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Quantifying metal values in e-waste in Australia: The value chain perspective

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ABSTRACT

The existing practices and opportunities for material recovery from end-of-life (EoL) consumer products depend on multiple factors. Some products are relatively simple in terms of metal and other material mix, while others are very complex often containing high concentration of precious and rare metals. With insufficient scale, feasible options for recycling are significantly limited. The major efforts in managing e-waste in Australia, under the Product Stewardship Act 2011, include the collection services for EoL TVs, computers and related products, through establishing industry-funded co-regulatory agreements. A further progression along the recycling value chain is however hindered by a lack of scale for establishing the full recovery operations in the country, as well as by a lack of domestic application for recovered metals. Based on our previous work of estimating the stocks and flows of electrical and electronic equipment and their metal content, this paper provides further analysis of metal flows and value associated with e-waste. Notably, we estimate how this is currently captured and/or lost, and overview barriers and opportunities for retaining the 'wealth from waste' through progression along the metal value chain in Australia.

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1. Introduction

The metal recycling sector in Australia can be characterised as matured and well-established (Brulliard et al., 2012), although a significant part of metal scrap is still present in the mixed municipal waste stream and ends up at landfills (Randell et al., 2014). The opportunities for improvement exist at different stages in the recycling value chain (Golev and Corder, 2014), but achieving higher levels of domestic processing and metal recovery for already collected materials could deliver the most immediate and tangible benefits.

The existing practices and opportunities for material recovery from EoL consumer products depend not only on the presence of valuable elements in their content, but also on the complexity of products as well as scale of economically viable processing operations. Some products are relatively simple in terms of metal and other material mix; in this case, the conventional recycling operations include shredding, magnetic separation and eddy current (e.g. fridges, washing machines) (Khaliq et al., 2014; UNEP, 2013). However, many electronic products (e.g. computers, TVs, and mobile phones) are very complex often containing high concentration of precious and rare metals; the recovery of the latter requires a separate advanced processing through pyro- and/or hydrometallurgical operations (Khaliq et al., 2014).

The most recent efforts in managing problematic waste streams in Australia, under the Product Stewardship Act 2011, include EoL household batteries, mobile phones, and TVs and computers, through establishing co-regulatory agreements and stewardship programs for funding the collection of EoL electronic products (Gumley, 2014; Lane, 2014). A further progression along the recycling value chain is however still hindered by a lack of scale for establishing full recovery operations in the country. Domestic application for recovered metals in Australia is limited, and restricts the closing of material loops. To uncover the opportunities for circular use of resources, new innovations and incentives at different stages in the recycling supply chain are needed.

Based on our previous work of estimating the stocks and flows of electrical and electronic equipment and their metal content, this paper provides further analysis of metal flows and value associated with e-waste, and overviews the barriers and opportunities for retaining the 'wealth from waste' through progression along the metal value chain in Australia.

The paper is structured as follows. Firstly, the estimated total e-waste generation and its current regulation in Australia are overviewed in detail. Secondly, based on 2014 data, metal content

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and value are characterised and discussed for different e-waste categories. Thirdly, a generic model describing the value chain for e-waste collection and processing is presented and demonstrated in an Australian context. Fourthly, combining recent quantitative investigations in the EU with existing estimations in Australia allows for forecasting the likely destiny for e-waste in Australia, including highlighting captured and lost metal value within the e-waste recycling value chain. Finally, the results are discussed in the context of providing a base line and in contributing to establishing a viable business case for capturing value from e-waste recycling in Australia.

2. Overview of e-waste and its regulation in Australia

Since 2000, there has been a significant increase in EEE sales in Australia resulting in an eventual sharp growth of e-waste generation. In 2014, the estimated total and per capita e-waste have reached 587 Mt and 25 kg accordingly (Golev et al., in press); being in line with the world estimates of e-waste generation in developed countries, which are in the range from 18 to 28 kg per capita (STEP, 2015). The future forecast (2015–2024), however, predicts stabilisation of e-waste in Australia at 28–29 kg per capita, with the total volume closely following the growth in population (Fig. 1).

