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Modelling metal flows in the Australian economy

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ABSTRACT

The modelling of metal flows provides a comprehensive picture of metal use in the economy and allows for effective investigation into barriers and enablers to increase the recycling rates. In the export-oriented economy, such as Australia, the modelling requires clearly distinguishing the cycles within and outside of a country, and needs an adequate metrics to assess the country's targets in "closing the material loop". This article investigates Australian position in the global cycles of metals production and use, and assesses the potential for circularity of metals within the country based on data from 2002 onwards. The analysis shows that over the period from 2002 to 2011 the overall estimate of metals final consumption grew from 8.8 million tonnes to 12.3 million tonnes, or from 445 to 551 kg per person. Similarly, the amount of generated waste metal is estimated to have grown from approximately 5 million tonnes to 6 million tonnes, or 250–270 kg per person respectively. The amount of collected metal scrap grew from 3.3 Mt to 3.9 Mt, with the overall collection rates being relatively stable at about 70%. However, the domestic processing of collected scrap decreased significantly – from 67% in early 2000s to 41% in early 2010s, while the export of scrap increased accordingly. The current levels of waste metal generation, metal scrap collection, and domestic processing of metal scrap in Australia equal approximately 50%, 35%, and 15% of the country's metals final consumption respectively.

1. Introduction

The Australian economy is one of the fastest growing among developed countries (OECD, 2014), allowing for higher individual incomes, consumption rates, and overall standard of life. This also means a higher level of urban stocks and waste generation, representing good potential for recycling and transition to a circular type economy. The accumulated stocks of metals in modern economies are estimated at around 10–15 tonnes per citizen, being more than 98% represented by five metals – iron, aluminium, copper, zinc, and manganese (UNEP, 2013). The same five metals represent more than 99% of Australia's metal export flows (weight based), and together with gold, nickel and lead, these metals form more than 98% of the country's metal export revenue (BREE, 2014).

The closed loop economy model actively promoted internationally presupposes predominantly cyclical use of metals within the system (Ellen Macarthur Foundation, 2012; World Economic Forum, 2014). It is however economically impractical to limit the system to national or regional borders, but should be considered achievable on a global scale. This means that some countries may need to play the role of net providers of primary (mined) material resources, while others could play key role in supplying secondary resources and recycling.

The investigations of metal cycles in the economy are usually metal and region specific. In this article we focus on Australia, and overview combined major (by weight) metal flows, including iron and steel, aluminium, copper, zinc, manganese, chromium, lead, and nickel over the period from 2002 to 2013. The main aim of the paper is to identify the Australia's position in the global cycles of metals production and use, provide recommendations to enhance recycling of metals within the country and overview potential pathways to a circular economy model in an Australian context.

2. Metal flows modelling and previous studies on metal flows in Australia

In general terms, the flow of metal in the economy starts from mineral extraction, goes through several stages of transformation (such as processing, refining, fabrication, and manufacturing), includes product use in the economy (consumption), and ends up with product disposal, or recycling of metal for the next cycle. Export and import flows of minerals, refined metals, and

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manufactured products also play a significant role in estimating material flows, and often require a separate investigation. The material flow analysis techniques are usually employed to represent the circulation of specific material in the economy (Rogich and Matos, 2008; UNEP, 2010). A simplified model of metal circulation in the economy is presented in Fig. 1.

Metal production and direct shipments are usually well recorded through national and international statistics allowing for the estimation of apparent consumption of major metals in the economy, equal to metal production plus direct metal imports less direct metal exports as illustrated in Fig. 1. The true metal consumption in the country, however, may be significantly higher or lower than the apparent consumption, as it also takes into account all indirect import and export flows, where metals are associated with fabricated and manufactured goods, e.g. preassembled construction structures, engineering equipment, vehicles, and consumer products. The true metal consumption and in-use stocks are not easy to estimate; this requires additional investigations, often relying on multiple assumptions and expert opinion as the data associated with these flow are not typically recorded. The challenges with selecting reliable and consistent data sources, appropriate geographic boundaries, representative product categories to estimate the metal content, and assumptions on missing data result in considerable differences in these estimations if based on the outcomes from a range of different studies (Pauliuk et al., 2013).

