

Indium: key issues in assessing mineral resources and long-term supply from recycling

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Indium and other geologically scarce metals are routinely integrated into green technologies and modern consumer electronics. The manufacture of solar cells and liquid crystal displays (LCDs) relies strongly on continued indium supply, yet very little research has been conducted to determine what total resources exist to meet future or even present needs. This paper provides an improved understanding of the nature of indium resources and the current and future production and supply of this critical metal through a summary of global trends in indium production and demand, and through a preliminary account of global code-based reporting of indium mineral resources. Authors also present an overview of the potential for indium extraction from mine wastes and recycled electronics using Canadian and Australian case studies. Our preliminary data suggest that considerable resources are likely to exist in a diversity of deposits globally, which have the potential to meet long-term demand for indium. However, it is clear that a secured future supply of this metal will require some shift of focus from conventional extraction practices. It will be necessary to revisit controls on the conversion of resources to reserves and to supply and the discovery of additional resources to replace those depleted by continuing production. The prospects for indium supply from mine wastes and recycled electronics are found to be substantial, and these sources warrant greater consideration given their probable environmental and social advantages over the discovery and development of new primary indium deposits.

Keywords: Indium, Indium resources, Mineral resources, Urban mining, Critical metals, Critical minerals, Companion metals, Tailings, Slag, Metal recycling, Indium mineralogy, Indium processing, WEEE recycling

Introduction

Throughout history, the supply and utility of metals has been key to the development and progress of human society. Just as the use of bronze or iron once defined an age, the present information age can also be defined by the use of particular metals. Indium is arguably one of today's defining metals, having been discovered relatively recently, yet already embedded into the renewable energy, automotive, aerospace and consumer electronics industries (Moss *et al.* 2011). Demand for indium has grown exponentially since the 1970s, in particular due to the use of indium in liquid crystal displays (LCDs) and solar panels (Schwarz-Schampera, 2014; Tolcin, 2014), although concern over the security of future supply has led some governments and institutions to classify indium as a so-called 'critical metal' (Moss *et al.* 2011; Skirrow *et al.* 2013, European Commission 2014a, 2014b). While indium is certainly one of the least abundant elements in the earth's crust at 0.052 ppm (copper, by comparison, is

approximately 520 times more abundant, Skirrow *et al.* 2013), the concern over supply is based on very limited knowledge of future or even current indium resources. Indeed, some research has suggested that stock estimates of critical metals, including indium, are 'almost non-existent' [United Nations Environment Programme (UNEP) *et al.* 2010, p. 25]. There are a few sources of information on indium resources (e.g. Ishihara, Murakami and Marquez-Zavalia 2011; Skirrow *et al.* 2013, Schwarz-Schampera 2014), although none of these contain a global summary of known indium resources using mineral resource reporting standards (e.g. JORC, SAMREC, PERC, NI 43-101, etc.). These standards (or codes) assist in the application of best practice methodology for mineral resource estimation within the minerals industry; this makes them crucial to analyses of resource quantities, as the magnitude of extractable metals ultimately depends on what the minerals industry deems profitable (Mudd, Weng and Jowitt 2013a).

Addressing this gap, the authors generate a preliminary collection of publicly reported indium resources using code-based reporting standards. This is accompanied with a detailed discussion of the factors that influence indium production, demand and availability. Authors further provide descriptions of indium-associated deposit types and discuss the best possible

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approach for future accounting studies, entailing possible statistical inferences from mineralogy, deposit type and historical production. Recognising that the long-term availability of indium should not be restricted to its geological abundance, the authors also analyse other measures that can contribute to increased supply of this critical metal, including:

- Enhanced recovery from the processing of raw indium ores.
- Exploration of new resource types such as mine tailings and slags, including a case study of selected Canadian zinc projects.
- Enhanced end-of-life (EOL) recovery from recycled electronic products, presented via a brief case study of end of life mobile phone recycling in Australia.

Authors conclude by reviewing the nature and sustainability of future indium supply, and by highlighting the future work necessary to solidify our current understanding of indium criticality.

The nature of indium demand, production and resources

A brief history of indium demand

Indium was first discovered in samples of zinc sulphide ore at the Freiberg School of Mines, Germany, in 1863. Its applications were few and were mostly reliant on small-scale research until about 1934 when it was first applied at the commercial scale as a coating for bearings in high-performance aircraft engines (Alfantazi and Moskalyk 2003). Production grew steadily until the latter decades of the twentieth century, when considerable expansion and diversification in indium consumption were observed. This is evident in Fig. 1, which shows the recent growth in total indium production globally (Fig. 1a) and the nature of indium consumption in the United States (Fig. 1b). These data indicate that indium consumption from the 1990s onwards was dominated by coating applications (Schwarz-Schampera 2014), primarily as a result of the development of copper–indium–gallium selenide (CIGS) solar cells and indium–tin oxide (ITO) coatings applied as thin films to LCDs and flat-panel displays (Fthenakis, Wang and Kim 2009; Li *et al.* 2011). The boom in these technologies has seen an unprecedented growth in indium production, a trend that remains strong to the

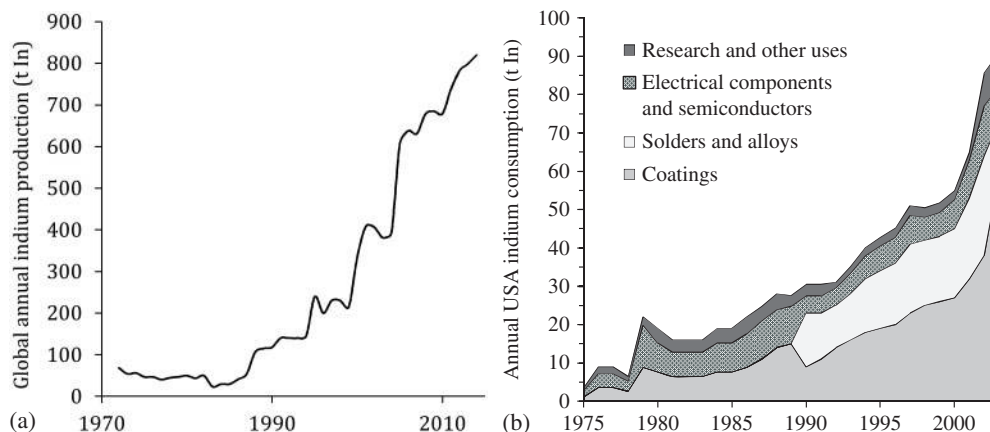
present day (White and Hemond 2012). Current consumption is dominated, in decreasing order, by Japan, the United States, the United Kingdom, the Republic of Korea and Germany, reflecting these countries' capacity for high-tech manufacturing (Skirrow *et al.* 2013). Demand within these countries and globally shows no signs of decline, with continued growth expected for decades to come (DoE 2011; Skirrow *et al.* 2013).