The definition and regulatory scope for e-waste typically can greatly vary between countries. In Australia, under the Product Stewardship Regulations 2011, the initial scope for 'regulated e-waste' has been limited to TVs, computers and monitors, printers, computer parts and peripherals. This has been followed by the introduction of the National Television and Computer Recycling Scheme (NTCRS), an industry-funded co-regulated product stewardship scheme. It supplements State, Territory and local government e-waste management, but does not entirely replace these activities yet. The level of coverage has been set to increase progressively, from 30% in 2012–13 to 80% in 2026–27 (OPC, 2015).

Up to a certain degree, the Australian NTCRS can be viewed as an analogue to the EU Directive on Waste Electrical and Electronic Equipment (2012). However, as mentioned earlier, its focus is primarily on TVs and computers, leaving other e-waste related items to traditional waste management practices. The latter includes the kerbside waste collection services and transfer stations managed by the State and Territory governments, commercial metal recycling operators, and to a lesser extent social enterprises (Lane et al., 2015).

There has been a recent critique of NTCRS, specifically for the lack of transparency of its financial mechanism, its prioritisation of the collection and disassembly services rather than product repair and reuse options, as well as its lack of incentive for material recovery domestically versus exporting segregated waste to international markets (Gumley, 2016; Lane et al., 2015). While there is public reporting by co-regulators of the Scheme (currently this includes four companies - ANZRP, MRI, E-cycle Solutions, and EPSA), the information on e-waste collection and recycling services provided outside of NTCRS is absent. This includes government and business funded collection services, as well as recycling operations that were not able to become or qualify for one of the co-regulatory arrangements. Nevertheless, despite the shortcomings, NTCRS helped to boost the development of e-waste collection and recycling services by providing a free of charge access for householders and small businesses in most locations across Australia.

The regulatory requirement for material recovery from e-waste in Australia is set at a minimum of 90% for the collection and segregation steps in the recycling value chain (in the regulatory documents, these are called recycling and processing steps). No requirement for the actual material/metal recovery (e.g. via smelting) currently exists (in the regulation, this step is called 'end market').

The mobile phones, printer cartridges and handheld batteries are examples of specific e-waste streams targeted by other waste management schemes in Australia. The Mobile Muster is the mobile phone industry's product stewardship program, started in 1998, with voluntary participation, accepting all brands and types of mobile phones, including associated batteries, chargers and accessories. Cartridges 4 Planet Ark (C4PA) is a part of voluntary Extended Producer Responsibility (EPR) program of major printer manufactures. Together with its partners, C4PA provides free of charge collection services for EoL printer cartridges in Australia, returning them back for remanufacturing and recycling. The Australian Battery Recycling Initiative (ABRI) was formed in 2008 by a group of diverse stakeholders involved in battery manufacturing, distribution, recycling, disposal, and related environmental regulation. Apart from promoting and assisting with existing battery collection services, the ABRI also leads the development and potential introduction of a product stewardship program for batteries in Australia. Table 1 summarises the regulatory schemes and industry programs for e-waste in Australia.

Some big household appliances (e.g. fridges and air conditioners) were also recently overviewed for potential regulatory control in the country (DE, 2014b). The assessment of different

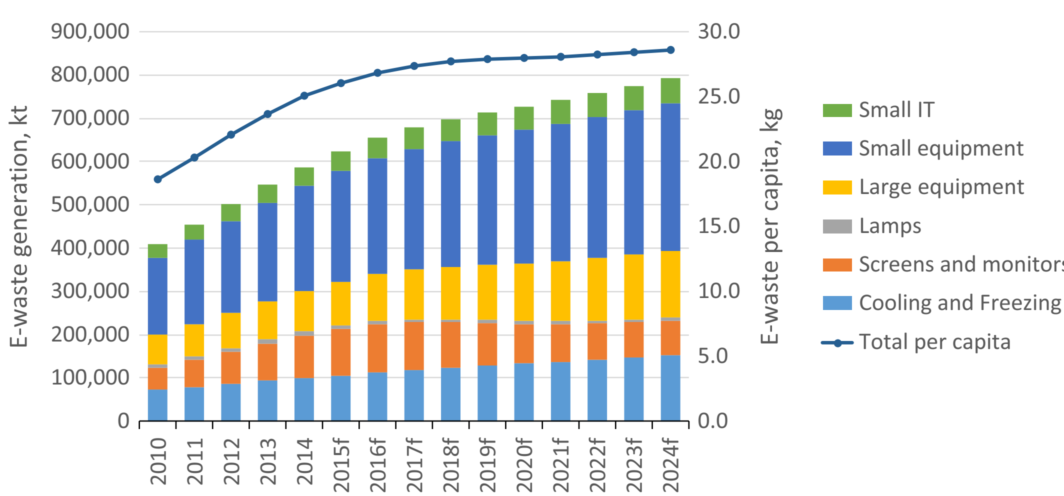

Fig. 1. Estimation of e-waste generation in Australia. *Data source:* Golev et al. (in press).

