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"Wealth from metal waste": Translating global knowledge on industrial ecology to metals recycling in Australia

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ABSTRACT

Australia's rich stocks of mineral resources have been the source of national wealth and competitive advantage in the past. However, the security of this wealth is not guaranteed into the future, and what were once considered waste materials from mining, infrastructure and products are now becoming accessible and valuable as 'above-ground' mineral resources. Globally there is growing capacity and innovation in recycling, closed-loop supply chains and Australia's role as a global leader in primary production must anticipate and adapt to the implications of a rise in the importance of recycling. However, both at a global level and in Australia, there are a broad range of factors and local influences affecting the successful application and implementation of industrial ecology beyond technical re-use solutions. This paper presents the initial outcomes from a major collaborative research project (Wealth from Waste Cluster), funded by the CSIRO Flagship Collaboration Fund and partner universities, focused on identifying viable options to 'mine' metals contained in discarded urban infrastructure, manufactured products and consumer goods. This paper presents initial estimates of the mass and current worth of metals in end-of-life products. Results from this analysis have identified that the value of metals in end-of-life products is more than AUD6 billion per year, and assuming existing recovery rates, the estimated potential for recovering metals from "waste" or end-of-life products is of the order of AUD2 billion per year. In addition a metal flow analysis of the Australian economy identified that approximately half the scrap metal collected in Australia (approximately 2.5 million tonnes per year) is currently being transported overseas which potentially could be recycled in Australia if suitable technology were available.

1. Introduction

Australia's rich stocks of mineral resources have in recent years been the source of national wealth and competitive advantage. The security of this wealth is not necessarily guaranteed into the future and therefore Australia as a nation needs to seek alternative sources of revenue generation and competitive advantage. Waste materials, which were once considered of little or no value, are now becoming accessible and valuable as 'above-ground' mineral resources. Globally there is growing capacity and innovation in recycling, and closed-loop supply chains (World Economic Forum, 2014).

The increase in recycling (and reuse and remanufacturing) is driven by a number of factors – for instance, recycling or secondary production of metals has in general a significantly lower energy footprint compared with producing metals from virgin ores (Grimes et al., 2008), which results in minimising environmental impacts and supporting sustainable development through the efficient use of resources. Other factors include the lack of available natural resources in certain counties such as those in the European Union and Japan where the closed loop economy model is actively promoted. However, the world demand for metals is still mostly met by primary production.

The closed loop economy presupposes predominantly cyclical use of metals within the system, yet it is economically impractical to limit the system to national or regional borders, and it should be rather justified and achievable at the global scale. This means that while some countries still play the role of net providers of primary (mined) material resources at the global level, there should be the initiative to develop and implement effective collection, reuse and recycling systems internally for end-of-life products.

Australia needs to balance its interest in raw materials exports with Australian leadership in stewardship, which is consistent with a resource efficient economy across the entire value chain. Achieving this balance will offer the potential to expand the

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resource base available to Australian operations and build new niche manufacturing and services companies based on recycling and re-use. Realising this potential requires an ability to analyse, explore, and conceptualise new business models and understand the linkages along the value chain and between supplier networks. Australia currently has significant expertise in mining and metallurgy and this provides a window of opportunity to build on this foundation and develop expertise in the distinct thermodynamics associated with 'urban' ores and secondary processing.

This paper presents the initial outcomes from a major collaborative research project (Wealth from Waste Cluster), funded by the CSIRO Flagship Collaboration Fund and partner universities, focused on identifying viable options to 'mine' metals contained in discarded manufactured products and consumer goods. An important initial focus of this research has been on understanding the current status of industrial ecology both globally and at a national level as well as producing quantitative estimates of the potential for metals recycling from end-of-life products.

2. Wealth from waste cluster

The Wealth from Waste Cluster is a three-year research program that aims to identify viable options for recycling metals from Australian products (CSIRO, 2014). It is focused on identifying viable options for 'mining' above ground resources, which are the metals contained in collections of discarded manufactured products and consumer goods (end-of-life products). The key focus of the Cluster is to address the pathways that will help Australia realise the above-mentioned potential for expanding its resource base to be both a primary and secondary metal producing nation. While technological solutions form an important part of this progress, a resource efficient circular economy requires more than technological solutions alone. Understanding what other factors – including the operation of collection systems, legislative constraints and market drivers – are required to underpin recycling economics is a key objective of the Cluster. The Cluster commenced in mid-2013 and builds on work undertaken by the Mineral Futures Collaboration Cluster that ran from 2009 to 2012 (CSIRO, 2013).

