Australia's National Science Agency

Modelling circular economy transition targets

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Important disclaimer

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Foreword

A report for the Department of Climate Change, Energy, the Environment and Water

This report has been prepared for the Department of Climate Change, Energy, the Environment and Water to inform target setting as part of Australia's national circular economy transition. Australia is committed to collaborating with the private sector to eliminate waste and pollution, keep materials in use, and foster markets to achieve a circular economy by 2030.

A key aspect could be the establishment of goals and targets that set the ambition for Australia's circular economy transition. In this report, we reviewed the modelling results of the United Nations Environment Programme (UNEP) International Resource Panel's Global Resources Outlook 2024 for Australia. This assessment aims to determine whether the ambitious sustainability policy scenario of the Global Resources Outlook can provide insights into Australia's ability to achieve its circularity targets. This analysis adds to the knowledge base supporting Australia's circular economy efforts.

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Executive summary

This study explores what can be achieved in Australia's transition toward increased resource efficiency and a circular economy if the necessary economic and policy conditions are created. Specifically, it investigates the extent to which the goal of doubling circularity by 2035 can be realised and whether the mooted policy interventions will enable Australia to reduce its per capita material footprint, increase material productivity, and lift the resource recovery rate.

The study utilises existing modelling from the UNEP International Resource Panel's flagship report, the Global Resources Outlook, to analyse the key model outcomes for Australia. This approach allows us to compare a baseline of 'historical trends' to a sustainability scenario, which serves as a proxy for circular economy policies in Australia.

By comparing the methodological assumptions and the sector coverage of the Global Resources Outlook to Australia's circular economy opportunities, we find sufficient similarities in the assumptions to justify using the existing data for interpreting Australia's circular economy pathway.

Our findings suggest that concerted efforts by governments, businesses, and the community could enable Australia to double its circularity by 2035, reduce its per capita material footprint by 10%, and increase material productivity by 30% by 2035. Furthermore, reducing waste to landfill by nearly 80% (achieving an 80% recovery rate) appears within reach (Figure 1 and Table 1).

The sophisticated multi-model framework of the Global Resources Outlook effectively captures the challenges and benefits of a profound and far-reaching economic transition, such as the shift to a circular economy. This transition will require significant changes in material supply chains, key provision systems, business and government procurement, and household behaviour. The study's results indicate that ample time will be needed to guide current investments, infrastructure decisions, and behaviours towards achieving Australia's low-carbon and circular economy goals.

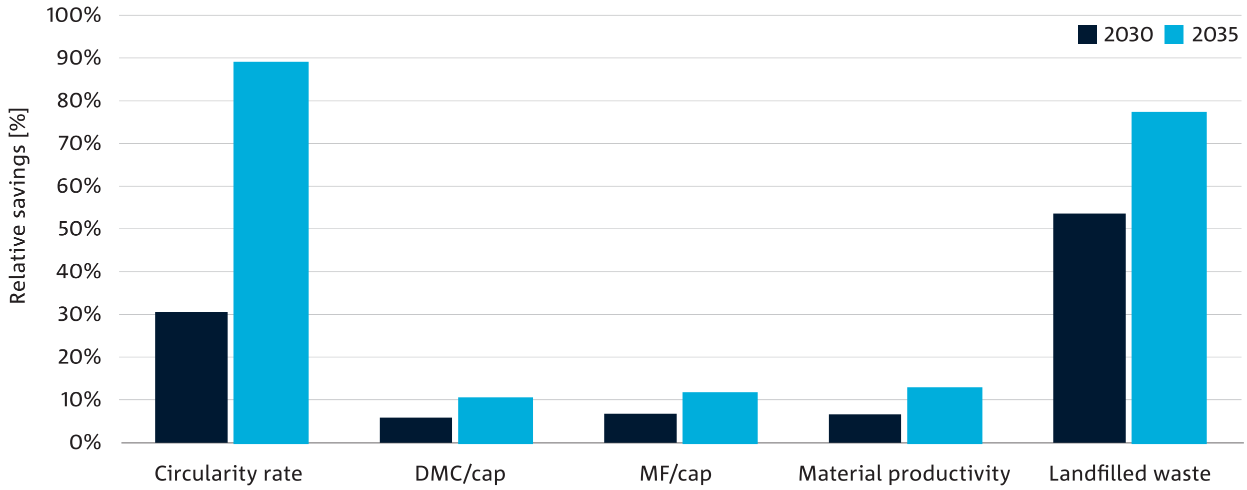
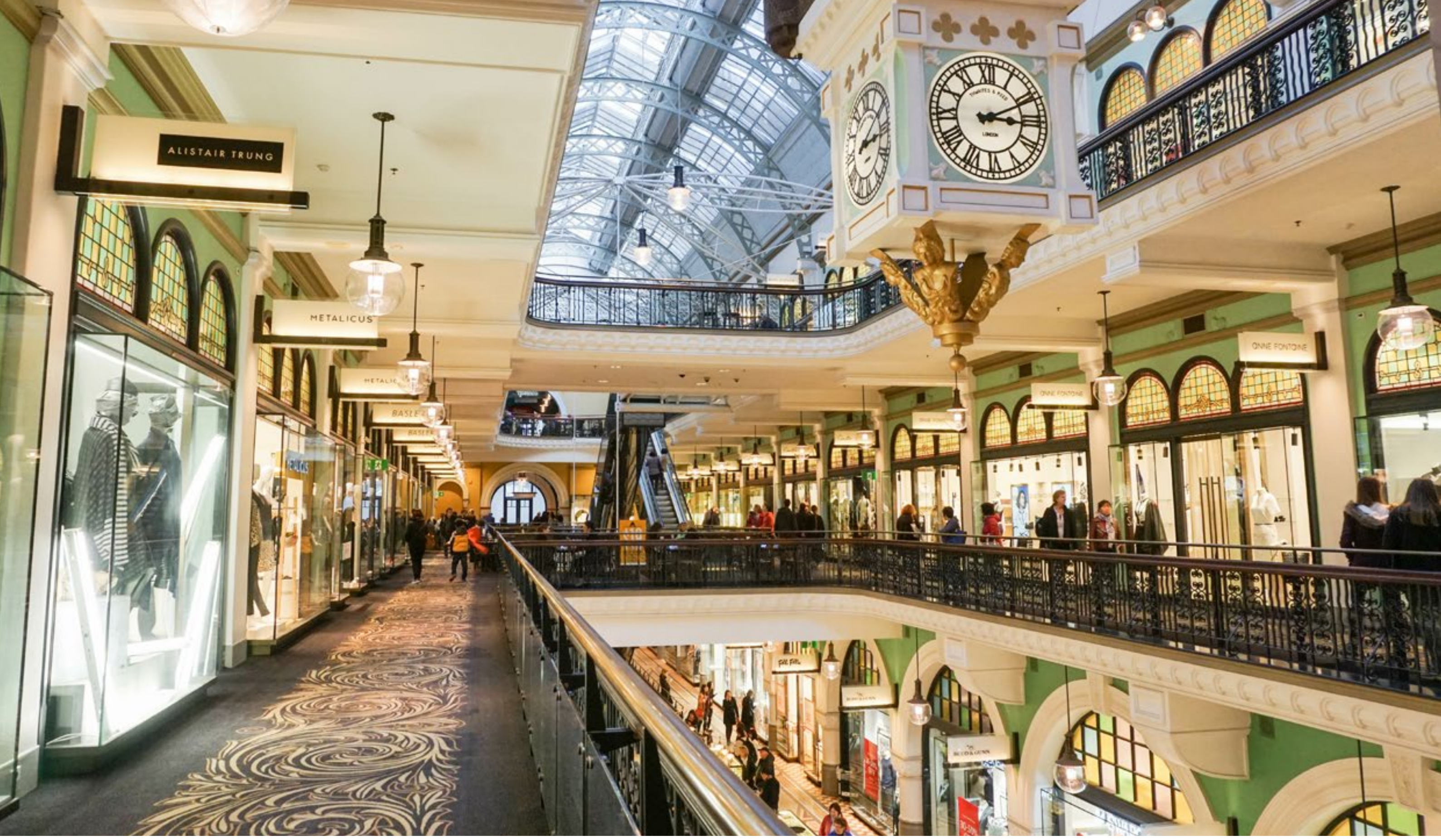