Table 1
Regulatory schemes and industry programs for e-waste in Australia.

Type of e-waste	E-waste category[a]	Applicable scheme or program	Collection results (latest reported)
TVs, monitors, laptops, tablets, desktops, printers, computer parts and peripherals	Screens and monitors, small IT	National Television and Computer Recycling Scheme, co-regulation, 2011	41,630 tonnes (2014/15)
Mobile phones (including batteries and accessories)	Small IT	Mobile Muster, voluntary, 1998	76 tonnes (including 423,000 handsets) (2015/16)
Household batteries	–	Australian Battery Recycling Initiative, voluntary, 2008	~403 tonnes (10 million batteries) (2012/13)
Printer cartridges	–	Cartridges 4 Planet Ark, voluntary, 2003	~1500 tonnes (4 million cartridges) (2015/16)

[a] According to WEEE-Directive 2012/19/EU (2012).

(co)regulatory scopes concluded that such a scheme would come at a significant additional cost to the public (DE, 2014a). Nevertheless, as the major content of fridges and air conditioners is steel and aluminium, these EoL products have been effectively scrapped for metal within conventional metal recycling operations in Australia, with the rest, also called shredder floc, being mainly disposed and lost for material recovery (e.g. plastic parts).

3. Metal content and value in e-waste

Metals represent a significant part of e-waste, both in volume and recovery value terms (UNEP, 2013). With limited options for recycling of mixed plastic, glass, and ceramics, metals are often the only truly recovered material from old electronic devices. The estimation for Australia shows that metal parts represented about 51 wt.% in total e-waste in 2014, followed by plastics (30%), glass (5%), and printed circuit boards (PCBs) (4%) (Golev et al., in press). The potential metal recovery value was estimated at US$ 370 million, with major contribution from iron/steel (29%), copper (26%), and gold (24%) (Fig. 2a).

Precious metals are mainly concentrated within PCBs, which has already made them a trading commodity on their own (as a raw material for metal recovery). Waste or discarded PCBs, while representing only about 4% by weight in total e-waste, contain about 40% (US$ 150 million) of metal recovery value (Fig. 2b). Among different electrical and electronic product groups, the EoL screens and monitors and small IT have the highest concentration of precious metals in PCBs on average and in total (Fig. 3). Not surprisingly, these are the only product groups covered by the e-waste regulatory scheme (NTCRS) in Australia. Overall, NTCRS covers about 20–25 wt.% of total arising e-waste in Australia, while in terms of metal recovery value it represents about 30–35% (US$ 120 m in 2014) (Golev et al., in press).

Data presented in Fig. 3 also shows that the recycling operations for EoL products can be driven by different metal groups, depending on their contribution to the total potential metal recovery value. For example, for small IT, screens and monitors, the major recovery value (~80%) is associated with PCBs (notably precious metals), while for other product groups the recovery of base metals makes the main economic sense. Other factors such as regulatory requirements for e-waste management and material recovery targets, selection of an appropriate technology and economic scale of operations have to be also taken into account for establishing (metal) recovery operations.

4. Value chain for e-waste recycling

In general terms, the recycling of e-waste starts with EoL products collection, followed by product disassembly and basic separation. The metal containing parts have to undergo several stages of transformation (such as shredding, separation, leaching, smelting, refining), including waste management for losses and/or by-products. The intermediate products in e-waste recycling can include ferrous and non-ferrous scrap, insulated metal cables, and PCBs, while final output is represented by refined metal or alloy, or fabricated metal products.

