WEALTH FROM WASTE

AUSTRALIAN OPPORTUNITIES IN A CIRCULAR ECONOMY FOR METALS

FINDINGS OF THE WEALTH FROM WASTE CLUSTER

WEALTH FROM WASTE CLUSTER

The Wealth from Waste Cluster is an international collaboration of researchers from the University of Technology Sydney (UTS), Monash University, The University of Queensland (UQ), Swinburne University of Technology (SUT) and Yale University.

In partnership with CSIRO and enabled by support from the Flagship Collaboration Fund and participating universities, the Cluster is charting a pathway to enable Australia's metals and minerals industries to prosper in a future circular economy and undertaking research to enable technologies and practices for secondary resource markets.

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Citation

Dominish, E., Florin, N., Giurco, D., Corder, G., Golev, A., Lane, R., Rhamdhani, A., Reck, B. and Graedel, T., Sharpe, S., Edwards, M., Benn, S., and Brooks, G. (2017). Australian Opportunities in a Circular Economy for Metals: Findings of the Wealth from Waste Cluster.

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ACKNOWLEDGEMENTS

The Cluster would like to acknowledge and thank the International Reference Panel members and supporters of the Cluster for their valuable contributions.

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EXECUTIVE SUMMARY

Wealth from Waste positions Australia for leadership in a future circular economy

In a circular economy of the future, new wealth will be created by designing for circular flows of materials and products. Waste would be avoided, and products, processes, and supply chains would be designed to maintain the usefulness of resources through multiple product-use cycles.

Metals are essential for society and vital for a circular economy. Currently only a small number of metals are recycled at a high rate and their production has significant adverse environmental and social impacts. The Wealth from Waste Cluster – bringing together the University of Technology Sydney, Monash University, The University of Queensland, Swinburne University of Technology, Yale University and CSIRO – has characterised Australian opportunities in a circular economy for metals; and, identified the key data, technologies and policy changes that will enable the transition.

The circular economy supports the broad global challenge of increasing the sustainability of resources. The Wealth from Waste research aims to position Australia for leadership in this shift.

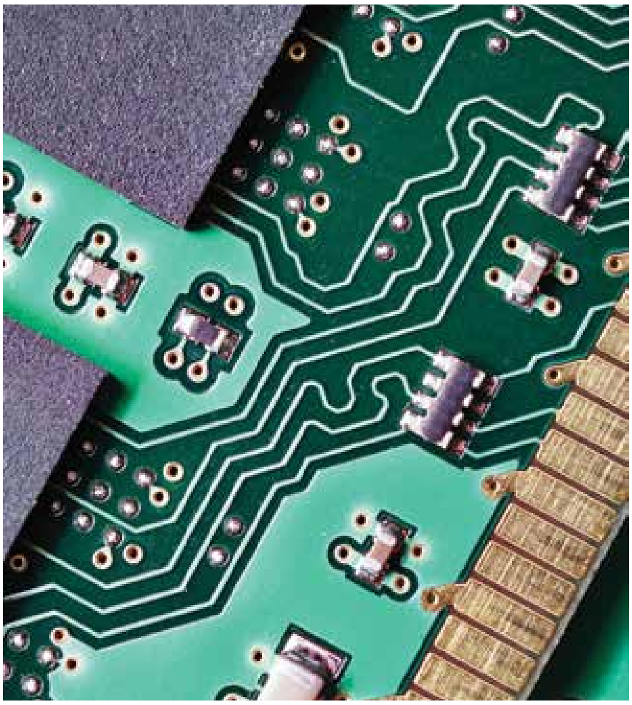
Circular economy opportunities for Australia at local and global scales

As one of the world's largest primary producers and exporters of metals, with comparatively low local demand for metals, Australia's shift to a circular economy will be embedded within global supply chains.

There is a significant opportunity to improve local recycling rates. Domestic processing of metal scrap is currently equivalent to 15 % of metal consumption, while up to 50 % may be possible, with a total material worth of $6 billion AUD.

Considering the global supply of 'critical metals', Australia not only has abundant domestic resources of major metals (aluminium, nickel, copper, iron ore and zinc) and specialty metals, but also has high potential for Australia's unconventional resources, such as mine tailings, to meet global demand.

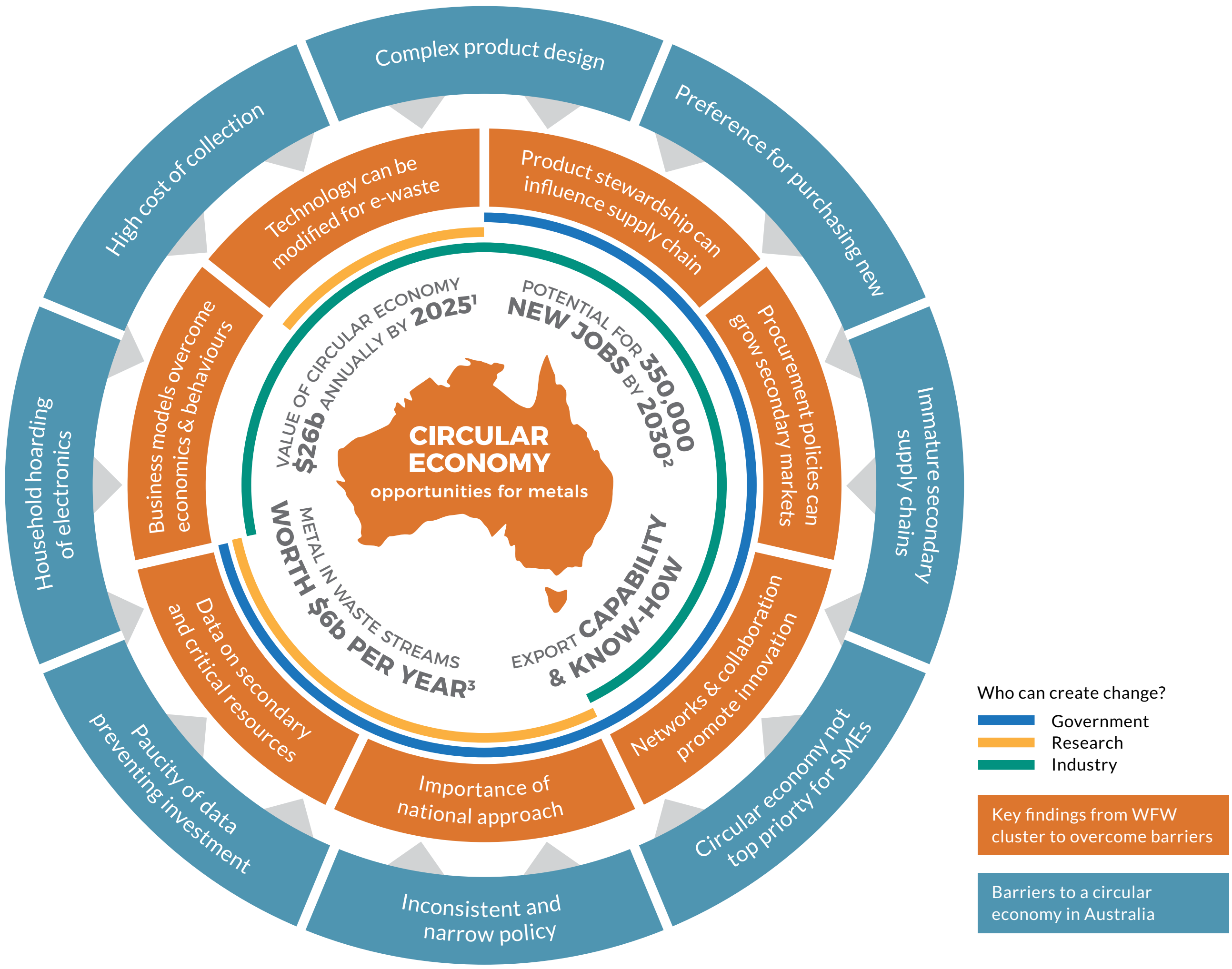
Australia has an opportunity to support the global shift to a circular economy through leading innovation in technology and new business models. Whilst the stocks of resources above ground and in mining waste represent a new opportunity to recover economic value and create new employment, the more significant value may not come from the resources, but from growing new local capabilities that can set Australia up as a future exporter of circular economy know-how.



Enabling the transition: identifying and overcoming barriers

Investment supporting a circular economy in Australia is limited by economic, technological, social and political barriers. Much of the un-recycled metals could technically be recycled but high costs of collection – owing to geography, market size, paucity of data and immature recycling and (re)manufacturing infrastructure – undermines economic drivers to recycle. There are also technological limitations arising from the complex design of products, and the lack of suitable existing technologies for processing. Social practices, such as hoarding of electronic products in households and a preference for new products, are a further barrier. At the same time, there is incomplete and inconsistent policy between jurisdictions, with a historical focus on policies for hazardous waste management, rather than on policies that focus on recovering waste as a resource in a circular economy.

Working collaboratively with government and industry stakeholders, the cluster research findings highlight key enablers connecting new above-ground resource data, technological innovation, novel business models, and policy change to help overcome these barriers to a future circular economy for metals. The figure below shows the major barriers (in grey) and summarises the cluster findings (in orange) that are aligned with the stakeholders who are best placed to create change.



A national approach encouraging investment in a circular economy

Developing a national circular economy approach for Australia – building on Wealth from Waste research and broadening the focus beyond metals – would encourage business and government to invest in innovative policy and strategies to increase the productive use of resources.

A national circular economy policy framework would build upon and connect success stories, already in train, across states like NSW, SA and Victoria. A nationally coordinated approach would bring a stronger focus on industry innovation, linking across Industry Growth Centre themes and connecting the whole supply chain.

In Australia, in addition to exporting bulk commodities, innovation in metals stewardship along the supply chain is a key enabler for accessing future high-value and sustainable markets where above-ground 'urban mines' are at least as important as below-ground ores. A national approach to a circular economy would help build a new local industry base, one which is prosperous in a global economic system being disrupted by resource and environmental constraints and the new business models of the digital economy. As a result, Australian industry will be more closely connected with the circular-focussed international landscape whilst delivering local economic, environmental, and social benefits.

1. Based on Australia's share of GDP and World Economic Forum (2014) estimates of the global material cost savings of a circular economy
2. Based on analysis by Lifecycles (2017), and scaled up to Australia according to population
3. From cluster research, see Corder et al. 2015

CONTENTS

HOW TO READ THIS DOCUMENT

After the Executive Summary, Chapter 1 describes the global context and drivers for a circular economy for metals. Reflecting on the global trends, Chapter 2 considers the Australian context and discusses the major barriers to change. These barriers provide a frame for the Cluster research that was targeted to address specific challenges. Chapter 3 presents the cluster research findings addressing resource data gaps, Chapter 4 is focused on essential technological innovation, Chapter 5 examines how new business models and practise can drive change, and policy research findings and recommendations are presented in Chapter 6. Drawing together the Cluster research findings, Chapter 7 articulates critical change pathways that support a transition to a circular economy for metals in Australia.

WEALTH FROM WASTE

INSPIRING SMARTER AUSTRALIAN RESOURCE INDUSTRIES OF THE FUTURE

The Wealth from Waste Cluster research starts from the premise that Australia's role as a global leader in primary production of minerals and metals must anticipate and adapt to the implications of the future economy where new wealth is created by redesigning for circular flows of resources. In a circular world, waste is treated as a valuable resource, and products, processes, and supply chains are transformed to exploit this opportunity.

The Cluster is an international collaboration of research groups bringing together the University of Technology Sydney, Monash University, The University of Queensland, Swinburne University of Technology and Yale University. In partnership with CSIRO and an International Reference Panel, the Cluster has established a new research network that has assembled the evidence base and is charting a pathway to future prosperity for Australia's metals and minerals industries.

Taking an integrated view of resource use and management along the whole metals and minerals value chain, the Cluster has developed new insights for Australian industry and research by:

(i) Evaluating the potential resource base from urban mines in Australia

(ii) Characterising viable technological approaches for recovery of metals from waste streams

(iii) Identifying and examining innovative business models for capturing new value

(iv) Appraising the key policy levers, including product stewardship approaches, to support successful recycling and collection systems

To see further outputs from the cluster including reports, journal papers and policy briefs, see **www.wealthfromwaste.net**

UTS UNIVERSITY OF TECHNOLOGY, SYDNEY

Yale SCHOOL OF FORESTRY & ENVIRONMENTAL STUDIES

CSIRO

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

MONASH University

SWINBURNE UNIVERSITY OF TECHNOLOGY

1 A GLOBAL VISION FOR SUSTAINABLE RESOURCE FUTURES

WHY ARE CIRCULAR FLOWS OF METALS IMPORTANT?

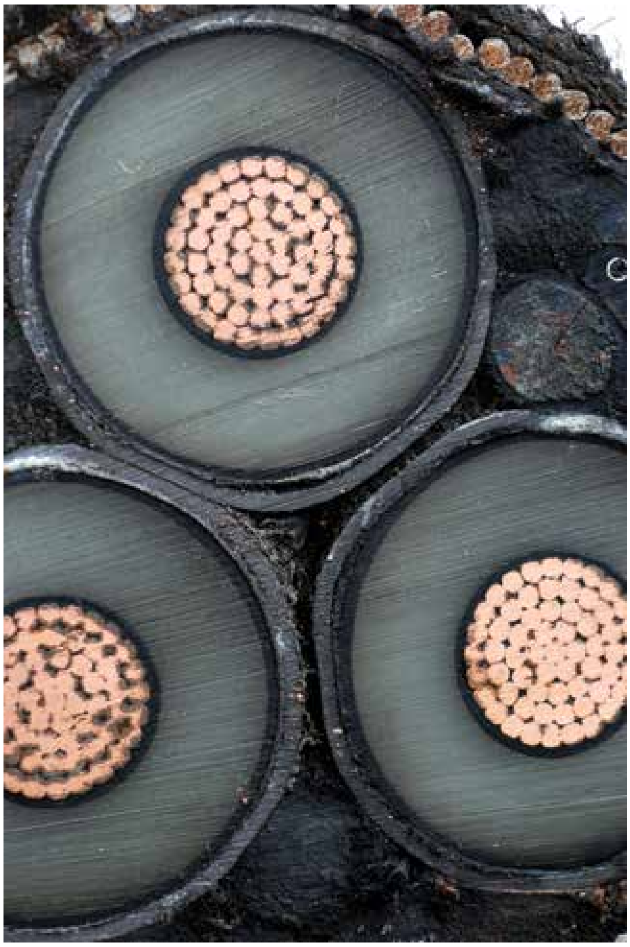
Modern society is deeply dependent on metals. They are essential materials for products and infrastructure in transport, food production, housing, water treatment, and energy generation. This dependence is anticipated to grow, particularly if we are to meet the ambitious targets of the United Nations Sustainable Development Goals and the Paris Agreement on climate change (Ali et al., 2017). New low-carbon technology and expanded infrastructure relies on the availability of diverse mineral resources in substantial quantities (Hertwich et al., 2015). At the same time the average quality of primary ore grades is declining, leading to rising impacts from primary production; and, stocks of secondary metals are increasing in products, infrastructure and waste. Thus, global metals recycling and reuse will be an increasingly important source for metal supply in the future (e.g. Mudd, 2010, Northey et al., 2014), for widely used metals such as copper, steel and aluminium, and for specialty metals such as lithium and indium.