By-product production and extraction efficiency

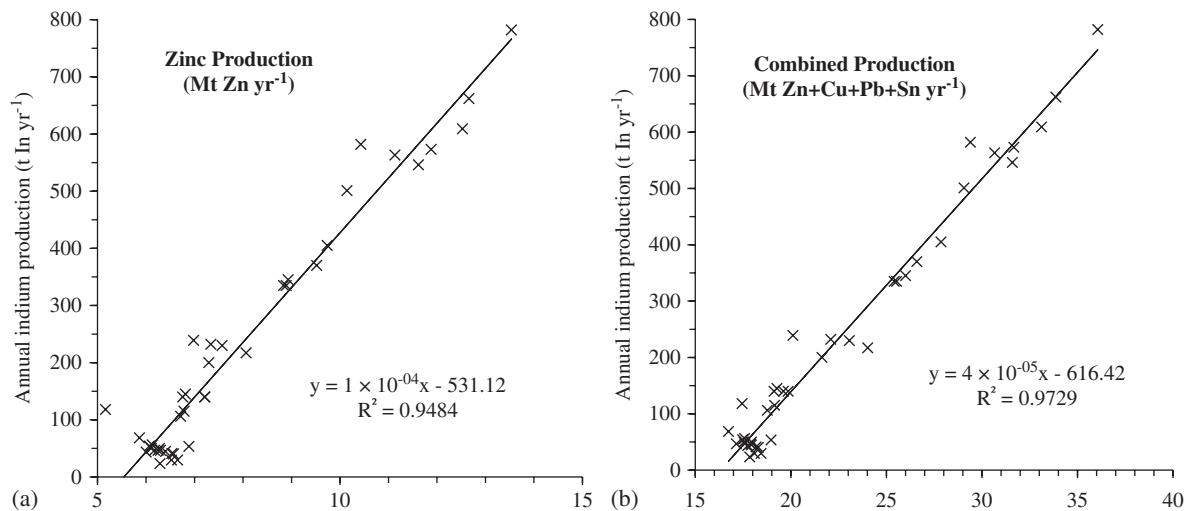
Indium most commonly combines with copper, iron and sulphur to produce roquesite (CuInS_2) and indite (FeIn_2S_4), although, as is the case for other critical metals like cobalt (e.g. Mudd *et al.* 2013b), these indium-rich minerals are of little commercial interest as they do not concentrate to form mineable deposits. Indium more typically substitutes into the structure of more common base-metal sulphide and oxide minerals such as chalcopyrite, cassiterite and stannite, and sphalerite, all of which are of significant economic interest for primary copper, tin, and zinc production, respectively (Cook, Ciobanu and Williams 2011a; Cook *et al.* 2011b). As such, in addition to being a critical metal, indium is like cobalt in that it is a 'companion' metal, as smaller quantities of indium can be isolated as a byproduct during the processing of primary copper, tin and zinc ores (Felix 2000; Graedel, Gunn and Tercero Espinoza 2014).

At present, about 95% of global indium production is derived from zinc refineries, with <5% derived from copper and tin operations (Schwarz-Schampera 2014). Figure 2 shows the strong correlations between annual indium and zinc (Fig. 2a) and combined base-metals production (Fig. 2b).

Although lead and zinc are commonly found together in mineral deposits, indium is preferentially associated with zinc (e.g. substitution in sphalerite) rather than lead (i.e. it does not substitute into galena); this is most likely because of the fact that the ionic radius of indium is similar (within $\sim 7\%$) to Zn but is dissimilar ($\sim 30\%$) to Pb (see Cook *et al.* 2011a, 2011b). This mineralogical difference means that indium therefore mostly reports to zinc concentrates (see Health Steele and Brunswick 6–12 case studies, presented in this paper) rather than any lead concentrates produced during mineral processing. This explains the strong individual correlation with zinc production; however, this does not imply that



1 Global indium production, 1972–2014 (a, USGS Var.); indium end-use statistics in the United States, 1975–2003 (b, USGS, 2005)

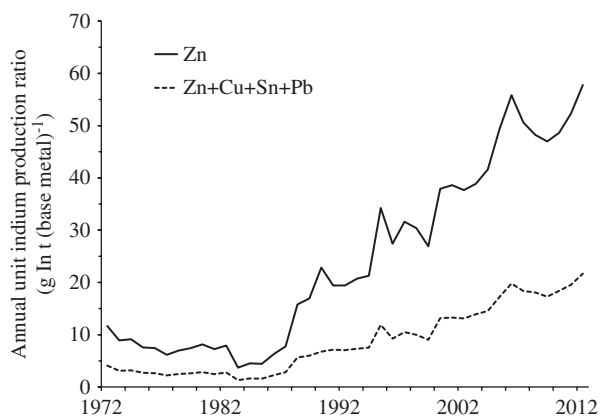


2 Comparison of global base metals and indium production from 1972 to 2012. Correlation with zinc production. a correlation with combined base-metal production; b Data compiled from USGS (Var.) and BREE (2013)

the production of other base metals can be ignored. The stronger correlation in Fig. 2b suggests that Pb, Sn and Cu are still mildly deterministic of indium availability.

It is also important to consider the behaviour of indium production within its context as a byproduct, primarily by considering changes in the amount of indium produced per tonne of base metal. Figure 3 shows that up to the mid-1980s, unit indium extraction was low and in decline, but extraction rose rapidly after this point. Thus, while Fig. 2 shows indium production strongly tied to the production of base metals, Fig. 3 indicates that by the mid-1980s, as indium became more important for new and developing technologies, distinct byproduct behaviour emerged. A breakdown of individual base-metal production in relation to indium is provided in Supplementary Material 1.

The unique behaviour of indium (at least compared to other metals) is also evident when considering rates of growth; global indium production has grown by an order of magnitude since the 1970s, whereas global zinc production, the metal most closely associated with indium (e.g. Figure 2a) has only doubled. The growth in indium production was, in fact, unequalled by any metal during this time and far outstripped the growth in the global economy itself (with 60% growth in global population and 160% growth in global GDP, Kleijn 2012, p. 95).



3 Indium produced per tonne of zinc and combined based metals (Zn, Cu, Sn and Pb) from 1972 to 2012, based on global mine production (sources: USGS Var.; BREE 2013)

Yet, the continued growth in production has been met with only marginal improvements to the efficiency of indium separation, as still today only some 20–35% of indium extracted in base-metal ores is separated during refining stages (Table 1).

The remaining indium is lost to wastes from the mining and refining industries such as tailings and slags. It should be noted that Table 1 only includes recovery from refineries and not from milling, meaning that substantial indium would also be lost to tailings (see Heath Steele and Brunswick 6–12 case studies below).

Estimates of indium waste from Zn concentrates

The substantial increases in Fig. 3 suggest not only that more zinc refineries extracted indium to meet growing demands and prices (Speirs, Gross, Candelise and Gross 2011; Schwarz-Schampera 2014) but also that there may have been a substantial quantity of indium in historical refinery slags and wastes that might be a potential future source of this critical metal (Andersson 2000; Mudd, Yellishetty, Reck and Graedel 2014). Here, the authors apply the values presented in Fig. 3 and Table 1 and produce estimates of the potential scale of waste resources from zinc processing, since the production of zinc supports approximately 95% of refined indium production.