Several value chain options can occur in relation to e-waste recycling. As shown in Fig. 4, economic value generated by recycling operations increases along the value chain, and can vary from relatively low (e.g. metal scrap export) to very high (e.g. fabrication

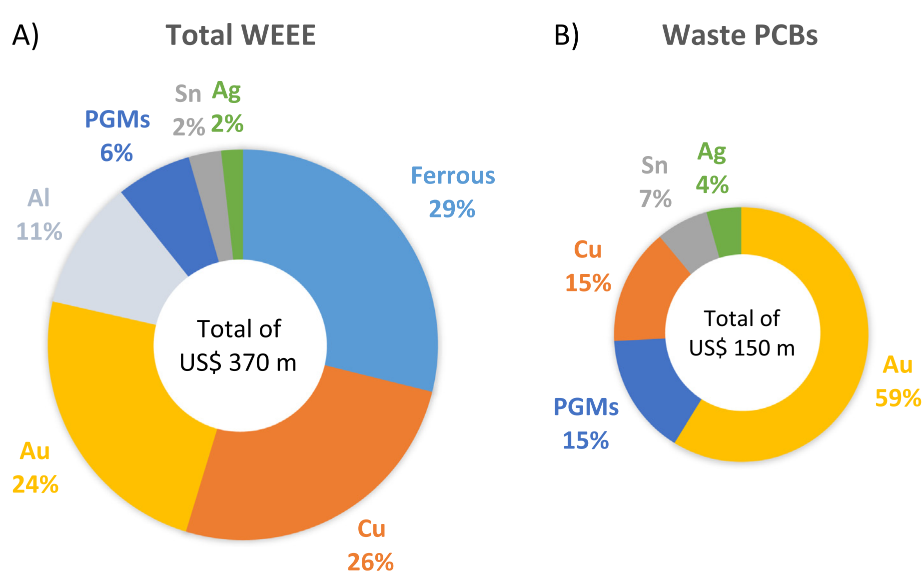

Fig. 2. Estimated major metals value in WEEE in Australia in 2014: (a) total WEEE; (b) waste PCBs. *Source:* Golev et al., (in press).

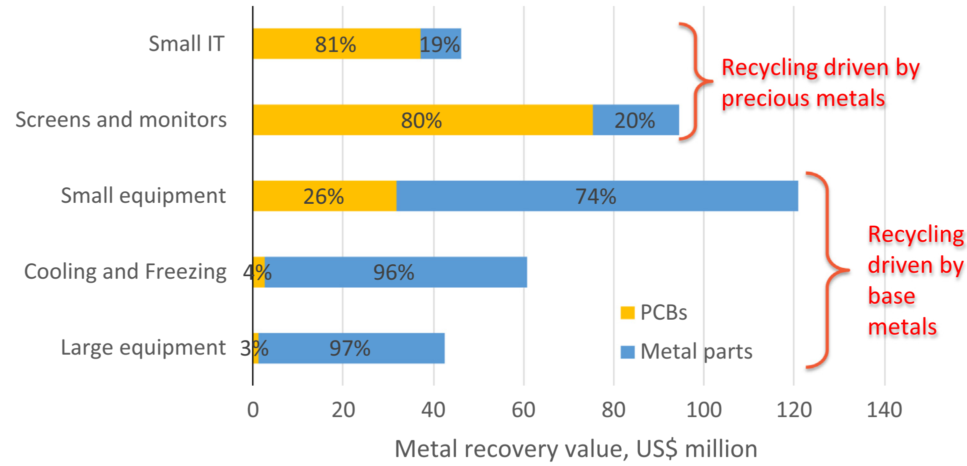

Fig. 3. Metal value in e-waste by product groups in Australia (2014). *Data source:* Golev et al. (in press).

