

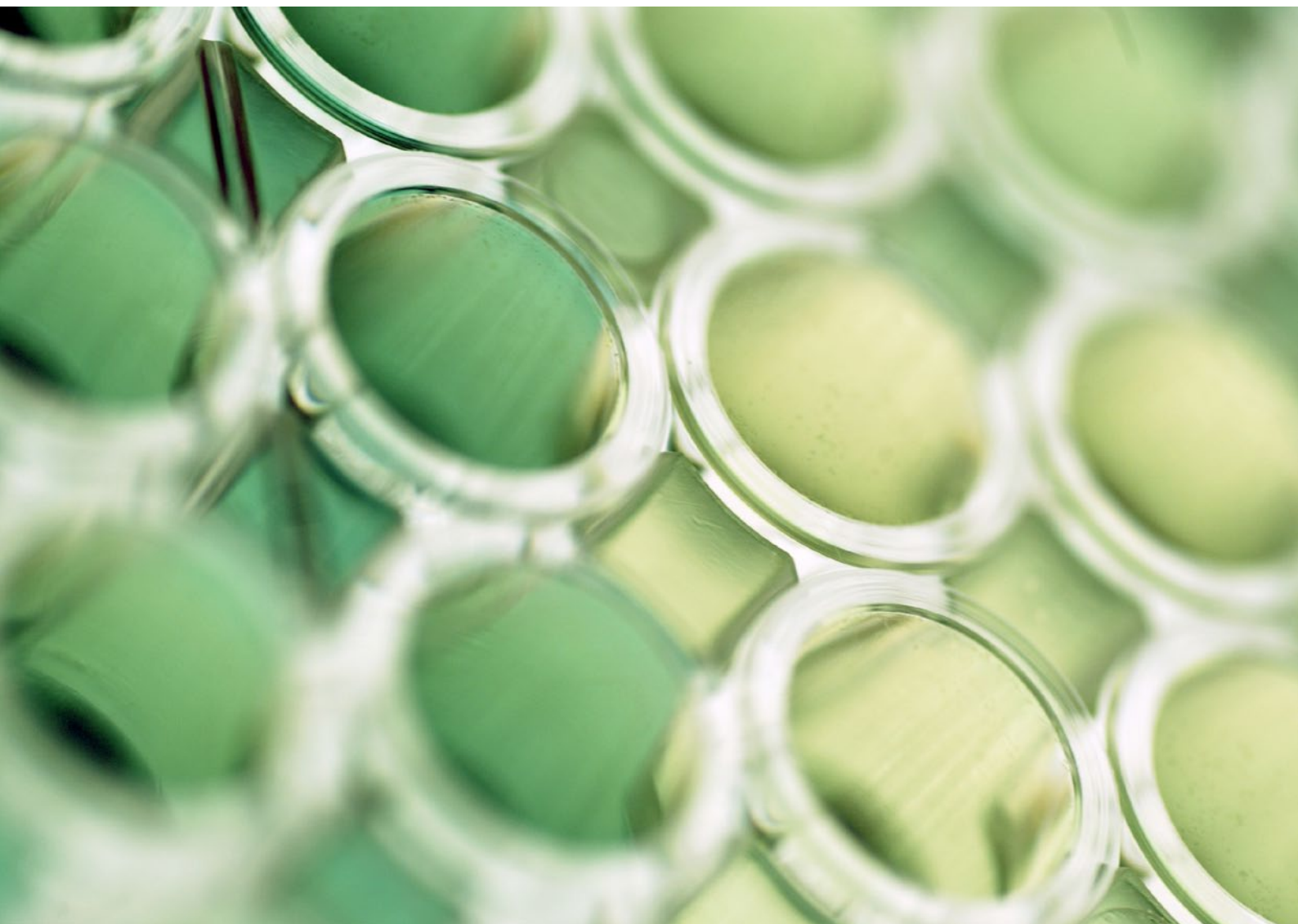


Australia's National
Science Agency

Australia's comparative and competitive advantages in transitioning to a circular economy

A report to the Office of the Chief Scientist

January 2024



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Executive summary

A circular economy recognises the scarcity and value of natural resources.

A circular economy emphasises the design of products and systems for reuse and recovery, aiming to establish business models, production and consumption practices that create a closed-loop system for resource utilisation. While the approach is comprehensive, a circular economy focuses on three key economic and industrial goals: **eliminating waste, maintaining and increasing the value of materials and products through repeated use, and conserving natural resources** (see Appendix A).

Australia has considerable potential for a more circular economy. Like many other countries, it can unlock vast economic value while reversing the substantial loss of natural capital.

- There are several industry sectors where Australia could leverage its plentiful natural resources, including critical minerals, renewable energy, and food, fibre and feed. This report focuses on the potential of mining, construction, manufacturing, agriculture and waste management, and resource recovery.
- Australia's strong foundation of a diverse and skilled workforce and strong research and innovation capabilities support these sectors' comparative advantages in maximising Australia's benefits from a more circular economy.
- Additionally, Australia's proximity to Asian manufacturing hubs and markets, supported by policy and institutional frameworks conducive to investment, further amplifies and reinforces the nation's potential for achieving favourable outcomes in a circular economy.

The five industries with the most potential to advance a circular economy are mining, construction, manufacturing, agriculture, and resource recovery.

The inherent advantages in these sectors stem from significant amounts of raw materials or products that can be reused or recycled, as well as the potential for reducing negative environmental impacts. There are identified opportunities for product and service development within these key sectors, each playing a crucial role in advancing towards a circular economy.

- **Mining opportunities** exist in the repurposing of mining rocks, tailings and closed mines. Novel mine-tailing beneficiation technologies are expanding, and smaller enterprises can play a significant role in reducing environmental impact if well supported.
- **Construction opportunities** include material production or enhancements from mining, agricultural and industrial by-products, prefabricated and modular housing, cross-laminated and recycled timber, low carbon concrete, and regional resource recovery centres.
- **Manufacturing opportunities** are available in four material sectors: lithium-ion batteries, e-waste, plastics, and apparel and textiles.
- **Agriculture opportunities** would transform Australia's abundant agri-food by-products (such as grape marc) into valuable chemicals and products, and feedstocks for other processes using biological, chemical and insect technologies. These advancements are underpinned by Australia's investment in synthetic biology and biotechnology research, with examples of Australian companies commercialising their innovations.
- **Resource recovery opportunities** (beyond those noted above) lie in the abundant waste of our consumer society, our capacity for technical innovation, and the new Recycling Modernisation Fund. Harmonising waste-management frameworks (education, regulation, infrastructure, waste levies and planning pathways), converting voluntary stewardship to extended producer responsibility schemes, and mandating government procurement of circular economy products and services would further extend these opportunities.

To fully leverage these industry opportunities, Australia can further develop its talent bank of 'hard' and 'supporting' skills. The hard skills include engineering and digital capabilities, while the supporting skills include the design, financial and regulatory expertise crucial to facilitating and governing a circular economy. Workforce diversity, a culture of innovation, and high educational attainment are also essential components in this context.

- **There is a shortfall in the engineering and digital skills** required for a circular economy. Although Australia has seen growth in its tertiary-educated workforce, there is high demand for these crucial 'hard' skills, and they remain in relatively short supply, particularly in regional areas.
- **Policies are being developed to enhance industry-ready training** more effectively and accessibly, with a particular focus on targeted immigration strategies. Further efforts could also be made in the Vocational Education and Training (VET) sector to upskill workers for roles in the circular economy. This could involve offering more short courses and micro-credentials co-designed with industry players and implementing a 'skills passport' system to recognise and transfer accredited skills across different industries.

While Australia has a significant comparative advantage in innovation in mining and agriculture and its professional service industry, ongoing strategic investment is needed.

- **Diverse professional fields exhibit Australia's comparative strengths**, including material tracking, accreditation, monitoring and evaluation, with expertise in circular design, production, upcycling, and energy recovery. Australia also excels in the field of reverse logistics and has effective platforms to facilitate material exchange between industries and businesses.
- **Remarkable examples of innovation that either enhance value or contribute to closing the loop** are found in various sectors, including construction, textiles, furniture and homeware, plastics and polymers, metal recycling, resource recovery and electronics.
- **Australia's private-sector and university-led innovation hubs can spearhead greater research and development (R&D) investment.** Though these initiatives remain relatively small by global standards, owing to Australia's remoteness and the smaller scale of businesses embracing the circular economy, opportunities exist to further extend the design and development of circular economy related technologies. With R&D investment falling to a 17-year low in 2022, programs that link R&D funding to mandatory participation in open innovation networks could support more collaborative business models in our relatively firm-centric industries.

Building on Australia's diverse trading relationships, strong opportunities exist for Australia to partner with other countries, particularly in Asia and the European Union, to create new demand for circular products and recycle Australia's end-of-life materials.

- **Australia has strong and diverse trading partnerships in manufactured goods, with opportunities to increase trade with the EU.** In 2021–2022, Australia exported A\$53.4 billion in manufactured goods, with each of the top 20 exports having circularity potential. These included advanced manufacturing goods to the US, New Zealand, China, Hong Kong, Singapore, Indonesia, the Netherlands, France, and the UAE; and chemical materials to New Zealand, China, the US, India, Japan and Thailand. Further trade with the EU would accelerate Australia's journey to a more circular economy. The EU is leading the world with its circular economy policy, such as its extended product responsibility and digital product passport, making it a future source for circular inputs and products.
- **Australia might aim to retain the value of 'end-of-life' materials.** In the same period, end-of-life materials valued at A\$4.36 billion were exported. Indonesia, Vietnam, Bangladesh, Malaysia, Thailand, South Korea and Taiwan were the top export destinations for plastic, tyres, textiles and metals. Sweden is a potential partner for commercial-scale chemical textile recycling, while South Korea, Singapore, Canada, and Belgium are the leading international partners for processing recycled lithium-ion batteries.

However, offshore end-of-life processing may not be a strategic solution in the long term, as the beneficiation of these materials onshore could provide Australia with a considerable boost to GDP and build Australia's reputation as a trusted supplier of high-quality secondary materials for international industries. The Recycling Modernisation Fund is also significantly boosting our onshore recycling and remanufacturing capacity for plastics, glass, paper and tyres.

To realise these opportunities, Australia will need to strengthen and forge new international partnerships to foster the purchase of Australian-made circular products, help close the loops for end-of-life materials, and supply circular inputs to domestic manufacturing.

1 Introduction

In 2022, the world extracted and used over 100 billion tonnes of biomass, fossil fuels, metal ores and non-metallic minerals, three times what it did 50 years ago, and on a path to 160 billion tonnes by 2060. One-third of all extracted material is discarded within a year (International Resource Panel, 2024).

Reversing this immense loss of natural capital and economic value could unlock US\$4.5 trillion of value by 2030 (Lacy and Rutqvist, 2015). It would also address 50 per cent of climate change impacts, 90 per cent of water stress and land-use related biodiversity loss, and 30 per cent of particulate matter health impacts. Doing so remains critical for Australia both as an economic opportunity and an environmental need.

Australia relies heavily on resource extraction and primary industries for economic growth and global economic participation. A circular economy may help foster new industries and technologies and add to Australia's role in the global economy and its relationship with natural capital.



This report explores whether Australia may have comparative or competitive advantages to assist in this potential transition. The following two questions were the foundation of this research.

- 1 As international economies become increasingly circular, what are Australia's comparative and competitive advantages in:
 - a. workforce capacity and capabilities
 - b. product and service development
 - c. research and innovation
 - d. economic activities.
- 2 Which countries represent valuable potential partners to complement Australia's strengths in the circular economy, and increase the circularity of our material supply chains?

The definitions of comparative and competitive advantage continue to evolve in the economic literature. We have adopted the following as being most constructive to the present study:

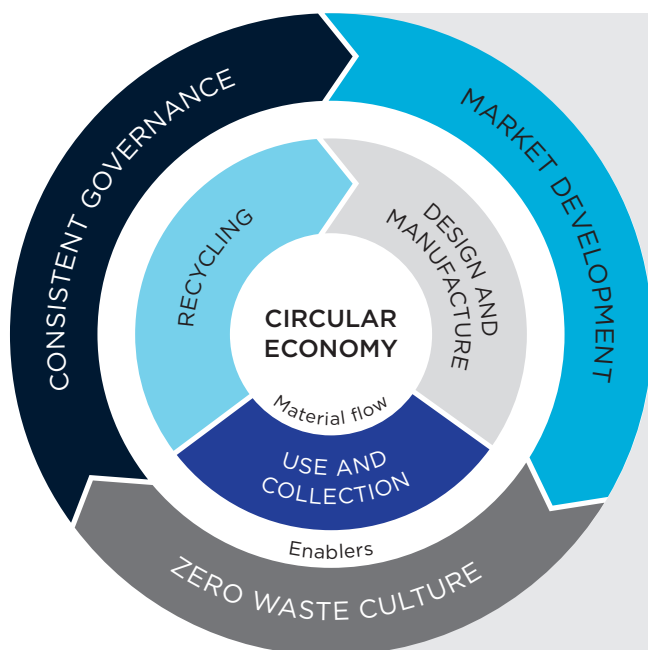
- **Comparative advantages:** 'Australia's factors of production (e.g., land, labour, and capital), and other conditions (e.g., regulatory environment, weather, policies, investments) that can be used to efficiently produce goods and services compared to others'. This is the area Australia is generally strong in.
- **Competitive advantages:** 'Australia's ability to generate products or services at lower cost or of higher value than other countries, allowing it to increase its global market share.' This is the area Australia needs to improve on.

Australia’s economy has a strong potential to be more circular

The Australian economy has high material flows yet relatively low circularity. Australia exports most of its primary materials to other countries and imports most of its consumer goods (Krausmann et al., 2015; Schandl et al., 2019). In 2019, Australia’s material extraction stood at 2,587 million tonnes, of which 917 million tonnes were consumed domestically, and only 39 million tonnes recycled, as shown in Figure 2. This resulted in a circularity rate of 5.4 per cent (Miatto et al., 2024), up slightly from 3.5 per cent in 2015 (Schandl et al., 2019). What we extract each year is equivalent to digging up Hobart to a depth of 7.5 metres, of which 2 metres is consumed in Australia.

Australia’s low economic complexity may also inhibit a circular economy. Australia has been assessed as having low economic complexity due to the large shares of primary industries and service sectors in the national economy (Harvard, 2023; Industry Innovation and Science Australia, 2023). The lack of economic complexity has not inhibited Australia’s economic growth to date, as those sectors are highly competitive in the global economy. However, it does matter for its transition to a circular economy, as the characteristics that define high economic complexity tend to correspond with those needed for a circular economy.

Nonetheless, Australia has several valuable comparative advantages in domestic production and global trade that could enable circularity in many sectors (Australian Trade and Investment Commission, 2023). These include a well-educated and diverse workforce with strong centres of innovation; abundant resources of critical minerals, renewable energy, food, fibre and feed; favourable policies and institutions for investment; and proximity to Asian manufacturing centres and markets. These advantages are implied in all our analyses in Section 2, to which we add specific comparative advantages for the identified sectors.



To pursue a circular economy, Australia must focus on six key elements (Figure 1): three aimed at increasing the circular flow of our materials (inner circle) and three focused on enabling the changes needed to be more circular (outer circle).

Key material flow strategies

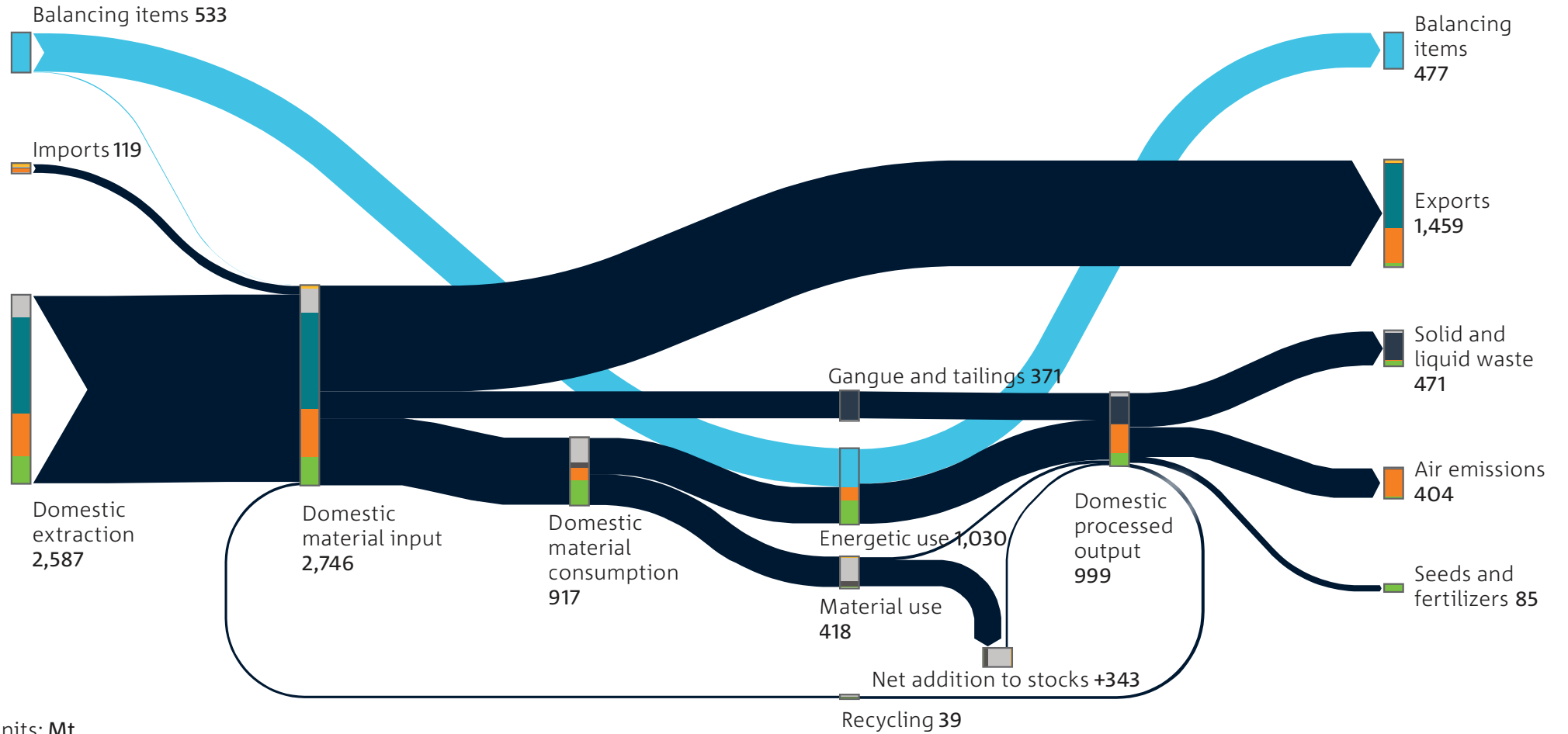
1. Retain material through use and collection
2. Upscale and innovate recycling technologies
3. Innovate and collaborate in design and manufacture

Key enablers

4. Develop markets for secondary materials and the products that use them
5. Streamline nationally consistent governance
6. Secure a national zero-waste culture

Figure 1 The six key elements that Australia must focus on to enable circular economy

Australia, 2019, material flows.