The research program is supported through CSIRO's Minerals Resources and Manufacturing flagships and partner universities, including:

- University of Technology (UTS), Sydney, Australia.
- Monash University, Melbourne, Australia.
- University of Queensland, Brisbane, Australia.
- Swinburne University of Technology, Melbourne, Australia.
- Yale University, New Haven, USA.

Teams drawn from the different universities and disciplines are undertaking four distinct, but interconnected, research programs to develop a better understanding of this complex landscape and possible pathways for change:

- Program 1: Recycling systems: barriers and enablers for industrial ecology in Australia.
- Program 2: Future resource value: characterising stocks and mapping impacts.
- Program 3: Developing business models for future value chains.
- Program 4: Transition pathways for leadership in resource stewardship.

Embarking on a long-term research project of this nature means that there are expectations that the research outcomes will make a major contribution in creating a paradigm shift in the way that the Australian economy considers sources of metal stocks. However, to begin with it is important to understand the outcomes from related research and practical activities on a global scale in industrial ecology and synthesise this knowledge to help progress the uptake of metals re-use and recycling within the Australian context (Section 3). In addition, the expected outcomes from this research need to be underpinned by a baseline analysis to determine the levels and justification for increasing recycling rates and uptake within the Australian context. This analysis compares Australia's primary metal producing capacity with an estimation of metals consumption in Australia and the estimated available metals in waste streams (Section 4).

3. Global knowledge on industrial ecology

3.1. Growing importance

The term industrial ecology was popularised 25 years ago by Frosch and Gallopoulos (1989). Using nature as a metaphor, industrial ecology aims to optimise the total material cycle from virgin material to product and to ultimate disposal, and closely examines the opportunities to reuse and recycle different waste streams arising in industrial and consumer activities, as well as reorganising the industrial systems to ensure resource efficiency and resilience.

The field of industrial ecology is becoming increasingly important for some countries and regions in the world. This is illustrated by the growing trend for mining development activity over the last 50 years from, in broad terms, countries that both produce and consume metals to countries that produce metals, which are then exported to metal consuming countries. Humphreys (2013) demonstrated this trend by examining the world in two groups – metal consuming regions (North America, Western Europe, Japan, China and the Former Soviet Union) and metal producing regions (Asia less China and Japan, Africa, Latin America and Oceania). This analysis showed that from 1960 to 2010 countries which both mined and consumed copper, supply dropped from 55% to 25% and similar changes have also occurred for bauxite, iron ore and nickel (Humphreys, 2013). This illustrates that some of the metal consuming countries now rely more heavily on metal producing countries for their supply of metals and minerals which in turn has led to a greater emphasis on seeking alternative sources for metals and minerals including their own stocks in end-of-life products. This has created significant activities for industrial ecology initiatives centred on the circular economy (World Economic Forum, 2014).

3.2. Global initiatives

Although industrial ecology can take on a product-based systems perspective or a geographically defined local–regional industrial ecosystem approach (Korhonen, 2002), the primary interest for this work is on utilising the industrial ecology concept to identify the pathways for higher levels of metals recycling in Australia. Due to their nature, metals are highly amenable to the industrial ecology model as – given sufficiently available energy and technology – they can be reused without losing their physical properties (Ayers, 1997) and can be used at various levels such as high volumes for example with iron and steel, aluminium, and copper, to critical and precious metals usually used in minor quantities, e.g. gold, PGMs, and rare earths. Others have pointed out that the recyclability of metals from non-dissipative uses, given appropriate energy inputs and technology availability, should focus attention on the operation of the value chain and less on the issue of resource scarcity within the value chain (Stewart and Weidema, 2005).