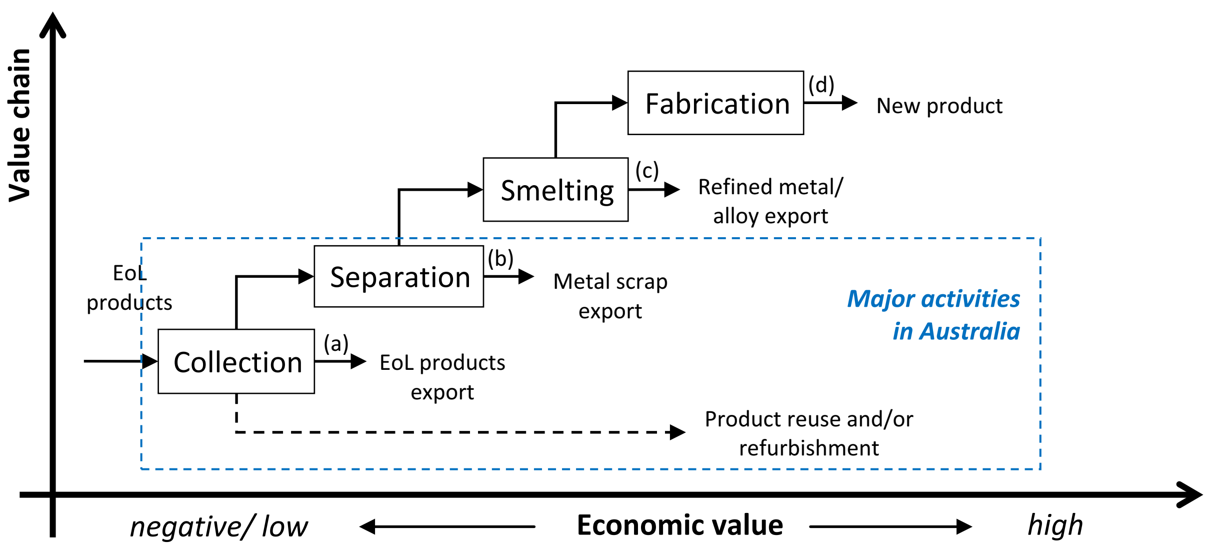

Fig. 4. Value chain for EoL products recycling. *Adopted from:* Golev and Corder (2016).

of new products). Although, the available options for progression along the value chain strongly depend on the associated costs for recycling in the specific region and/or the country under consideration (Golev and Corder, 2016).

Only the recovery of materials into new products (maintaining the original quality of recycled materials) can be characterised as a true circular use of resources. While this may be desirable to occur within one country, it is mainly achievable at the global scale due to the fact that many products are imported from overseas, and not all recovered materials/metals might be needed for domestic production. In every case, there should be a distinction for the appropriate supply loop for materials recovered from EoL products (WEF, 2014).

Existing e-waste recycling operations in Australia are mostly limited to collection and separation (disassembly) stages, indicated as (a) and (b) in Fig. 4. Only a small portion of ferrous scrap is processed domestically, while the majority of collected used electronics is sent for metal recovery overseas (Lane et al., 2015). Various commercial and not-for-profit organisations are involved in e-waste management in Australia. Local government and State government agencies, general waste recycling companies, e-waste collection and logistics actors, e-waste processing companies, industry associations and social enterprises are all playing their own role in this process (Gumley, 2016; Lane et al., 2015). The business model for bigger recycling companies usually incorporates most of the activities, while smaller players have to find their own niche in the e-waste recycling value chain.

The collected and separated e-waste also has to find its way to international markets for final material recovery. This includes processing facilities in China, Indonesia, Japan, Korea, Singapore, as well specialised metal smelting facilities in Europe (DE, 2016). It is still a question whether introducing these operations in Australia can make a viable business case (Golev and Corder, 2016); the starting point here would be an estimation of current destiny for e-waste, and its overall potential as a feedstock for a metal recovery plant. Nevertheless, the results in Fig. 3 suggest that there should be an economic incentive to focus on low-cost technology development (e.g. using hydro or pyro metallurgy approaches) that would allow Australia to extract greater value from e-waste and move further up the recycling value chain as shown in Fig. 4.

5. Understanding the destiny of e-waste

The information on e-waste arising and its destiny is limited worldwide. The reported data are mainly based on material flow analysis taking into account the annual sales of products and their

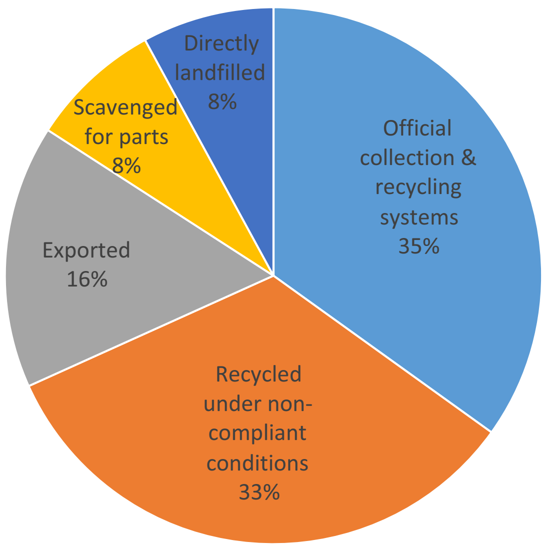

Fig. 5. E-waste destiny in the EU in 2012. *Data source:* Huisman et al. (2015).