Units: Mt

■ Biomass
 ■ Fossil fuels
 ■ Metals
 ■ Metal ores
 ■ Gangue and tailings
 ■ Nonmetallic minerals
 ■ Other products n.e.c.
 ■ Balancing items

Figure 2 Material flow account for Australia, 2019, in million tonnes

Source: Miatto et al., 2024

2 Industry opportunities for a circular economy

Many industries are transforming how resources are used through a product's life cycle. CSIRO has reviewed these industries to identify those with comparative advantages on which to build globally competitive products or services in a more circular global economy. It has selected five industries – mining, agriculture, construction, several manufacturing sub-sectors and waste management – as having the most potential.

For these industries:

- their successes demonstrate the value of cross-industry partnerships and strong government commitment. In particular, agricultural improvements that are helping to create circular textiles and waste recovery initiatives that are creating new construction materials
- they are achieving growth by tackling one link at a time in their supply chains and seeing these advancements spur on other important changes
- Australia has numerous comparative advantages that will help grow the momentum of its circular economy, including a well-educated and skilled workforce, attractive climate investment and a stable political environment
- leading the way is a growing list of globally competitive firms and sub-sectors.



Selection of industries with promising circular economy opportunities

This was based on economic activities that:

- produce large quantities of either raw materials or circular economy products, able to be reused or recycled within the circular economy
- currently have a high impact on the environment¹ and an opportunity to reduce that impact through adopting one or more of the six key elements of a circular economy (see Figure 1)
- have comparative strengths that can be leveraged.

Nineteen Australian and New Zealand Standard Industrial Classification (ANZSIC 2006) industrial divisions (ABS, 2008) were assessed according to the selection criteria. The following five industry divisions met the selection criteria:

- **Mining** – primarily involved in material extraction
- **Agriculture** – crop, fibre and livestock farming, fisheries and forestry
- **Construction** – construction of buildings and other structures, additions, alterations, reconstruction, installation, and maintenance and repairs of buildings and other structures
- **Manufacturing** – physical or chemical transformation of materials, substances, or components into new products
- **Waste management** – collection, treatment and disposal of waste materials; remediation of contaminated materials, including land; and materials recovery activities.

Each industry involves distinct circular economy enablers, raw materials, products, services, economic opportunities and comparative strengths that would reduce their environmental impact (Ellen MacArthur Foundation, 2017); see Table 1.

¹ High environmental impact is considered in terms of material footprint, land use, water use, energy use, contribution to climate change (GHG emission) and eutrophication, as per the Sustainable Consumption and Production Hotspots Analysis Tool (SCP-HAT).

Table 1 Summary of opportunities for Australian industries to accelerate circular economy

CIRCULAR ECONOMY ENABLERS, MATERIALS, PRODUCTS AND SERVICES	OPPORTUNITIES	COMPARATIVE STRENGTHS
Mining by-products (CE Ob 2) [Mining]	<ul style="list-style-type: none"> • Recovery of valuable materials • Repurposing of mining by-products • Sites for energy storage systems 	<ul style="list-style-type: none"> • Abundance of mining by-products • World-leading mining industry • Mature mining by-product recovery technologies • Leaders in the adoption of automation • Strategic international partnerships and trade agreements
Circular buildings and construction (CE Ob 1, 2 & 3) [Construction]	<ul style="list-style-type: none"> • Construction materials from mining and agricultural by-products • Recycling timber • Modular housing • Low carbon concrete • Regional resource recovery 	<ul style="list-style-type: none"> • Abundance of construction materials and by-products • Skilled and culturally diverse labour • Well established place-based co-innovation centres (living labs)
Lithium-ion batteries (CE Ob 2) [Manufacturing]	<ul style="list-style-type: none"> • Designing for disassembly and manufacturing • Recycling • Reusing lithium and other recovered metals for energy storage • Refurbishing commercial lithium-ion batteries for household use 	<ul style="list-style-type: none"> • Global supply-chain advantages: Australia has nine of the ten required lithium-ion battery mineral elements • World-leading and demonstrated expertise in resource extraction and processing (transferrable to metal recovery) • High-tech engineering and substantial investments into renewables research • Low sovereign risk and strategic international partnerships
Plastics (CE Ob 1, 2 & 3) [Manufacturing]	<ul style="list-style-type: none"> • Developing bioplastics • Advanced recycling of soft plastics 	<ul style="list-style-type: none"> • Abundance of plastic waste and organic biomass • Superior innovation in mixed plastic and dedicated bioplastic research centres • Supportive government policies • Significant investment in recycling technologies
Apparel and textile (CE Ob 1, 2 & 3) [Manufacturing]	<ul style="list-style-type: none"> • Upcycling cutting waste • Recovery of valuable materials • Regenerative apparel • Producing materials for art • Apparel repair services • First Nations apparel 	<ul style="list-style-type: none"> • Abundance of cotton and wool to support regenerative apparel, consistent with Australia as a globally recognised leader in the natural fibre sector • High innovation and R&D potential across the innovation system, together with small medium enterprises (SMEs), across natural and fossil-fuel based fibre types • Closed loop resource cycling for regenerative agriculture with pilot-scale/demonstrators in place at local scales • World-first branding • Strong, sustainable apparel education/skills expertise across regions, with 'clothing repair cafes' active at local scales, ready to expand/scale up • An emergent and growing circular economy based Aboriginal and Torres Strait Islander Apparel Sector, including designers, practitioners, and SMEs
Agricultural by-products (CE Ob 1 & 3) [Agriculture]	<ul style="list-style-type: none"> • Valorisation of agri-food wastes and by-products • Utilisation of organic biomass as feedstock • Insect technology 	<ul style="list-style-type: none"> • Favourable conditions for food, feed and fibre from abundant organic residues • High investment in biotechnology • Supportive industry policies • High innovation in agri-food waste and by-product utilisation
Waste management – resource recovery services (CE Ob 1, 2 & 3) [Waste Management]	<ul style="list-style-type: none"> • Resource recovery services • Materials for beneficiation • Promoting best international practice • Improving waste supply chain efficiency 	<ul style="list-style-type: none"> • National Reconstruction Fund • Abundance of by-product resource materials

Note: CE Ob 1,2,3 refer to circular economy objectives where CE Ob1 – Reduce use of natural resources; CE Ob2 – Maintain value of materials for as long as possible; CE Ob3 – Reduce pollution and negative environmental impact.

2.1 Mining

There are opportunities within the mining sector to repurpose common and often discarded material to benefit other products and industries (key material flow circular economy element – *use and collection*; key enablers element – *market development*²):

- **repurposing of mining rocks (waste rocks)** to be used as construction materials, rock fertiliser and mine void backfill (Lebre et al., 2017; Solismaa et al., 2018; Tayebi-Khorami et al., 2019; Simão et al., 2022; Thejas and Hossiney, 2022)
- **repurposing mining tails** to produce cement, ceramics, and sand substitute (ore sand) (Kiventerä et al., 2016; Peiravi et al., 2021; Liu et al., 2021; Golev et al., 2022)
- **repurposing closed mines** for energy storage systems (Kinnunen et al., 2022)
- **recovery of valuable minerals** such as critical minerals and rare earth minerals from tailings, slag, and laterite (Peng et al., 2015; Saha and Saker, 2017; Dold, 2020; Abaka-Wood et al., 2022; Makhathini et al., 2023).

Market drivers, comparative and competitive advantages

Market drivers include adopting circular economy principles (Guo et al., 2020) combined with increased demand for sustainably sourced critical minerals (Araya et al., 2021).

Australia's comparative advantages lie in:

- substantial mining by-products, with 620 million tonnes of mine by-products generated annually (Pickin et al., 2023; Valenta et al., 2023)
- strategic international partnerships and trade agreements (Australian Trade and Investment Commission, 2023)
- highly skilled workforce in the mining sector (Minerals Council of Australia, 2022).

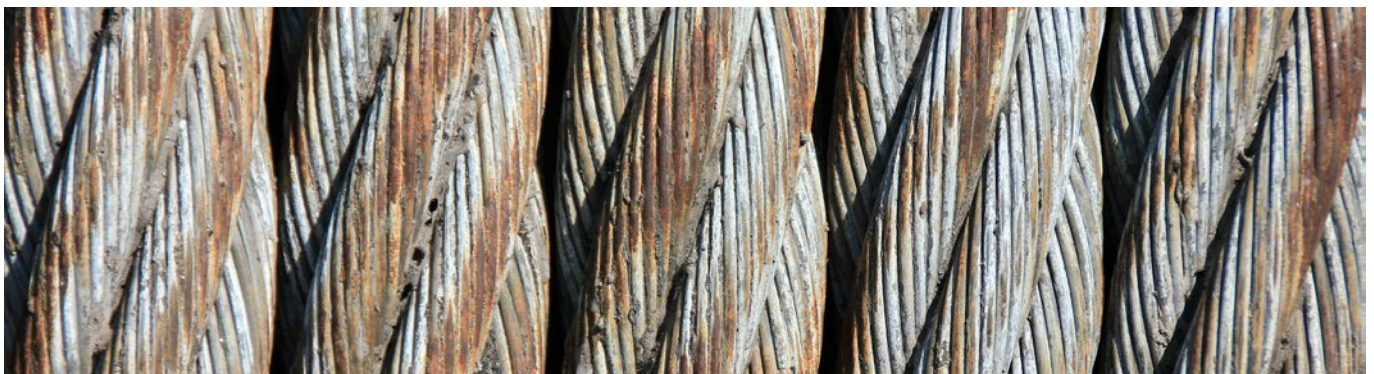
These have supported competitive advantages in novel mine-tailing beneficiation technologies (Minerals Council of Australia, 2022), for example:

- **NovaCell™** (Morgan et al., 2023; Han et al., 2023) – enabling the flotation of valuable minerals at larger particle size than current technology, allowing more energy-efficient reductions, the effective recovery of water, and the potential elimination of tailings dams.
- **Viper Tailings de-watering technology** (Whatnall et al., 2021) – large-scale de-watering of mine tailings utilising low energy and high production capacity.
- **REFLUX™ Classifier** (FLS, 2023a) – for de-sliming and beneficiation of ultrafine iron ore particles.
- **REFLUX™ Flotation Cell** (RCFTM) (FLS, 2023b) – which can operate at gas and wash water fluxes in an advanced manner compared to other flotation techniques.
- **Metso** (Metso, 2023) – which provides tailing management solutions, including mining wastewater treatment.

International case study

EnviCore is a startup company based in Canada that has developed a low-cost, energy-efficient technology with the potential to replace 20 per cent of cement used in construction. It does this by converting mining tailings into supplementary cementitious materials, reducing the need for cement mixers (EnviCore, 2023).

Transferrable learnings: Small-to-medium sized enterprises can be supported to utilise mining by-products and enhance the economic and environmental impacts of the circular economy.



² Refer to Figure 1 for additional information on the three key material flow strategies and three key enablers of the circular economy.

2.2 Construction

There are many opportunities in construction to repurpose waste in other building elements, create products to reduce environmental impacts, and replace single-use materials with recycled materials to extend a product's life cycle (key material flow circular economy elements – *use and collection, design and manufacture, recycling*; key enablers element – *market development*):

- **The production of construction material from mining by-products** can be transformed into masonry units for construction (Cobîrzan et al., 2022).
- **The production of construction material from agricultural and industrial by-products**, such as wood shavings, can be transformed into wood foams to increase their strength and performance and meet required standards (Parece et al., 2020).
- **Prefabricated houses** manufactured and constructed offsite are known to improve building quality and reduce embodied and operational emissions and construction waste.
- **Cross-laminated timber** (CLT) is an engineered wood product used for prefabricated structural applications, replacing concrete and steel to help reduce environmental impacts.
- **Recycled timber** can be used to make cross-laminated timber, which has properties similar to pre-cast concrete panels but is lighter in weight and has lower carbon emissions (Carrasco et al., 2023).
- **Modular housing** enables easier disassembly at the product's end-of-life phase (Green Industries SA, 2022; Minunno et al., 2020).
- **Low-carbon concrete** offers lower carbon emissions to decarbonise infrastructure delivery (Infrastructure NSW, 2022).
- **Regional resource recovery centres** would help increase the production of construction materials and reduce transport costs (Green Industries SA, 2022).

Market drivers, comparative and competitive advantages

The construction industry currently enjoys high demand for affordable and environmentally friendly housing (Horne et al., 2023). The comparative advantages include:

- abundant raw materials that can be transformed for construction, including mining by-products, timber, and wool (Whittle, 2019; Pickin et al., 2023)
- robust and credible building rating systems such as Green Star and NABERS, along with peak bodies such as the Green Building Council of Australia (Edge Environment, 2021)
- well established place-based co-innovation centres (e.g., urban living labs) (CSIRO, 2023)
- a culturally diverse and skilled workforce due to immigration policies that can bridge significant cultural gaps in the Asia-Pacific market (Lim, 1997).

These have supported competitive advantages in constructing high-rise multi-unit apartment buildings from cross-laminated timber (see case study below), helping to stimulate the industry using locally sourced raw materials and skills.

Local and international case studies

Next generation 5-dimensional building information modelling (5-D BIM) is an emerging technology that integrates design, cost, and schedule in a 3-dimensional output enabling better designs and analysis of the impact of changes to construction schedule and material. The 5-D BIM is currently being promoted in Britain, Singapore, and Finland (Agarwal et al., 2016).

Forté is Australia's first mass-timber high-rise apartment building, constructed by Lendlease in 2012 in Victoria Harbour, Melbourne (Durlinger et al., 2013).

Transferrable learnings: The 5-D BIM case study show that collaboration between architects and information and technology specialists will be critical to driving further circularity in construction. The Forté case study indicates that Australia can utilise its natural resources and innovation to build high-rise buildings and meet the demand for affordable housing.

2.3 Manufacturing – Lithium-ion batteries

Better and more sustainable design of lithium-ion batteries can enable an extension of primary life, a second life and a more efficient recovery of metals and materials (key material flow circular economy elements – *use and collection, design and manufacture, recycling*). The opportunities are:

- **designing and manufacturing lithium-ion batteries for disassembly** to ensure they are structurally rigid and open to automatic disassembly will ease the material recovery at the end-of-life phase (Wu et al., 2023)
- **recycling** allows the recovery of reusable parts and valuable metals (Chen and Ho, 2018)
- **reuse** of end-of-life electric vehicle batteries for large and small-scale energy storage systems (Baum et al., 2022)
- **refurbishment** of lithium-ion batteries for household applications (Islam et al., 2022).



Market drivers, comparative and competitive advantages

Global demand for electric vehicles leapt by 35 per cent in 2022 alone and is forecast to continue (International Energy Agency, 2020). Australia holds significant global supply-chain advantages:

- producer of nine of the ten minerals required to manufacture lithium-ion batteries
- world-leading expertise in mining resource extraction and processing, enabling quick response to global consumer demands (Cordano and Zevallos, 2021)
- high-tech engineering skills for designing, manufacturing and refurbishing lithium-ion batteries
- renewable energy sources that can be used to reduce the production cost of lithium-ion batteries (Australian Trade and Investment Commission, 2018)
- low sovereign risk, minimising the probability of defaulting on its obligations, and high environmental and labour standards.

Australia does not yet have internationally recognised competitive advantages in lithium-ion batteries.

International case study

Redwood Materials is a US\$3.8 billion Nevada-based startup offering services in recycling, hydrometallurgical metal refining, and remanufacturing of anode and cathode battery components (Redwood Materials, 2023). It shows that with substantial investments, small-to-medium enterprises can offer services across the lithium-ion battery supply chain. It shows that if Australia invests more in lithium-ion manufacturing, small-to-medium enterprises can offer services across the lithium-ion battery supply chain.

2.4 Manufacturing – Upcycling e-wastes

Waste generated from electrical goods (e-waste) are valuable sinks of metals and materials (key material flow circular economy elements – *use and collection, recycling*). There are opportunities in:

- **automated separation and disassembly** of e-waste
- **pulverising hazardous material** increases the efficiency of separating e-waste materials at the end-of-product life phase (Tiwary et al., 2017)
- **recovery of precious and base metals** from e-waste streams (Rene et al., 2021).

Market drivers, comparative and competitive advantages

The drivers of demand for e-waste recycling (Maximize Market Research, 2023) are:

- global surge in e-waste generation (53.6 million metric tonnes in 2022)
- technological advances in material recovery and recycling
- rising adoption of circular economy principles.

Australia has several comparative advantages:

- significant quantities of e-waste which can act as resources (Pickin et al., 2018)
- well-established e-waste recycling scheme for some e-waste (Dias et al., 2018).

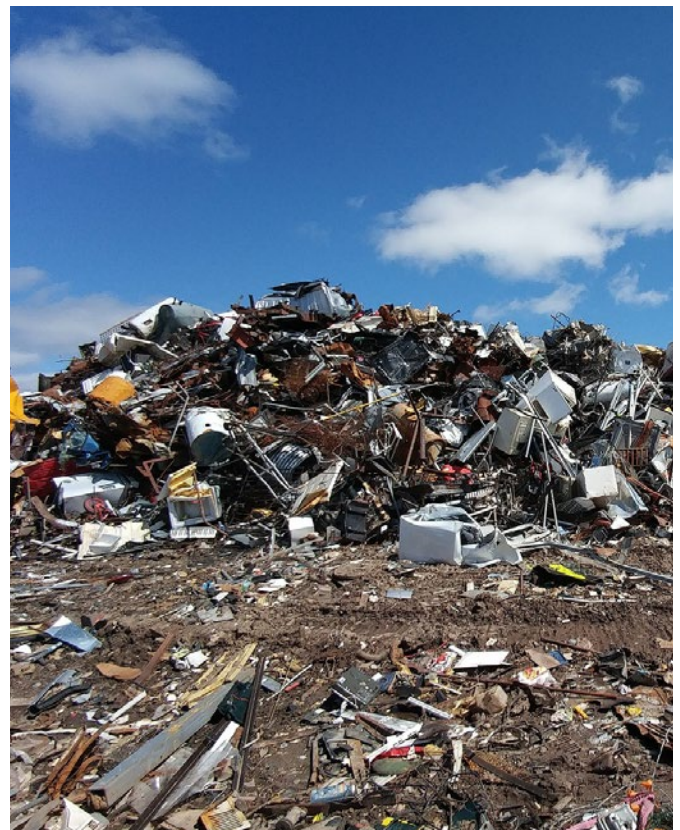
These have supported competitive advantages in superior e-waste innovation and large processing capacity. For example:

- **Mint Innovation** which can process 3,000 tonnes of circuit boards and recover valuable metals using green chemistry (Mint, 2023).
- **Microfactorie**[®] technology that uses thermal techniques to transform e-waste into valuable materials such as rare earth metals (UNSW, 2023).
- **Scipher Technologies** can process 539,000 tonnes of e-waste and solar panel waste (CEFC, 2022).

International case study

European Union's (EU) extended producer responsibility scheme requires electrical goods producers in the EU to bear the cost of recycling electrical goods in the EU. The rationale is that this gives them a financial incentive to maximise product lifecycles (ANZRP, 2015).

Transferable learnings: Australia has an extended producer responsibility scheme, currently limited to personal computers, computer accessories, and televisions. Australia would benefit from expanding the scope of products covered by its e-waste system and promoting shared responsibility (ANZRP, 2015).