Figure 1 Relative savings for five key indicators for the Circular Economy Policy scenario compared with the Historical Trends scenario. The table at the bottom of the figure reports the value for these five indicators for 2030 and 2035.

Table 1 Key numerical results of this report.

HISTORICAL DATA	CIRCULARITY RATE [%]	DMC/CAP [t/CAP]	MF/CAP [t/CAP]	MATERIAL PRODUCTIVITY [USD/kg]	WASTE TO LANDFILL [Mt]
2020	4.6%	45	32	$1.28	30
Historical Trends					
2030	4.4%	48	31	$1.36	34
2035	4.5%	48	31	$1.43	34
Circular Economy Policies					
2030	5.8%	45	29	$1.45	16
2035	8.4%	43	28	$1.61	8



1 Introduction

The growing awareness of escalating material consumption has brought the concept of the circular economy into the mainstream (Brody, 2022; Leipold et al., 2023). This concept has recently gained significant traction as a more sustainable alternative to the traditional linear economy (Stahel, 2019). In a linear economy, resources are extracted, processed, manufactured into products, used, and eventually discarded as waste. This economic model exerts excessive pressure on natural ecosystems, as highlighted by a recent study on planetary boundaries (Richardson et al., 2023). In contrast, the circular economy aims to shift this linear pattern by emphasising strategies that reduce material extraction, extend the lifespan of products, and minimise waste disposal. The transition from a linear to a circular model is intended to foster a more sustainable, resilient, and efficient economy (Mayer et al., 2019).

The circular economy's focus extends beyond environmental benefits, encompassing economic and social dimensions integral to the three pillars of sustainable development (Purvis et al., 2019). Economically, the circular economy aims to achieve more with less. By rethinking product design, such as eliminating waste at the design stage and incorporating secondary materials into final products, the circular economy can significantly reduce the demand for virgin materials (Haar, 2024). These strategies help conserve natural resources, alleviate pressure on natural ecosystems, and enhance resilience, particularly when resources are reprocessed locally. Furthermore, this innovative circular approach fosters innovation and creates business opportunities as companies explore new ways to repurpose materials, extend product lifespans, and develop additional revenue streams, as evidenced in Europe (Busu & Trica, 2019).

From an environmental perspective, the circular economy aims to tackle some of today's most urgent challenges: climate change, resource depletion, biodiversity loss, and pollution (Rockström et al., 2024). By promoting the principles of reducing, reusing, and recycling (the three Rs) (Russell, 1995), the circular economy contributes to lowering greenhouse gas emissions and reducing the environmental footprint of manufacturing. It also supports ecosystem conservation by minimising material extraction (Huuhka & Vestergaard, 2020). Furthermore, through efficient design, the circular economy reduces waste and pollution (Bovea & Powell, 2016), which significantly affect human health (Siddiqua et al., 2022).

From a social perspective, the contributions of the circular economy are equally significant (Mies & Gold, 2021). Through its innovative approach, the circular economy has the potential to create new jobs and enhance economic resilience by fostering local manufacturing, recycling, and repurposing industries (Suárez-Eiroa et al., 2021). The transition to a circular economy demands new skills, novel approaches, and creative thinking, generating employment opportunities (Pratt, 2022). These opportunities extend beyond manufacturing and product design, driving the need for education and upskilling, developing facilities to process materials differently, and promoting businesses that offer alternative business models to ownership (Ameli, 2017; Ferasso et al., 2020). Ultimately, from a social standpoint, the circular economy can contribute to social equity and an improved quality of life (Nikanorova et al., 2020; Schröder et al., 2020). People can benefit from reduced pollution, healthier natural ecosystems, and more resilient national economies.

Given that the circular economy can support all three pillars of sustainable development, it is unsurprising that national governments are increasingly recognising its importance and issuing roadmaps to transition their economic models towards circular ones (Calisto Friant et al., 2021; Zhu et al., 2019). However, roadmaps alone may not be most effective unless paired with measurable metrics. One of the key metrics for assessing progress towards a circular economy is the circularity rate, which measures the percentage of recycled materials used within a national economy compared to all materials (Corona et al., 2019; Haas et al., 2015; Kostakis & Tsagarakis, 2022; Mayer et al., 2019). This metric offers a snapshot of an economy's reliance on primary materials and, conversely, its use of secondary materials. Governments can set benchmarks for the circularity rate, as seen in Finland (Statistics Finland, 2024), the European Union (European Commission, 2023), and the Netherlands (Government of the Netherlands, 2023). Measuring the circularity rate over time is particularly valuable, as it allows for monitoring progress and ensuring that the current circular economy initiatives are achieving their intended outcomes. Additionally, it can help identify trends and signal the need for intervention if progress deviates from desired trajectories.

Material flow accounting provides a physical perspective on the economic process and measures the tonnes of materials mobilised within the economy. The accounts are guided by the System of Environmental Economic Accounting (SEEA) framework and complement the system of national accounts. They report on materials, whether domestically extracted or traded, and outputs, including exports, waste, and emissions. The accounts can also include sector-specific detail, recycled flows, and material stocks. The methodology for national material flow accounts is now standardised (UNEP, 2023) with additional methodological guidance for measuring circularity currently under development by the European Commission and with the OECD (UNECE, 2023).

In this study, we utilise CSIRO's Global Trade and Environment Model (GTEM), which integrates material flows, energy, and emissions into its economic modelling framework, and use existing model runs developed for the Global Resources Outlook (UNEP, 2024). Currently, no global and national models fully incorporate waste flows, so we used technology-based stock and flow modelling to estimate the waste potential of the Australian economy (Schandl & Miatto, 2018). We also created concordance between the material categories of the waste potential account derived from stock-flow dynamics and the product and end-of-life categories of the Australian Waste Statistics (Blue Environment, 2022).

This combination of existing model runs and additional modelling of stocks, flows, and waste has enabled us to establish forecasts to 2050. It allows us to assess the potential outcomes when Australia implements a system built on resource efficiency and circular economy interventions.