expected lifespans (e.g. based on household surveys). The recent investigation into e-waste destiny in the EU has found that only 35% of e-waste in 2012 was collected and recycled within the official e-waste recycling systems (Huisman et al., 2015). A significant part (33%) was estimated as recycled under non-compliant conditions, which includes bulk scrapping of mixed EoL products and metal waste. It was estimated that the materials received by metal scrapping companies in the EU contain at least 2% of WEEE (mainly steel dominated consumer appliances). It has also been found that a significant part of EoL EEE (16%) is exported, including both documented and undocumented exports of used equipment and waste (Fig. 5).

As there has been no similar investigation for e-waste destiny in Australia, we have used the EU results as a basis for estimating the likely e-waste destiny structure in Australia. We believe this to be a suitable assumption for the purposes of the estimation given the relative similarities in GDPs per capita, adjusted for purchasing power parity, between Australia and the EU countries (World Bank, 2016), as well as similar e-waste generation per capita (STEP, 2015).

Due to relatively isolated location of Australia, we have assumed that export for reuse is lower compared to Europe, and represents no more than 10% of arising e-waste. This is also supported by the trade statistics data which shows that EEE exports (including used EEE) account for up to 10% of imports in the same year (UN Comtrade, 2015). Australian and New Zealand Recycling Platform (ANZRP), one of the co-regulators for NTCRS, recently highlighted that there is a significant export of used IT products from Australia (up to 40–50%), especially business related equipment, while other types of e-waste are primarily collected for material recovery (ANZRP, 2015).

The EoL product collection rates significantly vary between different product groups, and can be as high as 90% for large appliances, e.g. assessed by industry experts in Australia for cooling and freezing equipment (DE, 2014b), and as low as 50% for small equipment (the low collection rates for this group have also been highlighted in the EU investigation). An additional consideration is also required regarding losses in the collection and disassembly processes. According to the NTCRS reports, these account for up to 10% (e.g. broken small pieces, and contaminated parts). Average material losses with shredder floc in conventional recycling operations, e.g. for large appliances via shredding and eddy current separation, are estimated at 35% (with major content being plastics, rubber, glass, textile, and a certain per cent of metal) (DE, 2014b). The metal content in shredder floc is in the range from 6 to 13 wt.% according to Sustainability Victoria (2014).

Combining these data with previous results from material flow analysis on e-waste in Australia (Golev et al., in press) allowed us to produce an indicative estimation of e-waste destiny (Fig. 6).

Out of total 587 kt of e-waste arising in Australia in 2014, about 10% were exported for reuse, 65% collected for material recovery, and 25% ended up in landfills (Fig. 6). About a quarter of collected and processed materials (26%, or 100 kt) is further lost in recycling operations (e.g. with shredder floc). This resulted in total for recovered materials at 280 kt or about 48% of arising e-waste. The same ratio for metals was estimated at 66% (200 kt of recovered metal scrap out of 302 kt of estimated metal content in arising e-waste). The total metal losses associated with e-waste in Australia are close to 100 kt (worth about US$60–70 m), with major loss occurring due to some of the EoL products being still landfilled.

Primarily exporting recovered metal scrap (and other metal contained commodities) from Australia for further processing overseas, versus domestic processing, also results in an economic