The detailed information on metal cycles in the economy is relatively limited worldwide (UNEP, 2010). World historic flows of selected technological metals were investigated in the Yale University stocks and flows (STAF) project, which included analysis of country level details for iron and steel (Wang et al., 2007), copper (Graedel et al., 2004), zinc (Graedel et al., 2005), lead (Mao et al., 2008), nickel (Reck et al., 2008; Reck and Rotter, 2012), chromium (Johnson et al., 2006), and silver (Johnson et al., 2005) as shown in Table 1. The Australian focused study was performed only for copper and zinc (van Beers et al., 2007). Data on iron and steel, and aluminium flows are available from international reports, e.g. of World Steel Association (Worldsteel, 2013) and International Aluminium Institute (www.world-aluminium.org), and relevant parts of this data were considered representative of the Australian situation for this study. These reports are usually regularly updated and provide the most recent information, while academic investigations are static and quite quickly become outdated. A summary and overview of recent studies and models used for metal stocks and flows modelling can be also found elsewhere (Chen and Graedel, 2012a; Müller et al., 2014).

Most studies listed in Table 1 cover all major stages of metal circulation – from mining to recycling. However, only a few of them include a deeper investigation into the sectoral structure of metal end use, in-use stocks, and waste metal generation. There have been no publically available studies on the analysis of combined metal flows for Australia that provide a comprehensive picture of metal circulation in the Australian economy.

3. Metal flows in the Australian economy

The major metals by weight used within modern economies include six metals – iron, aluminium, copper, zinc, manganese, and lead (UNEP, 2010). The statistics on iron and steel often accounts for major alloying elements (e.g. manganese, chromium, zinc, and nickel), as do the statistics on aluminium (e.g. manganese, zinc, and magnesium). Considering only metals in metallic rather than a minerals form, eight metals – iron, aluminium, copper, zinc, manganese, chromium, lead, and nickel – represent more than 99% of overall metal flows and in-use stocks in the economy. Therefore, in this investigation, we mainly focus on these metal streams.

The national statistics in Australia is primarily reported on a financial year basis (which runs from July to June), while international statistics is on a calendar year basis. This represents an additional challenge in compiling the datasets from the quarterly or monthly reports. For estimations in this paper we predominantly use the quarterly reports from the Australian Bureau of Statistics (ABS) and Bureau of Resources and Energy Economics (BREE) to get the data based on calendar year.

3.1. Metal mining and processing, and metal export and import

The abundance of natural resources and the relatively low population has predetermined the role of Australian economy on the global market as a resources supplier as illustrated in Fig. 2. Metals and metal concentrates currently deliver the country's main export revenue (A$b 113 in 2013), followed by energy resources such as coal, natural gas and uranium (A$b 68) (BREE, 2014). More than 90% of minerals mined in Australia are directly exported; for metals and metal concentrates this figure is close to 98% (BREE, 2014). In 2013, Australia exported 700 million tonnes of metallic minerals (contained about 400 million tonnes of recoverable metals) (Fig. 2). Some metals are primarily exported as concentrates (e.g. iron ore, bauxite and alumina, copper, zinc, lead, manganese), while others in the form of refined metals (e.g. nickel, gold, silver) or chemicals (e.g. titanium dioxide pigment).

The mining of metallic minerals in Australia is driven by iron ore, bauxite, and manganese ore (Fig. 2); the country covers about 20% of world needs in these metals (BREE, 2014). Australia is also one of the leading producers of zinc, copper, lead, gold and nickel.

In 2013 the mining output in Australia was more than 50 times that of refined metals – refer to Figs. 2 and 3 – and was mainly for export (Fig. 4). For smelting operations, the steel industry is equally oriented on domestic and international market, while the refined aluminium, zinc, copper, lead and nickel are also mainly exported – refer to Figs. 3 and 5. As shown in Fig. 5, Australia roughly exports

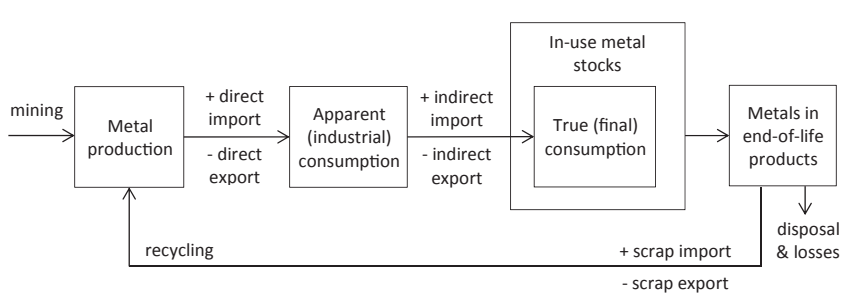

Fig. 1. Estimation of metal use in the economy.
Source: Corder et al., 2015.

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Table 1
The scope of selected studies on metal cycles in Australia.