The data in Table 1 indicate that recent indium extraction has a recovery rate of ~30–35%; this, combined with a production ratio of 57.8 g In t Zn⁻¹ for 2012 (Fig. 3), a total of 13.54 Mt Zn produced during year 2012 [Bureau of Resources and Energy Economics (BREE) 2013], a typical concentration of 50% Zn for a zinc concentrate and 90 and 70–95% efficiency of the extraction of zinc and indium from concentrates, respectively (Andersson 2000; Li *et al.* 2006), yields an average grade of indium in zinc concentrates of 107–138 g In t concentrates⁻¹. This is consistent with the expected values of 70–200 g In t⁻¹ suggested by the European Commission (2012) and Schwarz-Schampera (2014), indicating that the extraction efficiency estimates given in Table 1 are within acceptable range of present-day zinc concentrates. Applying the recovery factors of Table 1 to the production of zinc concentrates globally from 1972 to 2012 yields approximate estimates of the total indium that was extracted to zinc concentrates but

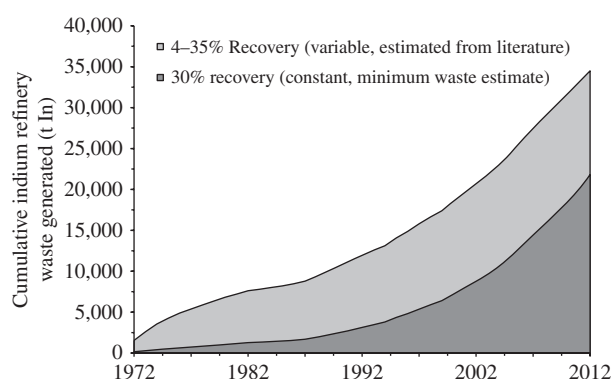
Table 1 Estimated proportions of indium in concentrates that was separated in refineries

Estimate	Source
20% for the period 1993–1997, with potential to increase up to 35–49%	Andersson (2000)
<20%, 'historically'	Phipps <i>et al.</i> (2008), p. 58
26% excluding China as at 2010	Moss <i>et al.</i> (2011), p. 61
~25% as at 2011	Tolcin (2011), p. 27
~33% as at 2011	Mikolajczak and Jackson (2011), p. 1
35% as at 2012	European Commission (2012), p. 1

not separated during this time, therefore reporting to slag wastes (Fig. 4). It should be noted that assuming already one-third of indium in ore is lost to tailings before this stage (as per case studies), the estimates for total indium waste could in fact increase by one-third above those given in Fig. 4.

The fact that a constant 30% recovery rate for the minimum estimate is generally higher than suggested in the literature (Table 1), particularly for production between 1972 and 1992, suggests that the lower bound illustrated in Fig. 4 is almost certainly a minimum estimate for the likely tonnage of indium that reported to wastes related to zinc production during this period. This conservative estimate could, in some capacity, account for the reduction in tonnage arising from previous efforts to extract indium from wastes, use of mine wastes to back-fill previous pits and/or inefficiencies experienced during their extraction. Figure 4 suggests that there are at least 21 800 t In that accumulated in zinc refinery wastes from 1972 to 2012. If the authors assume that only 25% of this is extractable because of high costs or other complexities, this quantity would still supply world demand for 2014 for 4–5 years (Fig. 6).

Figure 4 also presents a 'most likely' case, which assumes an increasing recovery yield over time, informed by linear regression of selected estimates from Table 1. In this case, some 34 500 t In accumulates from 1972 to 2012. Again, assuming only 25% of this is extractable, world demand for indium from 2014 could be met from this waste source for 6–9 years (Fig. 6). Whether or not it



4 Estimated cumulative tonnage of indium waste from zinc concentrate production, 1972–2012. Most likely estimate (light) based on linear regression of selected efficiency values presented in Table 1, and minimum estimate (dark) based on an assumed continuous rate of indium recovery from concentrates of 30%

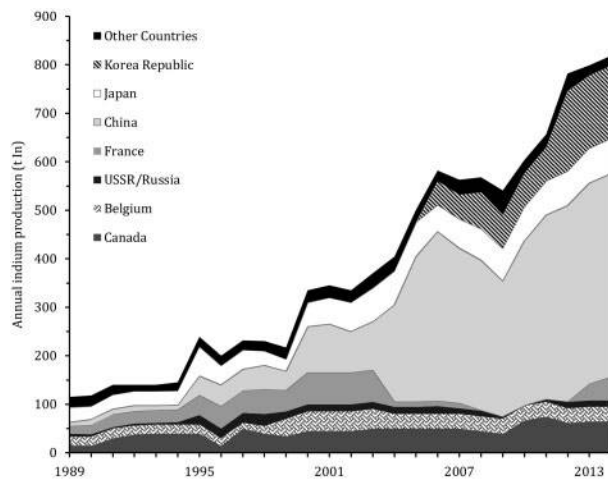
is realistic to extract companion metals such as indium from tailings and slags remains highly speculative, as it depends on a number of environmental, economic and technical factors (UNEP, *et al.* 2011a, 2011b), although any processing approach targeting the extraction of indium from mining and processing waste would also most likely target the extraction of other residual metals that are present in these waste products, providing additional streams of income that makes this approach more attractive. Although there are certainly some uncertainties relating to both the amount of indium within these wastes and the proportion of this indium that could be extracted (among other considerations), this is certainly an area that should be the focus of further research (Guézennec *et al.* 2013, Pan *et al.* 2014), and an area in which more detailed analysis is necessary. As such, the latter part of this paper provides a template by which this detail could be achieved by conducting an indium tailings resource characterisation at the per-deposit level.

Although this analysis has been restricted to zinc concentrates, this is primarily because the vast majority of indium production is a byproduct of zinc production (>95%, Schwarz-Schampera 2014); however, it should also be noted that indium is recoverable from other metal-production circuits, as has been demonstrated at the La Oroya lead refinery, Peru, Hoboken lead smelter, Belgium and from tin slag at Capper Pass, United Kingdom, among others (Felix 2000). Similar indium extraction efficiency and waste analyses are therefore possible for lead, tin and copper production and would add to the available information relating to indium resources in production wastes, but available data are insufficient for thorough analyses. An indication of the relative proportion of indium sent to various concentrate streams is provided in the Heath Steele and Brunswick 6–12 case studies.

Criticality and distribution of supply

Figure 5 depicts the per-country production of refined indium since 1989; these data indicate that global indium production is dominated by Japan, Korea and China, who produced ~9, 19 and 53% of 2013 global production, respectively (USGS 1989–2014). China produces approximately one-quarter of global lead and one-third of global zinc production (BREE 2013), indicating that Chinese indium production is consistent with the makeup of Chinese base-metal production capacity, as well as their considerable manufacturing capacity and demand for electronic goods. Authors have also provided details of the correlations between Chinese indium and base-metals production and trends in byproduct efficiency for China in Supplementary Materials 2 and 3. Additionally, potential shifts in the future distribution of indium supply is indicated in Supplementary Material 4 based on the distribution of known zinc resources.