While initiatives related to the circular economy and metals recycling are being advocated at the international level through the World Economic Forum (World Economic Forum, 2014) and through the United National Environment Programme (UNEP, 2013) respectively, there is significant activity in industrial ecology and the related sub-field of industrial symbiosis (which focuses on the material and energy exchanges between organisations) at a national level. As an example, China has developed since the early part of this century the largest national Eco-industrial Park (EIP) network, involving 15 national demonstration EIPs and 45 national trial EIPs which has included the cultivation of hundreds of researchers and professionals working in the field of EIP planning and consultancy (Shi et al., 2012). In Europe, the Resource Efficiency Flagship Initiative and the subsequent Roadmap for a Resource Efficient Europe have recommended that opportunities to exploit resource efficiency gains through industrial symbiosis should be a priority for members in the European Union (Laybourn and Lombardi, 2012). Furthermore, the UK's National Industrial Symbiosis Programme (NISP) has been cited as a best practice exemplar of "concrete action" and should be replicated elsewhere for instance across European Union member states (Laybourn and Lombardi, 2012). Although these initiatives go beyond metals, the growth in the area of industrial ecology provides a strong indication of the future direction for metals conservation and recycling.

In addition to national implementation schemes, there are relevant international research initiatives. The Center for Resource Recovery and Recycling (CR3) is a multi-university (Worcester Polytechnic Institute, Colorado School of Mines, and KU Leuven) member-driven collaborative focusing on advanced research for materials and metals recovery and recycling, stewardship programs, policy development and enhanced landfill mining (The Center for Resource Recovery and Recycling, 2014). The Critical Materials Institute operated by The Ames Laboratory for the U.S. Department of Energy broadly focuses research on technologies that make better use of materials and eliminate the need for materials that are subject to supply disruptions. A key research program is aimed at using available materials more efficiently by reducing waste in manufacturing processes, and increasing the adoption of recycling streams (Critical Materials Institute, 2014). These research centres demonstrate the heighten interest internationally in developing technologies and approaches that align strongly with the concept of industrial ecology.

Jackson et al. (2014) examined the potential implementation transition pathways promoting industrial ecology from the perspective of (a) the transitions management literature and (b) socio-technical transitions. They examined the multi-faceted dimensions of an enabling environment required for industrial ecology to develop, including policy and institutional settings for technology development and corporate governance. They proposed that the active development of industrial ecology is enabled by considering distinct phases of (i) considering the boundaries of the transition arena (ii) developing images, transition coalitions and agendas (iii) executing projects and experiments (iv) evaluating and learning. A key point was that depending on the initial framing of the transition arena (for example, all resources in the economy; or, for recycling a single commodity such as steel; or for recovering metals from waste) the leverage points to achieve change will differ.

3.3. Australian initiatives

While the international scene is actively pursuing and applying industrial ecology initiatives, the level of activity in Australia has been at best mixed. Industrial ecology in Australia has been demonstrated with a few heavy industrial regions studies, several mixed industrial parks and waste exchange initiatives, as well as with investigations of reuse options for specific waste flows. To a degree there have been challenges in Australia, due to its unique geographic location as a continent, long distances between major cities and industrial centres in regional areas. The most well documented and cited examples relate to the regional resource synergies studies, or industrial symbiosis, in such heavy industrial areas as Kwinana in Western Australia, and Gladstone in Queensland. Both are highly developed heavy industrial areas (including alumina, nickel, oil, iron, cement, and pigment industries) (Corder et al., 2014). Nevertheless the challenges in the Australian context can be the driver to create and adopt suitable innovative approaches to deliver successful outcomes and increase the uptake of metals recycling in a difficult environment. Lessons and case studies from international experiences, as highlighted in Section 3.2, where industrial ecology is at a higher level of maturity, should provide guidance and influence for Australia. A critical aspect is the multi-faceted and multi-disciplinary nature of industrial ecology, which requires more sophisticated and innovative approaches for progressing industrial ecology.

The latest report on waste generation and resource recovery in Australia from the Australian Government Department (Randell et al., 2014) indicated several similar key elements that are needed in a recycling framework required to achieve higher rates for resources recovery. In essence this work identified that significant opportunities remain in the following categories:

- Broad scale landfill disposal bans for untreated or unsorted solid wastes.
- Use of a wide range of resource recovery technologies.
- Comprehensive reporting requirements for waste management.
- Source segregation of solid waste collection (i.e. avoiding mixed loads).
- Hypothecation of levy landfill funds to waste initiatives and recovery infrastructure.

Randell et al. (2014) concluded that despite variations between different states in Australia in their waste frameworks and regulation, landfill levies rates, and direct government support, the long-term targets (2020 and beyond) for resource recovery in all states aim to achieve at least 70–80% recovery rates for all waste streams (municipal, construction and demolition, commercial and industrial). While metal recovery targets are not specified in this work, targets of 90% or higher (on a weight basis) seem feasible based on the analysis conducted through the research presented in this paper.