Metals covered	Base year	Reference	Stages covered					Sector split		
			Mining	Smelting	F&M	Waste metal	Recycling	End use	In-use stocks	Waste metal
I. Australia focused studies										
Zinc	1994	(van Beers et al., 2004)	+	+	+	+	+	+	−	+
Copper and zinc	2000	(van Beers et al., 2007)	−	−	−	+	+	−	+	+
II. International studies (with countries details)										
Iron and steel	2000	(Wang et al., 2007)	+	+	+	+	+	+	−	+
	2008	(Pauliuk et al., 2013)	−	−	−	−	−	−	+	−
	2003–2012	(Worldsteel, 2013)	+	+	+	−	−	−	−	−
Aluminium	2008	(Liu and Müller, 2013)	+	+	+	+	+	−	−	−
Copper	1994	(Graedel et al., 2004)	+	+	+	+	+	−	−	+
Zinc	1994	(Graedel et al., 2005)	+	+	+	+	+	−	−	+
Lead	2000	(Mao et al., 2008)	+	+	+	+	+	+	−	−
Nickel	2000	(Reck et al., 2008)	+	+	+	+	+	+	−	−
	2005	(Reck and Rotter, 2012)	+	+	+	+	+	+	−	−
Chromium	2000	(Johnson et al., 2006)	+	+	+	+	+	−	−	−
Silver	1997	(Johnson et al., 2005)	+	+	+	+	+	+	−	−

twice as much refined metal as it imports. Overall Australia is a significant net exporter of metals.

The metal production and direct shipments, recorded through national and international statistics, allow for estimation of the apparent (industrial) consumption of major metals (Fig. 6). The latter gives an estimation of metals use within domestic manufacturing (and construction) sectors. There was an increase in apparent consumption from 2002 to 2008, however in the recent years (2010–2013) the declining tendency has clearly prevailed. As a result, the total apparent consumption of metals increased from about 6 Mt in in early 2000s to more than 9 Mt in 2008, and then dropped back to 6 Mt in 2012–2013. The per capita apparent

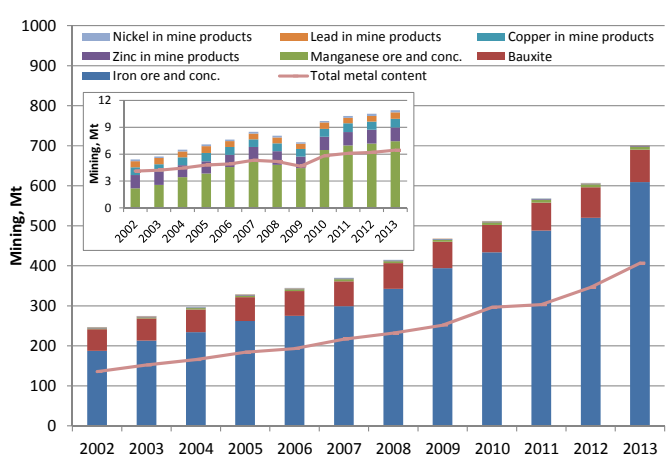

Fig. 2. Australian mining and minerals production statistics.
Data source: BREE, 2014.

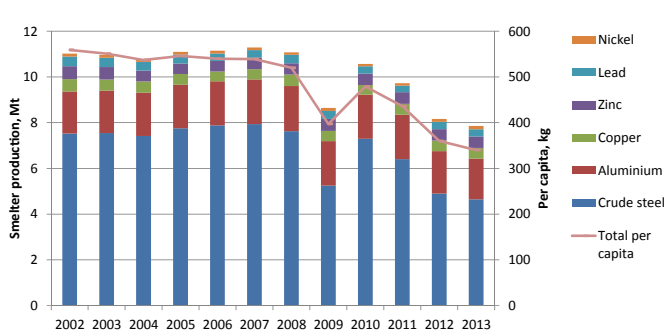

Fig. 3. Australian (primary) smelter production.
Data sources: BREE, 2014; Worldsteel, 2013.

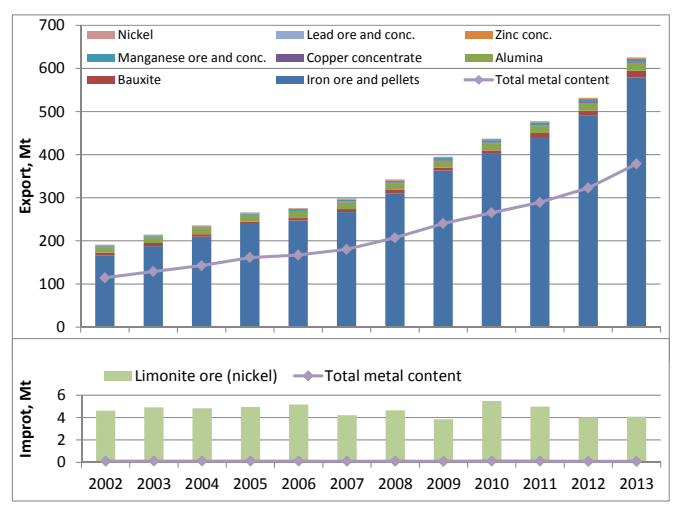

Fig. 4. Australian export and import of metal concentates.
Data source: BREE, 2014.