2.5 Manufacturing – Plastics

The opportunities for plastics are in (key material flow circular economy elements – *design and manufacture, recycling*; key enablers element – *market development*):

- **developing renewable, non-toxic, biodegradable and compostable plastics (bioplastics)** using organic feedstocks such as sugarcane, seaweed, and algae (Berry et al., 2022; Payne et al., 2019)
- **advanced recycling of plastics** to break down difficult plastics into chemical building blocks for conversion into new plastics (King et al., 2021).

Market drivers, comparative and competitive advantages

Demand for renewable plastics is driven by the impending Global Plastics Treaty (Recycling Plastics Australia, 2023) which is intended to be negotiated by the end of 2024.

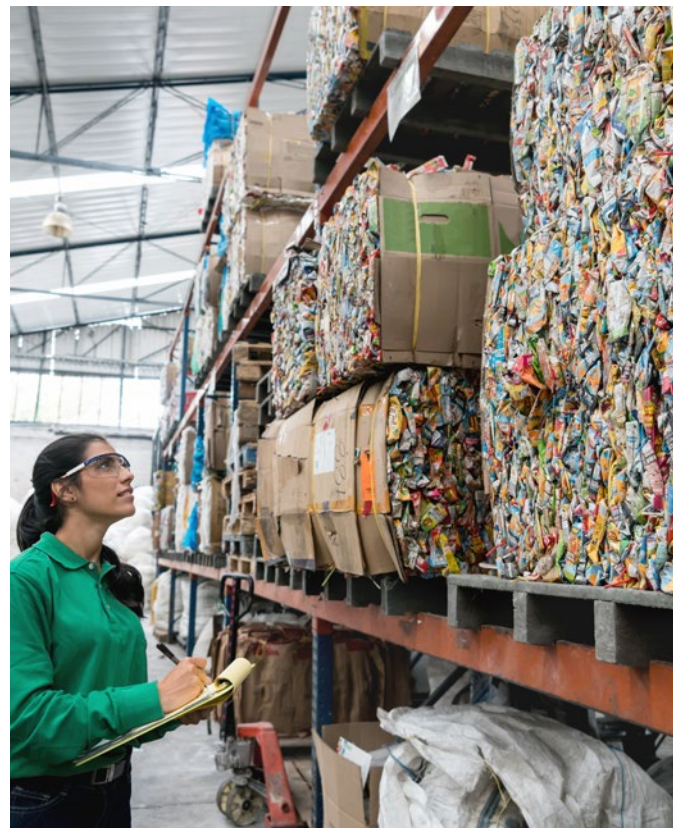
The comparative advantages for the Australian industry include:

- abundance of plastic waste (2.63 million metric tonnes annually with 66 per cent recyclability potential) and organic biomass (Pickin et al., 2023; Australian Packaging Covenant Organisation, 2021)
- expertise in processing and high-tech engineering research (Australian Trade and Investment Commission, 2023)
- Australian Research Council’s Training Centre for Bioplastics and Biocomposites enhances research in plastic recycling (Centre for Bioplastics, 2023)
- supportive government policies (Australian Packaging Covenant Organisation, 2021)
- significant investments in recycling and resource recovery, such as the Recycling Modernisation Fund (RMF) Plastics Technology stream (DCCEEW, 2023a).

These have supported competitive advantages in mixed plastic recycling. For example, Licella and BioLogiQ have developed their high-tech Catalytic Hydrothermal Reactor (**Cat-HTR™**), a chemical recycling solution that can break down mixed end-of-life plastics into oil (Licella, 2023).

Case study

The Australian Government has invested A\$2.5 million to develop a **fit-for-purpose mobile plastic recycling facility** to process single-use plastics into valuable products. Located in the Northern Territory, the project will connect remote communities to a global recycled plastic market (DCCEEW, 2023b). These mobile recycling technologies and facilities can help rural communities manage waste and enter the global market.



2.6 Manufacturing – Apparel and textiles

The opportunities to extend the life of textiles include (key material flow circular economy elements – *use and collection, design and manufacture, recycling*; key enablers elements – *market development, consistent governance*):

- **recovery of valuable materials**, including biodegradable fibres such as viscose and other cellulosic fibres (Ma et al., 2020; Ruuth et al., 2022)
- **reusing textile dye for art** involves pulverising textile waste into a powder that can be used in art (Deakin University, 2023)
- **regenerative apparel** that produces apparel using fibres sourced from regenerative farms rather than traditionally resource-intensive fibres such as wool (Gueye, 2021).

Market drivers, comparative and competitive advantages

Global environmental concerns are a key driver of demand for regenerative apparel (Gueye, 2021).

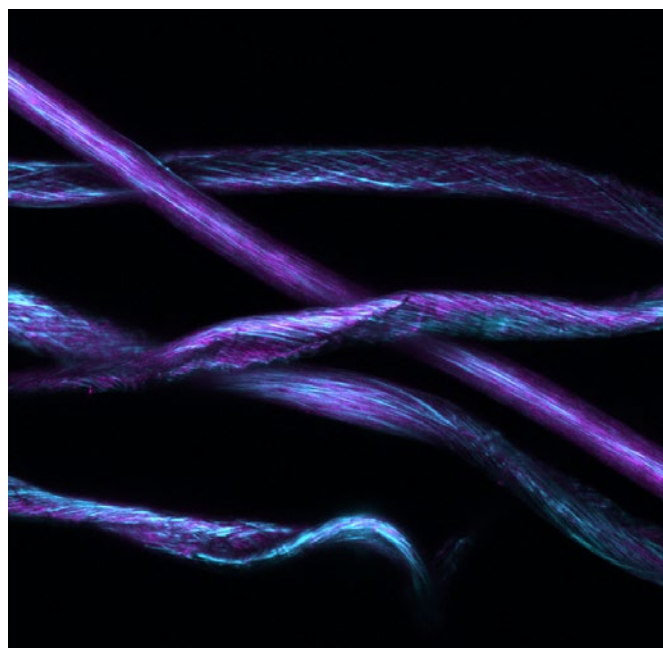
Australia's comparative advantages include:

- an abundance of cotton and wool as raw materials that can be used for regenerative apparel and a highly adaptive natural fibre industry in Australia (Cotton Australia, 2023; Wiedemann et al., 2022)
- a world-first fashion industry trademark, the Australian Fashion Certification Trademark, has been launched to help identify Australian brands globally (Australian Fashion Council, 2023)
- a National Clothing Product Stewardship Scheme for textiles established to accelerate extending clothing life and reducing textile waste at the brand/producer levels of the value chain (Australian Fashion Council and Consortium, 2023)
- an emergent and creative circular economy transdisciplinary fibre and textile Australian ecosystem tackling circularity in the textiles and apparel sector (MacMillan and Payne et al., 2022).

These have supported a competitive advantage in separating textiles. For example, a new ionic liquid (salt in a liquid state) developed by Deakin University can separate different blends of cotton-polyester, providing a breakthrough for recycling textiles (Deakin University, 2014).

International case study

Worn Again Technologies is a unique solvent capable of converting end-of-use polyester and cotton garments into polyester pellets and cellulosic pulp, developed in 2012 by a UK-based company. The business has since secured funding through partnerships to build a pilot plant with a 1,000 tonnes capacity and plans to build a 50,000 tonnes capacity plant by 2027 (Worn Again, 2023). The experience showed the value of support mechanisms, extensive R&D and strong partnerships to scale up and ensure longevity in the market.



2.7 Agriculture – food, fibre and feed

There are opportunities for transforming wastes and by-products for other industries, food sources and economic benefit (key enablers circular economy element – *market development*):

- **Agri-food by-products can be transformed into valuable food, fibre and feed** (Papaioannou et al., 2022; Isah and Ozbay, 2020; Hetherington, 2022). For example, grape marc can be processed to extract natural antioxidants, which is projected to see increasing demand, with Asia-Pacific being a primary market (Raju and Roshan, 2022).
- **Organic feedstock** uses by-products as feedstocks for fermentation processes, such as synthetic biology, to produce valuable products (CSIRO Futures, 2021).
- **Insect technology** involves creating more valuable and homogeneous biomass from agri-food waste (Leni et al., 2021). The insect protein market is expected to grow from US\$288.38 million in 2023 to US\$348.97 million by 2028, at a compound annual growth rate of 3.89 per cent (Mordor Intelligence, 2023).
- **Regenerative agriculture.** Biomass-based products cycling back through the farm with regeneration of soils, including diverting cotton fibre textile waste from landfill to enrich cotton farm soils for fibre production (CRDC, 2023).

Market drivers, comparative and competitive advantages

Drivers of market demand (Kaza et al., 2018) include:

- global concern on food waste
- consumer shift from chemical to bio-based products
- technical advances in the utilisation of agriculture
- rising adoption of circular bioeconomy.

Comparative advantages in Australia include:

- climatic conditions that support various agricultural products (Australian Trade and Investment Commission, 2023)
- abundance of different agricultural by-products that can be used as a feedstock across several sectors (Robertson, 2022)
- high investment in synthetic biology and biotechnology. For example, the Australian Research Council Centre of Excellence recently invested A\$35 million in synthetic biology (ARC, 2023)
- supportive policies such as the AgriFutures 2023–2028 Australia and the Australian Insect Industry research development and extension plan (Nolet and Lever, 2023).

These have supported competitive advantages in food biotech, with innovative bioeconomy startups including:

- **Farmed carbon**³, which uses novel mobile microwave pyrolysis technology to convert abundant rice straw destined to be burnt by farmers into bio-bitumen and biochar (Farmed Carbon, 2023). Microwave pyrolysis technology is an alternative to conventional thermal approaches and is more efficient with less emissions (Ethaib et al., 2020).
- **Nutri V**⁴, where the whole of crop is utilised by turning ugly but abundant waste vegetables into powders (Nutri V, 2023). Waste vegetables are dehydrated using an advanced process that retains essential nutrients, vitamins and minerals to produce all natural, fibre-rich and protein fuelled vegetable powders.

International case study

BioMADE is a non-profit organisation in the United States with members from industry, research and government seeking to enable domestic bio-industrial manufacturing at all scales (BioMADE, 2023). It shows that research collaborations can be used to promote collaboration, innovation, and Australia's comparativeness in the bioeconomy.

³ <https://www.farmedcarbon.com/>

⁴ <https://www.nutriv.com.au/>

2.8 Waste management and resource recovery sector

The opportunities within the waste management and resource recovery sector include (key material flow circular economy element – *use and collection*; key enablers elements – *consistent governance, zero waste culture, market development*):

- streamline policy, standards and practices across Australia’s waste management and resource recovery system
- implement international best practice of extended producer responsibility schemes, green public procurement, sustainable design standards and the right to repair, and provide incentives that support a circular economy
- provide waste management and recovery services (Pickin et al., 2023)
- divert abundant waste by-products for beneficiation (Pickin et al., 2023).

Drivers towards resource recovery as a comparative advantage

Demand for improvements in the waste management and resource recovery market is driven by:

- progressive new government regulations such as the *Recycling and Waste Reduction Act 2020* and waste export regulations
- rising adoption of circular economy internationally and at the Australian federal and state government levels (Grand View Research, 2022).



It may make more sense to think of waste management and resource recovery not so much in its own right, but as a comparative advantage supporting other sectors. Promising conditions for it to emerge as a comparative advantage in Australia include:

- abundance of by-product resource materials generated (Pickin et al., 2023)
- availability of R&D investments (DCCEEW, 2023c)
- supportive waste management frameworks at the jurisdictional levels, creating consistency and certainty through programs such as education, regulatory reform, infrastructure, waste levies and planning pathways (DCCEEW, 2023c)
- increased product stewardship, from voluntary stewardship schemes to extended producer responsibility schemes
- expanded green public procurement at all levels of government, ensuring a minimum standard of recycled material
- similar uptake of green procurement at the industry level, with consumer information provided on recycled content.

The \$250 million Recycling Modernisation Fund which is leveraging over \$1 billion in total investment (DCCEEW, 2023c) will accelerate this sector’s path to being a comparative advantage.

As yet, there are no internationally acknowledged competitive advantages in this industry.

International case study

Taiwan’s 4-in-1 Recycling Program was established to reduce municipal solid waste, increase recycling, and improve safety and efficiency in the recycling industry. Under the program, manufacturers and importers pay fees that subsidise recycling. This has helped reduce waste from 1.14 kg per day per person in 1997 to 0.4 kg per day per person in 2011 (United States Environmental Protection Agency, 2012). It shows how extended producer responsibility schemes can improve a range of outcomes in waste management.

3 Workforce capacity, capabilities, and training

To capitalise on the sectoral opportunities described in Section 2, Australia will need greater access to a broad range of both ‘hard’ skills (engineering and digital capability) and ‘supporting’ skills (such as design, circular business models and regulatory understandings) that enable the circular economy.

This section examines the available workforce data to support those needs and the critical gaps that remain:

- On the one hand, Australia boasts a high standard of education, research, workforce diversity and a culture of innovation and entrepreneurship – all valuable for a circular economy.
- At the same time, particular skills may be in short supply. Engineering is a priority skill to shape a circular economy, yet less than 3 per cent of the workforce has a formal engineering qualification. Despite growth in the number of workers with digital skills (up 66 per cent in the past decade), demand outstrips supply across the economy.
- Access to both these skills and others, is unevenly distributed across the country, with regional areas reporting the most difficulty in meeting workforce requirements.

To fill this gap, Australia is developing policies to offer more accessible and industry-ready education and training programs and boost its intake of migrants with relevant skills through targeted migration strategies.

3.1 The skills needed for a circular economy

The skills identified as most important to a circular economy are science, technology, data science, engineering, design,

professional services, trades and semi-skilled labour, see Table 2. These skills will not only support core circular economy jobs such as recycling and remanufacturing, but they will also help advance the circular economy through design, new business models, value-adding, and the digitisation and tracking of material flows and logistics (Bokkel et al., 2023; Burger et al., 2019). Additional and diverse occupations will further support the circular economy in areas such as education and government services.

Circular economy jobs will require different education and training. Core industries, such as repair, recycling and recovery, may not necessarily need high education levels (Burger et al., 2019). Many will require a general upskilling of the workforce (Brown et al., 2021).

Meanwhile, circular economy-enabling industries such as design, digital technology, business model development and joint-value creation will require more skilled and specialised labour (Burger et al., 2019). For example, engineering skills are essential for developing and implementing circular economy activities, while digital skills will enhance artificial intelligence, digital marketplaces, digital twins, material passports and various scanning technologies (Cetin et al., 2022).

Table 2 Circular economy job descriptions

CIRCULAR JOB	ECONOMIC SECTOR	CIRCULAR ECONOMY ELEMENT	EXAMPLE INDUSTRIES AND ACTIVITIES
Direct jobs	Core sectors	Sustain and preserve what is already there	Repair services
		Use waste as a resource	Recycling
		Prioritise regenerative resources	Renewable energy
	Enabling sectors	Design for the future	Industrial design and architecture
		Incorporate digital technology	Digital technology
		Rethink the business model	Renting or leasing activities
		Team up to create joint value	Professional and networking associations
Indirect jobs	Indirect sectors		Education
			Government services
			Professional services

Key circular economy skills

Technical skills, including those for housing, mobility, food, and energy (Burger et al., 2019).

Sustainability skills, including natural resource management, resource efficiency, resource recovery options, waste reduction and emissions reduction (Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Straub et al., 2023).

Digital skills, including data analysis and deploying digital platforms or the Internet of Things (IoT) to track materials usage (Kristoffersen et al., 2020).

Sustainability metrics and analysis skills, such as life-cycle analysis and carbon and waste footprinting (Moraga et al., 2019).

Systems and design thinking skills, including biomimicry, modularity and adaptability to design products for longevity, reuse, remanufacturing, recycling, disassembly and recovery.

Circular procurement skills, including the correct regulations, standards and certifications that govern sustainable products (Hartley et al., 2020).

Entrepreneurship and innovation skills, for new circular business models, such as product-as-a-service or creating value from end-of-life materials.

Collaboration and networking skills, for partnerships and business models to develop circular supply chains (Lombardi and Laybourn, 2012).

Business leadership skills, to build a culture to embrace circular practices and identify circular opportunities (Hartley et al., 2020).

Note: Skills list informed by the Australian Academy of Technology & Engineering, 2020

3.2 Australia’s workforce comparative advantages

Overview of Australia’s circular capabilities

Australia’s skilled labour force is anticipated to boost circular economy opportunities. For example, in the two decades from 2000 to 2020, the number of level-one qualifications (bachelor’s degree and above) has increased from 25.6 per cent to 32.4 per cent (National Skills Commission, 2021). Australia has a skilled engineering labour force, although fewer than 3 per cent have formal qualifications (Kaspura, 2019).

Meanwhile, digital skills have experienced tremendous growth between 2013 and 2020, particularly in artificial intelligence (Hope et al., 2022). Approximately 861,000 people now work in technology (Tech Council of Australia, 2022), which is still considered a shortfall given the demand for these skills (Hope et al., 2022).

High-level education (bachelor’s degree and above) statistics reveal that 97,676 postgraduate enrolments in 2019 were associated with the circular economy (Department of Education, Skills and Employment uCube data hub, 2023). Management, commerce and education courses had the highest postgraduate enrolments, as shown in Figure 3.

Engineering and IT courses remain male-dominated, while education tends to have more female enrolments (Australian Council of Engineering Deans, 2022). Promoting science, technology, engineering and mathematics (STEM) education for girls will help to improve the workforce gender balance (The Treasury, 2023).

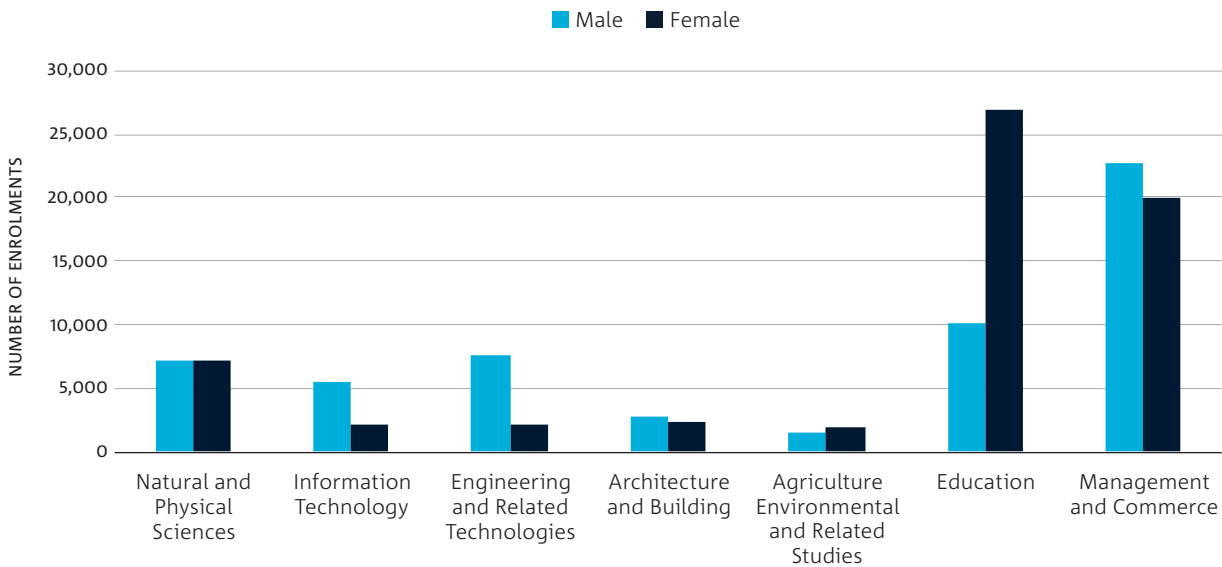


Figure 3 Circular economy related course enrolments by gender, 2019

Deepening Australia's capabilities

To build its circular economy workforce capabilities, Australia can draw on strong foundations in education, research, workforce diversity and a culture of innovation and entrepreneurship. This applies particularly to its agricultural and natural resource sectors. Australia's labour market regulations also allow for flexibility, ensuring businesses can innovate in response to changing conditions.