The importance of increasing the sustainability of resources in industry and society has been recognised globally through the inclusion of Goal 12: Responsible Production and Consumption as one of the 17 Sustainable Development Goals. The aim of the goal is to "do more and better with less" through the sustainable management and efficient use of resources and by substantially reducing waste generation through prevention, reduction, recycling and reuse by 2030 (United Nations, 2016).

The International Council on Mining and Metals acknowledges the importance of improving the efficiency of metals resource use to meeting this goal (ICMM, 2017). Increasing circular flows of metals will have benefits for many other sustainable development goals; promoting decent work, industrial innovation and action on climate change.

In Australia, research on a future vision for mining and metals positions innovation in metals stewardship along the supply chain as a key enabler to exporting high-value circular economy know-how, technology and services, in addition to bulk commodities (Mason et al., 2011). In this sustainable future, below-ground ores and above-ground 'urban mines' are both promising frontiers for sustainable resource utilisation and management.

Achieving this goal is challenging due to the transformation required in the structure of existing industries and markets, the concerted action required to scale-up niche innovation and to change consumer practices and regulatory environments, in addition to making technical breakthroughs. Yet, significant activity around the world is growing in response to this challenge, including through the EU Raw Materials Knowledge and Innovation Community (KIC) to promote innovation and entrepreneurship (EIT, 2017), the ProSUM project developing a database on secondary sources of critical raw materials in products and mining waste (ProSUM, 2017), and the 'Indicators for a Resource Efficient Green Asia and the Pacific' project (UNEP, 2015). There are also active research programs at Helmholtz Institute Freiberg for Resource Technology (Germany), the Critical Minerals Institute (USA) and National Institute of Environmental Studies (Japan). The Wealth from Waste Cluster was developed to ensure Australian industry, research and government are connected to the unfolding global opportunities for metals, and other resources, in a circular economy.



HOW CIRCULAR ARE GLOBAL FLOWS OF METALS TODAY?

Presently only a relatively small number of metals used in society are recycled at a high rate, excluding bulk metals such as steel (e.g. Graedel et al., 2011; Reuter et al., 2013) (Figure 1).

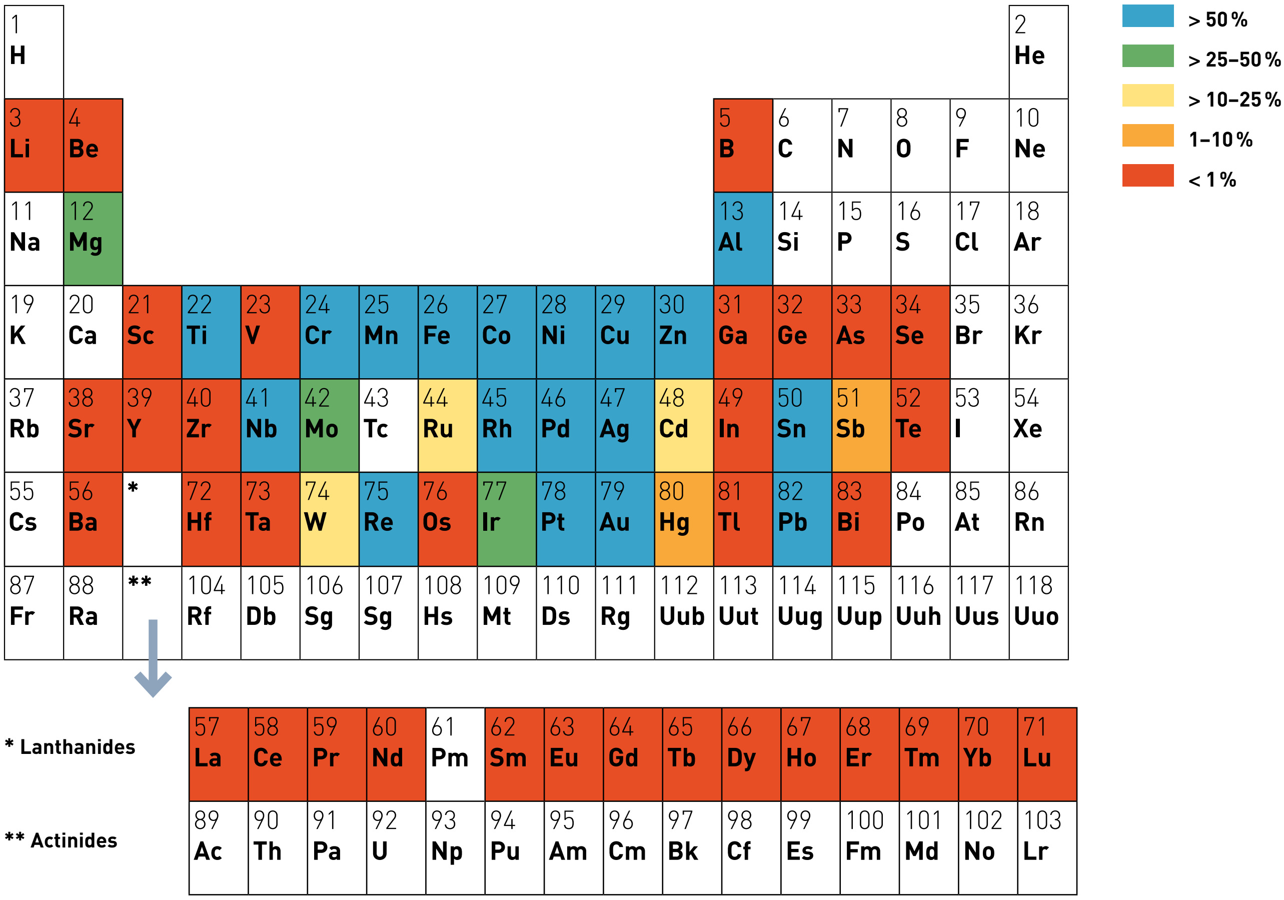


Figure 1: End-of-life recycling rates for sixty metals (Graedel et al., 2011)

In some cases, it is the cost associated with collection and separation that limit metal recycling rates; however, in many cases this cost barrier is also linked to technological limitations. It is not always possible to separate mixed metals from an alloyed form or product, for example, no technologies are presently available to recover rare earth metals from complex electronic products. The design of products and infrastructure plays a key role in recyclability, yet its importance is often overlooked and its influence has not been comprehensively assessed at the global scale. This type of 'loss by design' has been characterised by Yale researchers and provides a guide to where efforts could be focused to improve the circularity of metal cycles (Ciacci et al., 2015).

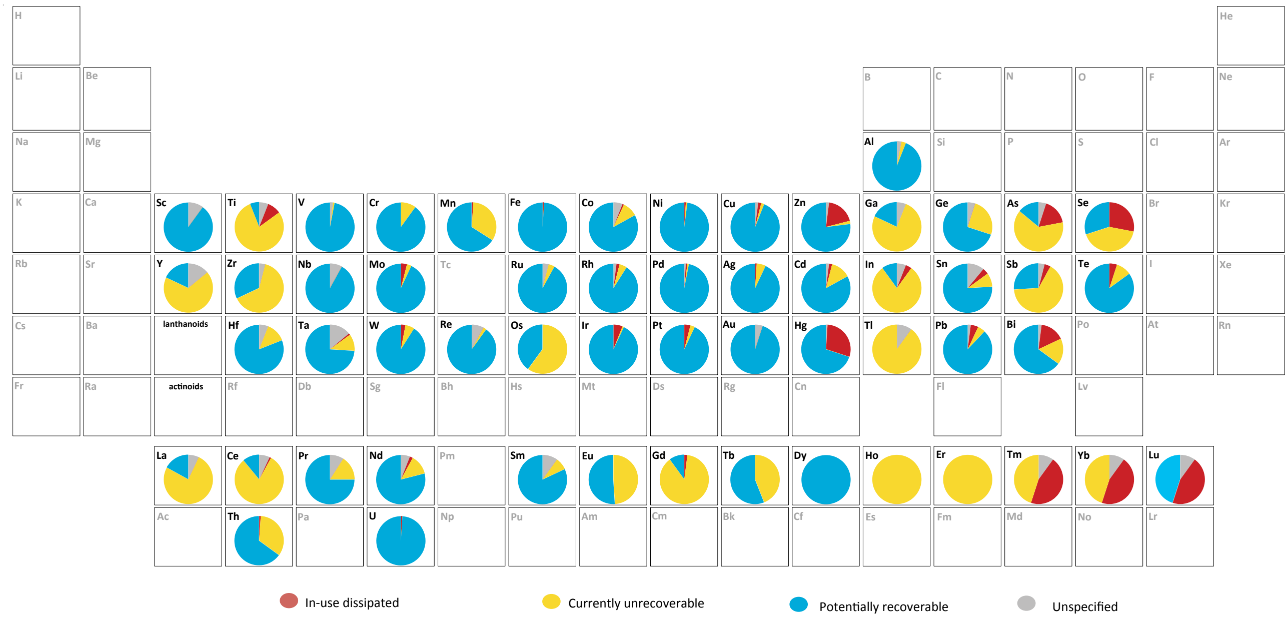


Figure 2: Distribution (%) of metal elements 'lost by design' from Ciacci et al., 2015

Four categories of how metals are 'lost by design' are defined as:

- i **In use dissipation:** the flow of materials for which dispersion into the environment occurs by design, preventing recovery at end-of-life, e.g., zinc for sacrificial anodes;
- ii **Currently unrecyclable:** material flows for which technological or economic barriers prevent end-of-life recovery, e.g., rare earth oxides used in glass polishing powders;
- iii **Potentially recyclable:** the flow of materials where today's technology could but isn't currently used for recovery, e.g., alloying elements;
- iv **Unspecified:** material flows that were not categorised owing to a lack of available data.

Figure 2 shows that most of the material losses currently occurring may be categorised as 'currently unrecyclable' and 'potentially recyclable'.

This implies that to increase the circularity of metals a broad focus on technology (for product design and processing) and business model innovation is required, as well as targeted policy interventions to overcome technological, economic and social barriers.

WHAT IS THE CIRCULAR ECONOMY?

The circular economy is a contemporary framing of ideas from industrial ecology (Graedel and Allenby, 1995) and other concepts such as cradle-to-cradle (McDonough and Braungart, 2002), regenerative design (Lyle, 1994) and biomimicry (Benyus, 2002). The essential focus of these perspectives is the imagining of industrial production and consumption systems as similar to biological systems, with minimal losses or waste, where waste and by-products from one set of industrial activities is treated as inputs for other activities. The circular economy framing gives explicit focus to the role of business in enabling circular resource flows.

A recent definition of the circular economy is "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by **slowing, closing, and narrowing material and energy loops.** This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling" (Geissdoerfer et al., 2017). 'Slowing' emphasises the importance of designing for durability and longevity, as well as modifying patterns of consumption to promote sufficiency; 'Closing' emphasises recycling, remanufacture, repair and reuse; and, 'narrowing' refers to efficient resource use by doing more with less.

Implementation of circular economy worldwide

The idea of a circular economy has gained prominence in the past decade – it is on the agenda of policy makers (e.g. EU, China, Japan, South Australia), organisations are promoting the opportunities for business e.g. the work of Ellen MacArthur Foundation, the World Economic Forum and World Resources Forum, and there is a growing body of academic research.

In Europe the growing interest in a circular economy is driven by the need for resource security and creating sustainable employment. Implementation has been led through EU level directives that mainly target responsibility of producers for collection and recycling of waste products and cleaner manufacturing. Japan was an early adopter of the idea of a "Sound Material-Cycle Society", driven by scarcity of land, materials and energy. In China, an initial focus on waste management and cleaner production has broadened its focus to closing the loop on resources, energy efficiency, conservation and environmental management.

A circular economy for metals

Metals are inherently recyclable, as they retain their utility for multiple product lifecycles. However, a range of technical, economic, and social factors limit current recycling and reuse rates. Considering metals recycling, a number of factors limit the extent to which we can close the loop:

- There is often a significant lag between the metals input to the market and when they become available for recycling (Graedel et al., 2011)
- As demand for metals grows, future reuse and *recycling can only meet a part of* future demand, as the amount of metals in today's market is larger than yesterday's input amount
- Collection and separation systems for recovering secondary metal stocks are insufficient
- Based on current technological processes there are material losses throughout a product's lifecycle (including dissipative losses during use such as corrosion)
- At a fundamental level, thermodynamics establishes a physical limit to the extent that metals can be 'unmixed' for recycling (Reuter et al., 2013)
- Recycling activities require large inputs of energy (despite the potential energy savings compared to primary supply)

The upper limit for recycling and reuse efficiencies highlights the importance of slowing and narrowing material loops, and emphasises the need to focus on sufficiency and changing patterns of consumption that can support a reduction in total demand for resources.