As part of the Wealth from Waste Cluster an Industrial Ecology Forum (workshop) was held in March 2014. The main aim of the workshop was to bring together different stakeholders and share experiences on the existing status of recycling activities in Australia to elicit the major barriers and opportunities for uptaking best international approaches and achieving higher levels of metal recycling in Australia. The key outcomes are presented below:

- Product design is an imperative for the circular economy and efficient recycling, however there is a limited influence that Australia can make on imported products. The best option would be to closely follow other countries legislative requirements in this area, e.g. European Union.
- Business models are crucial for successful recycling activities. The main focus should be on innovative systems as well as adopting technologies from other countries.
- A national approach should create grounds for recycling businesses becoming profitable. The market signals have to drive behaviour and investment in the recycling and waste

management sector. Stimulus is better than direct regulation. For example a co-regulation approach can be desirable in some cases, such as the National Television and Computer Recycling Scheme which includes a stepped implementation over several years, with industry taking responsibility for a progressively higher proportion of total waste televisions and computers each year, from 30 per cent in 2012–13 to 80 per cent by 2021–2022. Although television and computer waste beyond these targets remains the responsibility of state, territory and local governments (Department of Environment, 2014).
- There is a lack of data and understanding on potential lost opportunities, that is unrecovered materials. Additional investigation and mapping of above ground stocks, and material flows are needed.
- Different waste types require different approaches and thus there is a need to focus on a specific industry and its infrastructure needs/gaps for each waste stream.
- A characterisation of profitability zones (marginal costs of recycling for distances and types of waste) would provide a better understanding on how the national/state regulation influences the efficiency of recycling and may increase/decrease overall recycling rates.

The industry and government response to the above listed challenges would help to strengthen the recycling sector in Australia and align with world best practices, e.g. similar to recycling initiatives in the European Union where landfill or 'urban' mining has been strongly supported (Jones et al., 2013).

3.4. Summarising comments

The research and analysis presented above provides a substantial basis for highlighting the key aspects to concentrate on to effectively shift the resources paradigm towards the circular economy in the context of the Australian recycling landscape. This knowledge needs to be coupled with a quantitative estimation of the potential for metals recycling based on current metals usage and consumption rates in Australia and the results of this analysis are presented in the following sections.

4. Metals production, usage and consumption in Australia

4.1. Primary metal mining and processing

The Australian economy has relied on mining to generate export revenue. The abundance of natural resources and the relatively low population has predetermined the role of the Australian economy on the global market as a resources supplier. In addition, the mining equipment and services sector in Australia is a significant export industry in its own right, but is currently focussed on terrestrial ores.

The exported mineral resources can be subdivided into three main categories – energy related (coal, oil, natural gas, uranium), metal related (e.g. iron ore, alumina), and others (e.g. gems) – see Fig. 1. Metals and metal concentrates currently deliver the country's main resources export revenue (58% in 2012/13, worth AUD101.2 billion), followed by energy resources such as coal, natural gas and uranium (38%, worth AUD67.4 billion) with the remainder worth AUD7.3 billion. More than 90% of minerals mined in Australia are directly exported, and for metals and metal concentrates this figure is close to 98%.

In 2012–13, Australia exported more than 570 million tonnes of metallic content materials (contained more than 300 million tonnes of extractable metals). At the same time, the apparent domestic consumption of metals was about six million tonnes (BREE, 2013). Some metals are primarily exported as concentrates (e.g. iron ore, 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 metals and metal concentrates production in Australia is more than 99 wt% represented by five elements – iron, aluminium, copper, zinc, and manganese (BREE, 2013). Australia is the world's largest producer of iron ore and bauxite, covering more than 20% of world needs in resources to produce steel and aluminium (BREE, 2013; USGS, 2014). Australia is also a leading producer of titanium, and zirconium concentrates, and among the top five countries in the production of copper, zinc, manganese, nickel, and gold (USGS, 2014). Refer to Figs. 2 and 3.

4.2. Estimation of metals consumption

The Australian economy is one of the fast growing among developed countries (Trading Economics, 2014), allowing for higher individual incomes, consumption rates, and the overall standard of living. This also means a higher level of urban stocks and waste generation, representing good potential for recycling and transition to a circular type economy.