In addition, First Nations people offer unique contributions for realising circular economy opportunities. Indigenous businesses manage over A\$10 billion annually and employ over 70,000 workers. A total of 11,599 Indigenous businesses are estimated to operate in Australia, including 3,688 Supply Nation-registered Indigenous businesses (Langford, 2023). A significant proportion of these are in industries related to resource recovery activities such as construction and building maintenance, consulting, plant and equipment, mining and energy, transportation and logistics, and manufacturing.

Existing policies and programs by public, private and charitable organisations are committed to growing the Indigenous business sector, laying the foundations for potential partnerships with circular economy industries. Traditional knowledge of materials, such as bush products and natural resource management, inspires innovation and value-adding in the supply chain.

Risks of vocational and locational gaps

Despite the opportunities to upskill or reskill Australia's labour force for the circular economy, several challenges remain. These include:

- **Uneven regional employment** – For more than 25 years, a consistent 5-percentage point difference has remained in the unemployment rate for different regions in Australia (The Treasury, 2023). A systemic challenge for First Nations people's participation also extends to fewer education, training, and employment opportunities in remote and regional areas (Nicolaou et al., 2023).
- **Employment contraction in manufacturing** – With the exception of food production, the manufacturing industry has declined over the last 30 years (Productivity Commission, 2003). However, the circular economy could help improve business prospects for manufacturers.
- **Modest engineering and digital skill capability** – Despite the growth of skills over the past decade, Australia still lacks sufficient skill levels in engineering and technology (Kapsura, 2019; Hope et al., 2023).

To fully understand the circular economy capability and skills gaps in Australia more studies are required.



Table 3 Circular economy skills and workforce assessment

	OVERALL WORKFORCE CAPACITY	CAPACITY (LABOUR SHORTAGES)	CAPABILITY (SKILL GAPS)	TRAINING AND UPSKILLING NEEDS	POTENTIAL FOR CIRCULAR ECONOMY SKILL DEVELOPMENT AND TRANSFERABLE SKILLS
Mining by-products	Workforce capacity and capability exist if priorities shifted to secondary processing of mining by-products.	Capacity exists, though requires allocating labour to by-product valorisation versus primary processing.	Can draw on strong mining technical skills that already exist.	Training in circular approaches and secondary processing.	SMI UQ is offering professional development for secondary processing and repurposing. TiME CRC is also investing in training and development.
Circular buildings and construction	Residential sector (low). Apartment buildings and commercial sector (high).	Trade skill shortages.	Skill gaps in residential construction and design for a circular economy.	TAFE and vocational education programs, on-the-job training.	Learn from large developers and organise knowledge transfer.
Lithium-ion batteries	Workforce in development – supported by Australia’s critical minerals strategy and battery supply chain connections.	Engineering and digital shortages.	Design, engineering, circular business models, operators.	Greater capacity for the design of novel battery materials and whole battery systems.	FBI CRC facilitates university and VET education pathways to grow battery industries. Training relevant to all critical minerals production.
Apparel and textile	Very limited in manufacturing. Global leaders and expertise in research and design for sustainability exist in Australia but lack a broader workforce capability.	Shortage in labour for making clothes onshore – yarn, fabric, and garments – skills ‘dying out’. The lack of manufacturing infrastructure further limits labour capacity.	Design, repair, reuse, circular business models, and digital skills to accelerate upscaling.	Transition broker training. Circular business models. Apprenticeships and traineeships in repair.	Repair and reuse programs. Intermediaries/ transition brokers to accelerate the transition. Investment in programs and initiatives to support front runners.
Agricultural by-products Agri-food and fibre		Regional shortages in skilled labour and trades.	Processing, design, digital skills in circular business models, value adding. Particularly in regional areas.	Transition broker training – particularly in regional areas. TAFE and vocational education programs, on-the-job training.	Collaborations with TAFE and local employer groups to develop circularity related courses.
Resource recovery and plastics	Capacity limited by lack of infrastructure investment.	Technical skill shortages are not a key barrier; rather, they are a lack of circular economy implementation by industry. Regional shortages in skilled labour and trades. The lack of recycling infrastructure limits growth in workforce capacity.	Design, processing, circular business models, advanced recycling skills, market development for secondary materials, digital and AI skills. Focus on improved product stewardship, designing for circularity, smart waste management systems, and advanced resource recovery.	Education across the value chain is needed from product designers and manufacturers to retailers, to shift to a circular model focusing on reduced material use, repairability, durability, and recoverability.	TAFE and vocational education programs, on-the-job training. Opportunity for workers to develop transferable skills in sustainability, which will contribute more broadly to their employability in the green economy. Skills transferable to any WMRR* related industry.

*WMRR = Waste Management and Resource Recovery

3.3 Building circular economy skills

The following four areas would help to build circular economy skills quickly and efficiently by tapping into established resources.

Vocational educational and training (VET)

The VET sector and TAFE (Technical and Further Education) colleges are well-placed to upskill workers in sustainability transitions.

- Short courses and micro-credentials could be developed to enhance the skills and capabilities needed to increase Australia's environmental sustainability, targeting locally based industries (TAFE SA, 2023).
- Industries, sectors and educators could collaborate to co-design relevant training programs as new skill needs emerge, with governments providing support for access to such programs (Brown et al., 2021). Funding to support training for VET qualifications creates a pathway for First Nations people into higher-level training and more highly skilled jobs (Griffin and Andrahannadi, 2023).
- Green skills and digital skills could be a focus for VET and TAFE courses, given their transferability to the circular economy, different occupations and industries (European Commission, 2020; Summerton et al., 2019).
- A skills passport would help recognise accredited skills acquired during the employment process, given that these skills are needed across many industries.

Migration

The professional, scientific and technical services needed for a circular economy rely heavily on skilled migrant labour. Australia could continue to pursue required skilled migrants by promoting its comparatively high incomes, and its support schemes, including the Migration Program and Global Talent program, and its new Specialist Skills Pathway aimed at making it easier to attract highly skilled workers for industries such as green energy and technology (Department of Home Affairs, 2023a, b, c).

Non-government organisations training

Non-government programs (NGP) offered by non-government organisations (NGO) and approved by the Department of Employment and Workplace Relations (DEWR, 2023), enable individuals to upskill and become more employable through training and work experience (DEWR, 2023). These could provide a valuable pathway for individuals to enhance their circular economy skills.

Regional Australia initiatives

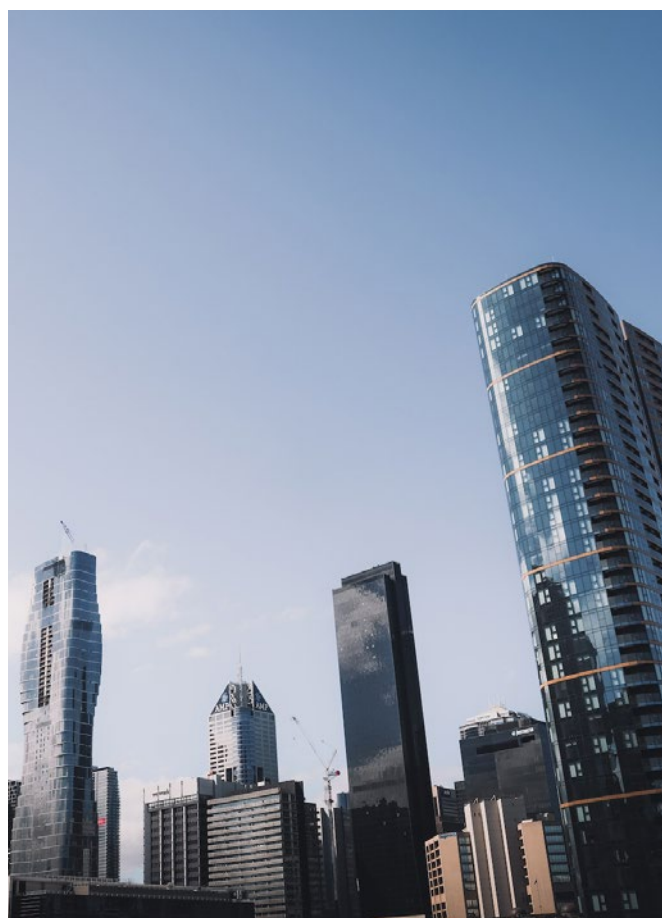
Many circular economy opportunities lie in industries located in regional Australia, where workforce planning and development has been identified as a strategic priority (The Treasury, 2023). Many of these regions are critical to Australia's transition to a low carbon future with the implementation of regional Renewable Energy Zones. This presents opportunities to attract and retain a skilled workforce to support a circular economy and rural liveability as a priority (Houghton et al., 2023). Growing relationships with First Nations businesses in remote and regional areas will also prepare partnering opportunities along the value chain.

Table 4 Number of jobs related to circular economy activities in 2022–23 (ABS, 2023)

CIRCULAR JOB	ECONOMIC SECTOR	INDUSTRIES AND ACTIVITIES	EMPLOYED PERSONS IN '000 (FULL-TIME EQUIVALENT)
Direct jobs	Core sectors	Repair service	210.1
		Agriculture, mining and construction	1,639.3
		Electricity, gas and waste services	115.7
	Enabling sectors	Digital technology	314.9
		Renting or leasing activities	70.7
Indirect jobs	Indirect sectors	Education	776.3
		Government services	431.1
		Professional services	814.8
Total			4,372.9

Table 5 Percentage growth of digital skills in Australia (2013 to 2020)

DIGITAL TECHNOLOGY SKILL	% GROWTH
Artificial Intelligence (AI)	4,412
IT Automation	3,817
Internet of Things (IoT)	3,645
Application Programming Interface (API)	780
Machine Learning (ML)	724
Natural Language Processing (NLP)	537
Distributed Computing	516
Data Visualisation	482
Software Development Methodologies	450
Big Data	384



4 Research and innovation

Most waves of 21st century innovation will support the circular economy, with real breakthroughs in biotechnology, nanotechnology, health, new materials, energy generation, transmission, storage and electromobility.

Australia has made several inroads in research and innovation to drive a circular economy, with private-sector and university-led innovation hubs drawing on the many innovations to emerge through the waves of digitalisation and automation.

However, the scale of these initiatives remains small by global standards, owing both to Australia's remoteness and the limited scale of businesses that might embrace the circular economy. Opportunities exist for more strategic leadership among Australian manufacturers and for government incentives to support the design and development of circular economy technologies.

4.1 Infrastructure for innovation

Overall, Australia's innovation ecosystem (its institutions, human capital, research, infrastructure, and market sophistication) was ranked 25 out of 132 countries in the World Economic Property Organisation's 2022 global innovation index (WEPO, 2022). Australia was marked down in market and business sophistication, which suppressed the nation's creative, knowledge and technology outputs, leading to underperformance by the world's 13th biggest economy. Australia's public investment in R&D is low by international comparison, both in absolute value and share of GDP, and is falling (The Treasury, 2023). While progress is being made at the design end of innovation, less is evident at the production end, where more industrial symbiosis may be needed.

Several of Australia's innovation hubs support circular economy innovation, including the Sydney Startup Hub, the University of Sydney's Sydney Knowledge Hub, the Melbourne Connect innovation hub and the RMIT Activator. Several other Australian universities have created similar innovation districts or hubs. They typically focus on a mix of high-tech development, commercialisation of research and support for entrepreneurs. Government initiatives play their part, too, with resources such as funding, networking events and educational programs to help promote key industries (Nnanna et al., 2012).

There has been only a slow uptake of business-to-business resource sharing platforms for production and no strong examples of co-located industrial symbiosis, eco-industrial parks, hubs and eco-industrial towns (King et al., 2020). This creates a significant opportunity for regional and secondary cities to achieve economies of scale as shared resource recovery hubs. Recycling capabilities and end-of-life waste management are improving with policy, government funding and co-investment. However, there needs to be greater co-located manufacturing capability to realise the value. Again, some businesses are reusing end-of-life materials within their own operations (for example, in the building sector and in sewerage), but more innovative shared infrastructure and business models are needed.

4.2 Innovation in design for circular materials, products, and processes

The principles of design for a circular economy are the longevity, renewability and recyclability of products and materials. Designers opt for non-toxic, renewable, or recycled materials that have minimal environmental impact. They pursue modularity and adaptability, allowing for easy repair or upgrade of products and prolonging their useful life. Products are designed to consume as little energy as possible through their life cycle. Service-based business models allow products to be leased or shared rather than owned, maximising usage and reducing disposability (Den Hollander et al., 2017).

Innovations that pursue these principles are becoming more common in the sectors prioritised in Section 2 (see Table 6), but they are few and business-as-usual generally prevails. Examples often sit at the interface of chemical, biological and engineering disciplines and involve digital opportunities as well. For example, the development of membrane technology for industrial applications mimics the functionality of membranes in biological processes at the ANU Centre for Entrepreneurial Agri-Technology and the UNSW Centre for Membrane Science and Technology (Voicu and Thakur, 2023).

Table 6 Assessment of Australia’s circular economy innovation capacity for key opportunities

	OVERALL INNOVATION CAPACITY	DESIGN FOR CIRCULAR ECONOMY	LOOP-CLOSING	DIGITAL INNOVATION	BUSINESS MODEL INNOVATION
Mining by-products	High	Mine planning is designed for net positive impact.	Use of by-products as building aggregates.	Material passports and material characterisation, provenance.	From extraction to material supplier (virgin and secondary).
Circular buildings and construction	Medium	Modular, prefabricated buildings and components, long building lifetimes.	Use of recycled materials and end-of-life separation and reuse of materials.	Building scorecards, material passports, measurement of embodied materials, waste, and emissions.	Vertical integration with material and component suppliers, Waste Management and Resource Recovery sector.
Lithium-ion batteries	High	Sustainable battery design and manufacturing.	Use of recovered materials for new batteries.	Material passports and automated separation and dismantling.	Domestic value adding.
Plastics	Medium	Design for extended use and disassembly.	Advanced recycling.	Recycled content standards and traceability.	
Apparel and textile	High	Natural fibre tech and high-tech polymers for extended use and designing out pollution.	Clothing Product Stewardship textile-to-textile loops; fibre and component separation technologies.	Textile and apparel digital twins and supply chain logistics optimisation.	Textile and clothing SMEs in partnership with STEM and place-based partners.
Agricultural by-products	High	Maximising use of pre- and post-farm gate primary resources and household biomass.	Whole-of-animal and whole-of-crop utilisation, i.e., innovative uses of different parts of organisms.	Digital-based decision support tools for bio-based resource upcycling and ‘real time’ biomass resource mapping at granular scales.	Agri-food and fibre SMEs in partnership with STEM and place-based partners.
Waste management and resource recovery services	Medium	Depending on manufacturing and design (not in control of the sector).	Depending on collection and separation system.	Sensors, AI and robotics for identification and separation.	Vertical integration of waste management and resource recovery with upstream sectors.

4.3 Innovation for value adding and closing the loop

In a circular economy, ‘value-adding’ means exploring ways to maintain or increase the value of products, components and materials. ‘Closing the loop’ means ensuring that products and materials circulate within the economy at their highest utility, rather than being downcycled into lower-value applications or sent to landfill (Geissdoerfer et al., 2017). Various businesses embrace these principles across Australia (Collins et al., 2023), including:

- **Construction and building sector**
– e.g., Mirvac and Close the Loop.
- **Apparel and textiles**
– e.g., Adrian Ramsey Design House and Spell.
- **Furniture and homeware**
– e.g., Koala.
- **Recycled plastics and polymers**
– e.g., Replas and Plasma.
- **Metal recycling**
– e.g., Sims Metal Management.
- **Waste management and resource recovery**
– e.g., Visy and Cleanaway.
- **Technology and electronics**
– e.g., Substation33.

4.4 Opportunities for digital innovation

Digitalisation helps industries implement circular economy principles through better resource management, efficiency and supply chain transparency. Various digital technologies can help transform manufacturing and supply chains, as highlighted in Figure 4 (Culot et al., 2020; Oztemel and Gursev, 2020). However, the uptake of digital innovation in Australia has been restricted by its relatively small domestic market, geographic isolation, and a manufacturing landscape dominated by small and medium enterprises, which has slowed the rollout of necessary standards and governance frameworks (Mason et al., 2022).

Digitisation is also critical to building strategic leadership among Australian manufacturers. Currently, businesses are tilting towards vertical rather than horizontal integration. Combined with a decline in digital comparativeness, this trend is diminishing potential gains such as advanced production planning and supply chain management (Mason et al., 2022). Researchers have identified the need for Australia’s circular economy to draw on open innovation, horizontal integration and robust investment in digital skill-building (Hizam-Hanafiah and Soomro, 2021; Messeni Petruzzelli et al., 2022). One potential way to address this is to tie R&D funding to mandatory participation in open innovation networks.

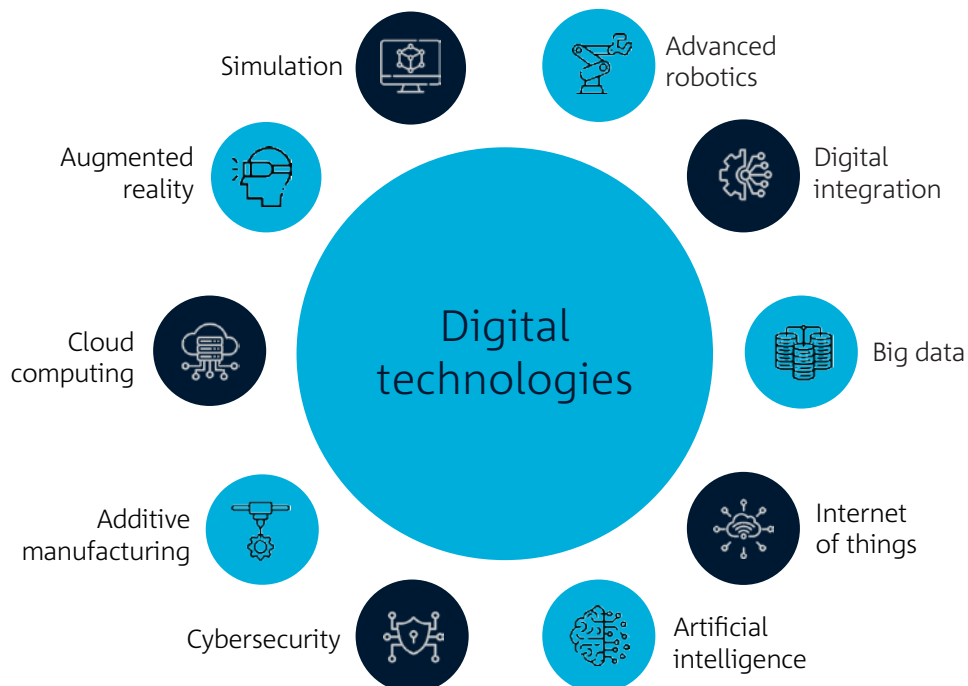


Figure 4 Digital technology innovation supporting a circular economy

4.5 Business model and supply chain innovation

Circular business models are designed to intensify, narrow, slow, close or even dematerialise resource loops while delivering value. They can take many different forms (Geissdoerfer et al., 2018; Lewandowski, 2016; Lacy and Rutqvist, 2015). Embracing circular business models entails a dedicated commitment to open innovation and investment in capacity building. This encompasses both tangible and intangible assets, such as digital technologies and supply chain management systems, as well as initiatives for business process improvements, leadership development, and comprehensive training programs

Though there are some green shoots, Australian businesses are limited in their adoption of circular economy business models. The circular economy requires strong alignment across entire supply chains (Planko and Cramer, 2021), with new ways of creating, delivering and capturing value that depends on collaboration. Yet, Australian business models tend to be firm-centric. While circular economy concepts are now reflected in some corporate business strategies (Australian Institute of Company Directors, 2019), there is no solid evidence base to understand this trend. If intangible assets such as product design, business process re-engineering and network formation are vital to business innovation and circular business models, the Australian System of National Accounts does not consider them (Commonwealth of Australia, 2019).