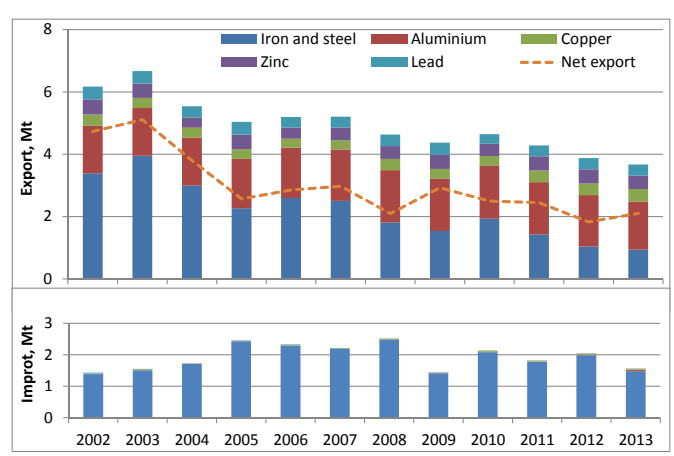

Fig. 5. Australian export and import of refined metals.
Data sources: BREE, 2014; UN Comtrade, 2014.

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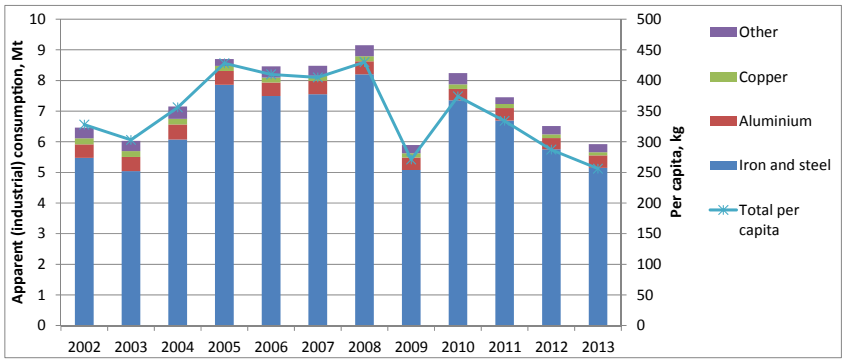

Fig. 6. Apparent (industrial) consumption of metals in Australia. Note: apparent consumption = primary and secondary production in Figs. 3 and 8, minus export in Fig. 5, plus import in Fig. 5.

consumption also declined from more than 400 kg in the peak years (2005–2008) to less than 300 kg in 2012–2013 (Fig. 6).

3.2. Indirect metal flows, and estimation of final consumption

The indirect import and export flows are associated with fabricated and manufactured goods, e.g. preassembled construction structures, machinery, vehicles, and consumer products. The calculation of indirect metal flows is usually based on the United Nations Commodity Trade Statistics Database (UN Comtrade), which includes statistics for about 200 countries. The trade flows of fabricated and manufactured goods are reported both in dollar value and volume terms. By applying special coefficients of metal content for different groups of products, the indirect metal export and import flows can be computed.[1] The latter allows for approximate estimation of true (final) metal consumption.

The estimation of final consumption for iron and steel, based on UN Comtrade data, can be obtained from Worldsteel reports (Worldsteel, 2013). To assess the final consumption of other major metals (Al, Cu, Zn, Mn, Cr, Pb, and Ni), we applied proportional distribution in the use of different metals combining findings from previous metal flows studies in Australia (see Table 1). The analysis of these studies revealed that these metals account for about 13% of final metal consumption in the country in 2000 (and the rest, 87%, is for iron).[2] There are some uncertainties in estimating these figures, as well as possible variations from one year to another. This estimation also shows a higher proportion for non-ferrous metals when compared with the world average: for example, the world metals production statistics indicates that iron (crude steel) would represent about 93% (USGS, 2014). However, this should be expected because the per capita use of non-ferrous metals in developed countries is significantly higher than in developing countries versus the same comparison for iron and steel (Rogich and Matos, 2008; UNEP, 2010).

The estimation of the overall final metal consumption in Australia is presented in Fig. 7. Over the ten years period, the metal use increased from 8760 kt in 2002 to 12,290 kt in 2011 (40% increase), or from 445 kg to 551 kg per capita (24% increase). The peak level of final metal consumption in Australia was registered in 2008 (before the global financial crisis) – at 12,990 kt or 610 kg per capita (Fig. 7).