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, fabricated and manufactured products also play a significant role in estimating material flows. Input–output and material flow analysis techniques are usually employed to represent the circulation of

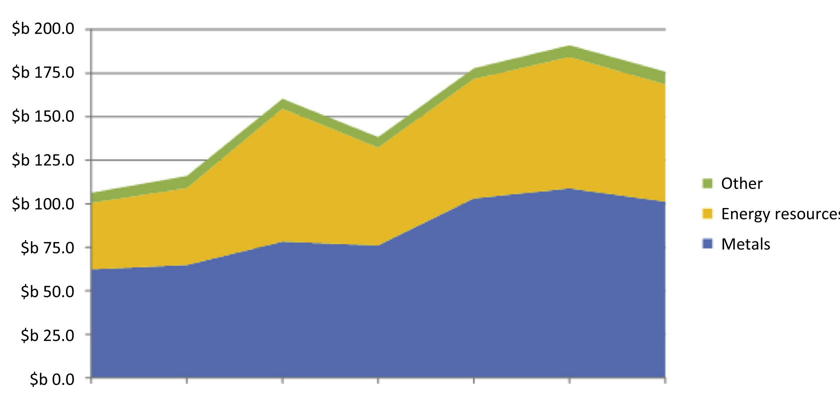

Fig. 1. Australian mineral resources export revenue. *Source:* BREE (2013).

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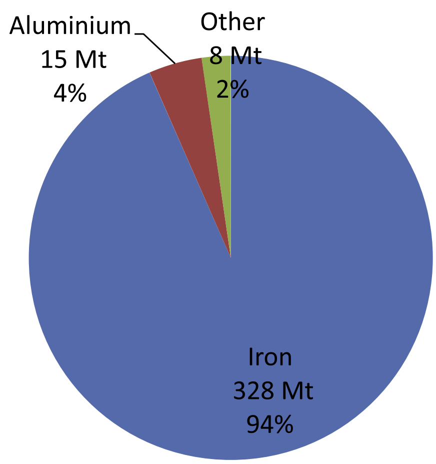

Fig. 2. Australian metals and metal concentrates exports (by net metal weight) in 2012/13. *Source:* BREE (2013).

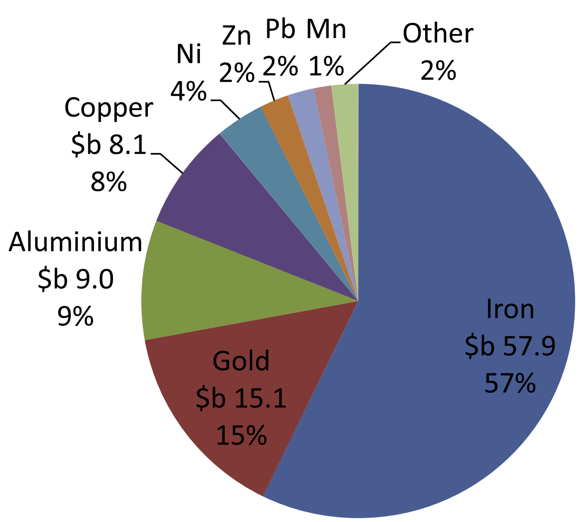

Fig. 3. Australian metals and metal concentrates export (by monetary value) in 2012/13. *Source:* BREE (2013).

specific material in the economy. The simplified model of metal circulation in the economy is presented in Fig. 4.

The metal production and direct shipments are usually well recorded through national and international statistics allowing for estimation of the apparent consumption of major metals (Table 1). The true metal consumption, however, may be significantly higher or lower than the apparent consumption. It takes into account all indirect import and export flows, where metals are associated with fabricated and manufactured goods, e.g. preassembled construction structures, machinery, vehicles, and consumer products. The true metal consumption and in-use stocks are not easy to estimate, it requires additional investigation, and often relies on multiple assumptions and expert opinion. In the future, it would be ideal to recycle as much metal as possible in end-of-life products locally and minimise disposal and losses. This would conserve the maximum amount of secondary metal in the economy.

The total joint ore reserves and demonstrated economic resources for metallic minerals in Australia exceed 30,000 Mt of metals content (Geoscience Australia, 2012), which is higher than metals production and consumption in the country by several orders of magnitude. This is to be expected given that Australia is a leading exporter of minerals with a comparatively small population base.