The likelihood that Australian businesses will adopt more circular business models depends on the political, economic, social, technological, legislative and environmental context (Lewandowski, 2016; Roos, 2014). In this regard, Australia has several advantages:

- professional service industry that has established capacity to support information and data management technologies for material tracking, monitoring and evaluation, and accreditation
- R&D sector that supports innovation in circular design and production, waste avoidance and reduction, upcycling, recycling, and recovery as energy
- reverse logistics and platforms that support material exchange between industries and businesses.

In many circumstances, however, the value of circularity and the social and environmental costs of current linear models are treated as externalities and not incorporated into short-term business decisions in a comparative marketplace (Barrett and Makale, 2019). Pricing these externalities through regulation would establish both an incentive and a level playing field. However, the social licence for that regulation is remote, particularly when placed against cost-of-living concerns. However, as the unsustainability of the current markets in housing, mobility, food and energy (for example) become more apparent, there may be more interest in circularity initiatives and investments.



5 International partnerships for a circular economy

As countries worldwide shift to a circular economy, the focus moves from creating new materials to reusing, repairing, remanufacturing and recycling existing ones (van der Ven, 2020). This change will transform global trade, especially regarding material exchange (Barrie and Schröder, 2022).

To date, Asia has been a favoured Australian export destination for recycling various end-of-life materials, including tyres, textiles and plastics. Apart from masking what had been a low extent of circularity in the Australian economy, this practice has since become subject to stringent new regulations.

This section identifies the international partners that would complement our strengths and close loops on our material supply chains by processing end-of-life materials, purchasing Australian-made circular products, and supplying circular inputs to Australian manufacturing.

As more trading partners adopt policies promoting the circular economy, Australia must build its reputation as a trusted participant in global circular value chains.

International partners are also essential to boosting direct foreign investment in industry opportunities for a circular economy, acquiring skilled workforce and technologies, and sharing policy insights on how to accelerate the circular transition in Australia (see Appendix B).

5.1 Leveraging existing partnerships for circular manufactured goods

Australia exported A\$53.4 billion in manufactured goods in 2021–2022 (Department of Foreign Affairs and Trade (DFAT) 2023). The main buyers of the top 20 exports are in Asia, Oceania, North America, Europe and the Middle East (Table 7). Any of these manufactured goods could become a circular product by meeting one or more of the three circular economy objectives: **eliminating waste, preserving and enhancing the value of materials and products through multiple uses, and conserving natural resources** (see Section 1).

While Australia exports to the global market, its circular products could be particularly attractive to markets that set a strong policy for sustainable consumption. For example, the EU's Second Circular Economy Action Plan includes adopting eco-friendly designs and introducing Digital Product Passports (DPPs) (Weick and Ray, 2022). Australia could access new sustainable markets by ensuring Australia's manufacturing exports meet these circular standards and can pass DPP requirements. Australia's circular products may also find comparative advantages in Oceania, due to proximity and several free-trade agreements.

Section 2 explored potentially valuable circular product opportunities involving manufacturing lithium-ion batteries and bioplastics, construction materials, upcycling mining by-products, e-waste, agricultural by-products, and textiles. Australian companies must build their capacity to navigate the relevant international standards, some of which may not yet exist for secondary materials and products made with secondary materials. Furthermore, the markets for some of these new circular products need to be developed. While waiting for such changes to come to fruition, Australia could prioritise trade partners and circular products with established systems already in place.

Table 7 Australia's top 20 manufactured good exports ranked by 2021–2022 value (in A\$ thousand), and top 3 destinations for each line item

MANUFACTURED GOODS	2019–20	2020–21	2021–22	TOP 3 EXPORT DESTINATIONS
684 Aluminium	3,760,536	3,828,480	5,816,671	Japan, Republic of Korea, United States
682 Copper	3,432,884	4,233,152	4,497,597	China, Malaysia, Taiwan
541 Pharm products (excl medicaments)	3,631,359	2,210,074	2,298,229	United States, China, New Zealand
764 Telecom equipment and parts	2,498,951	2,210,034	2,205,291	New Zealand, United States, Hong Kong (SAR of China)
874 Measuring and analysing instruments	2,043,363	1,956,500	2,125,425	United States, United Kingdom, China
872 Medical instruments (incl veterinary)	1,709,344	1,468,689	1,999,720	United States, Netherlands, New Zealand
542 Medicaments (incl veterinary)	2,911,754	1,961,013	1,577,643	New Zealand, China, United States
686 Zinc	1,302,306	1,522,183	1,507,868	Taiwan, China, Vietnam
792 Aircraft, spacecraft and parts	2,354,448	1,672,101	1,338,714	United States, Singapore, France
553 Perfumery and cosmetics (excl soap)	1,070,573	1,082,503	1,212,840	New Zealand, China, United States
533 Pigments, paints and varnishes	986,995	874,244	1,097,118	India, China, New Zealand
752 Computers	975,483	916,355	1,093,071	New Zealand, United States, United Arab Emirates
784 Vehicle parts and accessories	920,365	1,010,040	1,078,197	New Zealand, United States, United Arab Emirates
522 Inorganic chemical elements	613,730	580,541	1,033,164	Japan, China, Thailand
685 Lead	800,523	939,798	1,007,502	United Kingdom, United States, Philippines
641 Paper and paperboard	884,436	761,035	935,957	New Zealand, United States, China
592 Starches, inulin and wheat gluten	664,838	683,760	821,861	United States, Japan, China
728 Specialised machinery and parts	799,265	737,052	808,276	United States, Papua New Guinea, New Zealand
772 Electrical circuit equipment	631,715	683,821	718,349	New Zealand, United States, Indonesia
897 Jewellery	679,822	753,419	688,831	Singapore, Hong Kong (SAR of China), New Zealand

Data source: DFAT publication 'Composition of trade Australia', Last updated: November 2023 using ABS International Trade in Goods, Australia (September 2023 data).

Note: Manufactured Goods use UNCTAD (United Nations Conference on Trade and Development) Standard International Trade Classifications. https://unctadstat.unctad.org/EN/Classifications/DimSitrRev3Products_Official_Hierarchy.pdf

5.2 Investing in onshore beneficiation of end-of-life materials

Asian countries are the main trading partners for Australia’s end-of-life materials. In 2021–22, Australia exported 4.41 million tonnes of end-of-life materials valued at A\$4.36 billion⁵ (Lin et al., 2023). The top seven recipients of end-of-life plastics, tyres, textiles and metals were Indonesia, Vietnam, Bangladesh, Malaysia, Thailand, South Korea and Taiwan (Du et al., 2023; Lin et al., 2023). Plastics, tyres and textiles have relatively low recycling rates compared to other waste streams in Australia, given the lack of dedicated recycling infrastructure for these materials (Pickin et al., 2023; Schandl et al., 2020). Future collaborations with Sweden could also be explored, given Renewcell’s pioneering new commercial-scale chemical textile recycling plant (Santi, 2023).

In 2019, 80 per cent of Australia’s recycled e-waste yielded only scrap metals as a low-value export. Australia still depends on international partners for end-stage recycling (Van Yken et al., 2021; Islam and Huda, 2020). South Korea, Singapore, Canada and Belgium are the leading international partners for processing recycled lithium-ion batteries (Battery Stewardship Council, 2020). China, Indonesia and Japan are the main recycling partners for TVs and computers collected under the National Television and Computer Recycling Scheme (Van Yken et al., 2021). Australia’s e-waste sent to landfills is a lost economic opportunity. Alone, battery storage and photovoltaic solar waste are estimated to be worth between A\$603 million and A\$3.1 billion (Bontinck et al., 2021; King and Boxall, 2019).

Processing more end-of-life materials may build Australia’s reputation as a trusted supplier of high-quality secondary materials for international industries. Doing so requires upgrading recycling infrastructure and promoting R&D in material recovery technologies. Australia’s efforts to increase onshore recycling capability have accelerated since various government acts, funds and action plans were introduced. These include:

- **National Waste Policy Action Plan 2019** – setting a goal for an 80 per cent average recovery rate from all waste streams by 2030.
- **Recycling and Waste Reduction Act 2020** – regulating the export of scrap plastics, glass, paper and tyres that have not been converted to value-add materials.
- **Recycling Modernisation Fund** – boosting investment to increase the recycling and remanufacturing capacity for plastics, glass, paper and tyres to/by an anticipated 1.13 million tonnes annually by July 2024 (Pickin et al., 2023) (Table 8).

Table 8 Projected additional onshore resource recovery capacity funded through the Recycling Modernisation Fund (kilotonnes per year)

MATERIAL TYPE	REMOTE AND REGIONAL AREAS	METROPOLITAN CENTRES	TOTAL
Glass	130	197	327
Material recovery facility	30	124	154
Multi-material facility	7	3	10
Paper and cardboard	0	239	239
Plastics	55	239	293
Transfer stations	1	0	1
Tyres	5	84	89
Total	228	885	1,113

Source: National Waste Report 2022, Pickin et al., 2023.

⁵ Historical values are inflated based on the annualised consumer price index.

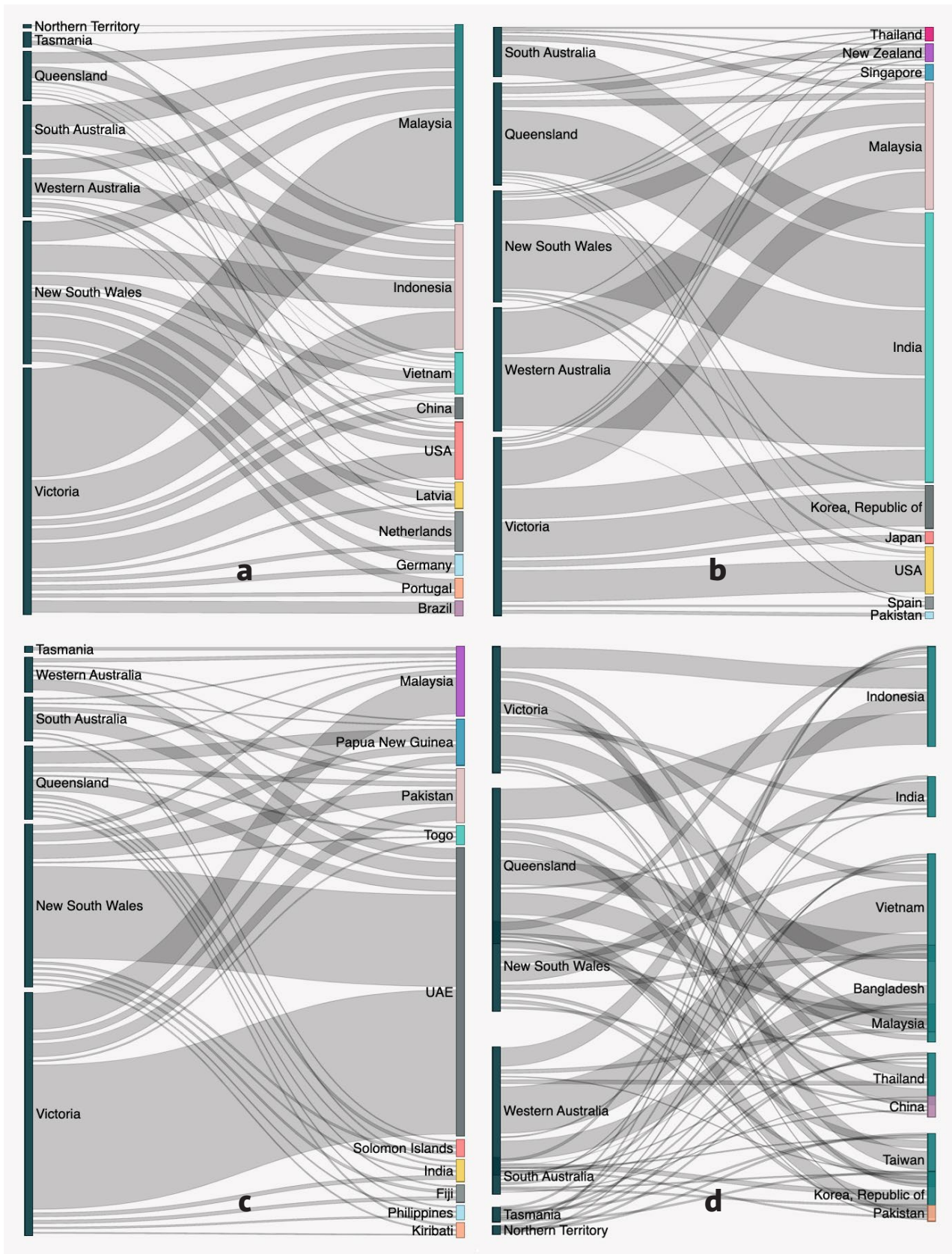


Figure 5 Sankey diagrams of scrap plastics (a), tyres (b), textiles (c), and metals (d) showing originating Australian state and international destinations

Source: <https://www.dcccew.gov.au/environment/protection/waste/how-we-manage-waste/data-hub/waste-export-data-viewer>

5.3 Ensuring that imports embody circular economy principles

Australia can promote environmental sustainability and foster responsible procurement by prioritising circular economy business inputs and consumer products among its imports. A strong Australian circular economy supply chain will require policies, guidelines, standards, infrastructure, and bilateral agreements with major trading partners.

Of the top 10 suppliers of manufacturing inputs to Australia, China and the United States are the leading partners and have differing degrees of regulation on circularity (Table 9).

On the one hand, China's Circular Economy Promotion Law and its recently launched 14th Five-Year Plan for Circular Economy Development highlight potential avenues for Australia to procure more circular inputs.

As a nation, the US lacks a comprehensive national policy, although individual states, including New York, California and Colorado, have championed localised circular economy policies and initiatives (Smol, 2023). Meanwhile, the EU's Second Circular Economy Action Plan prioritises extended producer responsibility and the use of secondary materials, making it a competitive future source for Australia's quest for circular inputs.

As Australia's import criteria increasingly shift to embrace principles of circularity, it will seek goods that contain secondary materials, are designed for ready maintenance and servicing, and include easy disassembly and manufacturer take-back in its business model. The EU's Second Circular Economy Action Plan resonates with these principles, fostering durability, reusability, repairability and upgradability (Smol, 2023; European Commission, 2022). The Plan is already helping regulate how packaging, batteries, construction and food are manufactured.

Table 9 Australia's top 10 manufactured parts imports ranked by 2021–2022 value (in A\$ thousand) and top 3 sources for each line item

IMPORTED MANUFACTURED PRODUCTS	2019–20	2020–21	2021–22	TOP 3 SOURCES
764 Telecom equipment and parts	15,230,342	14,465,586	15,524,730	China, Vietnam, United States
723 Civil engineering equipment and parts	4,452,859	5,360,360	6,182,941	United States, China, Japan
778 Electrical machinery and parts, nes*	3,952,642	4,618,086	5,291,775	China, United States, Republic of Korea
893 Plastic articles, nes	4,098,874	4,376,399	4,757,794	China, United States, Malaysia
598 Miscellaneous chemical products, nes	1,483,067	1,452,744	4,016,768	China, United States, Republic of Korea
699 Manufactures of base metal, nes	3,068,315	3,292,414	3,904,100	China, United States, India
784 Vehicle parts and accessories	2,955,558	3,358,826	3,695,881	China, United States, Thailand
741 Heating and cooling equipment and parts	3,134,628	3,529,027	3,675,323	China, Thailand, Italy
744 Mechanical handling equipment and parts	2,782,500	3,198,994	3,598,231	China, Germany, United States
728 Specialised machinery and parts	2,715,502	3,000,053	3,273,907	China, United States, Germany

Data source: DFAT publication 'Composition of trade Australia', Last updated: November 2023 using ABS International Trade in Goods, Australia (September 2023 data)

*nes = not elsewhere specified.