Notwithstanding these limitations – there is significant value in the circular economy agenda in engaging diverse stakeholders from business, politics, education and research to strive for circular flows of resources and developing strategies for mitigating the adverse social and environmental impacts associated with their production and use.

2 AUSTRALIAN CONTEXT

Australia's rich stocks of mineral resources are a significant source of national wealth and competitive advantage in the global economy. The mining and metal industries within Australia reflect the extractive economy, with many companies operating at the front-end of the supply chain.

The resources sector continues to be Australia's largest export earner as of 2016, with $110 billion of export revenue annually, despite weakening global prices for iron ore (Austrade 2017). The Mining Equipment, Technology and Services (METS) sector also exports $15 billion each year in products and services to 200 countries (Austmine, 2013).

The energy sector has historically also created a competitive advantage for the economy, as cheap energy has supported the success of energy-intensive businesses in Australia, including mining. This energy-price competitiveness has declined over the last decade owing to the rapid increase in energy prices compared to similar countries worldwide, which has been acknowledged through a focus on energy productivity in industry and government (Stadler et al., 2014). Productivity in the mining sector has also declined over the past decade, owing to declining ore grades as well as rising energy costs (Prior et al., 2012). Whilst there is now a focus on increasing resource productivity in the mining sector, its broader profile in the policy landscape needs strengthening.

At the end of the supply chain, there are a number of businesses active in the scrap metal and e-waste recycling industries. Recent years have been difficult for the sector owing to a decline in metal prices and a downturn in manufacturing resulting in lower demand. These pressures have led to industry consolidation such that a small number of major players dominate the Australian scrap industry for ferrous and non-ferrous scrap, and also for e-waste.

Currently there is very limited coordination between the mining and recycling sectors in Australia (Florin et al., 2015). In a more circular future, Australian industries will need to be engaged in wider business across the global value chain to support, and benefit from, new circular economies for metals.

HOW CIRCULAR ARE THE FLOWS OF METALS IN AUSTRALIA?

Australia's current supply chain is dominated by export

Australia's metal extraction capacity is much larger than local demand for metal bearing products and product manufacturing capabilities. Australia is one of the world's largest producers of aluminium, nickel, copper, iron ore and zinc – exporting several of these mined metals in refined form, while importing much smaller amounts of these metals in the form of semi-finished and finished products. This dominant role in global primary production means that Australia's ratio of primary resources to urban mine resources — resources available above ground in existing products and infrastructure — is atypical for countries with a long history of high living standards, generally associated with high metal use per capita (Werner et al., 2017a).

Explainer: categorising metals

Metals that are used in large quantities are referred to as 'base or engineering metals', e.g., aluminium for transportation, iron for steel and copper for wires and cables. 'Specialty metals', typically used in smaller quantities compared to engineering metals play an important role in manufacturing including 'rare earths' (RE) with diverse uses in high-technology manufacturing applications such as permanent magnets for hybrid electric vehicles and wind turbines. 'Precious metals' are generally characterised as scarce metals with high economic value, including: gold, silver, and platinum group metals. The application of precious metals is often in small quantities, e.g. platinum and palladium catalysts.

To appraise the value of above ground stocks in the context of primary resources the Cluster research from the University of Queensland provides new data on the size, composition, age and net increase in current in-use stocks (scrap generation and accumulation). Figure 3 shows the flows of major metals into and out of Australia for 2002 and 2011 (Golev and Corder, 2016). In-use stocks are in the same order of magnitude of Australia's annual metal production and the net increase in in-use stock is roughly equivalent to the metal content in waste streams, representing about 50 % of annual metal consumption (Figure 3 b). Over the decade of analysis the consumption rates have grown by about 40 %. The total volume of scrap metal generated is dependent on consumption with a 15–20 year delay in availability, and end-of-life recycling rates are currently well under their potential. Additionally, whilst the current trend shows an increase in scrap collection the proportion that is processed domestically has decreased and instead is exported overseas. Thus, recycled metal flows are only likely to make a small contribution toward reducing demand in the near-term.

Figure 3a. Metal flows in Australian economy 2002 (Golev and Corder, 2016)

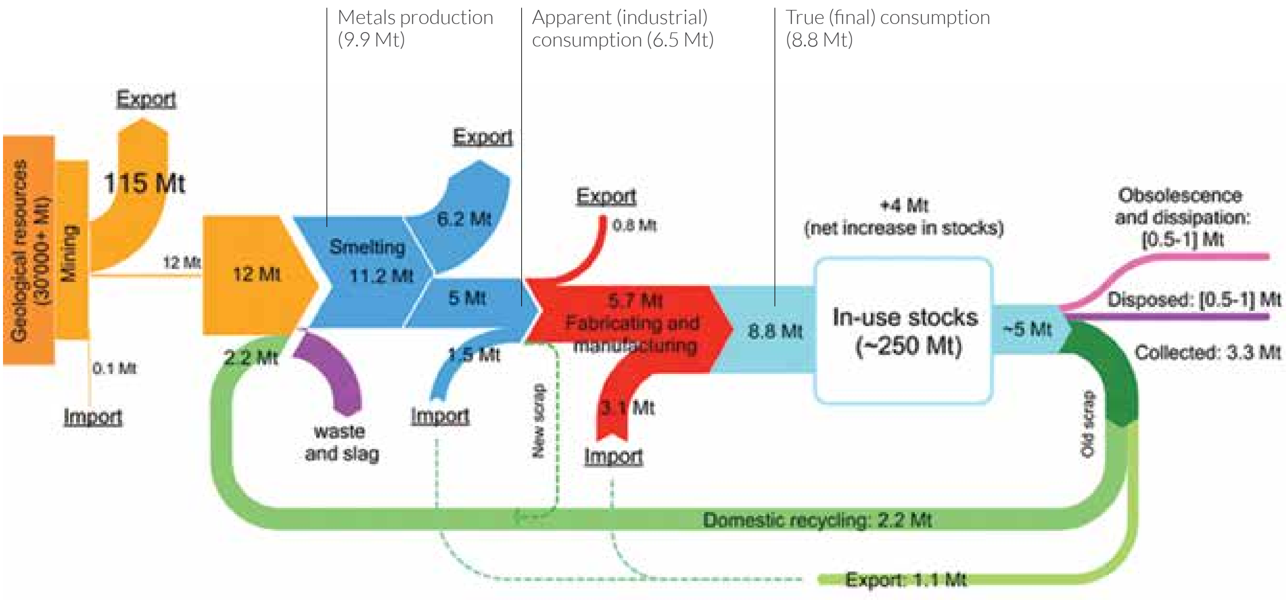
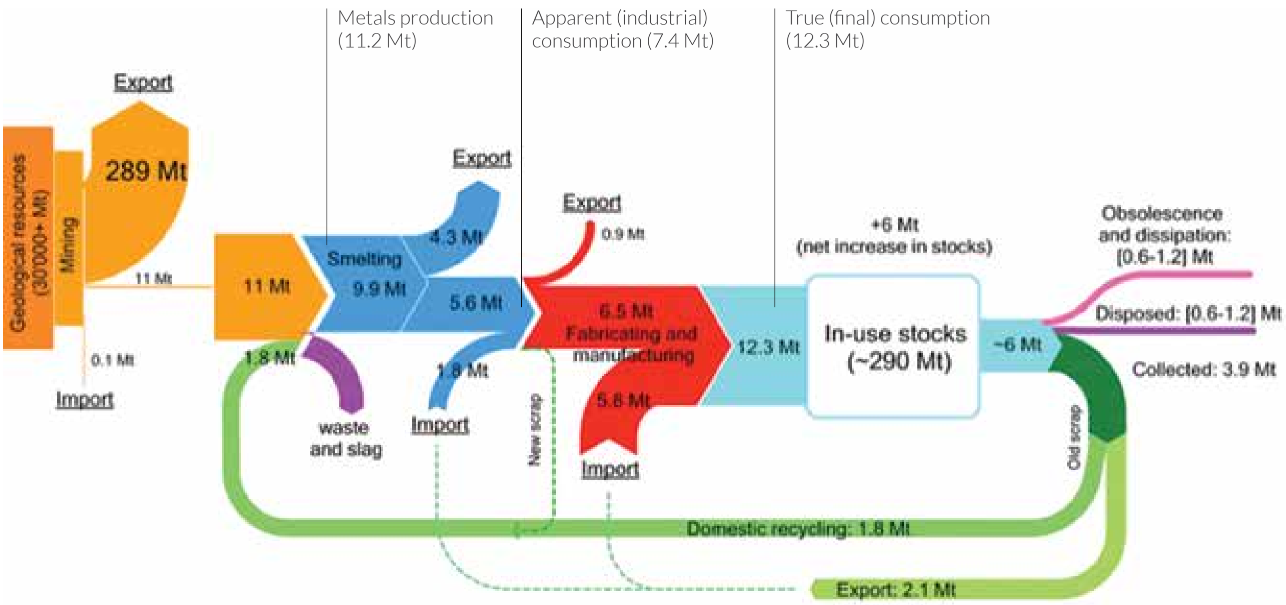


Figure 3b. Metal flows in Australian economy 2011 (Golev and Corder, 2016)



Note: all figures are estimated for 100% metal content.

Analysis by the University of Queensland 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 to 270 kg per person respectively. The amount of collected metal scrap grew from 3.3 million tonnes to 3.9 million tonnes, with the overall collection rates remaining 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 equals approximately 50% of the country's final metal consumption but current domestic processing of metal scrap is equivalent to 15% (Golev and Corder, 2016).

WHY FOCUS ON ELECTRONIC WASTE?

E-waste is a significant opportunity to minimise impacts through recovering valuable metals

The functioning and miniaturisation of electrical and electronic products — mobile phones, tablets, computers, and televisions — depends on the physical properties of precious and specialty metals, such as gold, silver and indium. The mining and processing of these metals often results in significant adverse environmental and social impacts which can be minimised by recycling these metals to create secondary sources, yet many electronic products end up in landfill at the end of their useful life (Figure 4). In some cases, they are exported to countries that do not have stringent management strategies to mitigate further environmental or social impacts from the recycling process. For example, Li-ion batteries ending up in landfill can cause environmental impacts if hazardous elements leach into the soil or water, and present a safety risk to waste handlers and processors owing to their flammability (Randell, 2016). Recently the recovery of valuable metals from e-waste has attracted significant attention to reduce these potentially adverse environmental and social impacts (Balde et al., 2015).

E-waste has been one of the fastest growing waste streams

University of Queensland cluster research has found that on average, each Australian purchased 35 kg of electrical and electronic equipment (EEE) in 2014 while disposing of 25 kg of waste electrical and electronic equipment (WEEE) and possessing approximately 320 kg of EEE. A future projection from 2015 to 2024 (with EEE sales fixed at the current level of 35 kg per capita in the base scenario) predicts stabilisation of e-waste generation in Australia at 28-29 kg per capita, with the total amount continuing to grow to 792,000 tonnes by 2024 aligned with population growth (Golev et al., 2016).

In total, 587,000 tonnes of e-waste was generated in Australia in 2014 with about 10 % exported for reuse, 65 % collected for material recovery, and 25 % ending up in landfills (Figure 4). Considering the fraction collected and processed for recycling, a further 26 % is lost in recycling operations (e.g. with shredder floc, a mix of metals and other waste streams from scrap metal processing) that is estimated at ~100,000 tonnes, worth about US$ 60–70m (based on 2014 data). The total economic losses across the metal value chain are assessed at approximately US$ 170 m per year, which also includes missed opportunities for domestic processing versus exporting metal scrap (Golev and Corder, 2017).

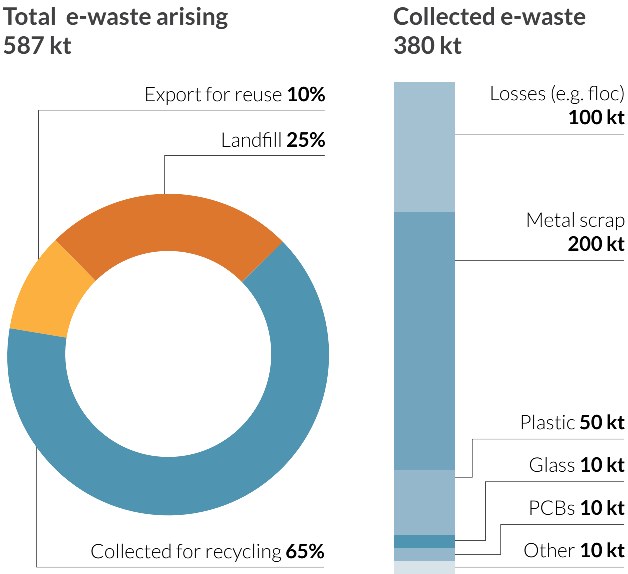
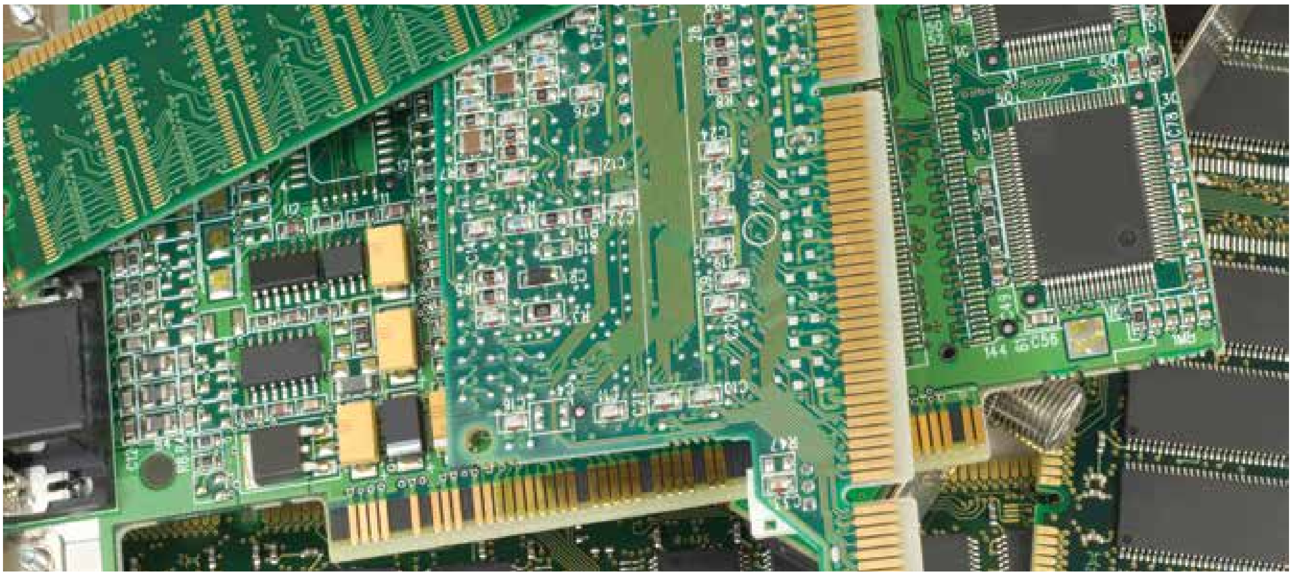


Figure 4. The best estimate of the destiny of WEEE in Australia (Golev and Corder, 2017)



E-waste processing and recycling is a growing market

E-waste processing is a growing sector in Australia, experiencing annualised growth rates of nearly 9 % for much of the past five years (IBISWorld, 2014). Presently e-waste business models are dependent on a variety of revenue sources including receiving revenue from councils for providing e-waste collection and processing services, from businesses to collect and transport waste off-site, from the sale of discarded electrical goods to repair and refurbishment companies, and from the sale of discarded e-waste for metals recovery. A major driver for industry activity in this sector is the National Television and Computer Product Stewardship Scheme (NTCRS) under the Product Stewardship Act 2011, discussed in detail in Chapter 6. Industry profitability depends upon contract wins, service costs, wage levels, the price of second-hand electrical and electronic goods, and the volumes and material value of recovered resources.