2 Australia's circularity goals and targets

Australia has substantial opportunities to capitalise on the global shift towards a more circular economy, and indicators that measure progress can play a key role in this. New indicators can help track Australia's circularity and set ambitious goals. These goals might include increasing the national circularity rate, reducing the country's material footprint, improving material productivity, and raising recycling rates.

The circularity rate measures how much a national economy depends on primary materials and how effectively it uses secondary materials in key economic activities to reduce reliance on primary resources. Circularity can be improved in several ways, such as increasing the circularity potential through structural economic adjustments and maximising this potential by keeping materials in use for longer.

The material footprint indicator represents the total amount of raw materials extracted to satisfy Australia's needs, including household and government consumption and capital investment. It links the Australian economy to both upstream (imported final goods) and downstream (primary material exports) material supply chains.

Crucially, the material footprint accounts for the materials "embodied" in both imports and exports. This means that if materials are used abroad to produce an item imported into Australia, those materials are included in Australia's material footprint, not the country of origin, even if they are not physically part of the final product. Similarly, if mine tailings are generated in Australia during the production of metal concentrate from ore, the waste is attributed to the importing country's material footprint rather than Australia's. A high per capita material footprint contributes to significant environmental impacts such as climate change, biodiversity loss, resource depletion, and pollution. In the long term, the environmental consequences can erode living standards, leading the country to a gradual decline (Brinsmead et al., 2019).

In addition, this report measures domestic material consumption and waste to landfill. Domestic material consumption (DMC) measures the total amount of materials an economy uses. It accounts for the sum of all raw materials extracted within a country, plus all imported materials, minus all exported materials. DMC includes various categories such as biomass, fossil fuels, metal ores, and non-metallic minerals.

Material productivity is a measure of resource efficiency and provides insight into the functioning of the economy vis-à-vis the environment. The relationship between material productivity and economic growth is crucial for understanding how economies can grow sustainably. Material productivity is defined as the economic output generated per unit of material input, typically measured as gross domestic product (GDP) per unit of material use (using the DMC indicator). Higher material productivity leads to higher economic growth. Improving material productivity is essential for achieving sustainable economic growth, as it involves producing more economic value with less material input, thereby decoupling economic growth from resource use and environmental degradation.

Resource recovery is the process of extracting valuable materials or energy from waste or by-products. It aims to divert waste from landfills, reduce environmental impact, and promote the efficient use of resources. This process is a crucial component of the circular economy, where the goal is to keep resources in use for as long as possible, extract maximum value from them, and then recover and regenerate products and materials at the end of their service life.

Waste-to-landfill refers to the disposal of waste materials by burying them in designated landfill sites. This method involves placing waste in large, excavated areas, which are then covered with soil. Despite being a common waste management practice, landfilling has significant environmental, social, and economic implications and hence needs to be addressed. Usually, landfilling end-of-life materials incurs a significant cost (waste levy) and involves the destruction of the potential value of the materials.

3 Scenario modelling and scenario settings

Scenario modelling is a valuable tool for policy formation because it helps anticipate future challenges, evaluate the potential impacts of different policy options, and guide informed decision-making. By simulating various scenarios, policymakers can better understand the consequences of their actions, identify risks and opportunities, and develop resilient and adaptable strategies to changing circumstances.

Scenario modelling is especially helpful when planning policy initiatives that aim to transform complex economic and environmental interactions, such as the national effort to transition to a circular economy. Designing for zero waste, keeping materials in circulation at their highest value, and conserving natural resources and ecosystems all imply profound shifts in cities, industries, energy, land, and food systems.

For a decade, CSIRO has invested in building integrated modelling capability to address such profound changes and better understand their economic, environmental, and policy implications. Building on the Australian approach, CSIRO has also coordinated the use of multi-model frameworks for the United Nations Environment Programme International Resource Panel for the Global Resources Outlook (UNEP, 2024).

In this report, we have focussed on the two core scenarios of the recent Global Resources Outlook, titled Historical Trends and Sustainability Transition. This contrasts a continuation of current policies with an alternative, encompassing ambitious policy initiatives for resource efficiency, climate mitigation, and land use change. The Sustainability Scenario is aimed at managing the global economy within planetary boundaries. These two scenarios are applied to the Australian national economy and analysed the implications of Australia's Circular Economy Policy for material flows, waste, and circularity.

The scenarios are developed around a core economic model, CSIRO's Global Trade and Environment Model (GTEM). This model is one of just two global models that have integrated material flows into their economic core, the other being the OECD model (OECD, 2019). This modelling draws on a resource efficiency scenario developed for the Global Resources Outlook 2024, which describes a suite of global circular economy interventions. The model has the flexibility to allow a standalone modelling package that can report Australia's results. Additionally, the model can produce an overarching estimate of Australia's greenhouse gas savings.

The sustainability transitions scenario is modelled in GTEM as a series of macroeconomic policies that deviate from historical trends, including individual packages focussed on resource efficiency, greenhouse gas abatement, and land use changes. The resource efficiency policy package is modelled by introducing a cost on the externalities of primary resource consumption (more on this in 3.1). This package uses shadow prices for the costs associated with policies, regulations, and initiatives. The proceeds are reinvested into innovation that enhances resource efficiency. The second component of the resource efficiency package involves shifting demand in key consumption areas, such as food, housing, mobility, and consumer goods, to reflect preferences and behaviours that favour resource efficiency. This component includes innovative solutions that reduce material use, promote recycling, and encourage reuse.

The climate and energy shift is modelled as a standalone package. The primary energy mix in the sustainability transitions scenario aligns with the International Energy Agency's (IEA) net zero emissions scenario (IEA, 2023). The global emissions budget used is derived from the Dutch Integrated Model to Assess the Global Environment (IMAGE) and met through a combination of the gradual deployment of technology-based carbon dioxide removal (CDR) and the introduction of a global carbon levy. IMAGE is a comprehensive, integrated assessment model that simulates the interactions between human activities and natural systems to assess global environmental change and its impacts (Stehfest et al., 2014). For this analysis, Australia's baseline emissions have been adjusted to align with previous CSIRO projects for the Climate Change Authority (Verikios et al., 2024). The net emissions are consistent with the National Greenhouse Gas Inventory (NGGI) June 2023 quarterly update (covering historical emissions up to 2023) and DCCEEW's 2023 baseline emissions projection (the "no measure" scenario) from 2024 to 2035. From 2035 to 2050, model outputs from the Climate Change Authority baseline were used. Additionally, emissions from broad sectors, including agriculture, the electricity sector, and LULUCF (Land Use, Land-Use Change, and Forestry), were targeted. However, transportation was not targeted, as modifying the model for that sector would require more significant adjustments. The renewable energy targets from the GRO work, as previously described, have also been implemented.

The land use policy package is informed by the projections of the Global Biosphere Management Model (GLOBIOM) and includes a diet shift scenario. GLOBIOM is a global economic-land use model with an integrated treatment of agriculture, forestry, and bioenergy sectors that identifies competition for land use and its impacts, including on the environment, food security, and greenhouse gas emissions (Havlík et al., 2011). Combining the three policy packages constitutes the sustainability transition scenario.