The number of detailed investigations for metal flows and in-use stocks is relatively limited worldwide (UNEP, 2010; Chen and Graedel, 2012; Pauliuk et al., 2013). Some data on iron and steel, and aluminium flows can be obtained from international reports, e.g. of World Steel Association (Worldsteel, 2013) and International Aluminium Institute (www.world-aluminium.org). World historic flows of selected technological metals were also investigated in the Yale stocks and flows (STAF) project (e.g. Chen and Graedel, 2012). In Australia, the only detailed study on metal flows in the economy was performed for copper and zinc (van Beers et al., 2007).

Net indirect imports (i.e. import minus export) of iron and steel in Australia, estimated by Worldsteel Association, for example, steadily grew over the last decade: from 1420 kt in 2002 to 4670 kt in 2011 (Worldsteel, 2013). Considering other metals, the likely overall indirect import and export flows add up to a metal consumption in the country of about six million tonnes a year. This results in the total metal consumption rate in Australia of about 12 million tonnes a year (2012/13), or about 520 kg per capita.

4.3. Metals in waste streams and recycling rates

The energy requirements and carbon footprint for most recycled metals is 50% to 99% lower compared with primary produced metals, e.g. ferrous metals (58%), aluminium (92%), copper (65%), nickel (90%), zinc (76%), lead and tin (99%) (Grimes et al., 2008). "On average, the metal stocks used in more-developed countries equate to between ten and fifteen metric tonnes per citizen. Of this amount, five metals – iron, aluminium, copper, zinc, and manganese – make up more than 98%" (UNEP, 2013). The combination of these two statements represents a strong incentive for promoting the recycling of metals.

The world demand for metals is predominantly covered by primary production. Only three metals (niobium, lead, and ruthenium) have more than 50% recycled content, and another 16 metals are in the 25–50% range (Graedel et al., 2011). A critically

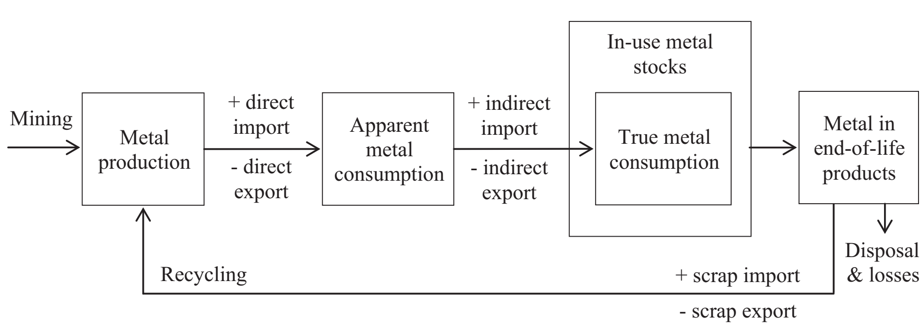

Fig. 4. Estimation of metal use in the economy.

Table 1
Apparent primary consumption for selected metals in Australia. *Source:* Bureau of Resources and Energy Economics (BREE, 2013).

Year	Iron and steel (kt)	Al(kt)	Cu (kt)	Zn (kt)	Pb (kt)	Total for selected metals (kt)	Per capita, kg
2006–07	7679.6	330.8	144.0	86.7	25.6	8266.6	401
2007–08	7868.0	314.1	153.0	84.9	24.9	8444.9	403
2008–09	5908.5	225.1	141.0	70.9	21.0	6366.6	299
2009–10	7073.1	294.4	131.0	70.6	20.6	7589.7	348
2010–11	7388.2	251.6	142.0	64.7	28.1	7874.6	357
2011–12	6038.3	234.6	111.0	55.1	19.7	6458.7	289
2012–13	5534.4	219.7	91.0	72.6	22.8	5940.6	262

Note: there is no similar data available for other major metals such as manganese, chromium, and nickel, which are mainly used in stainless steel production and as alloying elements. Part of these metals flows, however, may be represented within iron and steel statistics.