The presence of precious metals such as gold, silver and palladium as well as copper and iron/steel represent a significant part of the resource recovery value. The potential metal recovery value for Australian e-waste was estimated at US$ 370 million, with major contributions from iron/steel (29%), copper (26%), and gold (24%). For printed circuit boards (PCBs) alone, which represent about 4% by weight of e-waste, the potential metal recovery for domestic industries is about US$ 150 million per year (Figure 5) (Golev et al., 2016). Domestic metal recovery from waste PCBs (rich in precious metals) has been identified as specific opportunity for capturing additional value from e-waste and the technical pathway is discussed in Chapter 4.

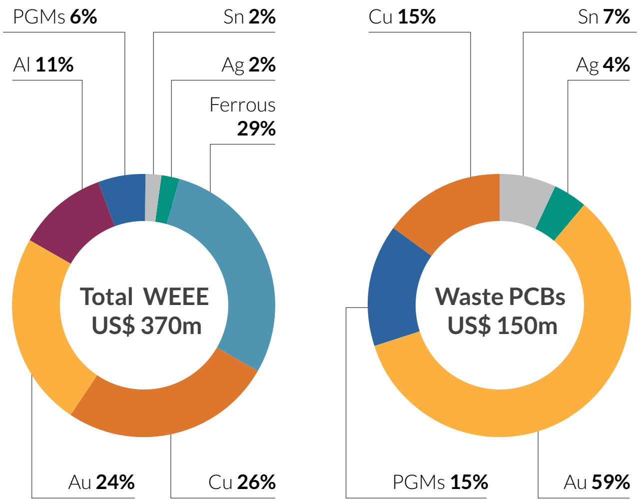


Figure 5. Estimated value of major metals contained in WEEE in Australia in 2014: a) total WEEE; b) waste PCBs (Golev et al., 2016)

ASSESSING CRITICALITY OF KEY METALS FOR SOCIETY

The importance of metals to society can be understood through the concept of material 'criticality'. Metals may be considered critical to society when they have high importance to providing essential services, such as copper or aluminium in electricity grids, or are used in technologies where substitution is difficult, such as indium in electronic products, combined with a supply risk due to geological or other factors and environmental implications. This raises the question of how vulnerable a society is to a disruption in the supply of a specific metal such as lithium for energy storage batteries. A systematic evaluation of 'criticality' provides important insights for future risk and enables new opportunities for industry and research to meet future demands for metals.

Graedel et al. (2015) have developed and quantified for 62 elements a measure of criticality (the 'Yale criticality methodology') based on three pillars:

(i) supply risk (based on geological, technological and economic, geopolitical, social and regulatory factors)

(ii) a country's vulnerability to supply restrictions (the importance, substitutability and susceptibility)

(iii) environmental implications.

Criticality is not a fixed value but changes over time in response to technology development and geopolitics, and varies between corporations or nations depending on who it is assessed for (Ciacci et al., 2016). National criticality assessments have been undertaken by most major economies and the results vary significantly at the country level owing to the existence of domestic resources and established production chains to meet demand. Geoscience Australia have assessed the potential for Australia's resources to meet demand for critical commodities, based on the commodities that are considered critical in assessments undertaken by major world economies including the UK, EU, US, South Korea and Japan (Skirrow et al., 2013), but this analysis does not consider how critical these metals are to Australia's economy and society (Ciacci et al., 2016).

As part of the Wealth from Waste cluster a criticality assessment was carried out for the first time for Australia, based on the Yale criticality methodology. The criticality of five major metals (Al, Fe, Ni, Cu, Zn) and for indium (In) in Australia is compared with the US and a global appraisal. At the country level, Australia's vulnerability to supply risk for Ni, Cu, and Zn is between 23% and 33% lower than that for the United States, largely because of Australia's abundant domestic resources. The assessment showed only a modest change in supply risk between 2008 and 2012 at both country and global levels; due to revisions in resource estimates. At the global level, supply risk is much higher for In, Ni, Cu, and Zn than for Al and Fe as a consequence of a longer time horizon and anticipated supply/demand constraints. The results emphasise the dynamic nature of criticality and its variance between countries and among metals (Ciacci et al., 2016).

There can be a perception that criticality is not of high importance to Australia due to our limited manufacturing industry, which require metal inputs, and our abundant resources. However understanding criticality from the point of view of Australia and the globe provides important insights highlighting new opportunities. For example, many of the specialty metals increasingly used in electronic devices are rated as critical (according to global measures). However, the stocks of these metals are poorly understood owing to many uncertainties relating to estimates of the resource of these metals, many of which are produced as a by-product of other base metal mining activities.

This highlights the value of measuring the criticality of metals to understand opportunity to recover them from unconventional resources such as e-waste and/or mine tailings. For example, later we discuss the case of indium that is produced as a by-product of zinc mining and exported at no added-value in zinc concentrate.

WHAT ARE THE BARRIERS TO A FUTURE CIRCULAR ECONOMY?

Stakeholder workshops with government, industry and researchers, held by UTS over the past three years have identified a range of barriers (see Table 1) which are preventing local investment in new infrastructure, technology and logistics, limiting the uptake of reuse and recycling and the creation of new circular economy businesses.

The Cluster research has contributed to addressing these barriers through research on data, technology, new business models and supporting policies, discussed in turn in Chapters 3-7.

Table 1: Barriers influencing investment in circular economy in Australia

ECONOMIC	TECHNOLOGICAL	SOCIAL & POLITICAL
High cost of collection: ■ Transport costs are high in Australia due to low population density ■ Low intrinsic value of products/ material per unit (despite potentially large value of volumes of products) ■ High capital cost for new recycling or manufacturing infrastructure **Immature secondary supply chains:** ■ A lack of local demand for recycled materials or reused components to drive investment **Circular economy not top priority for SMEs** ■ Business and consumers face technological and financial lock-in to current systems with financial implications of changing	**Complex product design:** ■ Products are not designed for disassembly, remanufacturing, repair or recycling ■ Products are not designed to be durable and have planned obsolescence, shortening lifespans and limiting the ability to reuse ■ Complexity of products with increasing numbers and mixes of materials, making them harder to recycle ■ Rapid technological development leading to demand for new materials limiting the potential to remanufacture new products using recycled materials. **Paucity of data preventing investment:** ■ Lack of recycling infrastructure and low incentive for recyclers to invest without security of supply	**Inconsistent and narrow policy:** ■ Waste policies are implemented at a state level and therefore inconsistent across states ■ National product stewardship policies only cover a small number of products ■ Collection systems inconsistent between different products and across local government areas ■ Existing policies are based on environmental goals, with a focus on reducing waste to landfill not increasing circularity ■ Lack of consumer awareness about recycling options **Preference for purchasing new:** ■ Reluctance to use second-hand or recycled products ■ Lack of standards to do this in certain sectors, e.g. in the building industry **Household hoarding of electronics:** ■ Perceived value of products prevents collection at end-of-life, leading to large volumes of e-waste hibernating in houses.

3 ARE ABOVE GROUND METAL RESOURCES ABUNDANT AND AVAILABLE?

BARRIER	KEY CHAPTER FINDING	WHO CAN CREATE CHANGE? GOVT	RESEARCH	INDUSTRY
Paucity of data preventing investment Household hoarding of electronics	Data on secondary and critical resources	✓		✓

Whilst global market demand and commodity prices impact overall global resource recovery rates, local investment is directly influenced by knowledge and certainty with regards to the resource volumes and value. The paucity of data on above ground resources creates uncertainty for the resource recovery industry, which discourages waste collectors, processors, and recyclers from investing in new technology and infrastructure for resource recovery. It also limits the ability of policy makers to develop strategies for resource management that might be rigorously appraised with benchmarks and targets. Cluster research has addressed this significant issue for metals bearing waste by developing new methodologies for estimating and locating aboveground stocks.

WHAT, WHERE AND WHEN ARE ABOVE-GROUND STOCKS OF METAL RESOURCES AVAILABLE FOR RECOVERY?

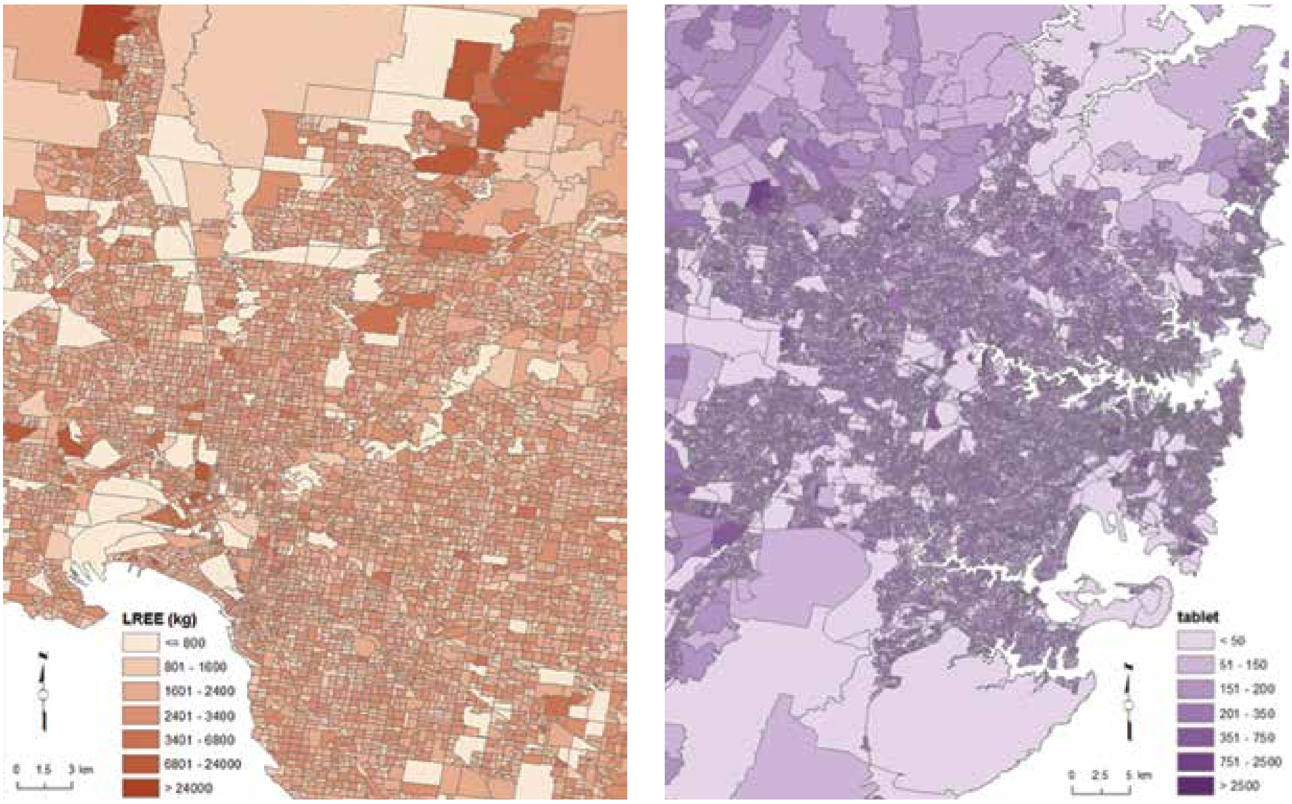


Figure 6: Maps from the Recyclable Resources Atlas.
The left map shows the amount of light rare earth element (LREE) contained in household electronic devices estimated for the SA1 (Statistical Area Level 1) area units in Melbourne CBD and surrounding areas. The right shows the number of tablets estimated for the SA1 area units in Sydney and surrounding areas.

What: Large stocks of metals exist in buildings, infrastructure and electronics

A bottom-up approach was used by Monash researchers to estimate in-use stocks of copper, zinc, iron and other valuable metals contained in buildings, urban infrastructure and household electronic device. Based on building and census data, it is estimated that Australia has over 6.4 million tonnes in-use stock of copper and over 3.2 million tonnes of in-use stock of zinc in buildings and urban infrastructure, and more than 79 million tonnes in-use stock of iron in buildings (Australian Recyclable Resources Atlas, 2017).