These macroeconomic policy interventions are complemented by more detailed sectoral initiatives for construction and buildings, transport and mobility, and electricity generation. They include reduced per capita residential floor space, extended service life, light-weighting and substitution, changes in modal split in mobility and transportation, and higher electrification. They also assume materials-specific end-of-life recycling rates.

Taken together, the three macroeconomic policy packages and the sectoral initiatives deliver the reduced material requirements, waste, and emissions outcomes of the Sustainability Transition scenario.

3.1 Scenario model assumptions

The model assumes two basic circular economy mechanisms: supply-side (production changes) and demand-side (behaviour change) interventions.

Production changes (mechanism 1): This mechanism involves introducing extraction shadow prices for sectors like forestry, fisheries, coal, oil, gas, and other mining activities. The shadow price represents the cost of measures to improve resource efficiency and circularity driven by policy initiatives. As such, a shadow price is not necessarily a tax but an additional production cost to comply with regulations. For coal, oil, and gas, the shadow price starts at 10% in 2020 and gradually increases to 45% by 2050. For other resource extraction sectors, it begins at 8% in 2020, rising to 31% by 2050.

Mechanism 1 acts as a proxy for either a tax on these industries or policy/legislation that achieves equivalent price effects (defined as a shadow price). Mechanism 1 assumes a suite of policies that effectively increase the price of raw materials, but this is offset by improved material efficiency enabled by investment in innovation and improved technologies, resulting in net-positive economic growth.

Mechanism 1 assumes the presence of harmonised standards, industrial symbiosis, and green chemistry in the remanufacturing space. It accounts for reduced food waste and a higher presence of recycling materials in the agricultural and industrial domains. It also includes longer-lasting buildings and infrastructure, as well as higher metal recovery throughout the nation.

In essence, mechanism 1 represents circular economy policies or programs that effectively disincentivise the use of primary materials or incentivise the use of secondary materials through a price signal and measures that support innovation to improve material value, longevity, and reusability.

Behaviour changes (mechanism 2): This mechanism focuses on reducing demand for fossil fuels, some organic products (fibre, timber), iron and steel, non-ferrous metals, non-metallic minerals, and fisheries. In Australia, demand for iron and steel, non-ferrous metals, and non-metallic minerals is reduced by 0.75% per year starting in 2020. Demand reduction is set at 0.5% annually from 2020 for other sectors.

Mechanism 2 considers both industry production and household preference changes, reflecting shifts driven by businesses adopting circular economy strategies for reasons like consumer reputation, economic benefits, or strategic development.

Mechanism 2 reflects circular economy interventions in the built environment (re-use over rebuild), household consumption changes (e.g., increased repair and re-use of consumable products), and changing procurement patterns (sustainable procurement).

3.2 Caveats

The economic impacts of resource efficiency and circularity measures crucially depend on the calibration of the price changes assumed in the model. In turn, these prices hinge on the detailed design and implementation of the policies used to achieve them. However, the current results provide a reasonable estimate of the quantum of potential abatement and the associated economic impact based on internationally recognised benchmarks.

It is important to note that the modelling of the current scenario does not explore the full potential of circular economy policies, including ambitious resource recovery and recycling, which would be expected to deliver greater reductions in resource use (relative to historical trends). The contribution of circular economy policies to Australia achieving its Nationally Determined Contributions (NDCs) needs to be incorporated into future modelling and outlooks.

3.3 Policy relevance to Australia

In 2022, Australia's environment ministers agreed to accelerate the national transition to a circular economy (Australian Government, 2022). Australia's transition to a circular economy is expected to be driven by policies and programs that reflect both mechanism 1 (shadow price) and mechanism 2 (behaviour change) assumptions.

Australia's transition to a circular economy is expected to be driven by policies and programs that reflect both Mechanism 1 (shadow price) and Mechanism 2 (behaviour change) assumptions.

Relevant interventions, which governments are using or planning to use, include:

- **State-based landfill levies:** These levies make it more expensive to dispose of waste, including waste from virgin materials, encouraging recycling and the use of secondary materials.
- **Sustainable Procurement Policies:** The Australian Government, and various state and territory governments, have introduced procurement connected policies that incentivise the use of circular goods and services. These policies include, for example, Victoria's Recycled First Policy for transport infrastructure, which is a market instrument deprioritising the use of virgin materials and incentivising innovation in recycled materials use and technology.

- **Product bans or stewardship schemes:** Various industry- and government-led product stewardship schemes have been established to improve consumer access to resource recovery initiatives and better reflect the external costs of resource recovery activities. Extended Producer Responsibility (EPR) schemes are increasingly being adopted as the preferred model to make manufacturers responsible for the entire lifecycle of their products, from design to disposal. These schemes encourage companies to factor in the costs of material recovery, recycling, and end-of-life management, driving more sustainable production and reducing waste.
- **Product and materials innovation schemes:** States and territories have introduced materials innovation programs to improve material productivity. For example, Green Industries SA offers various grants to support circular economy initiatives, including improving the value of recycled materials and reducing reliance on virgin materials.
- **Product efficiency scheme for energy and water:** Australia already has regulated schemes to improve the energy and water efficiency of products through star rating schemes. Since its establishment in 2006, the Water Efficiency Labelling Scheme has been estimated to have saved 27 million tonnes of emissions.

Although Australia has not traditionally included the circular economy as part of its net zero strategy or Nationally Determined Contributions (NDCs), the policy measures implemented at national, state, and territory levels are expected to reduce Australia's emissions significantly. Additionally, the Australian Government is looking to corral and expand these priorities as it accelerates Australia's transition to a circular economy.

4 Results

In this section, we first analyse the results for the material footprint and its division into six provision systems (section 4.1). We then move on to the domestic material consumption (section 4.2). In section 4.3, we assess Australia's material productivity. We then look at waste generation in section 4.4, recycling rates and recycled waste in section 4.5, and finally conclude with the circularity rate in section 4.6.

Each figure will present historical data from 2010-2014 to 2021-2024 (depending on the earliest/latest available data) and also model projections until 2050 under both the historical trends scenario and the sustainability scenario (Historical Trends Scenario). This analysis will also display the modelled achievable results to assess progress and identify gaps in meeting circular economy goals (Circular Economy Policy Scenario).

These indicators are twofold important. First, they are metrics that directly measure material use, which is directly linked with various environmental impacts, e.g., deforestation, biodiversity loss, soil erosion, and indirectly with many others, such as climate change and pollution. Second, they are an essential policy tool to measure the efficiency of the overall economy from a physical standpoint. When these indicators are tracked over extended periods, as done in this study, they reveal trends that signal progress or provide early warnings of movement in an unsustainable directions.

We include both absolute and per capita values where important to do so (e.g., domestic material consumption). Doing so will provide a comprehensive view of the progress and impact of the circular economy measures, offering insights into overall performance as well as individual contributions. The detailed analysis will help understand proposed targets' effectiveness and the necessary adjustments to achieve the desired outcomes.