Countries with major zinc mineral resources and/or existing zinc refineries, such as Australia, India and the USA are notable exclusions from Fig. 5. All have significant potential to produce indium as a byproduct, although this is obviously dependent on the indium content of the zinc concentrate that is being refined, something that in turn is dependent on the concentration of indium within the deposits being exploited in these zinc-production pipelines. In cases where indium is



5 World indium refinery production per country 1989–2014. Data sources: compiled from USGS (1989–2015). ‘Other countries’ include Germany, Italy, Netherlands, UK, Peru, Brazil and others. It should be noted that not all known indium refinery production is accounted for; for example, the Auby zinc refinery in France began extracting indium in 2012 (Nyrstar 2014), although this is not shown

indeed present within zinc concentrates, which is likely in Australia (DoE 2011, p. 58), the lack of any recorded indium production suggests that the cost of establishing or adapting existing zinc refineries to indium-enabled processing facilities has historically outstripped the potential profits to be made (Andersson 2000). Thus, despite the indium resource potential in countries like Australia, India and the USA, impacts on or decisions by individual organisations have so far affected the availability of indium to the global market. The influence of individual organisations was evident in the early-mid 2000s when the closure of indium refinery facilities in France and Japan took place during a time of continued growth in demand. This led to a significant reduction in global supply and subsequent spikes in the price for indium. This in turn affected indium’s accessibility to buyers, and hence its ratings of criticality. Another outcome was that, by 2007, production of indium from secondary ITO scrap had increased significantly to overtake primary production (DoE 2011).

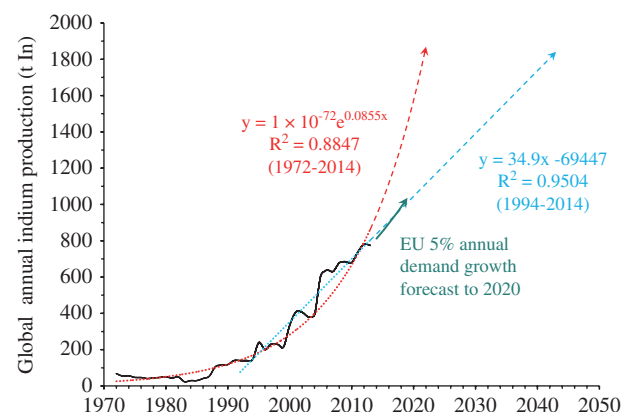
The criticality of a metal is often determined by factors of diversity of market and geopolitical stability of suppliers (Graedel *et al.* 2012), meaning that the site of indium production and the global perception of the scarcity of this metal cannot be separated. China’s known history of restricting indium exports (Schwarz-Schampera 2014), has created concern in the EU, USA, UK, Japan and Korea over the reliability of supply of this critical element, as is evidenced by their classification of indium among the most critical of commodities (Skirrow *et al.* 2013). The impact of this classification is worth considering, as criticality ratings themselves can influence decisions on whether certain metals should be relied upon for particular applications. For example, general electric considered that rhenium was a highly critical element, meaning that the company developed approaches to minimise the amount of rhenium used in their future jet engine designs (Duclos, Otto and Konitzer 2010). In addition, criticality from a national perspective also influences trade relationships, the degree to which individual countries stockpile

elements they consider critical and the exploitation (or not) of local resources of critical elements (Graedel *et al.* 2014). These factors demonstrate possible impacts to the consumption of indium arising from its criticality, although the data presented here indicate that many of these impacts and behaviours are actually based on perceptions of scarcity that are not directly related to the depletion of indium resources. While actual stock quantities have seemingly not inhibited availability thus far, much remains unclear on remaining quantities of extractable indium in base-metal deposits and the extent to which the current low extraction efficiencies can remain. The following section, therefore, presents projected trends in demand for indium and discusses the current state of knowledge on the actual global stocks of indium in extractable locations.

Projections and geological resources

Figure 6 shows extrapolations from historical indium production to indicate future demand. Exponential growth in indium production is clearly evident from 1972 onwards, although the growth in indium production can also be modelled linearly over the last ~20 years. Projecting to 2050, annual production is very likely to exceed 2000 t In per year, with cumulative production of at least 54 000 and 241 000 t In, assuming linear or exponential regressions, respectively. This projection assumes that demand remains stable; i.e., this modelling ignores a series of unknowns, including production bottlenecks, dematerialisation or substitution strategies and peak behaviour related to potential resource depletion and scarcity.

Fthenakis (2009) predicts that a peak in primary indium production is likely at some point between 2025 and 2060, with recycled sources making up a significantly greater proportion of global indium production from the peak point onwards. The USA’s Department of Energy highlights that potential price increases may stimulate both improved primary extraction efficiency and secondary recovery and reclamation, which already exceed primary sources (DoE 2011). However, these assessments still suggest that unprecedented primary production of indium will take place, which will have to



6 Historical and future indium refinery production, presented via exponential extrapolation from 1972 to 2013 data, linear extrapolation from 1992 to 2014 (USGS Var.) and projected production to 2020 responding to shorter term demand growth forecasts (European Commission 2014a, 2014b)

be met with further exploitation of geological resources, necessitating continued discovery success and possible adaptation of current zinc production pipelines to enhance indium recovery.

Selected published estimates of stocks are provided in Table 2; these represent a small sample of the many published papers and reports dealing with the concept of indium scarcity, particularly in relation to low-carbon technologies (e.g. Andersson 2000; Phipps, Mikolajczak and Guckes 2008, Murakami and Ishihara 2010; Candelise, Speirs and Gross 2012, Skirrow *et al.* 2013; European Commission 2014a, 2014b), although it is also important to note that these publications are among the few that actually present estimates of expected ore resource/reserve quantities and among the even fewer that are not simply republishing USGS estimates (Candelise *et al.* 2012), which provide limited information in terms of data provenance and reliability. Other examples that discuss the geological availability of indium in terms of crustal abundance or as inferred from trends in production have been published (Fthenakis 2009; Schwarz-Schampera 2014), but these analyses stray even further from the terminology and standards of mineral resource accounting as accepted within the mining and wider resource industry. This clearly indicates the considerable uncertainty surrounding indium resources, a factor that is evidenced by the diversity of estimates given in Table 2. The amount of extractable indium is likely to increase with time as extraction technology improves, prices increase and new deposits are found and/or become economic (as per general trends within the mineral sector; see Mudd 2010), although some of the estimates given in Table 2 are significantly lower than the amount required to meet the demand projected in Fig. 6, whereas other estimates far outstrip this increase in demand with time. This clearly demonstrates that reliance on these sources alone makes it impossible to draw a robust conclusion in terms of defining the extent to which known indium stocks will be

able to service future demands for this critical metal. The considerable discrepancy in the estimates has in fact meant that, despite the intentions of the publications listed in Table 2 and others, both the USGS (Tolcin 2014) and government agencies (e.g. Skirrow *et al.* 2013) officially recognise that accurate global estimates for indium stocks are non-existent or not available.

Interestingly, Candelise *et al.* (2012, p. 4975) also note that the USGS itself recognise that an ideal estimation process would entail 'comprehensive evaluations that apply the same criteria to deposits in different geographic areas and report the results by country', but that this would require large resources and significant international cooperation. This is supported by UNEP *et al.* (2011a, 2011b, 2012), who highlight the necessity for deposit-by-deposit analyses to provide surety of global stock estimates, yet these analyses have yet to be performed. The next section outlines the preliminary steps necessary to complete this process for indium.

