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Assessing the supply potential of high-tech metals – A general method

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ABSTRACT

The demand for some of the rarer elements in the Earth's crust, mostly from high-tech applications, is increasing rapidly. Many of these elements are produced exclusively as by-products resulting in potentially significant supply limitations. In this article, a general method for the assessment of the supply potential of such elements is developed from a conceptual model of the supply-chain. Namely, statistical and deterministic models are introduced to quantify both the variability in by-product concentrations in the relevant raw materials, as well as the effects of this variability on achievable recoveries. The assessment of uncertainties is implemented via Monte-Carlo-type simulations. Presentation of the results in availability curves ensures adaptability to future changes in market conditions, while extensive documentation of the assessment method, available as electronic supplementary material with this article, ensures reproducibility.

A simple example is used to illustrate the complete estimation process. It shows that in addition to ensuring future adaptability of the results, availability curves are also useful for the assessment of the current supply regime of a given by-product. An elastic and inelastic regime might be distinguished – in the elastic regime, significant demand-driven increases in by-product supply are possible without increases in the production of the main product, while in the inelastic regime this is not the case. The method presented in this article is the first to enable such an assessment to be made in a reliable and transparent manner.

1. Introduction

The human population has grown at an unprecedented rate over the last two centuries (Bongaarts, 2009). The same is true for its use of natural resources and energy (cf. data in Kelly and Matos (2013), World Energy Council (2010)). Although global population growth is expected to slow and eventually stall over the coming decades (Lutz et al., 2001; United Nations, 2013), resource and energy usage are set to increase further as developing nations strive for western standards of living (Halada et al., 2008). Not only is the total demand for raw materials growing, but the total number of materials used in industrial products is also increasing – while 10 different metals were required for the manufacture of computer chips in 1980, today it is more than 40 (National Research Council, 2007). The newer additions to the raw materials pool are variably called 'high-tech metals' (e.g. Steinbach and Wellmer, 2010), 'energy metals' (e.g. Graedel, 2011) or 'new age metals' (e.g. Huston, 2014) because of their unique combinations of properties without which many important technological advances would not have been possible. Of particular relevance is their role in many parts of the renewable energy sector (Fthenakis, 2009). They are therefore considered to be of great economic importance. Because there are at the same time concerns about the security of their supply, many have been identified as 'critical raw materials' (European Commission, 2014). The elements most commonly included in this group are listed in Table 1, together with their main uses, and the degree to which they are won as by-products. It is clearly seen that while some are won as the main product of specific mining operations, the majority are produced mainly or solely as by-products. This is in part a result of the small size of the respective markets for these metals (cf. Table 1). The resultant price volatility, development of oligopolies, and high market entry barriers for potential new producers inhibit the development of mines producing one or several of these high-tech metals as the main product (Wellmer et al., 1990). Another reason for this tendency is a lack of natural (ore) deposits in which these elements are sufficiently concentrated to warrant their production as a main product (e.g. Butcher and Brown, 2014). Many problems arise from this status, concerning both actual supply security and its assessment. The most prominent ones are

1) **Dependence on main products.** The low relative value of by-products compared to main products means they do not enact a

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Table 1
High-tech metals – overview of uses, by-product dependency and market sizes.

Element(s)	Major industrial use(s)	Per cent won as by-product	Ass. major products	Production (2012, t)	Market size[a] (2012, millions of US$)	Refs.
Te	Solar cells	100	Cu, Pb, Zn	> 100	> 15	[1,2]
Cd	Solar cells, batteries	100	Zn, Pb	20,900	42	[2,7]
Ga	Semiconductors	100	Al, Zn, Pb	383	203	[2,3]
Re	Super alloys, catalysts	100	Cu, (Mo)	53	212	[2,4]
Ge	Semiconductors, Fibre-optics, IR optics	~ 70[b]	Zn, Pb	155	254	[2,5,17]
Se	Glass decolouring, Mn-refining, catalysts, solar cells, alloys	100	Cu, Ni	2240	269	[2,6]
In	LCDs	100	Zn, Pb (Cu)	782	508	[2,8]
Hf	Superalloys, ceramics	100	Ti, Sn	N/A	N/A	[2,9]
Co	Batteries, super alloys catalysts	60	Cu, Ni	77,900	2370	[2,10,11]
REEs	Catalysts, alloys, magnets, phosphors	–	–	110,000	5630	[2,12]
PGEs	Catalysts	N/A	Ni, Cu	451	8790	[2,13]
Ag	Electronics, catalysts	70	Pb, Zn, Cu, Au	25,500	25,500	[2,14]
Zn[c]	Galvanisation, alloys	–	–	13,500,000	28,350	[2,15]
Cu[c]	Construction, electronics	–	–	16,900,000	137,000	[2,16]