4.1 Material footprint

The material footprint measures the mass of all raw materials needed to manufacture products ultimately used in a national economy, regardless of where these materials are extracted or processed. In this context, the material footprint is a "consumption-based" indicator, measuring material use based on the final consumer, irrespective of the origin of these materials or the potential waste generated during the manufacturing process. Thus, it better reflects the materials needed to meet the needs of the Australian population, excluding materials used in products destined for overseas consumption. This measurement considers the mass of all raw materials extracted to fulfil the needs of Australia's people, both historically and in the future (Figure 2).

Historically, Australia's material footprint has been stable, averaging around 816 Mt per year, with the lowest recorded footprint at 768 Mt in 2014 and the highest at 844 Mt in 2019. Looking ahead, the Historical Trend scenario predicts a progressive increase in the material footprint, reaching 1,159 Mt by 2050, with a compound annual growth rate (CAGR) of 1.2%. In contrast, the Circular Economy Policy scenario also anticipates growth in the material footprint but at a slower rate than the Historical Trends scenario. This sustainable scenario projects the material footprint to reach 890 Mt by 2050, resulting in a significantly lower CAGR of 0.3%.

The absolute values of the material footprint presented in Figure 2 are better understood when considering Australia's continuous population growth, both historical and forecasted. Material footprint data normalised by population are illustrated in Figure 3. Historical data on the per capita material footprint show a progressive decline in recent years. In 2010, Australians required approximately 38 t/cap to meet their material demands, which, despite some fluctuations, declined to 31 t/cap by 2024.

The two scenarios we present highlight contrasting trajectories. The Historical Trends scenario shows a slow but steady increase in the per capita material footprint, reaching 33 t/cap by 2050. Conversely, the Circular Economy Policy scenario continues to decrease slowly, with an expected value of 25 t/cap by 2050. This corresponds to a compound annual growth rate (CAGR) of -0.8% between 2024 and 2050.

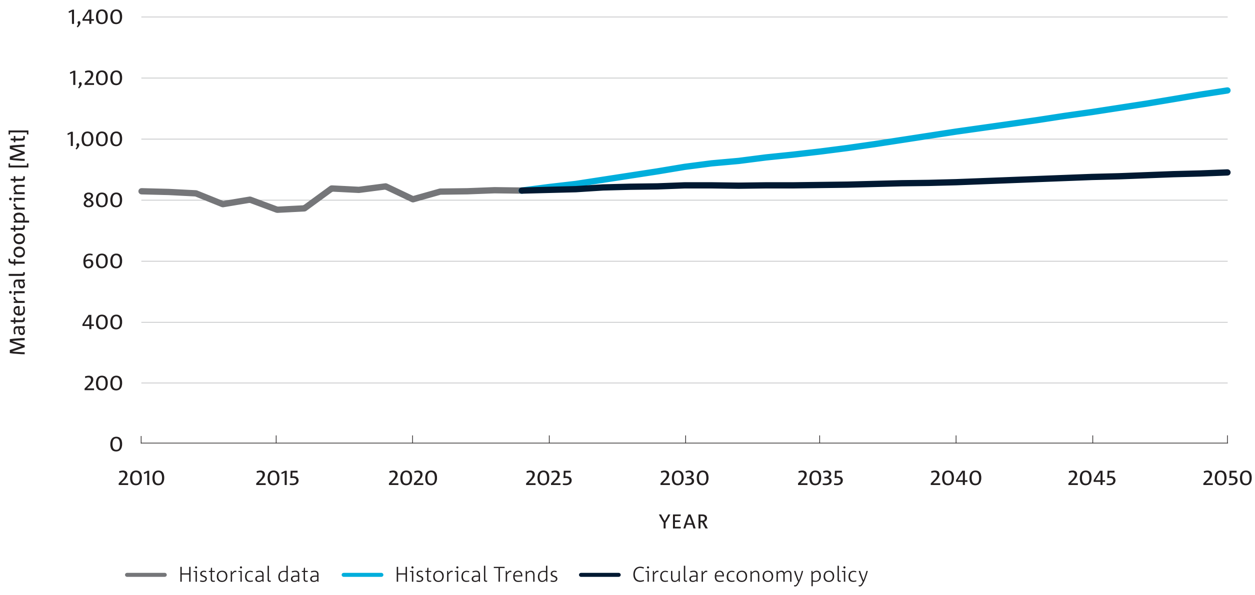


Figure 2 Australia's material footprint 2010-2050.

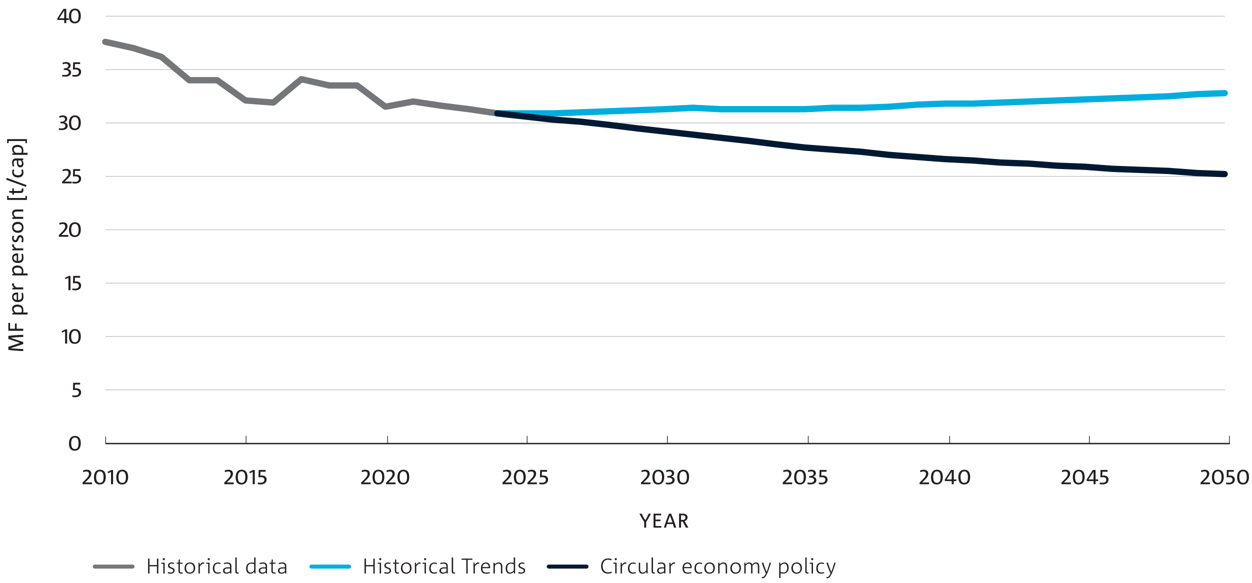


Figure 3 Australia's material footprint per capita 2010-2050.

We divide the overall material footprint into five systems of provision essential for fulfilling human well-being: Housing, Food, Mobility, Energy, and Communication (Figure 4). An additional sixth category, labelled "Other," includes sectors not previously covered, such as education, healthcare, and government. This analysis is crucial because it highlights the varying material dependencies of different sectors. For example, mobility is heavily material-dependent, while communication meets its needs with minimal material inputs.