3.3. End-of-life products and metal recycling

The official statistics on metal recycling in Australia is patchy, with no direct data on ferrous metal recycling and limited information regarding non-ferrous scrap. While the statistics on export and import flows represent major metal scrap trade relatively well, there is very limited information regarding domestic processing of metal scrap. To estimate waste metal and recycling flows the authors used indirect assessment methods and made feasible assumptions as explained below.

An approximate estimation for iron and steel domestic recycling can be done by comparing data on crude steel output (from basic oxygen furnace, BOF, and electric arc furnace, EAF, steelmaking) and pig iron (blast furnace) production – the difference between two figures roughly indicates the amount of scrap used to produce new steel. This scrap includes post-consumer, pre-consumer (industrial), as well as internal (steelmaking) scrap (Cullen et al., 2012; SSF, 2012). The latter, however, usually can be ignored in input–output analysis as it represents remelting of the original inputs.

Industry sustainability reports and some research investigations provide insights into details for type of scrap used in the production. For example, the estimate from Steel Stewardship Forum shows that the amount of post- and pre-consumer scrap used by steel producers in Australia was about 93% for EAF, and about 5% for BOF in 2007/08 (SSF, 2012). The ratio between post- and pre-consumer scrap, according to Arrium's – one of the two major steel producing companies in Australia (the other is BlueScope Steel) – sustainability reports over 2010–2013 is about 95%–5% (Arrium, 2014). There also was an estimation of 6.5 million tonnes in 2011/12 for domestic shipments of iron ore by the government transport agency (BITRE, 2014). This would cover raw material needs for about 70% of produced crude steel in Australia in the same year.

Thus, based on the information above, we estimated the total recycled content in raw steel output in Australia to be in the range from 20% to 30%, with a likely increase in recent years due to a higher proportion of steel produced by EAF technology (increasing from 17.8% in 2003 to 22.8% in 2012) (Worldsteel, 2013). This aligns well with a straightforward estimation of recycled content in steel output as a difference between crude steel output and pig iron production as shown in Fig. 8. Secondary metal production figures for other metals are also presented in Fig. 8.

[1] See for example assessments for iron flows in Wang et al., 2007. Forging the Anthropogenic Iron Cycle. Environmental Science & Technology 41, 5120–5129.; and aluminium flows in Liu and Müller (2013). Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis. Liu and Müller, 2013, 47, 11873–11881.

[2] See more details of this compilation work in the supplementary document.

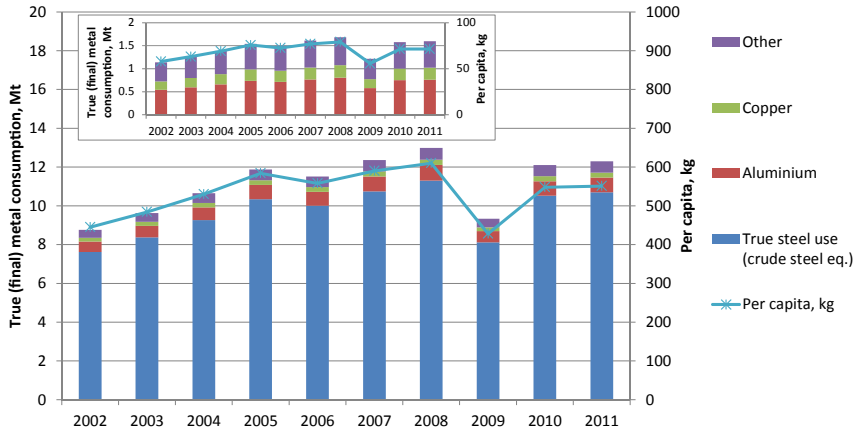

Fig. 7. Estimation of true (final) metal consumption in Australia.

There is no reliable statistics on metal scrap collection in Australia, with only two rough estimations made for financial years of 2008/09 (Hyder Consulting Pty Ltd, 2011) and 2010/11 (Randell et al., 2014). In this paper, we reconstructed data (Fig. 10) based on metals scrap export/import flows (Fig. 9), secondary metal production in Australia (Fig. 8), and assumptions for losses. Notably, we adjusted the secondary metal production in Fig. 8 by 6% for metal loss in smelting operations, based on iron losses with slag in BOF/EAF steelmaking (Pauliuk et al., 2013).