References

- Abaka-Wood, G.B., Ehrig, K., Addai-Mensah, J. and Skinner, W. (2022). Recovery of Rare Earth Elements Minerals from Iron-Oxide-Silicate-Rich Tailings: Research Review. *Eng*, 3(2), 259-275. <https://doi.org/10.3390/eng3020020>
- ABS (Australian Bureau of Statistics) (2008). *1292.0 – Australian and New Zealand Standard Industrial Classification (ANZSIC), 2006 (Revision 1.0)*.
- ABS (Australia Bureau of Statistics) (2023). *Australian National Accounts: Supply Use Tables*. <https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-supply-use-tables/latest-release>
- Alonso, B. (2013). *HygroSkin Sculpture Installation Mimics Real Skin*. <https://www.vice.com/en/article/aenwp5/hygroskin-sculpture-installation-mimics-real-skin>
- ANZRP (Australia New Zealand Recycling Platform) (2015). *Global e-waste systems: Insights for Australia from other developed countries*. <https://www.anzrp.com.au/wp/wp-content/uploads/Global-e-waste-systems-A-Report-for-ANZRP-by-EIU-FINAL-WEB.pdf>
- Araya, N., Ramírez, Y., Kraslawski, A. and Cisternas, L.A. (2021). Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis. *Journal of Environmental Management*, 284. <https://doi.org/10.1016/j.jenvman.2021.112060>.
- ARC (Australian Research Council) (2023). *2020 ARC Centre of Excellence in Synthetic Biology*. <https://www.arc.gov.au/funding-research/discovery-linkage/linkage-program/arc-centres-excellence/2020-arc-centre-excellence-synthetic-biology> [Accessed 25 November 2023].
- Agarwal, R., Chandrasekaran, S., Sridhar, M. (2016). *Imagining construction's digital future*. <https://www.mckinsey.com/capabilities/operations/our-insights/imagining-constructions-digital-future>
- Australian Academy of Technology and Engineering, (2020). *Towards a Waste Free Future, Technology readiness in waste and resource recovery*. ATSE Report. ISBN 978-0-6487511-0-6.
- Australian Council of Engineering Deans (2022). *Australian engineering higher education statistics 2010-20*. <https://www.aced.edu.au/index.php/features/statistics>
- Australian Fashion Council (2023). *Roadmap to clothing circularity: The vision and pathway for a just transition to a circular clothing economy in Australia by 2030, and Net Zero by 2050*. <https://ausfashioncouncil.com/wp-content/uploads/2023/06/Roadmap-to-Clothing-Circularity.pdf>
- Australian Fashion Council and Consortium (2023). *Seamless Scheme Design Summary Report*. <https://ausfashioncouncil.com/wp-content/uploads/2023/06/Seamless-Scheme-Design-Summary-Report.pdf>
- Australian Institute of Company Directors (2019). *Driving Innovation: The Boardroom Gap*. Australian Institute of Company Directors, Sydney.
- Australian Packaging Covenant Organisation (2021). *Australian Packaging consumption & recycling data 2018-19*. <https://documents.packagingcovenant.org.au/public-documents/Australian%20Packaging%20Consumption%20And%20Recycling%20Data%202018-19>
- Australian Trade and Investment Commission (2018). *The lithium-ion battery value chain: new economy opportunities for Australia*. <https://apo.org.au/node/210341>
- Australian Trade and Investment Commission (2023). *Why Australia: Benchmark Report 2023*. https://www.globalaustralia.gov.au/sites/default/files/2023-08/ATIC_Benchmark%20Report_2023.pdf
- Barrett, J. and Makale, K. (2019). The environment is not an externality: The circular economy and the tax working group. *Journal of Australian Taxation*, 21(2), 34.
- Barrie, J. and Schröder, P. (2022). Circular Economy and International Trade: A Systematic Literature Review. *Circular Economy and Sustainability*, 2(2), 447–471. <https://doi.org/10.1007/s43615-021-00126-w>
- Battery Stewardship Council (2020). *Australian battery market analysis*. Project report (final), 22 June 2020.
- Baum, Z.J., Bird, R.E., Yu, X. and Ma, J. (2022). Lithium-Ion Battery Recycling – Overview of Techniques and Trends. *ACS Energy Letters*, 7(2), 712-719. <https://doi.org/10.1021/acscenergylett.1c02602>
- Berry, F., Retamal, M., Kuzhiumparambil, U. and Ralph, P. (2022). *Market and sustainability potential for algal bioplastics in Australia*. UTS Institute for Sustainable Futures and UTS Climate Change Cluster.
- BioMADE (2023). *About BioMade*. <https://www.biomade.org/about-biomade> [Accessed 25 November 2023].
- Blomsma, F. and Brennan, G. (2017). The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology*, 21, 603-614. <https://doi.org/10.1111/jiec.12603>
- Bontinck, P.A., Bricout, J., Grant, T. and Legoe, G. (2021). *E-product stewardship in Australia: Evidence report*. A report prepared for the Commonwealth Department of Agriculture, Water and the Environment by Icen Group and Lifecycles, Sydney, Australia.
- Bokkel, L., Craig, F., Wotton, S., Brown, E.G. and Dufourmont, J. (2023). *The Future of Work: Baseline Employment Analysis and Skills Pathways for the Circular Economy in Scotland*. <https://www.zerowastescotland.org.uk/resources/future-work>
- Brown, E. G., Haigh, L., Schroder, A., Bozkurt, O., Bachus, K., O'Donnell, R., Herlevi, K. and Barrientos, K. (2021). *Closing the Skills Gap: Vocational Education and Training for the Circular Economy*. <https://www.circle-economy.com/resources/closing-the-skills-gap-vocational-education-and-training-for-the-circular-economy>
- Burger, M., Stavropoulos, S., Ramkumar, S., Dufourmont, J. and van Oort, F. (2019). The heterogeneous skill-base of circular economy employment. *Research Policy*, 48(1), 248–261. <https://doi.org/10.1016/j.respol.2018.08.015>
- CEFC (Clean Energy Finance Corporation) (2023). *Scipher Technologies targets Australia's mounting e-waste problem*. <https://www.cefc.com.au/where-we-invest/case-studies/scipher-technologies-targets-australia-s-mounting-e-waste-problem/> [Accessed 26 October 2023].

- Çetin, S., Gruis, V., and Straub, A. (2022). Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resources, Conservation and Recycling Advances*, 15, 200110. <https://doi.org/10.1016/j.rcradv.2022.200110>
- Carrasco, E.V.M., Pizzol, V.D., Smits, M.A., Alves, R.C., Oliveira, A.L.C. and Mantilla, J.N.R. (2023). CLT from recycled wood: Fabrication, influence of glue pressure and lamina quality on structural performance. *Construction and Building Materials*, 378. <https://doi.org/10.1016/j.conbuildmat.2023.131048>
- Centre for Bioplastics (2023). Advancing our transition to a sustainable plastics future. <https://centreforbioplastics.org.au/> [Accessed 24 October 2023].
- Chen, W-S. and Ho, H-J. (2018). Recovery of Valuable Metals from Lithium-Ion Batteries NMC Cathode Waste Materials by Hydrometallurgical Methods. *Metals*, 8(5):321. <https://doi.org/10.3390/met8050321>
- Cobîrzan, N., Muntean, R., Thalmaier, G., Felseghi, R.A. (2022). Recycling of Mining Waste in the Production of Masonry Units. *Materials (Basel)*, 15(2),594. <https://doi.org/10.3390/ma15020594>
- Collins, R., Laws, C. and Wadhvani, T. (2023). *Circularity in Australian Business 2023. Perceptions, Knowledge and Actions Beyond Recycling*. Australian Circular Economy Hub, Planet Ark.
- Commonwealth of Australia (2019). *Improving Innovation Indicators: Better Data to Track Innovation in Australia*. Canberra.
- Cordano, A.L.V. and Zevallos, R.P. (2021). Country competitiveness and investment allocation in the mining industry: A survey of the literature and new empirical evidence. *Resource Policy*, 73. <https://doi.org/10.1016/j.resourpol.2021.102136>.
- Cotton Australia (2023). The Australian Cotton Industry. <https://cottonaustralia.com.au/assets/general/Publications/Industry-overview-brochures/Cotton-Australia-Background-Brochure.pdf> [Accessed 31 August 2023].
- CRDC (Cotton Research and Development Corporation) (2023). *Important next step in diverting textile waste from landfill*. <https://www.crdc.com.au/important-next-step-diverting-textile-waste-landfill>
- CSIRO (2023). *Urban Living Lab: place based co-innovation for urban resilience*. <https://www.csiro.au/en/research/environmental-impacts/sustainability/urban-living-lab>
- CSIRO Futures (2021). *A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia*. CSIRO. Canberra. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/future-industries/synthetic-biology-roadmap>
- Culot, G., Nassimbeni, G., Orzes, G. and Sartor, M. (2020). Behind the definition of Industry 4.0: Analysis and open questions. *International Journal of Production Economics*, 226. <https://doi.org/10.1016/j.ijpe.2020.107617>
- DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2023a). *Recycling Modernisation Fund – Plastics Technology Stream*. <https://www.dcceew.gov.au/environment/protection/waste/how-we-manage-waste/recycling-modernisation-fund/plastics-technology-stream> [Accessed 25 November 2023].
- DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2023b). *National Plastics Plan: Research, Innovation and Data*. <https://www.dcceew.gov.au/environment/protection/waste/plastics-and-packaging/national-plastics-plan/research-innovation-data> [Accessed 25 November 2023].
- DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2023c). *Investing in Australia's waste and recycling infrastructure*. <https://www.dcceew.gov.au/environment/protection/waste/how-we-manage-waste/recycling-modernisation-fund>. [Accessed 13 October 2023].
- DEWR (Department of Employment and Workplace Relations) (2023). *Approved Non-Governmental Programs*. <https://www.dewr.gov.au/approved-nongovernment-programs-ngp> [Accessed 13 October 2023].
- DFAT (Department of Foreign Affairs and Trade) (2023). *Keynote address to the capability papers*. <https://ministers.dfat.gov.au/minister/tim-ayres/speech/keynote-address-capability-papers> [Accessed 1 September 2023].
- Deakin University (2014). *Process takes textile recycling to new level*. <https://www.deakin.edu.au/research/research-news-and-publications/articles/process-takes-textile-recycling-to-new-level>
- Deakin University (2023). *Textile waste diverted from landfill, pulverised into powder to produce works of art*. <https://www.deakin.edu.au/about-deakin/news-and-media-releases/articles/textile-waste-diverted-from-landfill,-pulverised-into-powder-to-produce-works-of-art>
- Den Hollander, M.C., Bakker, C.A. and Hultink, E.J. (2017). Product design in a circular economy: Development of a typology of key concepts and terms. *Journal of Industrial Ecology*, 21(3), 517-525. <https://doi.org/10.1111/jiec.12610>
- Department of Education, Skills and Employment uCUBE data hub (2023). *Enrolment Count by Citizenship*. <https://highereducationstatistics.education.gov.au/> [Accessed 12 October 2023].
- Department of Home Affairs (2023a). *Migration Program planning levels*. <https://immi.homeaffairs.gov.au/what-we-do/migration-program-planning-levels>. [Accessed 12 October 2023].
- Department of Home Affairs (2023b). *Global Talent Program*. <https://immi.homeaffairs.gov.au/visas/working-in-australia/visas-for-innovation/global-talent-independent-program>. [Accessed 12 October 2023].
- Department of Home Affairs (2023c). *Migration Strategy – At a Glance*. <https://immi.homeaffairs.gov.au/programs-subsite/migration-strategy/Documents/migration-strategy-at-a-glance.pdf> [Accessed 22 December 2023].
- Dias, P., Bernardes, A.M. and Huda, N. (2018). Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. *Journal of Cleaner Production*, 197(1), 750-764. <https://doi.org/10.1016/j.jclepro.2018.06.161>
- Dold, B. (2020). Sourcing of critical elements and industrial minerals from mine waste – The final evolutionary step back to sustainability of humankind? *Journal of Geochemical Exploration*, 219. <https://doi.org/10.1016/j.gexplo.2020.106638>
- Du, L., Zuo, J., O'Farrell, K., Chang, R., Zillante, G., and Li, L. (2023). Transnational recycling of Australian export waste: an exploratory study. *Resources, Conservation and Recycling*, 196, 107041. <https://doi.org/10.1016/j.resconrec.2023.107041>

- Durlinger, B., Crossin, E., and Wong, J.P.C. (2013). *Life cycle assessment of a cross laminated timber building*. Forest and Wood Products Australia.
- Edge Environment (2021). *A circular economy discussion paper*, from the Green Building Council of Australia.
- Ellen MacArthur Foundation (2017). *Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future*. <https://www.ellenmacarthurfoundation.org/a-new-textiles-economy>
- EnviCore Inc. (2023). *Promoting Circular Economy*. <https://www.envicoreinc.com/> [Accessed 13 October 2023].
- Ethaib, S., Omar, R., Kamal, S.M.M., Awang Biak, D.R. and Zubaidi, S.L. (2020). Microwave-Assisted Pyrolysis of Biomass Waste: A Mini Review. *Processes*, 8(9),1190. <https://doi.org/10.3390/pr8091190>
- European Commission (2020). *Innovation and digitalisation: A report from the ET2020 Working Group on vocational education and training* (pp.1–196, Rep.). Luxembourg: Publications Office of the European Union.
- European Commission (2022, March 30). *Circular Economy: Commission proposes new consumer rights and a ban on greenwashing*. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2098 [Accessed 1 September 2023].
- Farmed Carbon (2023). *Carbon Removal Technology*. <https://www.farmedcarbon.com/> [Accessed 24 October 2023].
- FLS (2023a). *REFLUX™ Classifier*. <https://www.flsmidth.com/en-gb/products/centrifugation-and-classification/reflux-classifier>
- FLS (2023b). *REFLUX™ Flotation Cell (RFCTM)*. <https://www.flsmidth.com/en-gb/products/flotation-and-attrition/reflux-flotation-cell> [Accessed 2 November 2023].
- Geissdoerfer, M., Savaget, P., Bocken, N.M.P. and Hultink, E.J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Geissdoerfer, M., Morioka, S.N., Monteiro De Carvalho, M. and Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production*, 190, 712-721. <https://doi.org/10.1016/j.jclepro.2018.04.159>
- Golev, A., Gallagher, L., Vander Velpen, A., Lynggaard, J.R., Friot, D., Stringer, M., Chuah, S., Arbelaez-Ruiz, D., Mazzinghy, D., Moura, L., Peduzzi, P. and Franks, D.M. (2022). *Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises*. Final Report. Version 1.4. The University of Queensland & University of Geneva. https://smi.uq.edu.au/files/83107/FinalReport_OreSand_v1.pdf
- Grand View Research (2022). *Waste Management Market Size, Share, Growth Report 2030*. Report ID: GVR-4-68039-917-8. <https://www.grandviewresearch.com/industry-analysis/global-waste-management-market>
- Green Industries SA (2022). *Circular Economy Opportunities Limestone Coast*. <https://www.greenindustries.sa.gov.au/documents/circular-economy-opportunities-limestone-coast.pdf>
- Griffin, T. and Andrahannadi, U. (2023). *VET Delivery in Regional, Rural and Remote Australia: Barriers and Facilitators. Research Report*. National Centre for Vocational Education Research (NCVER).
- Gueye, S. (2021). *The trends and trailblazers creating a circular economy for fashion*. <https://ellenmacarthurfoundation.org/articles/the-trends-and-trailblazers-creating-a-circular-economy-for-fashion> [Accessed 4 October 2023].
- Guo, R., Lv, S., Liao, T., Xi, F., Zhang, J., Zuo, X., Cao, X., Feng, Z. and Zhang, Y. (2020). Classifying green technologies for sustainable innovation and investment. *Resources, Conservation and Recycling*, 153. <https://doi.org/10.1016/j.resconrec.2019.104580>
- Han, J., Chen, J., Liu, T., and Li, Y. (2023). Research and application of fluidized flotation units: A review. *Journal of Industrial and Engineering Chemistry*, 126, 50-68. <https://doi.org/10.1016/j.jiec.2023.06.016>
- Hartley, K., Van Santen, R. and Kirchherr, J. (2020). Policies for transitioning towards a circular economy: Expectations from the European Union (EU). *Resources, Conservation and Recycling*, 155. <https://doi.org/10.1016/j.resconrec.2019.104634>
- Harvard Growth Lab (2023). *The Atlas of Economic Complexity*. <https://atlas.cid.harvard.edu/rankings>
- Hetherington, J., Juliano, P., Macmillan, C. and Loch, A. (2022). Circular economy opportunities and implementation barriers for Australia's food, feed, and fibre production. *Farm Policy Journals*, Spring 2022: Circular economies in agriculture, 19, 30–45.
- Hizam-Hanafiah, M., and Soomro, M.A. (2021). The Situation of Technology Companies in Industry 4.0 and the Open Innovation. *Journal of open innovation: technology, market, and complexity*, 7(1), 34. <https://doi.org/10.3390/joitmc7010034>
- Hope, A., Yemm, N., Nguyen, G., Raza, M.A., Sparke, E., Buhagier, C. and Neumann, R. (2022). *Digital skills in the Australian and International economies*. <https://www.jobsandskills.gov.au/sites/default/files/2022-03/ABS%20Paper%20-%20Digital%20Skills.pdf>
- Horne, R., Lawson, L., Dorignon, L., and Moore, T. (2023). *Turning the housing crisis around: how a circular economy can give us affordable, sustainable homes*. <https://theconversation.com/turning-the-housing-crisis-around-how-a-circular-economy-can-give-us-affordable-sustainable-homes-208745>
- Houghton, K., Barwick, A. and Pregellio, S. (2023). *Regional Jobs 2022: The Big Skills Challenge*. Regional Australia Institute, Canberra. <https://www.regionalaustralia.org.au/libraryviewer?ResourceID=105>
- Industry Innovation and Science Australia (2023). *Barriers to collaboration and commercialisation*. <https://www.industry.gov.au/sites/default/files/2023-11/barriers-to-collaboration-and-commercialisation-iisa.pdf>
- Infrastructure NSW (2022). *Decarbonising Infrastructure Delivery*. NSW Government Discussion Paper, October 2022.
- International Energy Agency (2020). *Global EV Outlook 2020: Entering the decade for electric drive?* <https://www.iea.org/reports/global-ev-outlook-2020> [Accessed 13 July 2023].
- International Resource Panel (2024). *Global Resources Outlook 2024*. Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya.
- Isah, S. and Ozbay, G. (2020). Valorization of Food Loss and Wastes: Feedstocks for Biofuels and Valuable Chemicals. *Frontiers in Sustainable Food Systems*, 4. <https://www.frontiersin.org/articles/10.3389/fsufs.2020.00082>