In both scenarios, the Housing provision system uses the most materials. Under the Historical Trends scenario, this system consumes 404 Mt in 2050, while it requires only 316 Mt in the more sustainable Circular Economy Policy scenario. This reduction is achieved through dematerialisation efforts and increased use of timber to replace concrete. The Food system ranks second, requiring 206 Mt in the Historical Trends scenario and 148 Mt in the Circular Economy Policy scenario.

One important aspect to note is the Energy system, which, despite being relatively small compared to the total material footprint, experiences the most significant relative reduction between the two scenarios. The Energy system uses 53% less material in the Circular Economy Policy scenario than in the Historical Trends scenario. This substantial reduction results from vastly different policies on energy generation and the adoption of renewable energy systems.

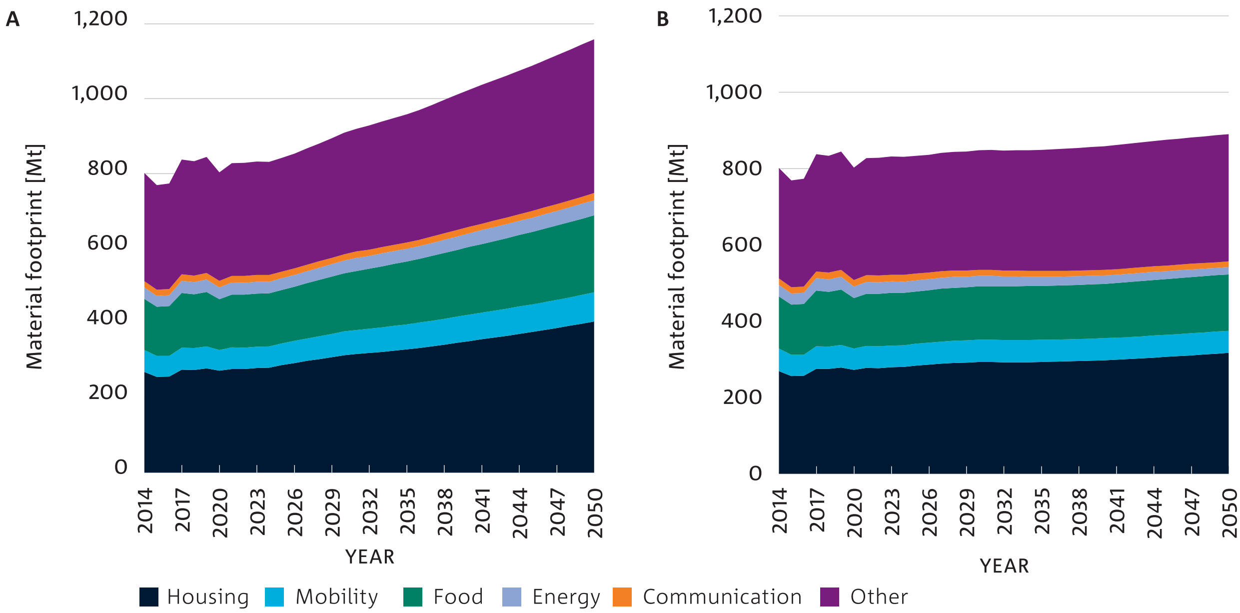


Figure 4 Australia's material footprint for six provision systems 2014-2050 and two scenarios. A: Historical Trends; B: Circular Economy Policy

In Figure 5, similar to our analysis of domestic material consumption in Figure 9, we examine the differences in material footprint between the two scenarios by exploring the material savings of the Circular Economy Policy scenario compared to the Historical Trends scenario. Material reductions start strong, with a 6% savings between 2025 and 2030. These reductions progressively slow down, with the last five years adding only an extra 3% reduction between the two scenarios. By 2050, the Circular Economy Policy scenario uses 269 Mt, or 23%, fewer materials than the Historical Trends scenario.

Most of these savings are in the Housing provision system, which uses 88 million tonnes fewer materials compared with the Historical Trends scenario. The Other category also shows significant savings, using 78 million tonnes fewer materials between the two scenarios.

4.2 Domestic material consumption

Domestic Material Consumption (DMC) is one of the headline indicators of material flow accounting. Material flow accounting and derived indicators have been adopted by the UNEP, the OECD, and the European Commission to monitor the progress of the circular economy. DMC denotes the materials managed in the domestic economy, whether domestically extracted or imported. Exported materials are subtracted from DMC, but the waste and emissions due to the exports are recorded in the DMC. For instance, we extract metal ores and export metal concentrates. The mining waste is recorded in Australia's DMC, and the exported volumes of concentrates are subtracted.

DMC hence informs about the total amount of materials—biomass, fossil fuels, metal ores, non-metallic minerals, and products thereof—managed in the domestic economy. Because every kilogram of material we manage has an environmental impact, DMC is a headline indicator for environmental impacts and the long-term waste potential of an economy. DMC can be managed by domestic and trade policies.

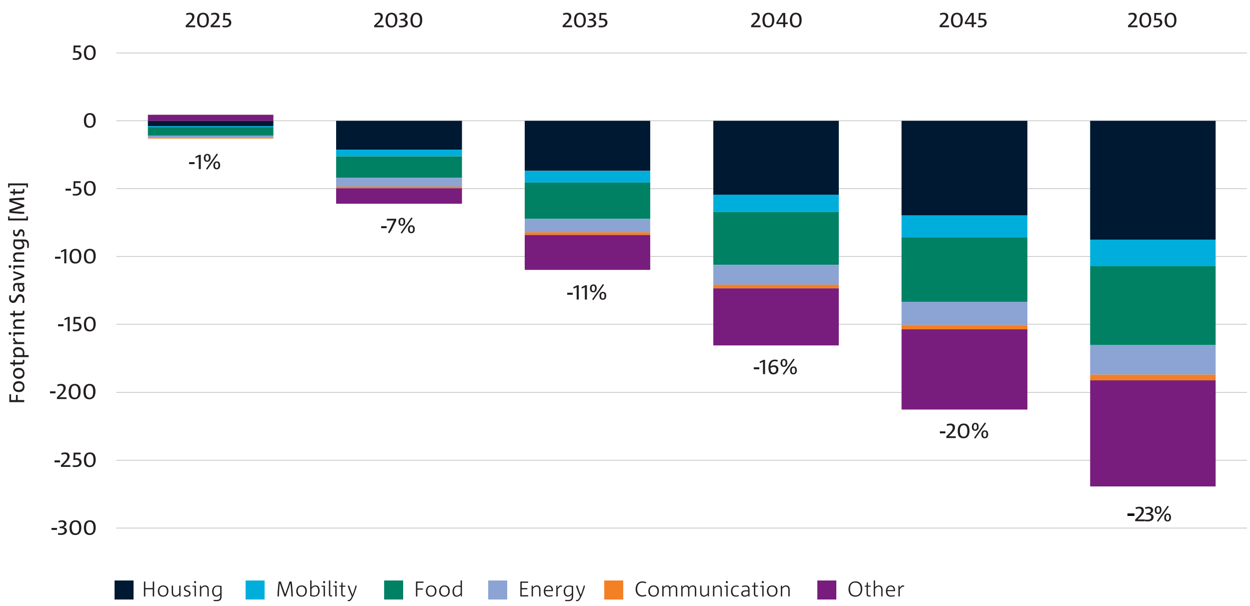


Figure 5 Changes in Australia's material footprint for six provision systems between the Historical Trends scenario and the Circular Economy Policy scenario in 2025, 2030, 2035, 2040, 2045, and 2050.