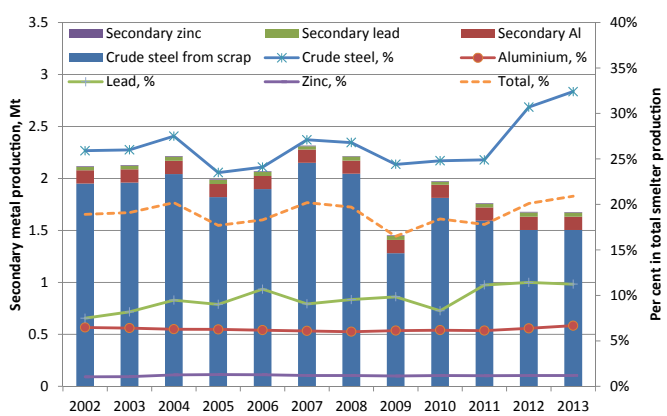

Fig. 8. Secondary metal production in Australia.
Data sources: authors estimation and BREE, 2014.

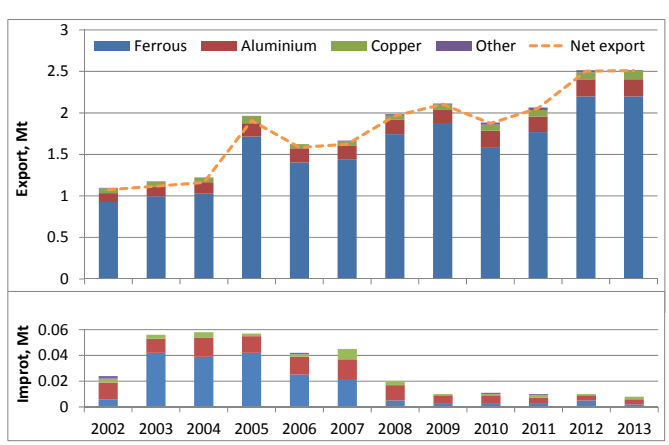

Fig. 9. Metal scrap export and import in Australia.
Data source: UN Comtrade, 2014.

More than half of metal scrap collected in Australia in recent years is exported for recycling overseas (Figs. 9 and 10). There are limited domestic facilities for separation and smelting of non-ferrous scrap (apart from secondary aluminium and lead smelting); most of it is shipped to and processed in Asia. The only well-established metal recycling system in the country is for iron and steel scrap, and this is part of the conventional iron smelting technology. The amounts of scrap import to Australia are negligible, and in total accounted for only 7 kt in 2013, versus 2519 kt for scrap export in the same year (Fig. 9).

The overall reported metal scrap collection rates in Australia exceed 90% (Brulliard et al., 2012), however these figures do not include losses in collection and processing of scrap, as well as metal dissipation in obsolete buildings, infrastructure, and abandoned end-of-life products. The real end-of-life (EoL) metal recycling rates are likely below 70%. There are still opportunities for enhancing metal scrap collection and recovery, including preventing metal losses at the disposal and stimulating secondary metal production within the country versus exporting scrap overseas (Corder et al., 2015). The recovery of precious and-or critical metals from consumer products is another area for research and potential establishment in Australia.

4. Analysis of metal flows circularity

An estimation of material flows in the economy through all main transformation stages – from mining to manufacturing, and

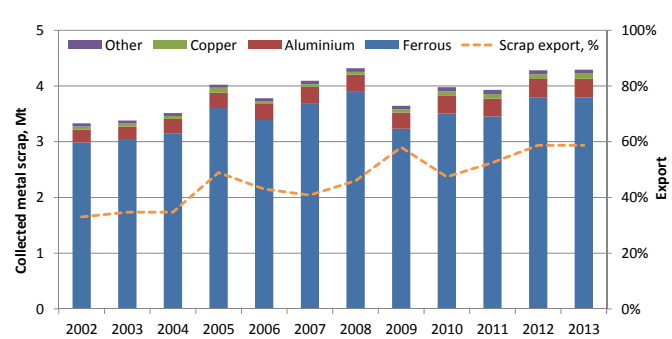

Fig. 10. Estimation for total collected scrap in Australia.