Where: A new Recyclable Resources Atlas shows where metals are located above ground

The Australian Recyclable Resources Atlas is a new GIS database developed by researchers at Monash University to illustrate the spatial distribution of above ground resources, in a similar way that Geoscience Australia's 'Australian Mines Atlas' provides information on below-ground resources. The maps can show resource data at four levels of geographical regions, from the smallest unit of census data (statistical area level 1 with an average of 400 households), to suburbs, local government areas, and states and territories. They are organised under 4 themes: household electronic devices, valuable metals in household electronic devices, copper in buildings and urban infrastructure, zinc in buildings and passenger motor vehicles, and iron in buildings (see http://wfw-atlas.monash.edu.au/atlas/build/). These maps are useful for showing the regions that are likely to be major above-ground mines in the future. Consistent with previous research on the stocks of copper and zinc, the metal densities in urban regions can be more than a hundred times higher than rural areas (Van Beers and Graedel, 2007).

When: Household hoarding behaviour creating a barrier to timely recovery of e-waste

To inform the in-use stocks analysis at the household scale, the stocks of 43 metals contained in mobile phones (older-style and smartphones), tablets, laptops, desktops, flat TVs, CRT TVs, monitors, and game devices were also estimated based on a 1500 household survey (Zhu et al., 2017). The research provides new insight into the accumulation of EEE in households. With the exception of plain mobile phones, computer monitors and old style televisions (CRTs), all other devices are accumulating in homes. Smart phones and laptops are accumulating the fastest, with approximately one in three households hoarding a smart phone and slightly less households hoarding a laptop in the last year. This means that products are being stored after they are no longer used and creating a time barrier to when they can be recovered.

AUSTRALIA COULD BE GAINING GREATER VALUE FROM ITS MINERAL WEALTH: THE CASE OF INDIUM

Indium is a technologically important metal because of its use in solar panels and LCD displays. Despite this importance there is a lack of data on the resource, usage and future supply. Indium is a geologically scarce metal generally considered at risk of supply disruptions, yet many countries that currently don't supply indium (including Australia) host large resources of this metal, which could augment future supplies. The Cluster research shows that recovering stocks of indium in mine wastes is likely to be valuable alternative to conventional mining and represents a larger stock than used electronics.

Cluster researchers have developed a new methodology (a proxy method using geochemical relationships between primary and critical or by-product metals) to allow resource estimates of any critical metal for which there is a lack of reported data (Werner et al., 2017b). This method has been applied in a comprehensive assessment of indium and shows that while Australia produces no refined indium at present, it holds some of the largest mineral resources and potentially substantial amounts in tailings at existing and former Australian mine sites. An analysis of trade of ore and concentrates containing indium confirms that most of Australia's milled indium is exported in zinc concentrates, although the value of this (and many other critical metals) is not captured within Australia. Australia could be gaining greater value from its mineral wealth and develop informed strategic policy supporting critical resource management.

4 WHAT TECHNOLOGICAL INNOVATIONS FACILITATE E-WASTE RECYCLING?

		WHO CAN CREATE CHANGE?		
BARRIER	KEY CHAPTER FINDING	GOVT	RESEARCH	INDUSTRY
High cost of collection Complex product design	Technology can be modified for e-waste		✓	✓

Technology development is needed that is capable of processing the complex and changing mixes of metals in e-waste streams and to overcome the high cost of collection. Emerging e-waste processing technology can be characterised as improved combinations of traditional extractive metallurgical processes (pyrometallurgy, hydrometallurgy and electrometallurgy) linked to base metal production (Cu, Pb, Zn, Ni). However, further development is needed to optimise and scale these technologies for e-waste streams containing different metal mixtures. Swinburne researchers have undertaken fundamental research and developed a novel methodological process for optimisation. The significance of this work is in enabling the Australian mining and metallurgical industries to leverage the breadth of technological and technical know-how from conventional mining, to access to a broader range of valuable metals in e-waste (Khaliq et al., 2014).

HOW DO WE OPTIMISE TECHNOLOGY FOR PROCESSING AND RECYCLING E-WASTE?

Optimisation of technology for processing and recycling e-waste requires the integration of fundamental science, techno-economics and environmental appraisal. The optimisation process developed by Swinburne involves four key steps shown in Figure 7. Owing to the new combination and concentrations of metals in e-waste, compared to conventional resources, the first step is thermodynamic analysis to identify suitable process operating conditions (e.g. temperature, pressure) for resource recovery. This new insight then enables the modification of existing industrial processes that can then be rigorously appraised in terms of potential environmental impacts using life cycle assessment tools, and techno-economic analysis to determine the economic viability that is impacted by capacity and recovery efficiencies.

WHAT WILL FUTURE E-WASTE PROCESSING LOOK LIKE?

Conventional metal processing is typically carried out at very large industrial scales that may not be sufficiently flexible to respond to a new and dynamic unconventional resource flow. This research has shown that small-scale plants provide a viable option for processing e-waste.

The high cost of transportation remains a challenge, particularly from rural areas (Van Beers, Kapur and Graedel, 2007). This suggests the possibility of **distributed or mobile** technology solutions. At the same time e-waste processing that deals with complex material inputs that vary between products and overtime requires a **flexible, multi-metal approach**. These technological developments can support new business models and provide an opportunity for Australian research and industry innovation.

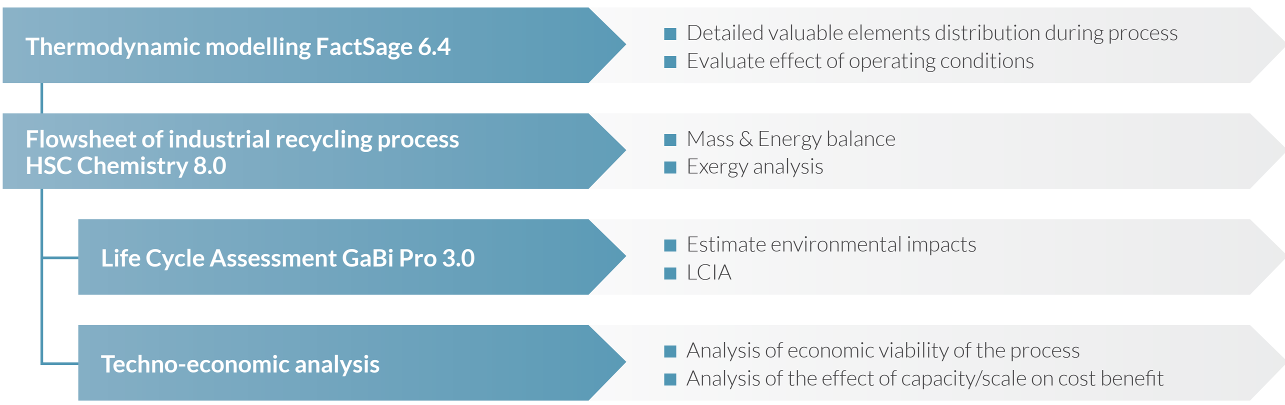


Figure 7. Methodological approach to modify and optimise existing technologies for ewaste processing (developed by Swinburne University of Technology)

OPTIMISING THE PROCESSING OF E-WASTE

The methodology developed by Swinburne University of Technology was used to evaluate metals recovery from printed circuit boards (PCBs) based on the black copper smelting process. This process was selected based on the maturity of the technology and its high flexibility in terms of scalability and capacity to handle different copper scrap feeds.

Development of systematic thermodynamic information for specialty metals

It was identified early in the research that there is a lack of vital thermodynamic data on specialty metals (such as germanium, palladium, gallium, tantalum and rare earth metals). This data is necessary for the development of a comprehensive and optimised technological processing route for e-waste (Shuva et al., 2016a). Swinburne researchers have established thermodynamic information for germanium, palladium under different processing conditions to identify which conditions enhance the maximum recovery of the metals (Shuva et al., 2016b, 2017a). The process of e-waste recovery needs to be adapted for the particular chemical requirements of specialty metals. This thermodynamic information forms the basis of the modification of multi-stage black copper smelting for e-waste (Shuva et al., 2017b).

Environmental impact dependent on waste transport distance and carbon intensity of the electricity used for smelting

A life cycle assessment (LCA) was carried out to appraise the environmental impacts of metal recovery from PCBs targeting copper, silver and gold recovery, showing better environmental performance as well as avoided impact of primary production. Key environmental impact factors assessed include climate change, human toxicity, photochemical oxidation formation, and particulate matter formation. E-waste processing embedded in secondary copper smelting was compared against conventional secondary smelting, demonstrating that the environmental impacts when processing PCBs (along with low grade scrap) in existing smelters is dependent on the distance the material feed travels to the smelter and the carbon intensity of electricity generation supplying the smelter. Additionally, it was shown that the metal and oxide dust needed to be further processed in order to refine metals such as nickel, lead and zinc (however this step was not assessed).

Economic viability identified for small-scale plant with a capacity 25,000 tonnes/year

A techno-economic analysis of the black copper smelting process determined that the annual benefit for a base case (100,000 tonnes per year) was competitive with the capital and operating cost of a conventional plant including the cost of fed raw material. A sensitivity analysis indicated that the largest impact on cost was found to be associated with the variation in the raw material cost, followed by the loan interest rate. It was found that the minimum plant capacity for the process to be still economically viable is about 25,000-30,000 tonnes/annum (Ghodrat et al., 2016).

The analysis assumed that there was no cost for the transportation of e-waste to the plant and that no value was gained from the recovery of the base metals in the metal and metal oxides dusts. Further work should include the recovery of other base metals (Zn and Pb) as well as incorporating the effect of transport of e-waste. Preliminary cost analysis of the effect of e-waste transportation from Melbourne, Adelaide and Brisbane (and assuming that the plant is built in Canberra) showed that for the process to be economically viable, the capacity of the plant should be doubled.

5 HOW CAN BUSINESS CONTRIBUTE TO A CIRCULAR ECONOMY?

		WHO CAN CREATE CHANGE?		
BARRIER	KEY CHAPTER FINDING	GOVT	RESEARCH	INDUSTRY
High cost of collection	Business models overcome economics and behaviours			✓
Household hoarding of electronics				
Circular economy not top priority for SMEs	Networks and collaboration promote innovation	✓		✓
Immature secondary supply chains				

There has been limited research to understand the role of business models to enable new value opportunities in a circular economy. Key to enabling future opportunities is in overcoming the challenges of return-logistics and immature secondary supply chains. These challenges are not unique to Australia, but the low population density contributes to the high costs.

New business models have an important role to play in supporting innovation in new technical systems for collection and processing (Chapter 4) and product design. Business model innovations are also evolving that support change in the way consumers own and use products and services.

WHAT STRATEGIES HAVE THE POTENTIAL TO CREATE SYSTEMIC CHANGE?

A need to focus on reducing total demand not just recycling

In the context of growing total demand, recycling offers the potential to minimise but not eliminate the adverse environmental and social impacts of extraction, production, and processing by reducing demand for primary resources.

Circular economy strategies that can reduce total demand, including increasing product longevity, remanufacturing, re-using components and dematerialisation (Allwood, 2011), tend to be focussed on consumer behaviours and modes of consumption. Thus, new business models that can influence these behaviours are very important for reducing total demand (Florin et al., 2017).

Support for new modes of consumption underpinned by ecological awareness

There is little incentive for a producer to extend product life when profit is based on volume of sales. For consumers, the desire for new products and the hoarding of products in homes at end of life increases demand for materials while preventing or delaying their return to the economy (Florin et al., 2017). Innovative business models, such as leasing and remanufacturing are important to address these barriers and limitations (see leasing case study below).

New business models not only offer new economic and technical systems but they also bring social benefits such as the potential to mainstream a renewed ecological awareness as producers and consumers recognise their interdependence with and impacts on the biosphere (Benn et al., 2017). At the same time, the emergence of new business models relies on such a realisation that economic growth is reliant on human well-being and a replenished biosphere. And as those implementing these new business models employ circular economy strategies as a basis, they develop collaborative forms of sustainability-based innovation networks that offer potential to transform markets and generate employment growth.

WHAT DOES A CIRCULAR BUSINESS LOOK LIKE?

A typology of circular business models

Circular businesses are emerging, with no established definition and multiple ways of presenting and categorising these emerging business models (e.g. Bocken et al., 2014). A business model encompasses all activities that form the basis of how a firm or organisation creates value (by exploiting materials, knowledge, technology, partnerships), delivers value (i.e. in the form of a product, process or service offering for customers, society and/or the environment), and captures value (i.e., the revenue model, e.g., leasing). Value is defined broadly, including economic value as well as positive societal and environmental outcomes.

Five typologies of new business models that are considered most applicable to a future circular economy were identified through the Cluster work and are illustrated in Figure 8, relative to their system transformation:

- substitute renewable and energy and material inputs,
- maximise material and energy productivity,
- adopt a stewardship role,
- deliver functionality rather than ownership,
- create wealth from waste.

An analysis by UTS of 70 business cases from a range of sectors identified the 'create wealth from waste' archetype as the most prevalent, and this may be considered an indicator for where new value opportunities have already been identified (Florin et al., 2015). The five archetypes give particular focus to the important role of producers, for example through product innovation for durability, repairability and recycling to 'maximise material and energy productivity'. However, there is significant scope for wider engagement across the value chain, for example opportunities for new value through cooperation across industries by 'adopting a stewardship role'. 'Delivering functionality rather than ownership' gives focus to new modes of consumption by promoting a shift from ownership to access models, such as the sharing or leasing of assets. These models also illuminate connections along the supply chain (e.g. from products to raw materials) and have the potential to lead to greater social and environmental accountability at the front-end of the supply chain, which is typically disconnected from consumers.

Detailed case study analysis demonstrated that leaders implementing and designing these models must understand the intrinsic value of waste as a resource as their business activities are interdependent with the biosphere. These businesses also took the initiative to demonstrate how this can be managed across the supply chain through the application of systems thinking (Perey et al., 2017). Often this requires a form of entrepreneurial action so that leaders can disrupt existing business models, so that designing waste out of the system can be viewed as an opportunity rather than a challenge (Edwards et al., 2017a). In larger corporate companies, those tasked with transitioning operations towards adoption of the circular practices to enable these archetypes encountered a much broader set of responsibilities. For instance, new roles for sustainability officers and change agents move beyond functional roles within the operation of the business, to collaborating and developing partnerships so opportunities for circularity can be enabled (Edwards et al, 2017b).