- Islam, M.T. and Huda, N. (2020). *E-Waste Management Practices in Australia*. In Handbook of Electronic Waste Management; Butterworth-Heinemann: Oxford, UK; pp.553–576. ISBN 9780128170304.
- Islam, M.T. and Iyer-Raniga, U. (2022). Lithium-Ion Battery Recycling in the Circular Economy: A Review. *Recycling*, 7(3),33. <https://doi.org/10.3390/recycling7030033>
- Kapsura, A. (2019). *The engineering profession: A statistical overview*. Fourteenth Edition. <https://www.engineersaustralia.org.au/sites/default/files/2022-11/engineering-profession-statistical-overview-14-edition.pdf>
- Kaza, S., Yao, L.C., Bhada-Tata, P. and Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Urban Development; © Washington, DC: World Bank. <http://hdl.handle.net/10986/30317> License: CC BY 3.0 IGO
- King, S. and Boxall, N.J. (2019). Lithium battery recycling in Australia: defining the status and identifying opportunities for the development of a new industry. *Journal of Cleaner Production*, 215, 1279–1287. <https://doi.org/10.1016/j.jclepro.2019.01.178>
- King, S., Hutchinson, S.A. and Boxall, N.J. (2021). Advanced recycling technologies to address Australia's plastic waste. CSIRO, Australia. <https://doi.org/10.25919/7stt-ke60>
- King, S., Lusher, D., Hopkins, J. and Simpson, G.W. (2020). Industrial symbiosis in Australia: The social relations of making contact in a matchmaking marketplace for SMEs. *Journal of Cleaner Production*, 270. <https://doi.org/10.1016/j.jclepro.2020.12.2146>
- Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P. and Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. *Cleaner Engineering and Technology*, 8. <https://doi.org/10.1016/j.clet.2022.100499>
- Kiventerä, J., Golek, L., Yliniemi, J., Ferreira, V., Deja, J. and Illikainen, M. (2016). Utilization of sulphidic tailings from gold mine as a raw material in geopolymerization. *International Journal of Mineral Processing*, 149, 104–110. <https://doi.org/10.1016/j.minpro.2016.02.012>
- Krausmann, F., Weisz, H., Eisenmenger, N., Schütz, H., Haas, W. and Schaffartzik, A. (2015). *Economy-wide material flow accounting introduction and guide*. Institute of Social Ecology: Vienna, Austria.
- Kristoffersen, E., Blomsma, F., Mikalef, P. and Li, J.Y. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research*, 120, 241-261. <https://doi.org/10.1016/j.jbusres.2020.07.044>
- Lacy, P., and Rutqvist, J. (2015). *Waste to wealth: The circular economy advantage* (Vol. 91). London: Palgrave Macmillan.
- Langford, Z. (2023). *The geographies of Indigenous business in Australia: An analysis of scale, industry and remoteness*. Report to Supply Nation. Supply Nation Research Report No. 8.
- Lèbre, E., Corder, G.D., Golev, A. (2017). Sustainable practices in the management of mining waste: A focus on the mineral resource. *Minerals Engineering*, 107, 34-42. <https://doi.org/10.1016/j.mineng.2016.12.004>
- Leni, G., Caligiani, A and Sforza, S. (2021). *Bioconversion of agri-food waste and by-products through insects: a new valorization opportunity*. In Valorization of Agri-Food Wastes and By-Products. Academic Press, 809–828.
- Lewandowski, M. (2016). Designing the Business Models for Circular Economy – Towards the Conceptual Framework. *Sustainability*, 8(1), 43. <https://doi.org/10.3390/su8010043>
- Licella (2023). *Licella and BioLogiQ join forces to accelerate commercialisation of Cat-HTR™ technology in Australia*. <https://www.licella.com/news/licella-and-biologiq-join-forces-to-accelerate-commercialisation-of-cat-htr-technology-in-australia/> [Accessed 23 October 2023].
- Lim., Y.H. (1997). *In search of Australian construction comparative advantages in southeast Asia*. https://ris.cdu.edu.au/ws/portalfiles/portal/35620182/Thesis_CDU_35307267_Lim_YH.pdf
- Lin, Y., Nyunt, P. and Pickin, J. (2023). *Australian exports of waste and recovered materials in 2021-22*. Report to The Department of Climate Change, Energy, the Environment and Water. Canberra.
- Liu, Q., Li, X., Cui, M., Wang, J. and Lyu, X. (2021). Preparation of eco-friendly one-part geopolymers from gold mine tailings by alkaline hydrothermal activation. *Journal of Cleaner Production*, 298. <https://doi.org/10.1016/j.jclepro.2021.12.6806>
- Lombardi, D.R. and Laybourn, P. (2012). Redefining Industrial Symbiosis. *Journal of Industrial Ecology*, 16, 28–37. <https://doi.org/10.1111/j.1530-9290.2011.00444.x>
- Ma, Y., Rosson, L., Wang, X., Byrne, N. (2020). Upcycling of waste textiles into regenerated cellulose fibres: impact of pretreatments. *The Journal of The Textile Institute*, 111(5), 630–638. <https://doi.org/10.1080/00405000.2019.1656355>
- MacMillan, C.P., Payne A., Knox, O., Pettolino, F.A., Gordon, S. and Webb, T. (2022). *Threads and Opportunities 2022 Symposium Report*. CSIRO, Australia. <https://doi.org/10.25919/m85p-vb72>
- Makhathini, T.P., Bwapwa, J.K. and Mtsweni, S. (2023). Various Options for Mining and Metallurgical Waste in the Circular Economy: A Review. *Sustainability*, 15(3), 2518. <https://doi.org/10.3390/su15032518>
- Mason, C.M., Ayre, M. and Burns, S.M. (2022). Implementing Industry 4.0 in Australia: Insights from Advanced Australian Manufacturers. *Journal of Open Innovation: Technology, Market, and Complexity*, 8(1). <https://doi.org/10.3390/joitmc8010053>
- Maximize Market Research (2023). *E-Waste Management Market Projected to Reach 137.60 Billion USD by 2029 – A Complete Global Analysis*. Report ID 188520. <https://www.maximizemarketresearch.com/market-report/e-waste-management-market/188520/>
- Metso (2023). *Tailings Management Solutions: Reshaping the future of tailings*. <https://www.metso.com/mining/solutions/tailings-management/> [Accessed 2 November 2023].
- Messenì Petruzzelli, A., Murgia, G., and Parmentola, A. (2022). How can open innovation support SMEs in the adoption of 14. 0 technologies? An empirical analysis. *R&D Management*, 52(4), 615-632. <https://doi.org/10.1111/radm.12507>
- Miatto, A., Emami, N., Goodwin, K., West, J., Taskhiri, S., Wiedmann, T., and Schandl, H. (2024). Australia's Circular Economy Metrics and Indicators. *Journal of Industrial Ecology*. <https://doi.org/10.1111/jiec.13458>
- Minerals Council of Australia (2022). *A review of Australia's mining ecosystem: The digital Mine*. https://minerals.org.au/wp-content/uploads/2022/12/The-Digital-Mine_2022-1.pdf.
- Mint (2023). *New generation circular green metals*. <https://www.mint.bio/> [Accessed 1 November 2023]

- Minunno, R., O'Grady, T., Morrison, G.M. and Gruner, R.L. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation and Recycling*, 160. <https://doi.org/10.1016/j.resconrec.2020.104855>
- Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S. and Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, 146, 452-461. <https://doi.org/10.1016/j.resconrec.2019.03.045>
- Mordor Intelligence (2023). *Insect Protein Market Size & Share Analysis – Growth Trends & Forecasts (2023 – 2028)*. <https://www.mordorintelligence.com/industry-reports/global-insect-protein-market>
- Morgan, S., Amelunxen, P., Akerstrom, B., and Cooper, L., (2023). *Pinto Valley Mine, Copper recovery study with the NovaCell™*. In Proceedings MetPlant 2023, 101-115.
- National Skills Commission (2021). *The state of Australia's skills 2021: now and into the future. Report Overview*. https://www.jobsandskills.gov.au/sites/default/files/2021-12/2021%20State%20of%20Australia%27s%20Skills_O.pdf
- Nicolaou, A., Neumann, R., Parker, S., Seyani, M., Ryan, N., Gransden, A., Yemm, N. and Hope, A., (2023). *First Nations People Workforce Analysis report*. Jobs and Skills Australia, Canberra. <https://www.jobsandskills.gov.au/publications/first-nations-people-workforce-analysis-report> [Accessed 6 July 2023]
- Nnanna, J., Charles, M.B., Noble, D. and Keast, R. (2023). Innovation Hubs in Australian Public Universities: An Appraisal of Their Public Value Claims. *International Journal of Public Administration*, 46(2), 133-143. <https://doi.org/10.1080/01900692.2021.1993900>
- Nolet, S. and Lever, B. (2023). *Australian Insect Industry RD&E Plan 2023-2028*. <https://agrifutures.com.au/product/australian-insect-industry-rde-plan-2023-2028/>
- Nutri V (2023). *Vegetables reimaged*. <https://www.nutriv.com.au/>
- Oztemel, E. and Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, 31, 127–182. <https://doi.org/10.1007/s10845-018-1433-8>
- Papaioannou, E.H., Mazzei, R., Bazzarelli, F., Piacentini, E., Giannakopoulos, V., Roberts, M.R. and Giorno, L. (2022). Agri-Food Industry Waste as Resource of Chemicals: The Role of Membrane Technology in Their Sustainable Recycling. *Sustainability*, 14(3), 1483. <https://doi.org/10.3390/su14031483>
- Parece, S., Rato, V., Resende, R., Pinto, P. and Stellacci, S. (2022). A Methodology to Qualitatively Select Upcycled Building Materials from Urban and Industrial Waste. *Sustainability*, 14(6), 3430. <https://doi.org/10.3390/su14063430>
- Payne, J., McKeown, P. and Jones, M.D. (2019). A circular economy approach to plastic waste. *Polymer Degradation and Stability*, 165, 170–181. <https://doi.org/10.1016/j.polymdegradstab.2019.05.014>
- Peiravi, M., Dehghani, F. Ackah, L., Baharlouei, A., Godbold, J., Liu, J., Mohanty, M. and Ghosh, T. (2021). A review of rare-earth elements extraction with emphasis on non-conventional sources: Coal and coal byproducts, iron ore tailings, apatite, and phosphate byproducts. *Mining, Metallurgy & Exploration*, 38, 1–26. <https://doi.org/10.1007/s42461-020-00307-5>
- Peng, K., Yang, H. and Ouyang, J. (2015). Tungsten tailing powders activated for use as cementitious material. *Powder Technology*, 286, 678–683. <https://doi.org/10.1016/j.powtec.2015.09.012>
- Pickin, J., Randell, P., Trinh, J. and Grant, B. (2018). *National Waste Report 2018*. <https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2018.pdf>
- Pickin, J., Wardle, C., O'Farrell, K., Stovell, L., Nyunt, P., Guazzo, S., ... and Edwards, C. (2023). *National Waste Report 2022*. Department of Climate Change, Energy, the Environment and Water, Ed, 142.
- Planko, J., and Cramer, J. (2021). *The Networked Business Model for Systems Change: Integrating a Systems Perspective in Business Model Development for Sustainability Transitions*. In Business Models for Sustainability Transitions: How Organisations Contribute to Societal Transformation (pp. 59-88). Cham: Springer International Publishing.
- Productivity Commission (2003). *Trends in Australian Manufacturing*. <https://www.pc.gov.au/research/completed/manufacturing/tiam.pdf>
- Raju, K. and Roshan, D. (2022). *Antioxidants Market*. Report Code: A01500. <https://www.alliedmarketresearch.com/antioxidants-market>
- Recycling and Waste Reduction Act 2020 (Cth). <https://www.legislation.gov.au/C2020A00119/latest/text>
- Recycling Plastics Australia (2023). *Recycling Plastics Australia*. <https://www.rpau.com.au/> [Accessed 25 November 2023].
- Redwood Materials (2023). *We're building a circular supply chain to power a sustainable world*. <https://www.redwoodmaterials.com/> [Accessed 25 November 2023].
- Rene, E.R., Sethurajan, M., Ponnusamy, V.K., Kumar, G., Dung, T.N.B., Brindhadevi, K., and Pugazhendhi, A. (2021). Electronic waste generation, recycling and resource recovery: Technological perspectives and trends. *Journal of Hazardous Materials*, 416. <https://doi.org/10.1016/j.jhazmat.2021.125664>
- Robertson, M. (2022). *Good to Grow: trends in agricultural innovation*. <https://www.csiro.au/en/news/all/articles/2022/november/a-thriving-future-trends-in-agricultural-innovation>
- Roos, G. (2014). Business model innovation to create and capture resource value in future circular material chains. *Resources*, 3(1), 248–274. <https://doi.org/10.3390/resources3010248>
- Ruuth, E., Sanchis-Sebastiá, M., Larsson, P.T., Telemán, A., Jiménez-Quero, A., Delestig, S., Sahlberg, V., Salén, P., Sanchez Ortiz, M., Vadher, S., et al. (2022). Reclaiming the Value of Cotton Waste Textiles: A New Improved Method to Recycle Cotton Waste Textiles via Acid Hydrolysis. *Recycling*, 7(4), 57. <https://doi.org/10.3390/recycling7040057>
- Saha, A.K. and Saker, P.K. (2017). Sustainable use of ferronickel slag fine aggregate and fly ash in structural concrete: Mechanical properties and leaching study. *Journal of Cleaner Production*, 162, 438–448. <https://doi.org/10.1016/j.jclepro.2017.06.035>
- Santi, A. (2023, February 28). *Can clothes ever be fully recycled?* BBC Future. <https://www.bbc.com/future/article/20230227-how-to-recycle-your-clothes>

- Schandl, H., West, J., Lu, Y., Baynes, T. and Wang, H. (2019). *Material Flow Account Australia. A comprehensive material flow account for the Australian economy*. Canberra: CSIRO. csiro: EP197565. <https://doi.org/10.25919/kzwx-0154>
- Schandl, H., King, S., Walton, A., Kaksonen, A.H., Tapsuwan, S. and Baynes, T.M. (2020). *National circular economy roadmap for plastics, glass, paper and tyres*. CSIRO, Australia. <https://www.csiro.au/en/research/natural-environment/Circular-Economy>
- Simão, F.V., Chambart, H., Vandemeulebroeke, L., Nielsen, P., Adrianto, L.R., Pfister, S., Cappuyns, V. (2022). Mine waste as a sustainable resource for facing bricks. *Journal of Cleaner Production*, 368. <https://doi.org/10.1016/j.jclepro.2022.133118>
- Smol, M. (2023). Chapter 3—Global directions for the green deal strategies—Americas, Europe, Australia, Asia, and Africa. In M. N. Vara Prasad and M. Smol (Eds.), *Sustainable and Circular Management of Resources and Waste Towards a Green Deal* (pp.39–46). Elsevier. <https://www.sciencedirect.com/science/article/pii/B978032395278100019X?via%3Dihub>
- Solismaa, S., Ismailov, A., Karhu, M., Sreenivasan, H., Lehtonen, M., Kinnunen, P., Illikainen, M., Räisänen, M.L. (2018). Valorization of Finnish mining tailings for use in the ceramics industry. *Bulletin of the Geological Society of Finland*, 90, 33–54. <https://doi.org/10.17741/bgsgf/90.1.002>
- Summerton, L., Clark, J.H., Hurst, G.A., Ball, P.D., Rylott, E.L., Carlsaw, N., ... and McElroy, C.R. (2019). Industry-informed workshops to develop graduate skill sets in the circular economy using systems thinking. *Journal of chemical education*, 96(12), 2959–2967. <https://doi.org/10.1021/acs.jchemed.9b00257>
- Straub, L., Hartley, K., Dyakonov, I., Gupta, H., van Vuuren, D. and Kirchherr, J. (2023). Employee skills for circular business model implementation: A taxonomy. *Journal of Cleaner Production*, 410. <https://doi.org/10.1016/j.jclepro.2023.137027>
- Tayebi-Khorami, M., Edraki, M., Corder, G. and Golev, A. (2019). Re-thinking mining waste through an integrative approach led by circular economy aspirations. *Minerals*, 9(5), 286. <https://doi.org/10.3390/min9050286>
- Tech Council of Australia (2022). *Australia's Tech Jobs Opportunity – Cracking the Code to Australia's Best Jobs*. <https://techcouncil.com.au/wp-content/uploads/2022/03/2022-Tech-Jobs-Opportunity-report.pdf>
- TAFE SA (2023). *Course Guide 2024*. https://www.tafesa.edu.au/docs/default-source/about_tafesa/tafesa-course-guide.pdf?sfvrsn=ac822214_36. [Accessed 24 October 2023].
- The Treasury (2023). *Working Future: The Australian Government's White Paper on Jobs and Opportunities*. <https://treasury.gov.au/employment-whitepaper/final-report>
- Thejas, H.K. and Hossiney, N. (2022). Compressed unfired blocks made with iron ore tailings and slag. *Cogent Engineering*, 9(1), 1–14. <https://doi.org/10.1080/23311916.2022.2032975>
- Tiwary, C.S., Kishore, S., Vasireddi, R., Mahapatra, D.R., Ajayan, P.M. and Chattopadhyay, K. (2017). Electronic waste recycling via cryo-milling and nanoparticle beneficiation. *Materials Today*, 20(2), 67–73. <https://doi.org/10.1016/j.mattod.2017.01.015>
- United States Environmental Protection Agency (2012). *Recycling and waste electrical and electronic equipment management in Taiwan: A case study*. https://www.epa.gov/sites/default/files/2014-08/documents/taiwan_iemn_case_study_12.7_final.pdf
- United States Environmental Protection Agency (2021). *New International Requirements for the Export and Import of Plastic Recyclables and Waste*. <https://www.epa.gov/hwgenerators/new-international-requirements-export-and-import-plastic-recyclables-and-waste>
- UNSW (University of New South Wales) (2023). *E-waste*. <https://www.smart.unsw.edu.au/technologies-products/microfactory-technologies/e-waste> [Accessed 26 October 2023].
- Valenta, R.K., Lèbre, E., Antonio, C., Franks, D.M., Jokovic, V., Micklethwaite, S., Parbhakar-Fox, A., Runge, K., Savinova, E., Segura-Salazar, J., Stringer, M., Verster, I. and Yahyaei, M. (2023). Decarbonisation to drive dramatic increase in mining waste – Options for reduction. *Resources, Conservation and Recycling*, 190. <https://doi.org/10.1016/j.resconrec.2022.106859>
- van der Ven, C. (2020). *The Circular Economy, Trade, and Development: Addressing Spillovers and Leveraging Opportunities*. Study commissioned by the Permanent Representation of the Netherlands to the WTO, Geneva. SSRN Electronic Journal. <http://dx.doi.org/10.2139/ssrn.3759786>
- Van Yken, J., Boxall, N.J., Cheng, K.Y., Nikoloski, A.N., Moheimani, N.R. and Kaksonen, A.H. (2021). E-Waste Recycling and Resource Recovery: A Review on Technologies, Barriers and Enablers with a Focus on Oceania. *Metals*, 11(8), 1313. <https://doi.org/10.3390/MET11081313>
- Voicu, S.I. and Thakur, V.K. (2023). Green polymers-based membranes for water reuse in a circular economy context. *Current Opinion in Green and Sustainable Chemistry*, 43. <https://doi.org/10.1016/j.cogsc.2023.100852>
- Weick, M. and Ray, N. (2022). *Regulatory landscape of the circular economy*. Ernest & Young report. https://www.ey.com/en_us/chemicals/circular-economy-navigating-the-evolving-global-policy-landscape
- Whatnall, O., Barber, K. and Robinson, P. (2021). Tailings Filtration Using Viper Filtration Technology—a Case Study. *Mining, Metallurgy & Exploration*, 38, 1297–1303. <https://doi.org/10.1007/s42461-021-00378-y>
- Whittle, L. (2019). *Australia's Forest Industry*. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, ABARES Insights, Issue 5. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1029804/0
- Wiedemann, S.G., Biggs, L., Clarke, S.J. and Russell, S.J. (2022). Reducing the Environmental Impacts of Garments through Industrially Scalable Closed-Loop Recycling: Life Cycle Assessment of a Recycled Wool Blend Sweater. *Sustainability*, 14(3), 1081. <https://doi.org/10.3390/su14031081>
- World Intellectual Property Organization (2022). *Global Innovation Index 2022: Australia*. <https://www.wipo.int/edocs/pubdocs/en/wipo-pub-2000-2022-en-main-report-global-innovation-index-2022-15th-edition.pdf>
- Worn Again (2023). *About Us. Worn Again has a unique, trail-blazing heritage*. <https://wornagain.co.uk/about-us/#technology> [Accessed 25 November 2023].
- Wu, S., Kaden, N. and Dröder, K. (2023). A Systematic Review on Lithium-Ion Battery Disassembly Processes for Efficient Recycling. *Batteries*, 9, 297. <https://doi.org/10.3390/batteries9060297>

Appendix A – Data, methods and concepts

A.1 Data and methods

This section presents the data sources and methodological approach taken to inform this report. The research team used a combination of literature review (peer reviewed and grey), basic existing databases, and key informant interviews to collect and analyse data. The literature review involved systematic searches of papers indicating research on the circular economy in Australia over the last five years (via databases such as Scopus and Google Scholar). Grey literature was obtained from official government reports (e.g., Australian Strategic Policy Institute Limited, Department of Industry, Science and Resources), trusted global reports including regional government websites (e.g., OECD reports, Ellen MacArthur Foundation, UNEP, Association of Southeast Asian Nations (ASEAN), Asia-Pacific Economic Cooperation (APEC), and industry reports (e.g., IBISWorld, Australian Packaging Covenant Organisation). Data was analysed from public sources such as the Australian Bureau of Statistics, DCCEEW's National Waste Report and the Australian Research Council Grant Connect Database. Key informant interviews were undertaken targeting major players in key circular economy industries, including the private sector and scientists with domain and regional knowledge.