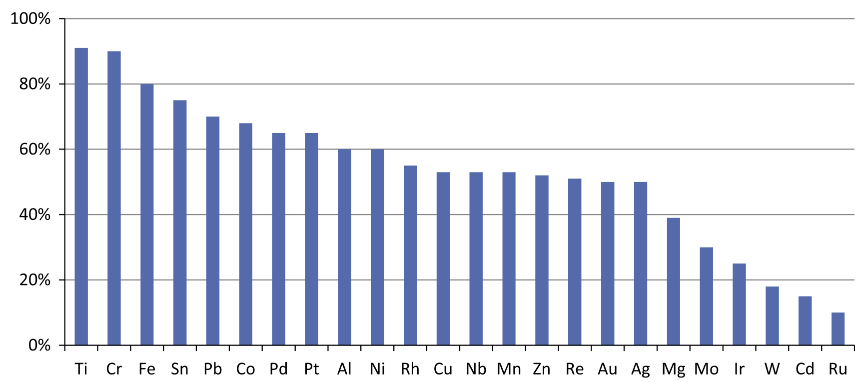

Fig. 5. World estimates for end-of-life recycling rates (EoL-RR). *Source:* UNEP (2011).

important question, however, is how much of metal content in the end-of-life products is actually recycled, and how much is lost in landfills. The existing estimations show that for 18 metals the recycling rate is above 50%, and for another six metals it is between 11% and 50%, (refer to Fig. 5) while many other metals mostly end up in the landfills (Graedel et al., 2011).

The recycling of metals includes several main stages such as collection, sorting, shredding, physical separation, hydrometallurgical treatment, and smelting. Metal recycling usually involves multiple companies at different stages. The number of recovered metals and level of recovery significantly depends on the waste stream and processing technology. The main challenge with improving recycling rates is that the complexity of consumer product mineralogy requires an industrial ecological network of a range of metallurgical production infrastructure to maximize recovery of all elements in end-of-life products (UNEP, 2013).

Based on reports from UNEP (UNEP, 2013) and USGS (USGS, 2014) we have estimated that the annual waste metal generation level could account for 50–60% of the current consumption (taking into account the average period of metal use within the economy, metal consumption and population growth over the last few decades). For Australia our estimated current consumption is 520 kg per person (as stated in Section 4.2) which results in about 300 kg per person or seven million tonnes, based on the Australian population of 23 million (ABS, 2014), in total of metals in waste streams a year. This figure is slightly higher than data derived from national waste reporting, i.e. 252 kg per person or 5.6 million tonnes in total of metal scrap in the accounted waste streams (collected for recycling, and landfilled) in 2011/12 (Randell et al., 2014). The latter, however, does not include a certain metal loss in obsolete (degraded) stocks and a loss during the collection and processing, and does not differentiate old scrap (from end-of-life products) from new scrap (waste metal and rejects from new manufacturing).

The combined loss in landfills and due to obsolescence is currently modelled at about 30% for major metals leaving the in-use stocks, e.g. iron and steel (Pauliuk et al., 2013), and aluminium (IAI, 2014). This accounts for about a million tonnes of metals a year leaving the Australian economy – refer to Fig. 6.

The waste streams outline the potential value for metal recycling, apart from metals in the obsolete stocks (i.e. due to metals degradation/oxidation in some applications over time, resulting in metals being dispersed in the environment and/or becoming useless for recovery). Based on 2012/13 metal prices (BREE, 2013) and the average metal composition in waste for Australia derived from Yale University's Center for Industrial Ecology STAF project investigations (Center for Industrial Ecology, 2014), there

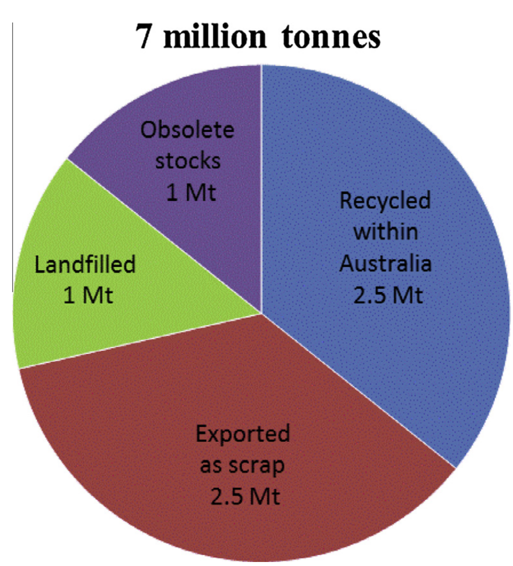

Fig. 6. Destination of metals in waste streams in Australia (2012/13). *Note:* based on Australian export–import statistics, waste reporting, and authors assumption for obsolete stocks and other losses.