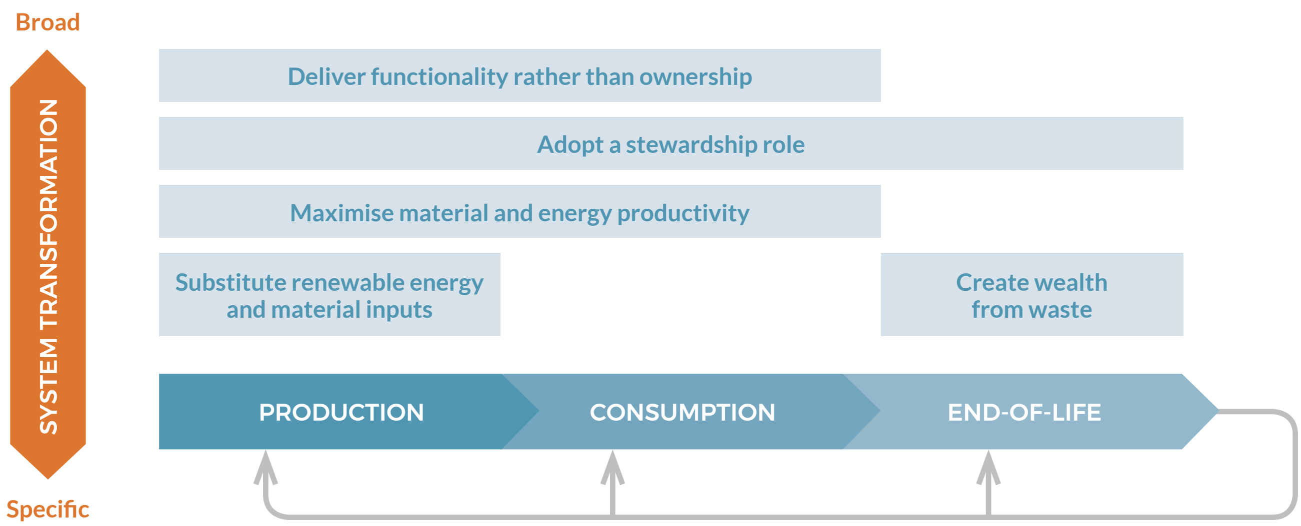


Figure 8. Typology of circular business models

NEW BUSINESS MODELS TO CHANGE EXISTING SOCIAL PRACTICES: LEASING OF MOBILE PHONES

A study by UTS has found that a leasing business model can potentially increase the recovery, reuse and recycling of mobile phones. As found in the Monash survey, a large barrier to recovery of products is that they are being stored in households after they are no longer used. Customers who lease a mobile phone pay less per month than the equivalent payment plan and must return their phone to the provider at the end of the 2-year lease. This overcomes the hoarding of mobile phones by households, currently a large barrier to recovery.

The product life of the phones is extended as the returned phones are then refurbished and resold. The length of the leasing model allows the phones to be reused – if the phones were kept by consumers for longer they would have very little value left at the end of their first life and would end up recycled at the end of first life (if they could be recovered) rather than reused. As Australia does not have a market for refurbished phones, these are exported for resale in Asia, with the result that it is harder to guarantee that phones are responsibly recycled at the end of their life. There is still further work to be done to create a local market for second-hand refurbished phones in Australia, which would both extend product life and ensure responsible recycling (Dominish et al., 2017a).

WHAT DOES INNOVATION AND COLLABORATION LOOK LIKE FOR A CIRCULAR BUSINESS?

Businesses are adopting circular economy principles through open innovation

Innovation is a central activity for all firms to maintain their competitiveness. For firms adopting circular economy principles innovation is a fundamental component of the business model, and because of the demand of circular economy principles (reduce, reuse and recycle) these businesses also need to be 'open' in these innovation processes.

Open innovation describes the modern process of innovating within firms: successful innovations rarely result in isolation, with a number of actors (firms, public research organisations and government) contributing to the innovation process. Businesses and their innovation processes have always been open to some extent, but this has become much more explicit in the past decade or so. This is in response to changing innovation structures within firms who, with the decreasing lifetimes of products, are less willing to take on the risks and costs of the whole innovation process enclosed within their firm, and second, as a mechanism to cope with global information flows.

An innovation survey undertaken by UTS of 250 Australian businesses shows that all firms are becoming more open in their innovation activities, but the type and extent of openness differs. The survey also shows that the majority of firms surveyed have some level of engagement with circular economy principles (for example designing for product longevity, or recycling products at end-of-life). There were only a small number of firms (5%) who have a deep engagement with the circular economy. Businesses who are adopting circular economy principles are also innovative, with varying degrees of the intensity and novelty of innovation (Sharpe et al., 2017).

The importance of networks for innovation is also critical for businesses operating with circular economy models. As these industrial activities are emerging, much of the knowledge associated with recycling and reuse across the supply chain is tacit, meaning networks are important conduits of knowledge. Research by UTS highlights the important function of these 'sustainability-focused' innovation networks and understanding how they contribute to knowledge flows and innovation in the circular economy. Government also plays a key facilitating role in their formation: they provide a platform for knowledge exchange, early resources, and 'honest broker' services to businesses (e.g. NSW Sustainability Advantage Program). Such initiatives also raise awareness, skills and collaboration amongst businesses as well as creating new business opportunities through innovation.

ADOPTING A STEWARDSHIP ROLE IN THE STEEL INDUSTRY: AUSTRALIAN STEEL STEWARDSHIP FORUM

Supply-chain certification schemes have been developed in recent years for metals with the aim to derive a competitive advantage by differentiating metals and metal products on the basis of superior environmental and social impacts across the whole life cycle, that are frequently overlooked by consumers. Examples include the Responsible Jewellery Council and Fairtrade certification for gold. For example the majority of emissions from value chains are not currently measured (Carbon Disclosure Project, 2012), which is highly relevant to metals given the energy and emission intensity of production and reprocessing.

The Australian Steel Stewardship Forum (ASSF) has developed a sustainability certification scheme for Australian 'ResponsibleSteel' (see http://www.responsiblesteel.org/). Key stakeholders from all major sectors of the Australian steel product lifecycle from mining, processing, product fabrication, use, re-use and recycling are involved; as well as government, non-government organisations (NGOs) and industry associations (Benn et al., 2014).

Drivers for certification

Managing risk is seen as a major driver, including legal and health and safety issues. For miners this risk management is about maintaining a 'social license to operate' avoiding disruption from protests, changing worker safety conditions, or adverse environmental releases. Benn et al (2014) also observe an emerging phenomenon of a 'social license to market', based on consumer demand for accountability in the supply chain. However, these schemes are also being pursued as a proactive strategy to secure market advantage, i.e., where opportunities for value creation arise from consumers being willing to pay a premium. Currently much of the scrap in Australia is melted down to be used in low-grade products and this is unlikely to incentivise an increase in the share of recycled materials relative to demand (Benn et al., 2014).

Opportunities for circular material flows

The ASSF provides an example and relevant learnings to support the adoption of new stewardship initiatives targeting new markets or products. For example, Australia could take a leadership role in the stewardship of lithium, an essential material for energy storage batteries and electric vehicles.

6 HOW CAN POLICY ENSURE SOCIAL, ENVIRONMENTAL AND ECONOMIC VALUE?

BARRIER	KEY CHAPTER FINDING	WHO CAN CREATE CHANGE? GOVT	RESEARCH	INDUSTRY
Inconsistent and incomplete policy Circular Economy not top priority for SMEs	Importance of a national approach to circular economy	✓	✓	
Complex product design Preference for purchasing new	Product stewardship can influence design	✓		✓
Immature secondary supply chains	Procurement policies can grow secondary markets	✓		✓

Policy interventions to promote a circular economy can overcome barriers and create incentives to encourage the circular flows of metals at all stages in the supply chain, not only at end-of-life. Whilst individual businesses and sectors are innovating, policy support is needed to ensure that system change is transformational.

Cluster research has identified policy and regulation that can support three goals of a circular economy: i) increasing collection, recycling, reuse and refurbishment, ii) supporting social enterprises and new business models for resource recovery and iii) creating an enabling environment for innovation. Significantly, some of the more influential areas of policy are in areas broader than environmental policy and are focused on supporting industry innovation for a circular economy.

Importance of a national circular economy strategy shown China, Japan and the EU

China, Japan and Europe have been leading the policy transition towards a circular economy, but have achieved this in different ways owing to their diverse political and business environments. Despite the different approaches between countries, a common set of key factors have been identified that can contribute to creating an enabling environment for a circular economy (shown in Figure 9).

In China a top-down approach has focused on regulations for cleaner production, waste management and developing new technologies, led by the national Circular Economy Promotion Law introduced in 2009. In the EU a Circular Economy Package was introduced in 2015 with new directives on waste management, including e-waste. It also includes an Action Plan with new initiatives for promoting ecodesign, reducing the use of hazardous substances in products, consumer product life guarantees, introducing circular economy criteria in green public procurement and promoting markets for secondary materials. Funding for investment in waste management, resource efficient production processes and research supports the package. EU directives are then implemented across countries either through policy (particularly regulations and economic incentives) or through business and NGO-led initiatives. In Japan, there has been an emphasis on coordinating and sharing the responsibility for implementation between national and local government, business, the public, NGOs and universities. All three examples highlight the importance of coordination of policies across sectors and from the national to local level, and for the making explicit the roles of government, research, the private sector and NGOs (Dominish et al., 2017b).

6. HOW CAN POLICY ENSURE SOCIAL, ENVIRONMENTAL AND ECONOMIC VALUE? CONTINUED

Policy options for implementing a circular economy

Government-led

ROLE OF GOVERNMENT

Regulatory instruments including revisions to existing regulations that act as a barrier to a circular economy or creating new regulations. Regulations can include product policy (e.g. extended producer responsibility, requirements on packaging and labelling, extended warranty periods), targets (e.g. on the percentage of resource recovery), selective bans (e.g. banning recyclable materials in landfill) and mandatory processes (e.g. mandatory resource recovery during production)

Economic incentives including taxes, charges and levies. These could target primary resources, pollution (e.g. greenhouse gas emissions) and waste (e.g. landfill levies).

Public investment can be useful for supporting R&D and innovation, upgrading or developing new infrastructure, funding training and new skills development and green procurement policies.

Awareness raising e.g. providing information and advice to businesses, or campaigns targeted at consumers.

Network building within a sector, along the supply chain and between stakeholders to encourage knowledge sharing and collaboration e.g. connecting businesses to promote industrial ecology activities.

Voluntary agreements within a sector or along the supply chain, developed and managed by industry, government or a third party. These could include minimum industry standards (such as for responsible sourcing of products), product certification that can influence business and consumer behaviour (such as a recyclability index) and industry led take-back and recycling initiatives (product stewardship).

Government plays a supporting role to industry

Figure 9: Enabling factors for implementing circular economy

Benefits of a national circular economy

Developing a national circular economy framework in Australia – broadening the focus beyond metals to include water, food, chemicals and plastics – would encourage business and government to invest in innovative policy and strategies to increase the productive use of resources.

A national circular economy framework could build upon and connect success stories, already in train, across NSW (Sustainability Advantage), SA (Green Industries) and Victoria (Sustainability Victoria). A nationally coordinated approach would bring a stronger focus on industry innovation, linking across Industry Growth Centre themes and connecting the whole supply chain. This would build on the ambitions of the National Waste Policy.

A national approach to a circular economy would help build a new local industry base, one which is prosperous in a global economic system being disrupted by resource and environmental constraints and the new business models of the digital economy. As a result, Australian industry will be more closely connected with the circular-focussed international landscape whilst delivering local economic, environmental, and social benefits.

HOW CAN POLICY ENCOURAGE RECYCLING AND REUSE?

The major barriers to the collection of used electronics are economic, owing to the lack of viable markets and established supply chains for both disused products and their component materials. The regulatory system was designed to support a linear model for the management of hazardous waste, rather than a circular economy approach focused on recovering value from the waste stream or changing behaviours. The recycling and reuse of building components and scrap metal faces similar challenges, with a lack of local markets to drive demand. Innovative regulatory interventions designed around an increasing circularity could help overcome these economic barriers, as discussed below.

	CURRENT SITUATION	POLICY OPTIONS
E-waste	The legislation around e-waste in Australia is primarily driven by product stewardship and co-regulatory arrangements, with the National Television and Computer Recycling Scheme (NTCRS) being the major scheme defining the development of e-waste collection and recycling services. Overall, the NTCRS covers about 20-25% of total arising e-waste in Australia by volume, representing 30-35% in terms of metal recovery value (US$ 120 m in 2014). Other forms of e-waste that are not yet included in product stewardship arrangements, including PV panels and energy storage batteries, are predicted to grow in volume in the future	■ Establishment of product stewardship schemes for other e-waste products, such PV panels and batteries, which have both been listed for consideration for accreditation or regulation under the Product Stewardship Act; ■ Updated export regulations with specific codes for each e-waste type and training for customs officers to determine illegal exports; ■ Amendments (currently proposed) to the Hazardous Waste Act that increase the cost for export of e-waste and may provide a driver for investment in local recycling infrastructure; ■ The banning of e-waste to landfill, as legislated in South Australia and proposed in Victoria.
Building components	The reuse of steel components in building is an opportunity to promote more sustainable steel. Policy interventions to support this can be made at three different 'life stages': demolition, scrap recycling and construction but these need to be coordinated to ensure they align. Policy changes could lead to more reuse and the increased uptake of domestically sourced steel from secondary sources (Santos and Lane, 2017)	■ In the demolition stage, building disassembly as opposed to demolition could be encouraged, which could lead to more reuse instead of recycling, which is less energy intensive and promotes longer lifespans for materials. At the same time, new buildings need to be designed and constructed to better enable disassembly at end-of-life. ■ Policy changes would also need to be made for the construction stage, which could include: – The development of standards which restrict imports of inferior products and more formally recognize reused and prefabricated components – Requirements to label building components to make future reuse an easier option. – Procurement policies to encourage uptake of reused components and recycled products manufactured by Australia's scrap recycling industry.