Mineral resource accounting and deposit classification

This section presents a summary of indium resources within mineral deposits classified according to industry standard (e.g. JORC) procedures for mineral resource estimation and outlines a preliminary but robust approach to the development of a global database on indium deposits and resources.

Accounting by mineral resource code reports

Mineral resource reporting codes ensure that the quantities reported distinguish between what is economically extractable at a site (reserves) and what may be economic to extract in future (resources) (Mudd *et al.* 2013a; Graedel *et al.* 2014). In doing so, they encapsulate multiple factors affecting the extractability of the quantities present. These include: the local mineralogy, structural features, logistical considerations

Table 2 Selected published estimates of remaining geological indium stocks

Paper/report	Data source quoted	Indium resource estimate (t In)
United States Geological Survey: Mineral Commodity Summaries – Indium (Tolcin 2008)*	Own research	Reserves [#] : 11 000 Reserves Base [#] : 16 000
UNEP <i>et al.</i> (2011a, 2011b, 2012)	Own research	Reserves [#] : 310 000 Reserves Base [#] : 570 000
Mikolajczak and Jackson (2011)	Not specified	50 000
European Commission (2012)	Own research	12 400 reserves and 95 000 resources in zinc deposits, as at 2010
Murakami and Ishihara (2013)	(Schwarz-Schampera and Herzig 2002; Ishihara, Hoshino, Murakami and Endo 2006; Ishihara <i>et al.</i> 2011)	65 183 from 27 selected deposits (not a global resource estimate)
Schwarz-Schampera (2014)	Not specified	31 770 in known deposits 12 500 reserves and 95 000 resources in zinc deposits (total, based on 50 ppm In in deposits) 6 300 reserves and 30 000 resources in copper deposits (total, based on 10 ppm In) Total 125 000 resources and 18 800 reserves

* The USGS last reported indium reserve and reserves base for 2007, with no data since this time. The reporting of USGS estimates for reserves and reserves base are provided in Supplementary Material 5.

[#] Reserves and Reserves Base are USGS categories for classifying mineral resources, which are broadly similar to formal reporting guidelines and industry codes such as JORC, CIM Code, PERC, NI43-101, etc. For further discussion of resource reporting codes and comparisons, see Lambert, Meizitis and McKay (2009); Nickless *et al.* (2014) and CRIRSCO. (CRIRSCO is the 'Committee for Mineral Reserves International Reporting Standards' and was established in 1994 as a global effort to harmonise mineral resource reporting codes.)

and access to technology and expertise within the organisation implementing the resource assessment. Errors pertaining to the exclusion of these factors can be further magnified at national or global scales, as has been shown in previous resource accounting studies (e.g. Mudd *et al.* 2013a; Mudd and Jowitt 2014).

Table 3 provides a summary of global indium deposits reported using the JORC (Australian) and NI 43-101 (Canadian) codes. These data indicate that 6051 t In is present within code-based resources associated with these 10 deposits alone, one of which is, rather unusually, a slag waste deposit (Zeehan, Tasmania, Australia). The small number of listed deposits reflects the small scale of the indium market in value terms, in comparison to other metals, as well as a certain bias towards countries likely to employ the use of these types of code-based assessments. However, these data suggest that it is possible to use a select handful of well-classified deposits to obtain *in situ* values for In to give an indication of the potential scale of global resources when considering the size of the host base-metal resources (e.g. zinc, copper, tin, etc.).

No Chinese deposits are present within Table 3, primarily as Chinese data are not readily available and public reporting of mineral resources in China is primarily performed at the provincial or national level by geological survey groups (e.g. Ziran, Qihai, Haiqing and Xiaobo 2012, although this report lacks indium data). However, this is beginning to change as more Chinese mining companies begin to operate internationally and global efforts to harmonise mineral resource reporting codes through CRIRSCO continue. Zheng (2011) estimated that Chinese reserves were in the order of 12 000 t In for 2011.

Although our compiled data are up to date in terms of publicly available information, they certainly highlight that more work is required to determine resource estimates from deposits where code-based tonnage and grades of base metals are known, but indium grades (i.e. g In t⁻¹) are not, usually as a result of the company involved not having or not releasing the data. One possible method to address this is to statistically infer grades using the known range and average indium grades for differing deposit types to determine an average grade for that type. Indium grades are available through high-quality information such as JORC and NI43-101/CIM Code reporting but are also available in lower quality form through published geological field studies such as Tong, Song, He and Lopez-Valdivieso (2008) and Cook *et al.* (2011a, 2011b); this is not to say that the data presented in the latter type of study are of lower quality, but rather it is unclear how representative these data are within sections of or within entire mineralising systems, such as those defined by formal code-based resource reporting. Other possible methods include statistical determination of indium grades using relationships with the base metals present within the same orebody, or analysis of processing behaviour in order to backtrack from production statistics to ore grades, as was briefly discussed above where concentrate grades were inferred from production ratios. These approaches would enable better estimates of the size of the potential orebodies containing indium and therefore allow more robust estimates of global indium mineral resources. This is the focus of current research by the authors of this paper.

Indium-associated deposit types

Indium is known to be present in a variety of different mineral deposit types, especially (as discussed above) those hosting Zn, Cu, Pb and Sn mineralisation with minor amounts of cadmium, silver, gold and bismuth also potentially present. Here, the authors summarise the key deposit types associated with indium, briefly describing the processes by which they form and their significance to global indium resources. Although the presence of indium has been identified in other deposit types (e.g. the Axial Seamount active seafloor hydrothermal vent site in the Northeast Pacific, see Schwarz-Schampera 2014), this section focuses on the main base-metal deposit types that currently appear to contribute the bulk of identified indium resources. A clear definition is necessary for these deposit types, if statistical inferences of indium grade are to be applied in future research that goes one level beyond that of attempts to determine an average content in, for example, 'zinc ores' (e.g. Schwarz-Schampera 2014).

Sediment-hosted Pb–Zn

These deposits are sediment-hosted, have Pb and/or Zn as their primary commodity and, in many cases, represent orebodies that have no direct genetic relationship to igneous activity (Leach *et al.* 2005). These deposits can in most cases be further categorised into the subsidiary classification of sedimentary exhalative (SEDEX) deposits or Mississippi Valley-type (MVT) deposits; however, a number of other classifications exist, including sub-types that include carbonate replacement, Irish-type and Broken Hill-type mineralisation (Leach *et al.* 2005, 2010). Broadly speaking, SEDEX deposits are dominated by Zn–Pb mineralisation with lesser amounts of Cu and commonly with Ba and Ag and form by the venting of hydrothermal fluids onto the seafloor or the replacement of existing sediments by these same hydrothermal fluids. These deposits form at lower temperatures than volcanogenic massive sulphide (VMS) deposits, primarily as the latter are directly linked to magmatism and/or volcanism, whereas the former do not have any clear genetic link to igneous activity (e.g. Leach *et al.* 2005; Robb 2005). In comparison, MVT deposits form as a result of the circulation of high-salinity and relatively low temperature (compared to, e.g. VMS systems) basinal or connate fluids during the diagenesis of sediments in sedimentary basins (e.g. Robb 2005). The deposition of metals in MVT systems is generally restricted to the sedimentary sequences that host the fluid flow.

