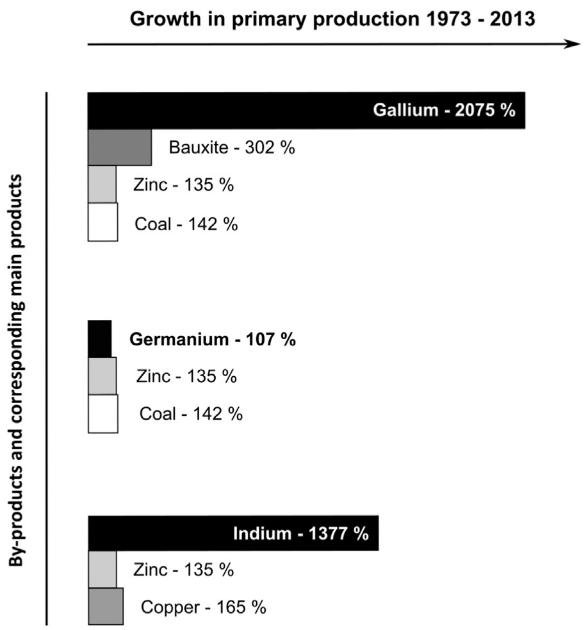

Fig. 1. Relative growth in the primary production of Ga, Ge and In, and their associated source materials from 1973 to 2013. Based on data from Kelly and Matos (2014).

Graedel et al. (2015a), for instance, consider the proportion of elements produced as by-products, they do not distinguish between cases where by-product production is close to its theoretical limit, and those where it is not. To a large extent, this reflects a lack of suitable data.

Indeed, it is emphasised by a number of recent studies that there is a lack of reliable assessments of the availability of by-products in general and In in particular (Candelise et al., 2012; Fthenakis, 2015; Olivetti et al., 2015). Nevertheless, the general tenor is that sufficient amounts to cover future demand are available within primary reserves and resources (Frenzel et al., 2014; Schwarz-Schampera, 2014; Werner et al., 2015). However, reference to reserves and resources is not relevant for by-products. Instead, assessments of by-product supply should focus on the amounts extractable from the ores of other metals *per year* given current economic conditions (prices) and existing technologies, i.e. their supply potentials (Frenzel et al., 2015, 2016b; Løvik et al., 2015).

In this contribution, we estimate the supply potential of In as a by-product from zinc and copper production using a high-quality dataset. We then normalise it to current primary production and compare the resultant ratio to similarly normalised previous estimates for Ga and Ge (Frenzel et al., 2014, 2015, 2016b). All our estimates include the effects of both geological variability, and technological and economic factors determining extractable amounts (cf. Frenzel et al., 2015). This is achieved by estimating the supply potential on a mine-by-mine basis and using realistic recovery functions. Thus, these estimates represent a major improvement on previous approaches.

We do not consider the supply potential from End-of-Life (EoL) recycling. EoL recycling rates for all three elements are currently below < 1% of primary supply due to their high dispersion in the final products (cf. Nassar et al., 2015). EoL recycling is in fact expected to remain more costly than primary production, and thus unlikely to contribute considerably to supply over the next few decades (Redlinger et al., 2015). The continuous recycling of new production scrap as well as production residues (e.g. spent indium-tin-oxide sputtering targets, grinding residues in GaAs- and Ge-wafer production), on the other hand, is part of the primary production process. Under this premise, the main quantity of interest is the amount of primary feed material entering the overall production system.

Finally, we use the results of our estimates of (primary) supply potentials, in conjunction with relevant observations on historic trends in primary production, to make inferences about the future availabilities of the three elements and the resulting longer-term supply risks resulting from them. To this end, we introduce a new indicator (time-to-maximum extraction as a by-product – TMEB) that estimates the expected time until the primary production of a given by-product becomes equal to its supply potential. Only from this time onwards are persistent global shortages likely to develop at all.

2. Materials and methods

Given the central importance of the supply potential concept for the following considerations, it is useful to quickly give a definition of it before proceeding with the description of our concrete estimation method. As already hinted above, we define supply potential as *the amount of by-product extractable per year from the ongoing primary production of other raw materials (the main products or main-product ores) given current price-levels and extraction technologies* (cf. Frenzel et al., 2015). Thus, it depends not only on the composition of the raw materials, but also on their production volumes, the current price of the by-product, and the technology used for smelting and by-product extraction. Importantly, the supply potential does not contain contributions from sources not viable under current economic conditions. Therefore, it is always smaller than the total amount of by-product contained in current main-product streams.

In particular, none of our estimated supply potentials include contributions from the mill-tailings produced in ore beneficiation. While we briefly consider historical smelter residues in Section 3.3 as a potential additional source, this only includes such materials as are currently viable for the recovery of the by-products, but not those which are not. It is useful to note in this context that the economics of the re-processing of most relevant waste sources, particularly mill-tailings, will ultimately depend on the value of the contained main products (e.g. Cu and Zn in tailings from sulphide base-metal mines) rather than the by-products. Therefore, such sources can only contribute significantly to by-product supply once they account for a significant proportion of main-product supply. Currently, such a scenario is extremely unlikely for most industrial metals.

2.1. Supply potentials of Ga and Ge

While we took the data for the supply potentials of gallium from bauxite and sulphidic zinc ores directly from earlier work (Frenzel et al., 2016b), the supply potentials of germanium from sulphidic zinc ores and coal had to be recalculated from estimates of extractable amounts in reserves and resources (Frenzel et al., 2014). This was done assuming that current production volumes of sulphidic zinc ores and coal have the same mean composition and proportion of extractable germanium as the corresponding reserves/resources for which the original calculations were made, and that market conditions have not changed sufficiently to warrant re-calculation.

2.2. Supply potentials of In

For In, the supply potentials from sulphidic zinc and copper ores were estimated following procedures adapted from the general method of Frenzel et al. (2015). We only give a summary of these procedures here to keep the length of this article to a minimum. The details necessary to ensure the reproducibility of this work are provided in Appendix A.

To make the following easier to understand it is helpful to quickly recapitulate some key aspects of primary by-product supply. In particular, readers should note that:

1) The concentrations of by-product elements are often highly variable in the raw materials from which they are extracted,