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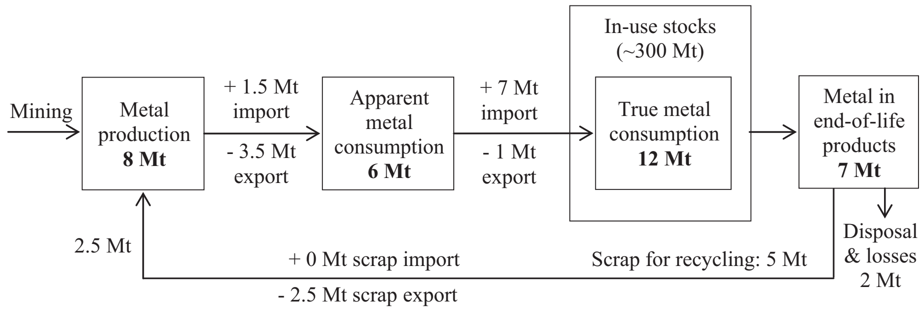

Fig. 7. Metal use in the Australian economy (2012/13). *Source:* Authors estimation.

is an estimated worth of more than AUD6 billion if the waste metals were fully recovered. The estimated potential for "wealth from (metal) waste" in Australia is of the order of AUD2 billion a year, consisted of the value lost with landfilled metals and lost opportunities in domestic processing of collected metal scrap. Currently, only about half of collected waste metal is processed in Australia (Fig. 6). There are no domestic facilities for separation and smelting non-ferrous scrap (apart from secondary aluminium production); and 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.

4.4. Model of metal flows in Australian economy

Building on the outcomes above, this section summarises the estimates of the flows of metals into and out of Australia. These results establish the current level of metals circularity in the Australian economy, and provide important estimates of the magnitude of scrap metal that is currently being transported overseas, which could potentially be recycled in Australia.

The overall amount of consumed metals is estimated at 12 million tonnes, while the amount of generated scrap and waste metal is 7 million tonnes which amounts to about 520 kg per person or about 300 kg per person respectively based on an Australian population of 23 million (ABS, 2014) - see Fig. 7. There is limited information on the type of metal and metal contained products consumed and scrapped in Australia. While detailed investigations are required for specific metal or commodity cycles in the economy, it is evident that the major part of metals is utilised in buildings, infrastructure, machinery, and vehicles. Regarding specific examples of metals not currently recycled in Australia, these include tinned-steel food cans (which are exported) and a secondary aluminium smelter (Yennora, NSW) is planned to close. Secondary steel is recycled, however the problem of down-cycling (different specialist alloy steels being recycled into mixed steel) remains.

5. Conclusions

The closed loop economy assumes a largely cyclical use of metals within the system, although it is economically unrealistic to limit the system to the national or regional borders, and any justification for a circular economy should be achievable at the global scale. Consequently countries like Australia play a role of net providers of primary (mined) material resources but should still have focus at the national and regional levels on enhancing the collection, reuse and recycling of materials, including metals.

This paper has presented the initial findings from the program of work in Wealth from Waste Cluster focussing on the institutional and other non-technical barriers and enablers for existing and emerging recycling systems in Australian. This was underpinned by an initial analysis in which we estimated:

- there is about six million tonnes of metal content in the waste streams in Australia a year,
- which could cover 50% of annual metal consumption within the country,
- with an estimated worth of more than AUD6 billion if the metals are fully recovered.

Based on existing waste and recycling statistics in Australia, the estimated potential for "wealth from (metal) waste" is of the order of AUD2 billion a year.

However, Australia's unique geographic location as a continent, long distances between major cities and industrial centres in regional areas, presents challenges from a metals recycling perspective. In addition, mining and minerals processing is a well-established industry in Australia, which provides significant revenue (over AUD100 billion annually) and has allowed the Australian economy to stably grow over the last few decades. Nevertheless, achieving a balance between the extraction and processing of raw materials, predominantly for export, requires Australian leadership in the stewardship of material resources. This will allow for an expansion of the Australian resource base and be the catalyst for new niche manufacturing and services companies based on recycling and re-use, which can then be exported to the rest of the world.

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