For the purposes of mineral resource accounting, Mudd *et al.* (2013a) sub-categorised sediment-hosted Pb–Zn deposits exclusively to SEDEX and MVT because of the often limited amount of available information in industry technical reports. In terms of commodities, SEDEX and MVT deposit types are dominated by Pb and Zn, with Leach *et al.* (2005) indicating that these deposits are also important sources of Ag and Cu, and often produce byproduct Mn, Tl, As, Ba, Bi, Ge, Hg, Ni, P and Sb. The Zn-rich nature of these deposits also indicates that these deposit types are an important source of In, as evidenced by the relationship between Zn and In discussed above. This, combined with the substantial quantity of indium within the sediment-hosted Pb–Zn deposit at Malku Khota,

Table 3 Summary of deposits with code-based reporting of indium quantities

Mine name and location	Resources Mt	Reserves Mt ore	Total Mt	Grade g In t ⁻¹	Total In t In	Zn%	Sn%	Cu%	Pb%	Ag g t ⁻¹	Au g t ⁻¹	Res. code	Deposit type	Indium mineralogy	Primary commodities
Maliku Khoia, Bolivia	485	–	485	5.01	2431	0.05	–	0.02	0.07	23.71	–	C	Sed-Pb-Zn	Jam, owy	Zn, Ag, Pb, Cu
West Desert, UT, USA	59.0	–	59.0	25.98	1533	1.85	–	0.22	–	–	–	C	Skarn	Sph	Zn, Cu
Mount Pleasant (North Zone), NB, Canada	15.2	–	15.2	64.7	983	0.91	0.37	–	–	–	–	C	Gran-rel	Stn, sph and others	Zn, Sn
Geyer Southwest, Germany	12.6	–	12.6	35	439	0.58	0.46	–	–	–	–	A, C	Skarn	Sph	Sn, Zn, Ga
Keg (Main Zone), YT, Canada	39.8	–	39.8	5.77	229	0.77	0.03	0.15	0.26	30.25	–	C	Sed-Pb-Zn	Sph, op	Zn, Sn, Ag, Pb, Cu
Baal Gammon, QLD, Australia	2.80	3.11	5.91	33.7	199	–	0.2	0.98	–	36.95	–	A	Skarn	Sph, op	Sn, Ag, Cu
Pingüino, Argentina	10.6	–	10.6	11.5	122	–	–	–	0.62	62.87	0.38	C	Epi	Sph, op, stn	Ag, Au, Pb
Brunswick 12, Bathurst, NB, Canada	0.79	0.73	1.52	48.75	74.1	7.6	–	0.34	3	92	–	C	VMS	Sph, op	Sn, Ag, Pb, Cu
Zeehan (Slag), TAS, Australia	–	–	0.46	48	22.0	13.6	–	–	1.5	55	–	A	Slag	Slag	Zn, Ag
Conrad & King, Conrad, NSW, Australia	2.65	–	2.65	6.8	18.0	0.53	0.22	0.2	1.33	105.3	–	A	Skarn	Sph, op, gal, cas, stn	Zn, Sn, Ag, Pb, Cu
Total	628	4	633		6051										

Resource code: A = Australian Joint Ore Reserves Committee (JORC) resource code; C = Canadian National Instrument 43–101 (NI 43–101) resource code. Deposit Type: Sed-Pb-Zn = Sediment-hosted Lead-Zinc, Gran-rel = Granite-related, Epi = Epithermal, VMS = Volcanogenic massive sulphide. Indium mineralogy: jam = jamesonite, owy = owyheeite, sph = sphalerite, stn = stannite, op = chalcopyrite, gal = galena, cas = cassiterite.

Bolivia (Table 3) suggests that indium should also be added to this list of important byproducts.

Granite-related

Granites are coarse-grained igneous rocks formed from highly evolved magmas that are generally the result of extreme fractionation of mafic magmas, the anhydrous melting of the lower crust (e.g. during mantle plume-related underplating) or the melting of igneous or sedimentary rocks during metamorphism. The fine-grained equivalents of granites are termed rhyolites, which are either erupted or intruded near the Earth's surface and are compositionally identical to granites. Both granites and rhyolites are important sources of companion metals (e.g. Weng, Jowitt, Mudd and Haque 2014, 2015), and are known to host indium mineralisation (e.g. Andersen, Stickland and Rollinson 2014; Simons, Andersen and Shail 2013) although the overall current and potential future contribution to global indium supplies is currently unclear. The most significant granite-related indium deposit thus far identified is the Mount Pleasant deposit, New Brunswick, Canada, containing over 983 t In (Table 3), although undoubtedly other granite-related indium mineralisation is yet to be identified or fully quantified.

Volcanic-hosted or volcanogenic massive sulphide (VHMS/VMS)

Volcanogenic massive sulphide deposits are major contributors to global base-metal supplies, for example, hosting over 31.56 Mt Cu (Mudd *et al.* 2013a), as well as significant quantities of Zn, Pb, Ag and Au resources. They form via the discharge of hot, metal-rich hydrothermal fluids that source metals by interaction between modified sea water and source rocks such as epidiosites (e.g. Jowitt, Jenkin, Coogan and Naden 2012); these metal-rich fluids then precipitate massive sulphides at or near the seafloor in submarine volcanic environments (Allen and Weihed 2002). Although the focus of this paper is not to provide a detailed explanation of these mineral systems, it is worth noting that Galley, Hannington and Jonasson (2007) highlight that the polymetallic nature of VMS deposits means that although they are often smaller (but higher grade) than, e.g. porphyry deposits, they are resistant to fluctuations in the prices of different metals, making them economically attractive and hence more likely to provide base-metal concentrates from which indium may be extracted. The high metal tonnages and grades of VMS deposits make them particularly relevant to indium mineral resource accounting. Indium concentrations vary considerably in VMS deposits (1–320 g In t⁻¹, data in preparation).

Epithermal

Epithermal mineral deposits form within generally sub-aerial hydrothermal systems driven by magmatic heat sources at temperatures <300°C and at depths up to 1.5 km below the water table (Simmons, White and John 2005; Tosdal, Dilles and Cooke 2009). These types of deposit form within shallow parts of hydrothermal systems, usually within volcanic arc settings, and may form parts of larger co-genetic epithermal–porphyry–skarn systems (e.g., Jowitt, Mudd and Weng 2013). Epithermal deposits can be enriched in a wide range of

metals, most commonly Au and Ag, but (importantly for indium) may also contain Zn, Cu, Pb, As, Sb and Sn (e.g., Simmons *et al.* 2005). Epithermal deposits can be broadly split into low, intermediate and high sulfidation types according to the oxidation state of sulphur in the ore fluid, which also reflects the pH of the system (Hedenquist, Arribas and Gonzalez-Urien 2000); the most important of these, in terms of indium resources, is likely to be intermediate sulfidation type epithermal systems that are associated with Pb and Zn mineralisation, although this does not rule out the presence of indium within other types of epithermal systems. This uncertainty highlights the need for more research in this area.