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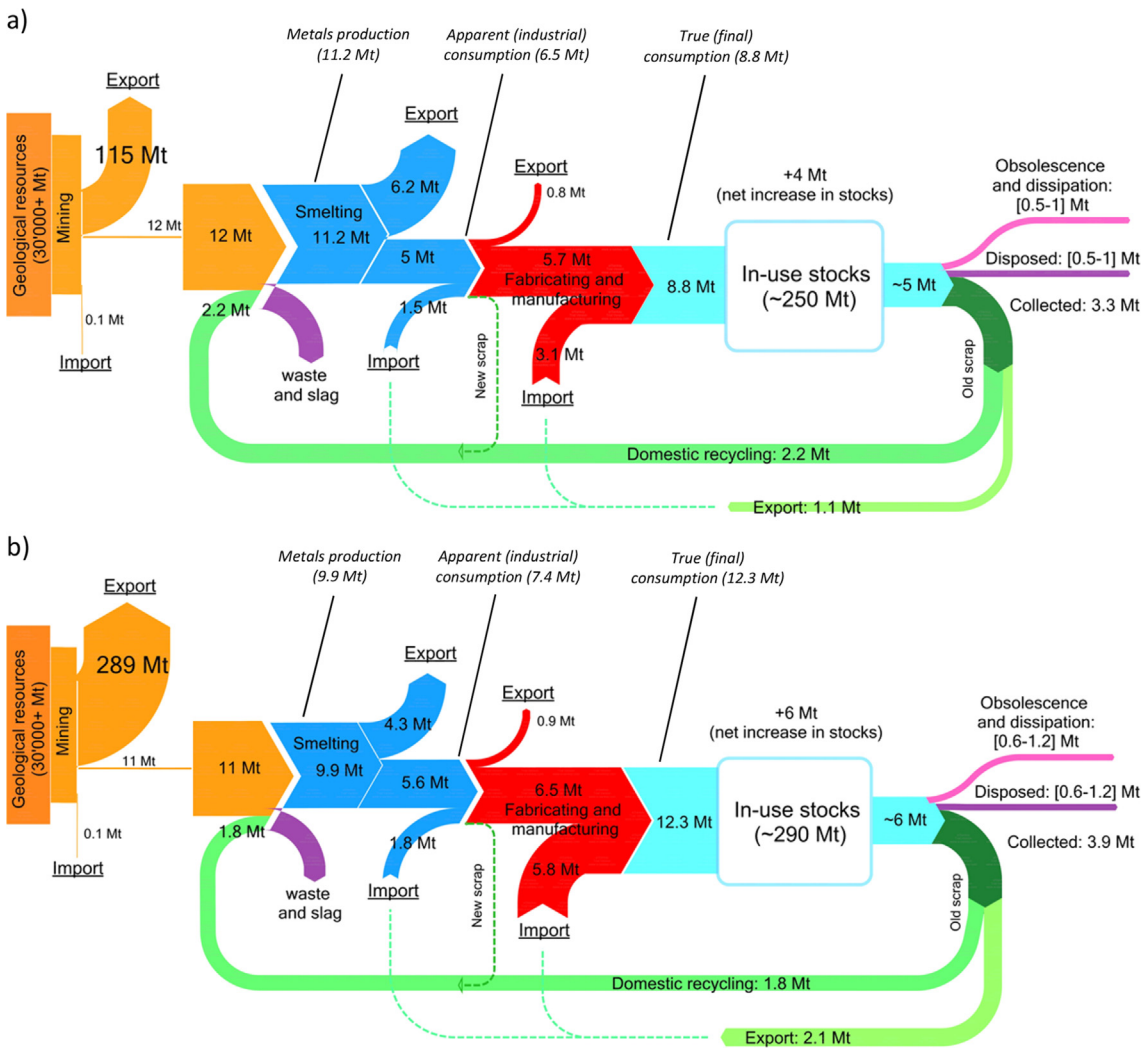

Fig. 11. Metal flows in Australian economy: a) 2002, b) 2011. Note: all figures are estimated for 100% metal content.

accounting for export and import flows – allows for a more detailed metal flows model. This model establishes a basis for analysis of metal circulation in the Australian economy, helps to investigate further the barriers and enablers for waste collection and recovery, and to develop recommendations for achieving higher recycling rates in the country.

The data presented in Section 3 was compiled together to estimate the circulation of metals in Australia for every respective year. The influence of metal stocks at the different processing stages was omitted in this model. Although changes in these stocks may have a significant influence over a short period of time, in the longer run these stocks are considered to be stationary in most models, with relatively negligible influence to the overall metal flows (Müller et al., 2014). There is a level of uncertainty for some numbers in the model primarily due to the quality of available statistics and assumptions made to cover the lack of data. Nevertheless, we believe the overall result provides a representative indication of the metal cycle flows in Australia and its dynamics.

The metal flows for 2002 and 2011 are presented in Fig. 11(a and b) respectively.[3] Over this ten-year period, the overall amount of metals use has grown from 8.8 million tonnes to 12.3 million tonnes (+40%), or from 445 to 551 kg per person (+24%). At the same time, the amount of generated waste metal is estimated to have grown from approximately 5 million tonnes to 6 million tonnes, being in the range from 250 to 270 kg per person, and roughly equal to 50% of final metal consumption. This can be viewed as an indicator for metals circularity potential.