Historically, Australia has a very high DMC, which is driven by Australia's economic focus on primary industries. It is high in both absolute and per-capita terms (see Figure 6 and Figure 7). Between 2010-2024 Australia's domestic material consumption grew from 994 million tonnes to 1,278 million tonnes. The two scenarios we present display progressively diverging trends. The Historical Trends scenario projects that, in 2050, Australia will manage 1,722 million tonnes of materials, a yearly average growth of 1.1%. The Circular Economy Policy scenario would see a much slower increase in Australia's DMC, which would reach 1,350 million tonnes by 2050 (an average annual growth rate of 0.2%), almost 400 million tonnes less compared with the Historical Trends scenario forecast. Some of the reduction in DMC for the Circular Economy Policy scenario would be achieved by domestic circular economy efforts paired with a significant reduction in global demand for primary materials in a global low carbon and circular economy.

Because Australia's population is expected to continue growing, per-capita DMC is forecast to stabilise under Historical Trends assumptions and is predicted to decline with the domestic (and global) Circular Economy Policy (Figure 7). The Historical Trend scenario would see per capita DMC stabilise at just under 50 tonnes per capita. The Circular Economy Policy would see per capita DMC progressively fall from 48 tonnes per capita in 2024 to 38 tonnes per capita in 2050.

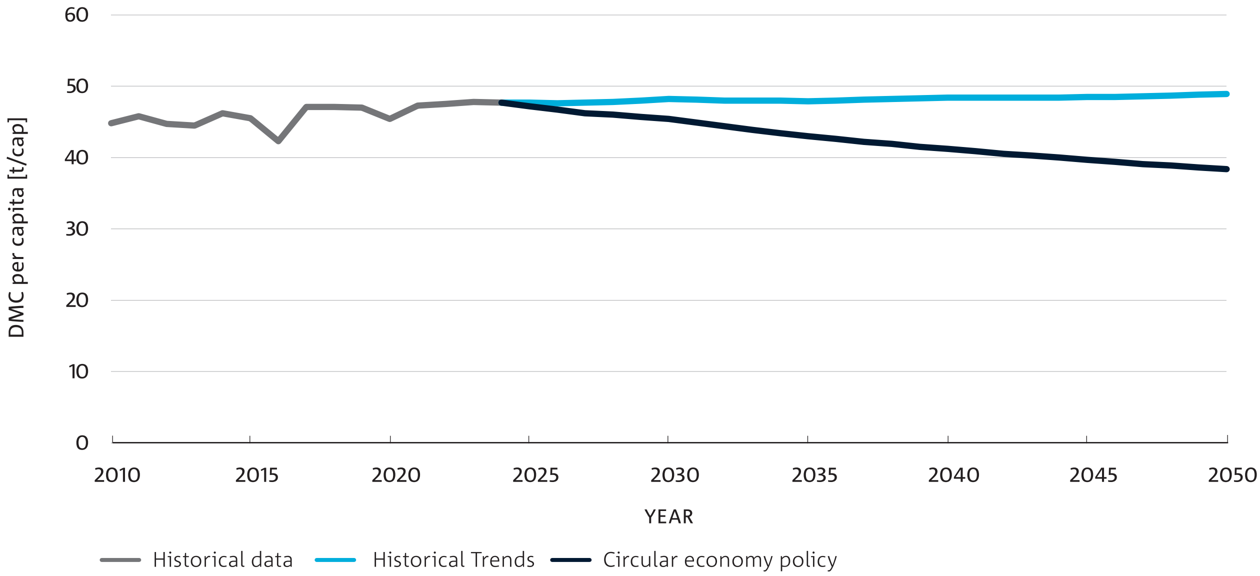


Figure 6 Australia's per capita domestic material consumption 2010-2050.

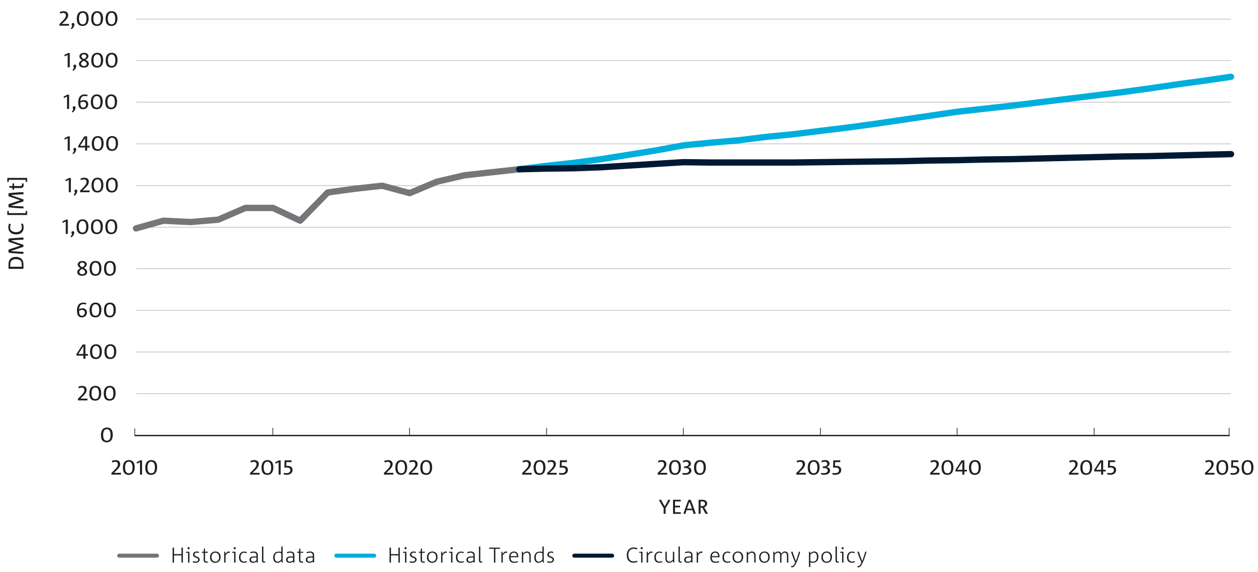


Figure 7 Australia's domestic material consumption 2010-2050. The figure covers historical data (2010-2024) and two scenarios (2024-2050).

Figure 8 presents the domestic material consumption composition by four material categories for the two scenarios analysed. Figure 8A shows the composition under Historical Trends, while Figure 8B depicts the Circular Economy Policy scenario. The totals correspond to those shown in Figure 6. Under Historical Trends, metal ores represent the largest flow, with a cumulative total of 13.9 billion tonnes for 2024-2050. Similarly, the Circular Economy Policy scenario also shows metal ores as the largest cumulative flow, totalling 11.9 billion tonnes for the same period. However, the most intriguing aspect is the comparison of the differences between the two scenarios, which we explore in Figure 9.