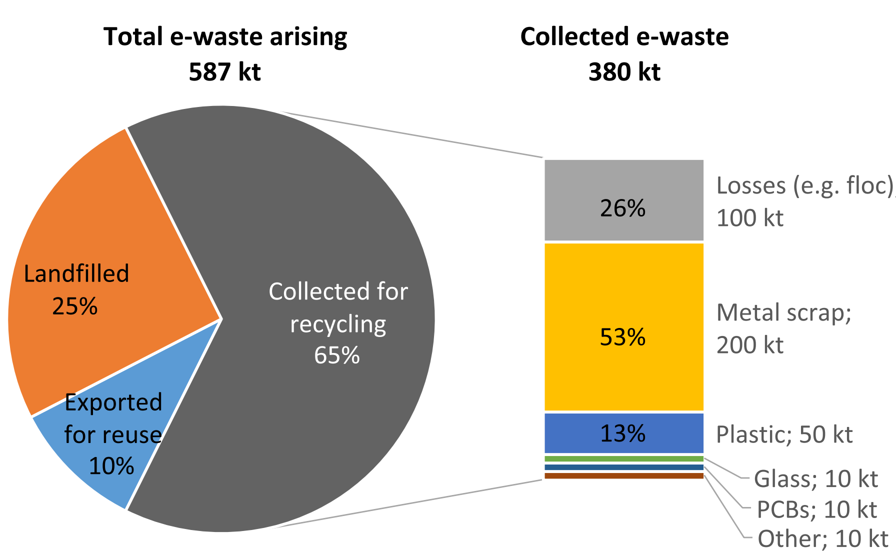

Fig. 6. Estimated e-waste destiny in Australia (2014).

loss. We estimated this loss in the range from 40 to 50% of potential revenue for recovered metals, which equals up to US$100 m a year. A significant part of the latter is attributed to precious and other metals contained in PCBs.

Compared to primary ores, PCBs have much higher content of copper, gold, silver, and PGMs. For example, gold content in discarded PCBs vary from 10 to 20 g/t (low grade materials) to up to 600 g/t (high grade materials), while existing open-pit mines can be profitable with gold grades close to 1 g/t of ore (Reuter and van Schaik, 2016). Our estimation for Australia in 2014 shows that an average gold content in discarded PCBs from small IT, screens and monitors was in the range of 120–150 g/t (Golev et al., in press). This evidences that there may be already good opportunities for a feasible small scale operation for metals recovery from PCBs in Australia, e.g. through pyro-metallurgical route (Ghodrat et al., 2016), versus current practices of their export for processing at large specialised recycling facilities in Asia and Europe (Khaliq et al., 2014).

In order to analyse the recovery (or loss) for specific metal in e-waste, the results presented in this section can be also combined with information on metal content for different product groups. Apart from identifying losses in the collection and disassembly processes, this analysis also helps uncover new opportunities across the metal value chain and specific commodity collection and processing pathways.

6. Conclusion

The EoL products, specifically e-waste, can represent a waste burden if handled inappropriately or a secondary resources supply opportunity if managed responsibly. Australia generates a significant amount of e-waste, estimated at 587 kt in total or 25 kg per capita in 2014. The legislation around e-waste in Australia is primarily driven by product stewardship and co-regulatory arrangements, with NTCRS being the major scheme defining the development of e-waste collection and recycling services. Despite some shortcomings, it undoubtedly has accelerated the establishment of accessible and free-of-charge e-waste collection services across the country resulting in significantly reduced amounts of e-waste going to landfill.

The estimated metal recovery value from e-waste in Australia in 2014 was about US$ 370 million, including US$ 120 m (or 32%) for EoL products covered by NTCRS. Waste PCBs represent the most valuable part for recycling, accounting for about 40% of metal recovery value in total e-waste, and up to 80% for EoL products under the NTCRS due to significantly higher precious metals content in the TV screens and computer monitors, and small IT.

Combining the results from the EU study on e-waste destiny with existing information on e-waste in Australia indicates that:

- up to 10% of total arising e-waste in Australia is exported for reuse;
- about 65% is captured for recycling through different collection systems;
- and up to 25% ends up in landfills.

Out of 65% of collected e-waste, about a quarter is further lost in recovery operations. As a result, we estimated that total recovered materials account for about 48% of arising e-waste, while the same ratio for metals is 66%. From a metal recycling point of view, only a small portion of recovered scrap is processed domestically, while the majority of material streams obtained in the processes of EoL products disassembling, and/or shredding and separation are sent overseas.

The total metal losses with e-waste collection and recovery in Australia are estimated at 100 kt a year worth about $60–70 m (based on 2014 data), including landfilled products and recovery inefficiencies. The total economic losses across the metal value chain are assessed at about US170 m a year, which includes missed opportunities for domestic processing versus exporting metal scrap. Domestic metal recovery from waste PCBs has been identified as the major pathway for seizing additional value from e-waste. The development and establishment of feasible low-cost and small-scale hydro or pyro metallurgical operations is one viable pathway for achieving this.

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