Skarn

Skarns form during interaction between wall rocks and magmato-hydrothermal fluids derived from plutons and associated deeper magma chamber systems (Einaudi, Meinert and Newberry 1981; Meinert, Dipple and Nicolescu 2005), generally form during contact metamorphism and by a variety of different metasomatic processes (Meinert 1992; Meinert *et al.* 2005). These types of mineral deposits are generally associated with and can form beside or within magmatic plutons and, as mentioned above, may be genetically related to porphyry and epithermal deposits within larger magmato-hydrothermal systems, although this is certainly not always the case. Skarn mineral deposits host a wide variety of metals including W, Sn, Mo, Cu, Fe, Pb, Zn, Au, Ag, Bi, Te and As, with the metals present within a given skarn dependent on differences in composition, oxidation state and the metallogenic affinity of the pluton (e.g., Einaudi *et al.* 1981). Of these different types, it is thought that Zn, Sn and Cu skarns are probably the most important for In mineralisation, as exemplified by the Dachang and Geiju skarns in China, although again more research is required in this area.

Slags

Although they are not naturally occurring, slags represent an important class of anthropogenic mineral deposit type that may be an important future resource of critical metals such as indium. The physical composition of slags is highly dependent on metallurgical processes from which they are derived. In some cases, they are viewed as secondary resources rather than end wastes, although their heavy metal content is often of environmental concern and conventional disposal often entails dumping. This, however, makes them an attractive source of metals, if their removal results in net reductions to local pollution (Shen and Forssberg 2003). At present, the Zeehan resource in Tasmania, Australia is the only known instance of code-based reporting of slag-hosted indium resources. It is somewhat surprising that the In grade of the resource has been reported, given that the quantities shown in Table 3 suggest that the value of indium within the slag represents only about 1% of the total value of the contained metals within the resource, with the majority of the value coming from zinc (~13% of the total resource value) and silver (~84%), although this is obviously somewhat controlled by the prevailing metal prices.

Indium from mine waste: case studies in Canada

In Fig. 3, it was shown that the production of indium per unit of base-metals has increased substantially in recent decades; however, it was discussed that the economics of indium extraction and processing still leads to extensive wastage. In the previous section, the authors also discussed the need for an exhaustive assessment of indium stocks on a per-deposit basis. Here, two case studies are presented that combine these concepts to identify the potential accumulation of indium resources in the wastes of individual zinc operations in Canada. This was achieved through an analysis of past production, deportment and tailings data, which were available at the Heath Steele and Brunswick 6–12 deposits.

Heath Steele and Brunswick 6–12 are both VMS deposits with indium mineralisation associated with sphalerite and chalcopyrite and produced Zn and Cu concentrates throughout periods of considerable growth in indium demand, but without reported indium production. Theoretically, the quantities of indium not transported to product concentrates from base-metal mining and refinery operations should still reside within the host deposit, or appear in tailings (see Chen and Petruk 1980; Petruk and Schnarr 1981). While it is recognised that the extraction of metals from tailings leads to economic and technical complexities that the market may yet to be properly prepared for (Speirs *et al.* 2011), our analysis is not aiming to present an economic case, but rather to identify the potential quantities of indium that could contribute to future supply as conditions become more favourable for extraction.

Table 4 shows how the indium that is present in the milling feed apportioned to various processing streams at the two sites.

The deportment values shown are representative of the production characteristics at the time of sampling (August to September, 1977), meaning that a number of local factors arising from mining different parts of the orebody and changes in technology are likely to affect where and how indium was apportioned to processing streams over time. These potential changes were monitored by tracking ore grades throughout the life of both mines; these data indicate that the base-metal grades at the time of sampling were approximately 9 and 40% below the all-time average at Heath Steele and Brunswick 6–12 mines, respectively, suggesting that our estimates of total indium content are conservative. It should also be noted that Table 4 lists grade and percentage apportionments, meaning that the estimation of process stream indium quantities can be

calculated in two ways: as a fraction of what was fed into the mill, or as a fraction of the tonnage of each stream itself.

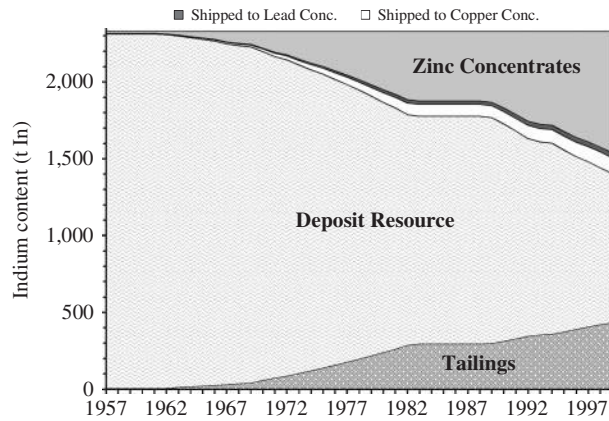
Data for both sites were collected on the quantities of concentrates and product metals produced each year from each mine and were primarily sourced from the Canadian Minerals Yearbook [Energy, Mines, Resources (EMR) 1975–1982], in addition to datasets compiled from Mudd (2009). Where concentrate production data were not reported, the average content of base metals in concentrates from reported years was used to interpolate or extrapolate for concentrate quantities for unreported years. Resource estimates from various years were obtained from a review of processing and geological literature, allowing an original indium quantity known to exist in the deposit at a given year to be used as a reference (Chen and Petruk 1980; Schwarz-Schampera and Herzig 2002, Xstrata 2013). This in turn allowed values from Table 4 to be used to develop the material balance analyses shown in Figs. 7 and 8.

The effect of mining almost the entirety of economically extractable orebodies at Brunswick 6–12 from 1964 onwards has resulted in a significant accumulation of indium (over 3500 t of contained indium metal) in the tailings at the site (Fig. 8). In comparison, the Heath Steele orebody contained ~1,000 t In at the time of closure of the mine with a further ~400 t In in tailings (Fig. 7). Comparing these data with Fig. 4 shows that the indium contained within the tailings of these two sites alone contributes over 10% of the estimates for indium in zinc processing wastes globally. Besides highlighting the conservative nature of that analysis, these case studies suggest that, if all base-metal deposits with indium mineralisation were to be the subject of individual assessments like the ones presented, global estimates of indium stocks could increase enormously, and hence substantially alter perceptions of global indium scarcity.

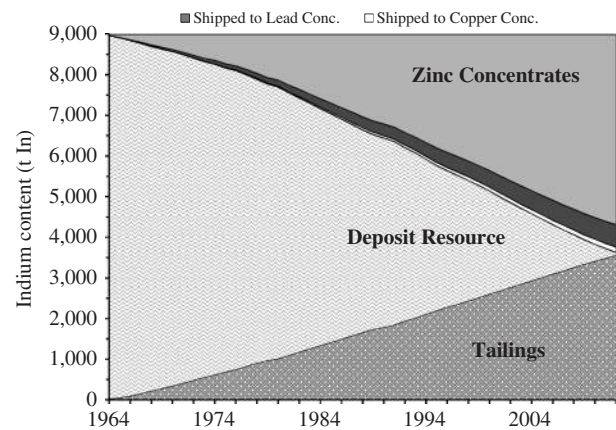
Naturally, it remains to be seen whether the extraction of metal from tailings at Heath Steele, Brunswick 6–12, or indeed tailings generally, represents a more attractive option for future indium supply. Tailings may, in some instances, be used to back-fill mines, making them less accessible and hence further complicating the extraction process. In addition, although the economics of tailings extraction is extremely important in terms of determining the availability of indium, this is beyond the remit of this paper, which aims to simply highlight the enormous size of the potential indium resources available within mine wastes.