	CURRENT SITUATION	POLICY OPTIONS
Scrap metal	The collection and recycling of scrap metal in Australia is mainly driven by international supply and demand. Prices for scrap are determined by international commodity markets and affect the volumes that scrap recyclers will buy and collect from domestic sources such as waste transfer stations. Because demand is also driven globally, scrap is often exported overseas for further processing and recycling. This is particularly the case for non-ferrous metals because the processing infrastructure is currently not widely available in Australia.	■ Regulations restricting exports and imposing stricter licensing and policing on recycling operations to prevent illegal exports; ■ Investment in recycling infrastructure and support for Australian-based manufacturing; ■ Increased domestic demand for Australian recycled products through stricter standards on imports and domestic procurement requirements in construction and infrastructure projects; ■ Collection systems can align with container deposit legislation soon to be introduced in NSW and Qld, for example through shared collection points or reverse vending machines.

HOW CAN POLICY SUPPORT ENTERPRISES ALSO DELIVER SOCIAL GOOD?

Innovation is not restricted to activities around technology, products and processes, but is also seen in the emergence of enterprise models that allow organisations to achieve their economic, environmental and social goals. Within the spectrum of circular and sustainable businesses there is a growing range of enterprise types, including for profit, not for profit, and various models of social enterprises.

A diverse range of organisations are involved in collection and reprocessing used electronics ranging from transnational waste management companies for which electronics is only part of their activities, through to large and medium size companies specialising in used electronics, to large and small charities and social enterprises, with local government agencies also being very important in collection activities (Lane et al., 2015, Lane and Gumley 2017., in press). This mix of enterprise types can be helped and hindered by existing industrial structures, and the regulations and legislation at various levels of government (Sharpe et al., 2017).

Policy needs to account for social value of support social enterprises

The review of the NCTRS found that the policy has changed the local recycling industry, as commercial organisations have taken on work previously done by social enterprises. The position of non-profit organisations has shifted away from collection activities and towards sorting and disassembly in centralised facilities, in contractual arrangements with commercial organisations (Lane et al., 2015, Lane and Gumley 2017., in press).

While commercial organisations are motivated to generate profits and minimise costs associated with collection logistics, charities and social enterprises are more strongly motivated by opportunities for employment training while still covering costs, and find it hard to compete with larger companies. Policies are needed to account for the additional value of social enterprises to help them compete with commercial organisations.

Existing legislation on public procurement, such as the NSW Government Resource Efficiency Policy (GREP), uses the purchasing power of the government to drive down the cost of resource-efficient technologies and services in a cost-efficient way (NSW OEH, 2014). The purchasing of products made from recycled or sustainably sourced materials can be expanded to metal-bearing products (the current focus is on paper and construction materials). Procurement policies can also be a useful tool to promote products and services delivered by organisations that also create social benefits.

PRODUCT STEWARDSHIP: CURRENT STATUS IN AUSTRALIA

The Australian *Product Stewardship Act 2011* guides the lifecycle management of products in Australia with the aim of minimising health and environmental impacts. The Act, which is currently under review, is designed to distribute responsibility among producers, sellers, users and disposers. Each year a list is published of products being considered for inclusion under the Act, providing a signal to the market of the Government's interest in stewardship for the product. Under the Act there are three categories of stewardship:

(1) Voluntary stewardship schemes are industry-led schemes that are accredited under the act and are obligated to operate transparently without regulation. Currently there are two accredited voluntary schemes: Mobile Muster (mobile phones) and Flurocycle (mercury containing lamps); (2) Co-regulatory schemes are run by industry in a similar way to voluntary schemes, however they are regulated by government in terms of specific operational requirements, such as waste management targets. The National Television and Computer Recycling Scheme (NTCRS) is the only example of a co-regulatory approach; (3) Mandatory product stewardship legally obliges specific parties towards specific management actions of products. Compliance is legally enforceable and parties can be penalised for breaches. Currently there are no mandatory schemes.

Insights and learning from established product stewardship organisations

In addition to the schemes under the Act there are approximately 15 other un-accredited voluntary industry-led product stewardship organisations in Australia including schemes that have been running for more than two decades. Paintback is an example of a recently established scheme with waste levy approved by ACCC applied to consumers directly at the point of sale. Important elements for a successful product stewardship scheme include:

- Acknowledging timing to develop and implement a successful scheme (~ 10 years);
- Recognising the challenge and importance of getting all stakeholders on board and successful mechanisms to engage all stakeholders;
- Leveraging synergies with other policy levers, e.g. e-waste bans to landfill;
- The need for data on material and value flows at the national level (Florin et al., 2016).

Designing product stewardship schemes to promote reuse over recycling

A review of the impact of the NTCRS by Monash highlighted that this scheme had significant impacts on streamlining the commodity chain for used electronics towards end of life destructive materials recycling rather than repair, reuse and resale. Product stewardship schemes must be designed to promote higher order reuse compared to recycling.

The Monash survey of 1500 households found that most products electronic devices stored in households still work and the resale value of many items is much higher than the value of their contained metals extracted through recycling. Therefore, product stewardship schemes could be expanded to encompass certification and standards for reuse as well as materials recycling (Lane et al., 2015).

HOW CAN POLICY CREATE AN ENABLING ENVIRONMENT FOR INNOVATION?

Innovation policy needs to adapt to new ways of innovating

Changing innovation processes in a circular economy require a change in the support activities provided by government, for educational institutions and the entrepreneurial environment. The usual activities of R&D grants and development support will not provide sufficient early market development activities for circular economy innovations to be successful. Policy will need to be more reflexive and consider the full range of public activities including procurement, entrepreneurial support as well as regulation and examining public sector business operations.

The lack of complexity in Australia's economy creates a challenge for the country to shift towards new circular industries higher up the supply chain, for example the development of advanced manufacturing to support the remanufacturing of products. Industry policy needs to focus on how the existing highly skilled manufacturing industry can transition towards new circular industries before the know-how is lost as the size of the industry declines (Dominish et al., 2017b). The national Industry Growth Centres, which drive innovation in high-value and strategic industries, could be expanded to have a broader focus on circular economy across the sectors.

START-UP SUCCESS STORY: REUSING BATTERIES FOR A "SECOND-LIFE" IN ENERGY STORAGE

"Policy needs to be based on the understanding that to have impact then you have to take on risk. Start-ups need to be allowed to try something and fail."

Relectrify is a start-up that develops and supplies advanced battery technology to create value out of used electric vehicle batteries by repurposing them for use in stationary energy storage. This extends the life of the batteries, capturing additional value from the resource before recycling. The factors that can support innovative start-ups focusing on resource efficiency were identified through an interview with UTS. These include:

- Accelerator programs modelled on Climate KIC and Elemental Excelerator that encourage companies to focus on technology and waste reduction, and are based on tackling problems in a way that makes business sense. Relectrify went through the Melbourne Accelerator Program connected with the University of Melbourne.
- Increased capital and relevant infrastructure such as accessible manufacturing and testing facilities since start-ups working on resource efficiency often have hardware needs, which cause a greater need for upfront capital compared to software start-ups in the broader economy.
- Government grants intended to encourage innovation need to make sure their conditions don't prevent start-ups from applying, for example through having requirements for multi-year financial track records or current turnover.
- Public procurement for government projects can be leveraged to encourage early adoption of new initiatives and give developing companies strong demonstration opportunities. This approach is increasingly seen in innovative nations internationally, including Germany and the US.

7 WHAT WILL ENABLE THE TRANSITION TO A CIRCULAR ECONOMY FOR METALS?

To transition to a circular economy, we need to transform the existing industrial, economic and social systems, rather than seeking incremental improvements to individual production and consumption systems. There are significant opportunities for Australia in moving to a circular economy, but to access the full extent of these, we need purposeful system interventions.

WHAT ARE THE VALUABLE OPPORTUNITIES FOR AUSTRALIA?

The stocks of resources above ground and in mining waste represent a new opportunity to recover economic value from unconventional resources, and at the same time grow secure employment and create environmental benefit. **However, the more significant value may not come from the resources but from exporting the know-how and capabilities developed to access them**. By becoming a leader in recovering and reusing metals Australia will continue to have an advantage in the resources sector and be able to take the technology and service solutions, such as new processing technologies and viable collection business models, to larger stocks of secondary resources globally. With international value chains adopting a more circular focus, Australia must position its research and business development strategically into this changing landscape.

Capturing material value and environmental opportunity

Analysis by the University of Queensland estimated that there was about 6 million tonnes of metal content in waste streams in Australia each year, based on 2011 figures. As mentioned above this is equivalent to about half of annual metal consumption within the country, with an estimated worth of more than six billion Australian dollars assuming the metals are fully recovered. Based on existing waste and recycling statistics in Australia, it is estimated that the potential for wealth from metal bearing waste is of the order of two billion Australian dollars a year (Corder et al., 2015). E-waste is an important source of metals and represents a significant opportunity to recover material value, discussed in detail in the following section.

New employment can be generated by promoting sustainability and resource efficiency

Work commissioned by Green Industries SA and reviewed by the Cluster (Lifecycles, 2017) identifies that, in South Australia alone, over 25,000 jobs can be created by 2030 together with a 27 % reduction in greenhouse gas emissions. This builds on the high-level estimate of value of $26 billion per year by 2025 of material cost savings for all resources in Australia, as presented at the World Resources Forum Asia-Pacific in Sydney (organised in collaboration with Wealth from Waste). The South Australian study is the first to be commissioned by a Government in Australia on the potential of the circular economy, and shows that materials efficiency and energy efficiency powered by renewables can work in tandem to achieve impact.

Maintaining Australia's position as an exporter of resources by exporting Australian knowledge into global markets

The economic opportunity to Australia for a circular economy is not only associated with the material value available in local urban mines (that is limited by the local consumption of metal bearing products); the more significant opportunity exists in supporting innovation in technology and business models to improve reuse, remanufacturing and recycling industries. Growing these capabilities locally is an important first step that enables resource recovery and mitigates adverse environmental impacts locally, and grows new knowledge and capabilities that can be exported by Australian businesses to capture wealth from waste in international markets.

There are also opportunities to generate value from a circular economy approach at the front-end of the supply chain. The current systems for managing mining waste, where waste is viewed as a necessary expense and large-scale storage is the only option, are costly, inefficient and comprise inherent safety and environmental risks, which can have disastrous consequences. The different strategies for limiting mining waste can be characterised by their ability to decrease risks and consequences of environmental legacy, as well as in terms of generating economic value out of waste. Properly developed and designed mining waste reprocessing operations can simultaneously deliver additional economic revenue (from minerals and other useful materials sale/use) and result in a relatively benign remaining waste, with eliminated or drastically reduced environmental and human health related risks at present and in the future. These also can contribute to extending the life of mines.

WHAT ARE THE PRIORITY INTERVENTIONS TO PROMOTE A CIRCULAR ECONOMY FOR METALS IN AUSTRALIA?

Transitioning to a circular economy for metals requires radically changing business activities towards more circular material flows, across product design, disruptive technologies for manufacturing or material processing, and new consumption models. The innovation that is needed in business is challenged by a lack of markets for secondary resources and products, complex global supply chains, a paucity of data on the availability of secondary resources, consumer behaviour, and inconsistent government policy that creates risk and uncertainty for first movers. For new start-ups based on the idea of circular economy these challenges are even greater. To overcome this, supportive policies need to be introduced across sectors for mining, manufacturing, waste management and consumption, as well as ongoing research and education. Cluster research has identified the key pathways to promote transition to a future circular economy for metals (Figure 10). These build upon the key findings from the cluster research, and look to what needs to be done for the future.

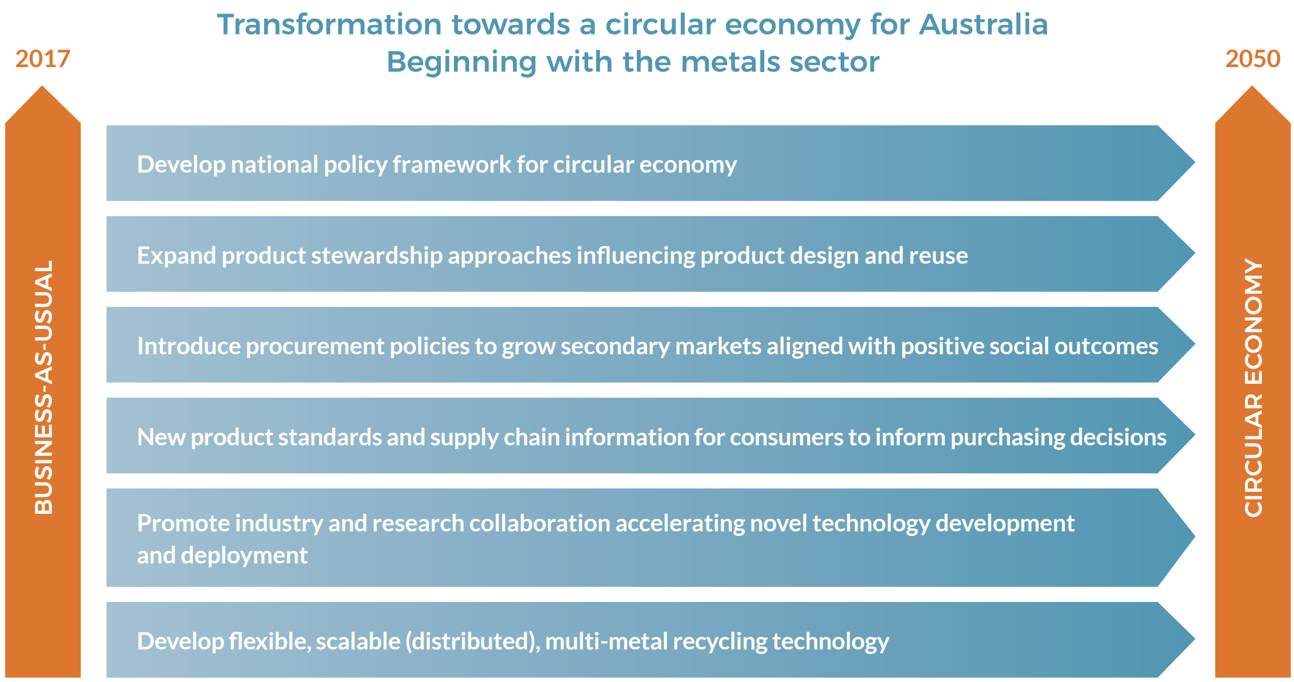


Figure 10: Pathways forward for the transition towards a circular economy for Australia

WHAT ARE THE NEXT STEPS FOR GOVERNMENT, RESEARCH AND INDUSTRY?