LCDs – Liquid crystal displays; REEs – rare earth elements; PGEs – platinum-group elements; N/A – no data available.
References: 1 – George, 2014b; 2 – Kelly and Matos, 2013; 3 – Jaskula, 2014; 4 – Polyak, 2014; 5 – Guberman, 2014; 6 – George, 2014a; 7 – Tolcin, 2014a; 8 – Tolcin, 2014b; 9 – Bedinger, 2014; 10 – Shedd, 2014; 11 – Graedel, 2011; 12 – Gambogi, 2014; 13 – Loferski, 2014; 14 – Silver Institute, 2014; 15 – Tolcin, 2014c; 16 – Brininstool, 2014; 17 – Bleiwas, 2010.

[a] Average market value of annual production.
[b] Taking the amount of Ge produced from Ge-coal deposits in China and Russia as being equal to 50 t in 2012. In this setting, Ge is probably the main product and not a by-product – its value exceeds that of the host-coal by a significant margin.
[c] Only included for comparative purposes.

major influence on economic decisions during mining operations (Campbell, 1985). This might result in a direct dependence on main product supply and sets an upper limit to their production. The result is a significant potential for imbalances in supply and demand driven by the economics of the main products (Campbell, 1985; Fizaine, 2013; Afflerbach et al., 2014).

2) **Intransparency.** The lack of both legal requirements and economic incentives (see above) to measure their concentrations in ore materials results in a very limited amount of freely available data on the distribution of the high-tech metals in relevant raw materials. This situation is very different from that of the main products where regulatory requirements exist for the measurement and reporting of metal concentrations, and the delineation and reporting of reserves and resources (e.g. JORC, 2012). For metals like copper or zinc, average concentrations are usually provided in annual company reports (e.g. Lundin Mining Co., 2014). Data on high-tech element concentrations, on the other hand, is usually available only to a strictly limited degree. For the vast majority of high-tech metals, comprehensive collections of data covering many different geological environments, deposit types, etc. do not exist. Detailed published data on the behaviour of the high-tech metals during main product smelting is also often lacking, particularly for Ga, Ge and In. Both of these factors generally make estimates of their supply potential extremely difficult.
3) **Underutilisation of production potentials.** As discussed above, high market entry barriers result in a limited number of dominant producers. Many smelters, despite processing suitable raw materials, do not appear to extract certain by-product metals. This leads to a situation where extraction by those producers which do practise it probably happens at lower concentrations than would theoretically be possible in the most efficient conceivable market, resulting in a corresponding waste of high-tech metal-enriched residues and higher prices.

In conjunction, these factors mean that we currently have only a vague understanding of the actual amounts of many by-product high-tech metals such as Ga, Ge and In contained in relevant raw material streams, while it is not clear at all what proportion of this content could be economically extractable. Despite the obvious relevance of such figures for decisions about the large-scale implementation of new technologies, particularly in the renewable energy sector (e.g. Andersson, 2000; Fthenakis, 2009; Wadia et al., 2009; Zuser and Rechenberger, 2011; Candelise et al., 2012), only a limited amount of work has been done to address this problem (e.g. Watts et al., 1980; Katrak and Agarwal, 1981; Kramer, 1988; Green, 2006; Ojebouoh, 2008; Mudd et al., 2013; Frenzel et al., 2014). In order to be useful, estimates of by-product supply potential should

a) Consider the whole chain of production from mine to end-product and assess losses at different stages (e.g. Ojebouoh, 2008; Mudd et al., 2013),
b) Quantify the effects of the natural variability in raw material compositions on recovery and losses in all parts of the production chain (e.g. Mudd et al., 2013; Singer, 2013; Frenzel et al., 2014),
c) Quantify, as far as possible, uncertainties arising from the limited amounts of data available on raw material composition and the nature of this data, variability in processing conditions or lack of information about certain steps in the production chain (e.g. Singer, 2013; Frenzel et al., 2014),
d) Present estimates (including uncertainties) in a form that makes them easily adaptable to changes in market conditions (e.g. Katrak and Agarwal, 1981), and finally,
e) Be methodologically transparent and consistent to ensure reproducibility and enable later modification of results by the scientific community and corporate entities (e.g. Frenzel et al., 2014).

Although individual studies have incorporated one or several of these points (as indicated by citations), to the best knowledge of the authors, none has addressed all of them. The need for an integrated approach is therefore apparent. It is the objective of this article to present such an approach, with a particular focus on the treatment of discrepancies between the data required and that available for estimates. Inadequate procedures to treat these discrepancies are one of the major reasons for the shortcomings of previous studies. Ultimately, the aim of this article is to show how an assessment can be made of the degree to which the supply