The most significant changes occurred for indirect import flows and scrap metal export. The amount of metals imported in the form of fabricated and manufactured products increased from 3.1 Mt to 5.8 Mt (+85%), covering about 36% in 2002 and 47% in 2011 of total metal use in the country. Due to the higher volumes of collected metal scrap and fewer opportunities to recycle this scrap domestically (primarily due to decreased steel output), the export of scrap from Australia has almost doubled – from 1.1 Mt to 2.1 Mt. The domestic processing of metal scrap decreased from 2.2 Mt to 1.8 Mt accordingly, and covers less than 15% of final metal consumption in the country in 2011. The latter can be considered as a representation for the actual domestic circularity of metals.

The in-use stocks of metals in Australia were assessed at 250 Mt in 2002 and 290 Mt in 2011 level respectively (Fig. 11), based on existing studies for accumulated metal stocks in modern

[3] To supplement the total metal flows presented in Fig. 11, indicative metal flows for iron, aluminium and copper in 2002 and 2011 are presented in the supplementary document for this paper.

economies (notably 10–15 tonnes per capita) (UNEP, 2013). It should be noted however that detailed modelling of overall in-use stocks and end-of-life metals flows for individual metals is typically based on the lifespan for each end-use application and the historical apparent consumption, e.g. (Chen and Graedel, 2012b; Hatayama et al., 2010; Pauliuk et al., 2013). Applying the same approach for the combined major metals flows would be not only much more complicated, but also requires many additional assumptions and therefore the final results would be far less reliable. This was the main reason for estimating metals stocks and end-of-life metal flows in Fig. 11 based primarily on other existing studies. In addition a key aim of the analysis in this paper is to present indicative results and identify trends over time rather than conduct a detailed investigation with limited data. The crosscheck of these estimations with the changes that occurred within the model showed that they adequately correlated with and supported the assumptions for metal losses in the landfills and due to obsolescence and dissipation which was estimated at 30% (±10%) in total metal outflows in Fig. 11.

While the in-use metal stocks (i.e. 290 Mt in 2011) may appear small compared to Australia's demonstrated economic resources for metals which is more than 30,000 Mt (Geoscience Australia, 2012), the fact that they represent an ever growing resource base and are relatively easily accessible highlights their importance for the future circular economy model.

5. Conclusion

Australia remains a strong net exporter of a wide range of mineral commodities, and especially metallic minerals. This has allowed the country's economy to stably grow over the last few decades. At the same time, being among the most developed countries in the world and allowing for higher level of resources consumption, Australia generates a significant amount of waste materials per capita which could provide the economy with the secondary resources and partially offset the need for virgin raw materials.

The amount of metals in the extracted and exported mineral concentrates in the last decade was about 30 times higher than Australia's needs in metals. Net export of metal concentrates (in 100% metal content) grew from about 114 Mt in 2002 to 289 Mt in 2011, while the domestic use of metals accounted for 8.8 Mt and 12.3 Mt of metals in the corresponding years. While not denying the dependence of Australia on mining and minerals industry revenue for economic growth, we believe that a better understanding of metal cycles in the economy can provide a pathway to Australia's leading role in resources stewardship, including accounting and highlighting the need for both primary and secondary resources in the economy, and comprehensively targeting the associated economic, environmental, and community related impacts from resources supply.

The analysis of metal flows in the Australian economy over the period from 2002 to 2011 has shown that current levels of waste metal generation in the country could cover up to 50% of Australia's needs in metals, if the waste materials are fully collected and recovered. The current level of domestic recycling, however, hardly contributes to 20% of refined metals production, and covers even a smaller percentage of final consumption of metals in the country. Although, taking into account metal scrap exported and recycled overseas, this figure is rising to about 30–35%. The share of domestic recycling for collected metal scrap in the country decreased from about 67% in early 2000s to about 41% in early 2010s, and is expected to decline further.

In our opinion, significant opportunities remain for both – improving the collection system for waste metals, and supporting higher levels of domestic recycling for collected materials. While primary extraction of mineral resources has inevitable environmental impacts, and leads to the exhaustion of country's geological reserves, recycling typically has much lower environmental impacts and provides an alternative and potential stable (and growing) resource base for future metal production. Achieving a balance between the extraction and processing of raw materials, predominantly for export, and recovery of metals from waste streams requires Australian leadership in stewardship of material resources. A more innovative approach is needed to financially benefit the economy from domestic recycling. This will allow for an expansion of the Australian resource base and could be the catalyst for new niche manufacturing and services companies based on recycling and re-use, which can then be exported to rest of the world.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.07.083.

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