A.2 Concepts

'Circular economy' and 'Industrial ecology'

A circular economy based on industrial ecology thinking is a concept that aims to create a regenerative and sustainable economic system by mimicking natural ecosystems. It integrates principles from both the circular economy and industrial ecology, two complementary approaches that focus on reducing waste, conserving resources, and minimising environmental impacts.

Industrial ecology is a systems-based approach that draws inspiration from ecosystems, where waste from one organism becomes a resource for another. It seeks to create industrial systems that function more like natural ecosystems, optimising resource use and minimising waste through interdependent relationships among industries and processes. By considering the broader interactions between different economic sectors and their impacts on the environment, industrial ecology aims to enhance the overall efficiency and sustainability of industrial activities.

When combined, the circular economy and industrial ecology principles offer a powerful framework for creating a more sustainable economic system. Key features of a circular economy based on industrial ecology thinking can be thought of as key principles and include:

- **Resource efficiency:** Maximising the efficient use of resources, including raw materials, energy, and water, to reduce waste and decrease the environmental footprint of industrial processes.
- **Closed-loop systems:** Designing products and industrial processes to enable materials and components to be reused, refurbished, or recycled, thereby minimising waste generation and the need for new raw materials.
- **Ecosystem thinking:** Emphasising a holistic approach that considers the interconnectedness of industries, supply chains, and environmental impacts to identify synergies and opportunities for resource exchange.
- **Biomimicry:** Drawing inspiration from nature's design principles to create innovative and sustainable solutions replicating natural systems' efficiency and resilience.
- **Collaboration and networks:** Encouraging collaboration among industries, businesses, governments, and other stakeholders to share resources, knowledge, and best practices to optimise resource use and reduce waste generation.
- **Product life extension:** Encouraging the design of durable products that can be repaired, upgraded, or remanufactured, extending their useful life and reducing the demand for new products.

By adopting a circular economy based on industrial ecology thinking, societies can move towards a more sustainable and regenerative economic model that not only minimises environmental impacts but also fosters economic growth and innovation. It requires a collective effort from all stakeholders, including businesses, policymakers, and consumers, to transform the way we produce, consume, and manage resources.

Appendix B – International partnerships additional information

This appendix elaborates on two additional ways international partnerships can enhance Australia’s competitive and comparative advantages in its transition to a circular economy: boosting circular Foreign Direct Investment and sharing learnings and innovation to accelerate the circular transition.

B.1 Boosting circular Foreign Direct Investment (FDI)

Linking FDI to circular economy outcomes ensures that investments facilitate sustainable growth and responsible resource management. To position Australia as a prime destination for ‘green investments’, it could revise FDI guidelines to favour circular economy-oriented projects, organise international investor summits, and offer tax benefits or incentives for circular economy-compliant FDI.

In 2021, the dominant sectors for Australia’s US\$770 billion in FDI (United Nations Conference on Trade and Development, 2022) were mining, real estate, finance and insurance⁶, with less FDI in sectors central to the circular economy such as manufacturing, electricity and construction (Figure B.1). In terms of total foreign investment⁷, the leading investors are the United States, United Kingdom, Belgium⁸ and Japan (Table B.1) and circular economy deliverables are not yet pivotal in their investments. However, the US Inflation Reduction Act (IRA) and the European Green Deal offer fresh avenues to promote circular economy narratives into new foreign investments.

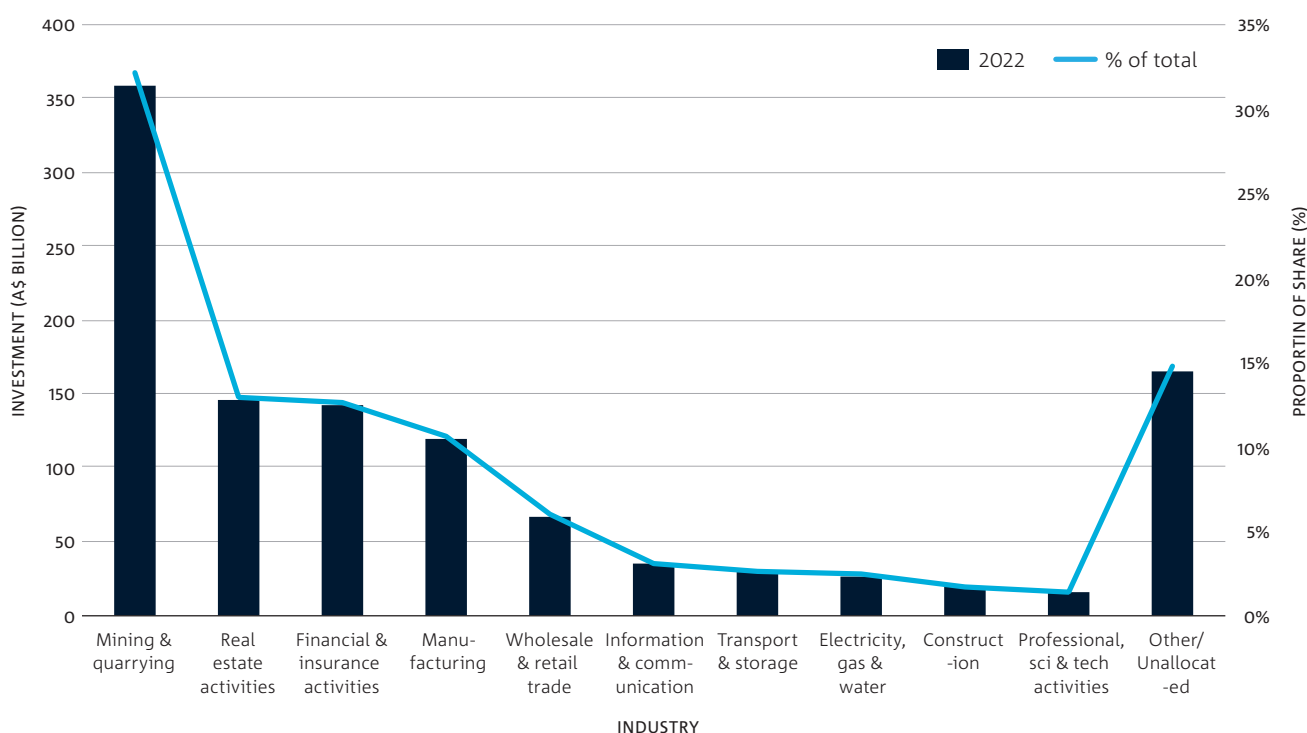


Figure B.1 Foreign direct investment by industry in 2022

Source: Based on ABS catalogue 5352.0. Prepared from table downloaded from <https://www.dfat.gov.au/trade/trade-and-investment-data-information-and-publications/foreign-investment-statistics/uropeian-industries-and-foreign-investment>

⁶ FDI is when an individual or entity from outside Australia establishes a new business or acquires 10 per cent or more of an Australian enterprise, and so has some control over its operations.

⁷ Total foreign investment is broader than FDI and includes portfolio investment, financial derivatives and other investment.

⁸ The majority of total investment from Belgium is portfolio investment liabilities in the form of debt securities (Belgium hosts a major clearing house and depository for euro-denominated bonds and other securities, Euroclear).

Table B.1 Top 20 countries investing in Australia between 2020 and 2022

RANK IN 2022	ECONOMY	A\$ BILLION			% OF TOTAL
		2020	2021	2022	
1	United States	926	1050	1,092	24.1
2	United Kingdom	770	722	1,007	22.2
3	Belgium (a)	409	394	359	7.9
4	Japan	265	258	257	5.7
5	Singapore	116	122	149	3.3
6	Hong Kong (SAR of China)	139	124	133	2.9
7	Canada	64.7	75.5	99.6	2.2
8	Luxembourg	107	92.4	89.0	2.0
9	Netherlands	84.4	88.3	87.6	1.9
10	China	81.2	91.4	85.1	1.9
11	Switzerland	61.9	69.5	74.1	1.6
12	New Zealand	68.4	69.1	72.2	1.6
13	France	42.9	43.4	54.0	1.2
14	Germany	46.9	48.6	52.5	1.2
15	Bermuda	42.4	42.5	45.4	1.0
16	Ireland	37.6	40.4	38.5	0.9
17	India	np	27.8	34.5	0.8
18	Norway	25.6	28.3	30.1	0.7
19	Republic of Korea	31.1	29.8	28.1	0.6
20	Virgin Islands, British	25.4	23.5	23.0	0.5
	Other economies	669	665	720	16
	All economies	4,014	4,104	4,531	100

Based on ABS catalogue 5352.0. Last Updated: May 2023. Table downloaded from: <https://www.dfat.gov.au/trade/trade-and-investment-data-information-and-publications/foreign-investment-statistics/statistics-on-who-invests-in-australia>

Note: Foreign investment includes direct investment, portfolio investment, financial derivatives and other investment. (a) The majority of total investment from Belgium is portfolio investment liabilities in the form of debt securities (Belgium hosts a major clearing house and depository for euro-denominated bonds and other securities, Euroclear). np = not published.

Australia and the US have entered into the Climate, Critical Minerals and Clean Energy Transformation Compact ('the Compact'), to dovetail with the IRA and bolster both nations' manufacturing prowess in renewable and clean energy (Prime Minister of Australia, 2023). The IRA earmarks US\$369 billion for hydrogen, green technology manufacturing, green metals, and clean energy generation (DFAT, 2023), and the Compact sets milestones for clean energy supply chains, critical mineral sourcing, and battery innovations. Australia can tap into IRA funds to supplement its A\$40 billion pledge for renewable energy capability⁹, including A\$20 billion in the Rewiring the Nation Plan and A\$1 billion in the National Reconstruction Fund (DFAT, 2023). This investment may enable Australia to carve niches in the value chains of seven net-zero economy opportunities¹⁰ (DFAT, 2023; Advanced Manufacturing Growth Centre, 2022).

For example, Box 1 sets out the potential and repercussions of Australia's participation in the global battery value chain, including magnifying demand for secondary materials and paving the way for reuse, remanufacturing, repurposing, and recycling within the renewable and clean energy sector.

The circular economy is a core tenet of the European Green Deal, which has a €1 trillion Investment Plan and €100 billion reserved for a Just Transition Mechanism spanning 2021–27 (Smol, 2023). If Australia can forge stronger trade and investment alliances with the EU, it may access FDI into digital technology, digitisation, recycling, building renovation, low-carbon transport, and sustainable food – priorities identified in the European Green Deal.

⁹ A large-scale local hydrogen industry could generate A\$50 billion in additional GDP by 2050 and create more than 16,000 jobs in regional Australia.

An additional 13,000 jobs could result from the construction of the renewable energy infrastructure required to power the production of green hydrogen.

¹⁰ The seven priority areas are: value-add in agriculture, forestry and fisheries; transport; medical science; defence capability; and enabling capabilities; renewables and low emission technologies; and value-add in resources.

Box 1: Example of strategic partners to expand Australia's participation in the battery value chain

By expanding Australia's participation further down the global value chain for batteries, including the capability to reuse, refurbish and recycle batteries, could almost double the economic gains between now and 2030, resulting in A\$7.4 billion in value-added and around 34,700 jobs (Future Battery Industries Cooperative Research Centre (FBICRC) 2021). Increasing recycling of e-waste from 54 per cent to 80 per cent and high efficiency recycling systems would result in an additional A\$440 million worth of materials recovered, 0.34 million tonnes of e-waste being dismantled for high-value recycling, creating local jobs, and saving 2.5 million tonnes of CO₂e emission (Bontinck et al., 2021). Batteries will be critical to transitioning the Australian energy system to low carbon over the next decade, with battery sales expected to reach US\$133–151 billion by 2030 (World Economic Forum, 2019; Roskill, 2020). With growing demand, the value added from battery reuse, refurbishment and recycling will likely increase substantially over the next decade.

Australia has a competitive advantage in supplying about half of the world's lithium market and being a major supplier of other critical metals (FBICRC, 2021). The position as a key supplier of critical energy minerals provides leverage for negotiating strategic international partnerships with countries that either have (e.g. China, Chile, Japan and South Korea) or are developing capability further down the value chain (e.g. United States, Germany, the UK, Finland and Canada) (FBICRC, 2021). However, the committed investment between 2018 and 2021 in battery manufacturing (A\$130 million) and integration and services (A\$103 million) pales in comparison to the investment in battery material extraction and refining (A\$3,850 million). More investment is needed to build capability further down the value chain if Australia is to realise the benefits of reusing, refurbishing and recycling batteries.

B.2 Learning from advanced circular economy countries

Countries like the Netherlands, Finland, and Japan have been progressing a circular economy agenda, and their experience can offer valuable insights into policy, regulations, programs and innovations to increase circularity in their economies. Australia could engage in international forums, bilateral workshops and exchange programs, and import successful pilot projects from these countries, adapting them to the Australian context.

Australia's 17 free trade agreements (Table B.2) encompass frameworks for skilled workforce exchanges and funding avenues for collaborative international research. Such partnerships can accelerate Australia's acquisition of advanced skills and technologies for a more active role in the global circular value chains.

Table B.2 List of free trade agreements in force

Australia–New Zealand
Singapore–Australia
Australia–United States
Thailand–Australia
Australia–Chile
ASEAN–Australia–New Zealand
Malaysia–Australia
Korea–Australia
Japan–Australia
China–Australia
Peru–Australia
Comprehensive and Progressive Agreement for Trans-Pacific Partnership
Australia-Hong Kong and associated Investment Agreement
Indonesia- Australia Comprehensive Economic Partnership Agreement
Pacific Agreement on Closer Economic Relations Plus
Regional Comprehensive Economic Partnership
Australia-India Economic Cooperation and Trade Agreement

Source: <https://www.dfat.gov.au/trade/agreements/in-force>

Regional platforms like the ASEAN and the APEC are also now promoting the circular economy. The ASEAN Framework for Circular Economy and the APEC Sub-committee on Standards and Conformance (ASEAN, 2021; APEC, 2021) provide opportunities for Australia to partner for collaborative projects, push standards harmonisation and exchange innovation.

Other initiatives that Australia might consider for its circular economy journey include:

- China's Circular Economy Promotion Law catalyses resource efficiency, particularly in high-tech and export-focused manufacturing. Yet areas such as construction and agriculture lag behind (Bleischwitz et al., 2022). More robust policy evaluation, surveys, accountability measures, and independent oversight are essential (Domenech and Bahn-Walkowiak, 2019).
- Taiwan's ambitious 5+2 Major Innovative Industries Plan champions research and innovation in recycling and resource recovery.
- South Korea's Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles underscores a design-for-recycle ethos, ensuring easy accessibility and reusability of components rich in critical minerals and building domestic stockpiles.
- Chile's Circular Chile by 2040 vision was developed inclusively, with a myriad of stakeholders from the public and private sectors, NGOs, academia, and the general populace (Ellen MacArthur Foundation, 2022).
- The EU's Waste Electrical and Electronic Equipment Directive surpasses Australia's National Television and Computer Recycling Scheme regarding product and population scope (Van Yken et al., 2021). Producers must shoulder the responsibility of collecting and treating their end-of-life products, enabling the EU to achieve the highest global e-waste recycling rate in 2019 (Baldé et al., 2020).

In summary, Australia has a wealth of global experiences to draw upon. By meticulously analysing these global best practices and integrating them with domestic strategies, Australia can design a bespoke, effective, and accelerated pathway towards a circular economy.

B.3 References

Advanced Manufacturing Growth Centre (2022). *Manufacturing Competitiveness Plan 2022*.

APEC (Asia-Pacific Economic Cooperation) (2021). *13th SCSC Conference: Standardisation in Circular Economy for a More Sustainable Trade*. APEC Sub-Committee on Standards and Conformance. Malaysia (Virtual Format), 7-9 September 2021.

ASEAN (Association of Southeast Asian Nations) (2021, October 21). *ASEAN adopts framework for Circular Economy*. <https://asean.org/asean-adopts-framework-for-circular-economy/> [Accessed 1 September 2023].

Baldé, C.P., Bel, G., Forti, V. and Kuehr, R. (2022). *The Global Transboundary E-waste Flows Monitor – 22*. United Nations Institute for Training and Research (UNITAR), Bonn, Germany.

Bleischwitz, R., Yang, M., Huang, B., Xu, X., Zhou, J., McDowall, W., Andrews-Speed, P., Liu, Z. and Yong, G. (2022). The circular economy in China: Achievements, challenges and potential implications for decarbonisation. *Resources, Conservation and Recycling*, 183, 106350. <https://doi.org/10.1016/j.resconrec.2022.106350>

Bontinck, P.A., Bricout, J., Grant, T. and Legoe, G. (2021). *E-product stewardship in Australia: Evidence report*. A report prepared for the Commonwealth Department of Agriculture, Water and the Environment by Icen Group and Lifecycles, Sydney, Australia.

DFAT (Department of Foreign Affairs and Trade) (2023). *Keynote address to the capability papers*. <https://ministers.dfat.gov.au/minister/tim-ayres/speech/keynote-address-capability-papers> [Accessed 1 September 2023].

Domenech, T. and Bahn-Walkowiak, B. (2019). Transition Towards a Resource Efficient Circular Economy in Europe: Policy Lessons from the EU and the Member States. *Ecological Economics*, 155, 7–19. <https://doi.org/10.1016/j.ecolecon.2017.11.001>

Ellen MacArthur Foundation (2022). *Chile's Circular Economy Roadmap*. <https://ellenmacarthurfoundation.org/circular-examples/chiles-circular-economy-roadmap> [Accessed 1 September 2023].

Future Battery Industries Cooperative Research Centre (FBICRC) (2021). *Future Charge: Building Australia's Battery Industries*. Accenture Consulting. Report to Future Battery Industries CRC.

Prime Minister of Australia (2023). *A joint statement by the Prime Minister, President of the United States of America on the Climate, Critical Minerals and Clean Energy Transformation Compact, 20 May 2023*. <https://www.pm.gov.au/media/australia-united-states-climate-critical-minerals-and-clean-energy-transformation-compact> [Accessed 1 September 2023].

Roskill (2020). *Lithium-ion Batteries: Outlook to 2029*, 4th Edition; Accenture analysis.

Smol, M. (2023). *Chapter 3 – Global directions for the green deal strategies – Americas, Europe, Australia, Asia, and Africa*. In M.N. Vara Prasad and M. Smol (Eds.), *Sustainable and Circular Management of Resources and Waste Towards a Green Deal*, pp.39–46. Elsevier. <https://doi.org/10.1016/B978-0-323-95278-1.00019-X>

United Nations Conference on Trade and Development (2022). *World Investment Report – Annex tables*. Last Updated: October 2022.

Van Yken, J., Boxall, N.J., Cheng, K.Y., Nikoloski, A.N., Moheimani, N.R. and Kaksonen, A.H. (2021). E-Waste Recycling and Resource Recovery: A Review on Technologies, Barriers and Enablers with a Focus on Oceania. *Metals*, 11(8), 1313. <https://doi.org/10.3390/MET11081313>

World Economic Forum (2019). *A vision for a Sustainable Battery Value Chain in 2030*.



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