Government:

Australian federal, state and territory governments can develop and expand circular economy policies to promote resource recovery, beyond the current dominant focus on waste policy. A national framework for a circular economy would help to coordinate initiatives across supply chains and sectors, and between jurisdictions. This would put circular economy firmly on the agenda of Australian businesses supporting innovation. At the same time, state governments can build on the success of government facilitated sustainability-focused innovation networks to help scale-up and mainstream new technology and practice and support resource exchange.

The current product stewardship framework can be expanded to contain a larger number of metal-bearing products, and promote reuse as well as recycling. Procurement policies from government agencies can drive demand for circular products. Without a strong manufacturing industry to influence the design of new products, product stewardship and procurement policies are a way Australia can influence global production towards more durable and recyclable circular products.

Government also has a role to coordinate and maintain nationally important data-sets on the stocks of above-ground and critical resources, to unlock the full value of Australia's resources and ensure resource security.

Research:

The transition to a circular economy needs to be underpinned by robust and real-time data to track material and product flows along the supply chain and map available secondary and critical resource stocks. This is important to promote investment in new recovery technology, support business models based on access over ownership, and to guide circular economy policy targets.

Fundamental research is needed to support the development of new cost-efficient technologies for e-waste collection and recycling technologies capable of processing the complex and changing mixes of metals in waste streams.

Researchers have an important role to characterise and evaluate to what degree new circular business models meet environmental, social and economic goals, and the barriers and enablers to implementation. Research can also assist in the development of policy, through policy analysis of the success of international policies and understanding these can be applied to the Australian context.

Industry:

Australian industry has a significant opportunity to lead the transition towards a circular economy locally and internationally through the development of new business models that create wealth from waste, maximise material productivity and deliver functionality over ownership. To support this, industry can lead the development of new standards and labelling, providing better information to support consumer purchasing decisions. Industry can take the lead in developing stewardship schemes and supply chain certification, complementary with and supported by government policy and initiatives. At the same time, there is a need for deeper collaboration along the supply chain, for example between material scientists, product designers and waste managers, to accelerate technology development and deployment.

The work towards a circular economy in Australia has begun. To realise the opportunities and deliver value, the transition requires cooperation between government, research, industry and the community.

8 REFERENCES

Cluster Reports and Papers

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A. and Meinert, L.D., (2017). Mineral supply for sustainable development requires resource governance. Nature, 543(7645), pp.367-372

Australian Recyclable Resources Atlas. (2017). Retrieved from http://wfw-atlas.monash.edu.au/atlas/build/

Benn, S., Giurco, D., Brown, P., & Agarwal, R. (2014). Towards Responsible Steel: Preliminary Insights. Resources, 3(1), 275–290

Benn, S., Perey, R. Edwards, M. Corder, G., and Golev, A. (2017). The circular economy and implications for the socially sustainable development. Manuscript in preparation.

Ciacci, L., B. K. Reck, N. T. Nassar, and T. E. Graedel. (2015). Lost by Design. Environmental Science & Technology 49(16), 9443-9451.

Ciacci, L., P. Nuss, B. K. Reck, T. T. Werner, and T. E. Graedel. (2016). Metal Criticality Determination for Australia, the US, and the Planet – Comparing 2008 and 2012 Results. Resources 5(29), 1-8.

Ciacci, L., B. K. Reck, A. E. Elshkaki, and T. E. Graedel. (2017). Scenarios for Australian Supply and Demand of Major Metals. Manuscript in preparation.

Dominish, E., Florin, N., Madden, B. and Giurco, D. (2017a). How effective is leasing as a business model for resource-efficient product lifecycles?, Powering the Change to a Circular Economy Conference, Adelaide.

Dominish et al., (2017b), Manuscript in preparation.

Edwards, M., Williams, T., Angus-Leppan, T. and Benn, S. (2017b). Transitioning to a Circular Economy: Extending the Role of Sustainability Officers, Powering the Change to a Circular Economy Conference, Adelaide.

Edwards, M., Benn, S., Angus-Leppan, T. & Perey, R. (2017a). Enacting Sustainable Entrepreneurial Action for a Circular Economy. Manuscript in preparation.

Florin, N., Madden, B., Sharpe, S., Agarwal, R., Perey, R. and Giurco, D. (2015). Shifting business models for a circular economy: metals management for multi-product-use cycles, UTS, Sydney.

Florin et al., (2017). Manuscript in preparation.

Ghodrat, M, Rhamdhani, M.A., Brooks, G.A., Masood, S., Corder, G., (2016). Technoeconomic analysis of electronic waste processing through black copper smelting route, Journal of Cleaner Production, 126, 178-190.

Golev, A. and Corder, G. (2016). Modelling Metal Flows in the Australian Economy. Journal of Cleaner Production 112(5), 4296-303.

Golev, A., Schmeda-Lopez, D., Smart, S., Corder, G. and McFarland, E. (2016). Where Next on E-Waste in Australia?. Waste Management 58, 348-58.

Golev, A., and Corder, G. (2017). Quantifying Metal Values in E-Waste in Australia: The Value Chain Perspective. Minerals Engineering 107, 81-87.

Khaliq, A., Rhamdhani, M.A., Brooks, G. and Masood, S., (2014). Metal extraction processes for electronic waste and existing industrial routes: a review and Australian perspective. Resources, 3(1), 152-179.

Lane, R., Gumley, W., Santos, D. (2015). Mapping, Characterising and Evaluating Collection Systems and Organisations, Monash University, Australia. http://artsonline.monash.edu.au/wfw/files/2016/03/WfWMonash-Mapping-Characterising-Evaluating-CollSystemsOrgs-Dec2015.pdf

Lane, R. and Gumley, W. (in press 2017). What role for the social enterprises in the circular economy? In Crocker, R. (ed.) Unmaking Waste, Springer

Perey, R., Agarwal, R., Benn, S. & Edwards, M. (in press 2017). The Place of Waste: Changing business value for the circular economy, Business Strategy and the Environment, in press. Special issue.

Santos, D. and Lane, R. (2017). A material lens on socio-technical transitions: The case of steel in Australian buildings. Geoforum 82, 40-50.

Sharpe et al., (2017). Manuscript in preparation.

Shuva, M.A.H., Rhamdhani, M.A., Brooks, G.A., Masood, S., Reuter, M.A., (2016a). Thermodynamics data of valuable elements relevant to e-waste processing through primary and secondary copper production: A review, Journal of Cleaner Production, 131, 795-809.

Shuva, M.A.H., Rhamdhani, M.A., Brooks, G.A., Masood, S., Reuter, M.A., (2016b). Thermodynamics behaviour of Germanium during equilibrium reactions between FeOx-CaO-SiO2-MgO slag and molten copper, Metallurgical and Materials Transactions B, 47B(5), 2889-903.

Shuva, M.A.H., Rhamdhani, M.A., Brooks, G.A., Masood, S., Reuter, M.A., (2017a). Thermodynamics of palladium (Pd) and tantalum (Ta) relevant to secondary copper smelting, Metallurgical and Materials Transactions B, 48B(1), 317-27.

Shuva, M.A.H., Rhamdhani, M.A., Brooks, G.A., Masood, S., Reuter, M.A., Firdaus, M., (2017b). Analysis for optimum conditions for recovery of valuable metals from e-waste through black copper smelting, 8th International Symposium on High Temperature Metallurgical Processing, Chapter VII, Springer International Publishing, pp.419-27.

Werner et al., 2017a, Manuscript in preparation.

Werner, T., Mudd, G., and Jowitt, S., (2017b). The world's by-product and critical metal resources part II: A method for quantifying the resources of rarely reported metals, Ore Geology Reviews 80, 658–675

Zhu, X., Lane, R. and Werner, T. (2017). Modelling in-use stocks and spatial distributions of household electronic devices and their contained metals based on household survey data. Resources, Conservation and Recycling 120: 27-37. http://dx.doi.org/10.1016/j.resconrec.2017.01.002

Other references

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. Resources, Conservation and Recycling, 55(3), 362–381

Austrade. (2017). Australia's economic performance in 2015-16. Retrieved from https://www.austrade.gov.au/news/economic-analysis/australias-export-performance-in-2015-16

Austmine. (2013). Australia's new driver for growth: Mining equipment, technology and services. Retrieved from http://www.austmine.com.au/Portals/25/Content/Documents/Austmine%20Survey%20Highlights.pdf

Balde, C.P., Kuehr, R., Blumenthal, K., Gill, S.F., Kern, M., Micheli, P., Magpantay, E.,Huisman, J., (2015). E-Waste Statistics: Guidelines on Classifications, Reporting and Indicators. United Nations University, IAS -SCYCLE, Bonn, Germany.

Benyus, J. M. (2002). Biomimicry: Innovation inspired by nature.

Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. Journal of Cleaner Production, 65, 42–56.

Carbon Disclosure Project. (2012). Reducing Risk And Driving Business Value.

European Institute of Innovation and Technology (EIT). (2017). EIT Raw Materials. Retrieved from https://eit.europa.eu/eit-community/eit-raw-materials

Florin, N., McIntosh, B., Giurco, D., Wyndham, J. & Ison, N. (2016). PV Systems Stewardship Workshop: Stakeholder Workshop Synthesis, Prepared by UTS Institute for Sustainable Futures for Queensland Department of Environment and Heritage Protection.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. Journal of Cleaner Production, 143, 757-768.

Graedel, T. E. and B. R. Allenby. (1995). Industrial Ecology. New York: Prentice Hall.

Graedel, T.E., Allwood, J., Birat, J.P., Reck, B.K., Sibley, S.F., Sonnemann, G., Buchert, M. and Hagelüken, C., (2011). Recycling Rates of Metals-A Status Report. A Report of the Working Group on the Global Metal Flows to the International Resource Panel, United Nations Environment Programme UNEP (2011)

Graedel, T. E., E. M. Harper, N. T. Nassar, P. Nuss, and B. K. Reck. (2015). The criticality of metals and metalloids. Proceedings of the National Academy of Sciences of the United States of America 112(14): 4257-4262.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I. and Shi, L., (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences, 112(20), pp.6277-6282.

IBISWorld. (2014). E-waste collection and processing in Australia [Report OD5420].

International Council on Mining and Metals (ICMM). (2017). Ensure sustainable production and consumption patterns. Retrieved from https://www.icmm.com/en-gb/metals-and-minerals/making-a-positive-contribution/responsible-consumption-and-production

Lifecycles. (2017). Creating value: The potential benefits of a circular economy in South Australia. Report prepared for Green Industries SA.

Lyle, J. (1994). Regenerative Design for Sustainable Communities.

Mason, L., Lederwasch, A., Daly, J., Prior, T., Buckley, A., Hoath, A., Giurco, D. (2011). Vision 2040: Mining, minerals and innovation – A vision for Australia's mineral future, [prepared for CSIRO Minerals Down Under Flagship], Institute for Sustainable Futures, UTS (Sydney, Australia) and Curtin University (Perth, Australia).

McDonough, W., & Braungart, M. (2002). Remaking the way we make things: Cradle to cradle. New York: North Point Press. ISBN, 1224942886, 104.

Mudd, G.M., (2010). Global trends and environmental issues in nickel mining: Sulfides versus laterites. Ore Geology Reviews, 38(1), pp.9-26.

NamiRo. (2017). BMBF research project NamiRo (2015-2017). Retrieved from https://www.namiro-projekt.org/english/

Northey, S., Mohr, S., Mudd, G.M., Weng, Z. and Giurco, D., (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resources, Conservation and Recycling, 83, pp.190-201.

NSW OEH: State of NSW and Office of Environment and Heritage. (2014). Retrieved from http://www.environment.nsw.gov.au/resources/government/140567NSWGREP.pdf

Prior, T., Giurco, D., Mudd, G., Mason, L., & Behrisch, J. (2012). Resource depletion, peak minerals and the implications for sustainable resource management. Global Environmental Change, 22(3), 577-587.

ProSUM: Prospecting Secondary raw materials from the Urban Mine and Mining waste. (2017). About the project. Retrieved from http://www.prosumproject.eu/about-project

Randell P. (2016). Waste lithium-ion battery projections Lithium-ion forums: Recycling, transport and warehousing. Report prepared for the Australian Department of the Environment. 19 July 2016

Reuter, M. A., Hudson, C., Van Schaik, A., Heiskanen, K., Meskers, C., & Hagelüken, C. (2013). Metal recycling: Opportunities, limits, infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel.

Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thorne, J.P., Dulfer, H., & Senior, A.B. (2013). Critical commodities for a high-tech world: Australia's potential to supply global demand. Geoscience Australia, Canberra.

Stadler, A., Jutsen, J., Pears, A., & Smith, M. (2014). 2xEP: Australia's energy productivity opportunity, Draft Version 1.2. Sydney: Australian Alliance to Save Energy

United Nations. (2016). Goal 12: Ensure sustainable consumption and production patterns. Retrieved from http://www.un.org/sustainabledevelopment/sustainable-consumption-production/

UNEP. (2015). Indicators for a Resource Efficient and Green Asia and the Pacific – Measuring progressof sustainable consumption and production, green economy and resource efficiency policies in theAsia-Pacific region, Schandl, H., West, J., Baynes, T., Hosking, K., Reinhardt, W., Geschke, A.,Lenzen, M. United Nations Environment Programme, Bangkok

Van Beers D., Kapur A., Graedel T.E. (2007). Copper and Zinc Recycling in Australia: Potential Quantities and Policy Options. Journal of Cleaner Production, Special Australia and New Zealand Issue, vol. 15, pp. 849-861.

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