Table 4 Measured concentrations and deportment of indium in process streams at the Heath Steele and Brunswick 6/12 mines, adapted from Chen and Petruk (1980) and Petruk and Schnarr (1981)

Process stream	Heath Steele		Brunswick 6–12	
	In grade (ppm)	% Apportionment	In grade (ppm)	% Apportionment
Milling feed	50	100 (feed)	49	100 (feed)
Cu concentrate	200	10.51	76	0.7
Pb concentrate	40	2.3	57	6.7
Zn concentrate	400	51.43	220	58.9
Secondary Zn concentrate	–	–	220	2.7
Bulk sulphide concentrate	–	–	166	2.7
Tailings	20	35.75	30	28.3



7 Indium stocks at the Heath Steele deposit, New Brunswick, Canada from 1957 to 1999



8 Indium stocks at the Brunswick 6–12 deposits, New Brunswick, Canada from 1964 to 2012

Urban mining and end-of-life recycling

In recent years, increasing emphasis has been placed on the concepts of the 'urban mine' and a 'closed-loop' or 'circular' economy, whereby the supply of materials comes from the extraction and reuse of urban material stocks, to the point that traditional mining practice becomes largely obsolete (Brunner 2011). In the case of indium, a closed-loop economy would require that discarded products such as smartphones and decommissioned solar arrays become a central source of supply. Measures to 'close the loop' on indium may contribute to significant improvements in its long-term environmental sustainability (Graedel and Allenby 2010), and so, given the unprecedented quantities in which it is produced at present (Fig. 1), it is worth considering the potential scale of urban indium stocks to see if this is indeed feasible. It has been estimated that currently <1% of global indium supply comes from EOL recycled materials, and 25–50% from recycled scrap produced during manufacturing (UNEP *et al.* 2011a, 2011b, 2012), suggesting that there is at least some potential for improvement in this space.

Using Australia as a case study, it is estimated that 23.5 million old and unused phones sit within homes and workplaces (Mobile Muster 2014). With 1 t of mobile phones estimated at 13 000 units (Hagelüken 2014), this equates to approximately 1808 t of waste. 'Display waste' is said to contain 174 g In t^{-1} (Buchert, Manhart, Bleher and Pingel 2012), meaning that only approximately 0.3 t of indium could be found, assuming all this stock did in fact contain LCDs. While a number of other sources have not been included in this calculation, for example, indium contents in computers, notebooks, tablets and TVs, as well as any other consumer goods that have been sent to landfill, these quantities are clearly not sufficient to economically outperform traditional mining practices, or even extraction from mine wastes, as the potential resource from a single mine is orders of magnitude higher (e.g. Figure 8).

Geyer and Doctori Blass (2010) assessed the economics of mobile phone recycling and found that the recovery of materials other than the current suite of precious metals and copper would in fact not increase profit margins for recyclers, suggesting that the value of indium is not likely to significantly affect the likelihood of large-scale recovery from phones. More generally, urban mining has

been known to face institutional and governmental challenges, as significant economic changes are likely to be necessary to facilitate a transition, and notable discrepancies have been found in terms of subsidies for the mining and recycling industries, despite the apparent benefits of recycling (Johansson, Krook and Eklund 2014). This is particularly true for Australia, which lacks facilities for e-waste collection, faces unique challenges because of distance and transportation and lacks integrated smelter capacity (Khaliq, Rhamdhani, Brooks and Masood 2014). If Australia is to develop this infrastructure, it must further overcome the scarcity of available data on future quantities and physical compositions of products like EOL LCD screens (Salhofer, Spitzbart and Maurer 2011). Should these data become available, there are still numerous technical challenges because of the low concentrations and physical complexity of indium in some electronic products (Gotze and Rotter 2012).

Yet, the future of EOL recycling of indium is not entirely bleak. There are significant drivers leading towards increased metallurgical recovery from waste electrical and electronic equipment (WEEE) globally. These include:

- Concern over the toxicity of electronics in landfills (Cui and Zhang 2008);
- Conventional mining systems themselves facing a number of challenges, including trends of declining ore grades and hence increasing mine wastes and energy consumption (Prior, Daly, Mason and Giurco 2013);
- Exponential growth in demand for consumer electronics and hence their contained metals, combined with decreased efficiency of materials use, contributing to greater waste volumes (UNEP 2013); and
- Increasing focus on critical metals contained in WEEE including palladium, tantalum, cobalt, rare earths and others (Manhart, Buchert, Bleher and Pingel 2012), as well as gold and silver, which contain most of the monetary value of WEEE and can, therefore, drive improved collection and metallurgical recovery from WEEE independent of indium prices. The increased focus on critical metals is also likely to foster increased incidences of stockpiling to ensure stability of supply (Hagelüken 2014).

Additionally, the EU has established an enhanced landfill mining project linked to their landfill directive, which entails specific performance targets (European

Commission 2014a, 2014b), suggesting that there is precedence for overcoming the aforementioned institutional and governmental challenges. Also within the EU, there are indeed examples of economically viable e-waste collection facilities, which extract and sell indium (e.g. Umicore, Hoboken, Belgium, Rombach and Friedrich 2014). Comprehensive economic evaluations and feasibility studies for large-scale urban mining in Australia are yet to be completed, although this process is known to be under way (CSIRO 2014). It has been recognised that a key part of this will be to understand the stocks and flows of metals, which is where the authors believe that the methods outlined in this paper have the potential to make a significant contribution. Case studies have been identified, which track EOL flows of indium and other critical metals in individual product waste streams (e.g. Zimmermann and Gößling-Reisemann 2014), although a comprehensive analysis of Australia's total endowment of indium (and other companion metals) in mineral resources and urban stocks remains a significant gap in knowledge if the potential wealth from companion metals is to be further capitalised upon. This is anticipated to be the subject of future work by the authors of this paper.

Conclusion

This paper has provided:

- A preliminary analysis of global indium resources based on a summary of its reported presence in individual deposits.
- Estimations of indium resources in tailings and slag wastes through analysis of past company, national production and indium department datasets.
- A summary of indium-associated deposit classifications.
- A discussion of the potential for supply from recycled products.

It was found that:

Based on the limited code-based reporting of indium resources, a geological resource of this critical metal is likely to exist that is capable of meeting demand well into the twenty-first century, though further research is necessary to estimate precise resource quantities.

The economic factors controlling indium extraction and processing have led to significant wastage in the past, and, given the substantial quantities calculated, it will be important to consider mine wastes as a major contributor to future supply.

There is some potential for indium supply from EOL electronics given expected increases in WEEE quantities and potential price, though significant governmental, institutional and technical challenges must first be overcome.

The concepts and procedures presented in this paper will form the basis of future work in the fields of mineral resource accounting and material flow analysis for companion metals in Australia and globally.

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