Figure 9 compares the differences between the Historical Trends and Circular Economy Policy scenarios, focusing on material savings under the Circular Economy Policy scenario compared to continuing current material use trends. The Circular Economy Policy scenario shows progressively greater savings, culminating in 22% fewer materials used by 2050 than the Historical Trends scenario. This 22% reduction equates to 372 million tonnes of material savings, predominantly in metal ores and biomass. Notably, the fossil fuel category sees the most significant reduction at 25%, driven by decarbonisation efforts, marking the steepest change across all material categories. Conversely, the non-metallic mineral category experiences the slowest decline at 18%. Despite this relatively smaller percentage, the substantial share of non-metallic minerals in the economy means this reduction translates to a net saving of 89 million tonnes.

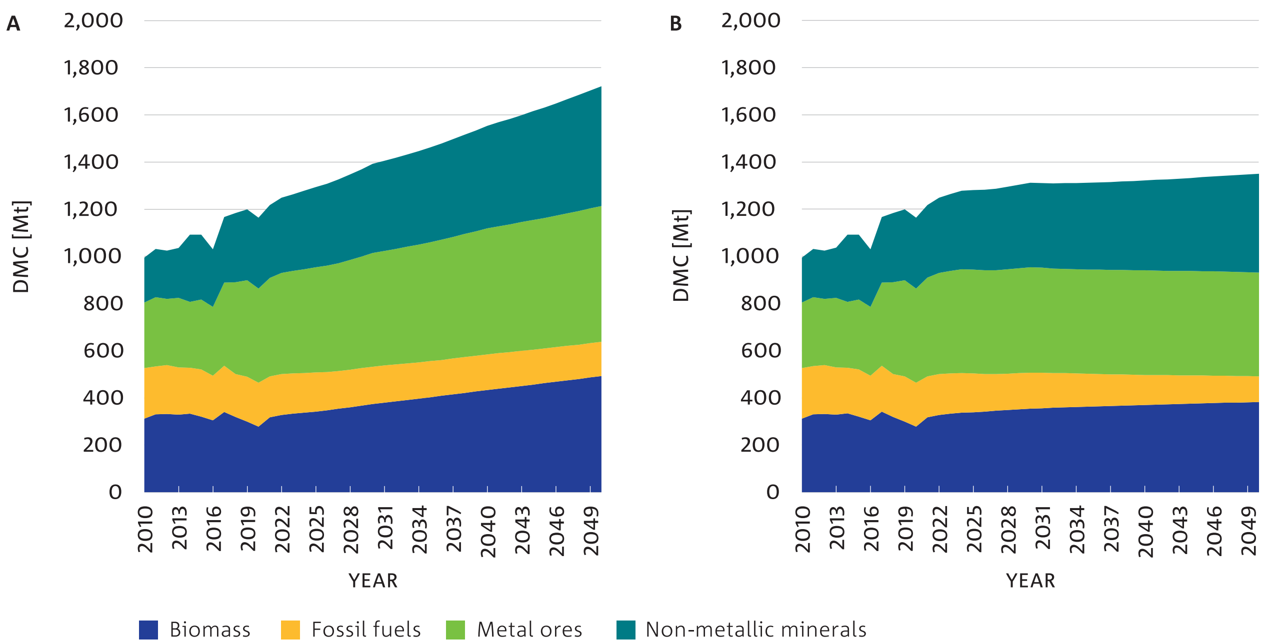


Figure 8 Composition of Australia's domestic material consumption for two different scenarios 2010-2050. A: Historical Trends; B: Circular Economy Policy

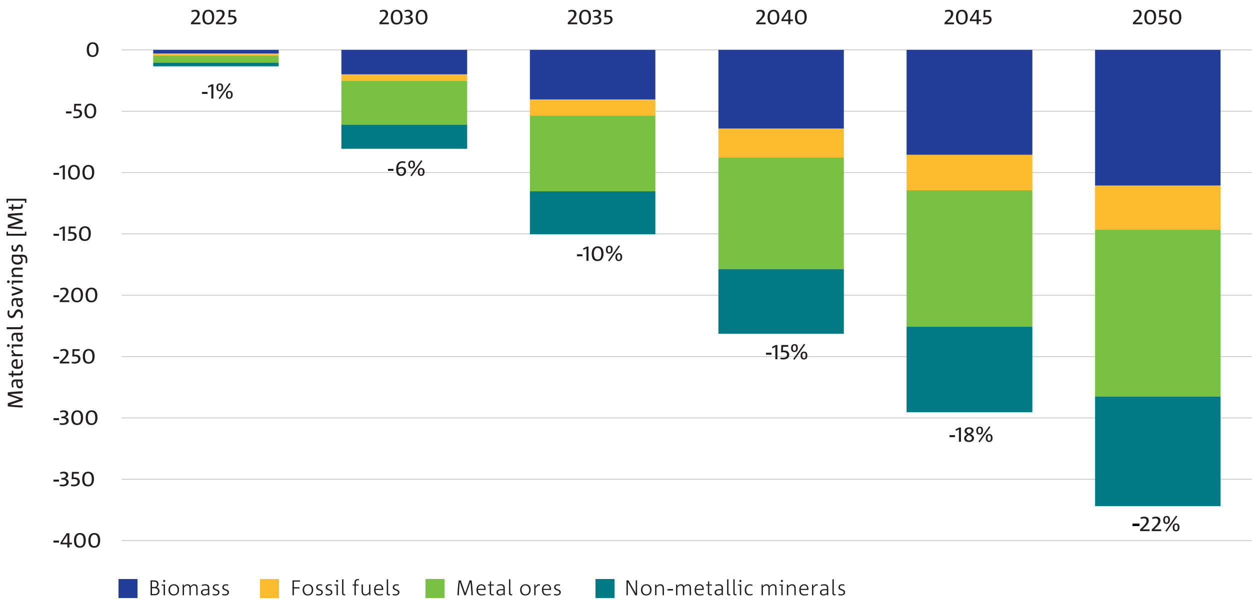


Figure 9 Changes in Australia's domestic material consumption between the Historical Trends scenario and the Circular Economy Policy scenario in 2025, 2030, 2035, 2040, 2045, and 2050.

4.3 Material productivity

Material productivity measures how much gross domestic product is generated for each kilogram of domestic material consumption (DMC). This high-level indicator is useful because it compares economic growth with the use of physical resources within a nation's territory, which, as previously mentioned, are always associated with some environmental impact. Ideally, we would like to see an increasing trend in material productivity because it indicates that, over time, more wealth is produced with each unit of materials used. To obtain meaningful results, we use constant dollars, which means that inflation is accounted for and does not artificially inflate material productivity. We note that we report our results in constant 2015 U.S. dollars to enable comparison with other countries, as is often done in material productivity analyses.

We explore Australia's material productivity in Figure 10. Historically, Australia's material productivity has slowly moved up. It started at $1.19 per kilogram in 2010 and reached $1.27 per kilogram in 2024. From this point, both scenarios calculated a progressive increase, albeit at two different rates. The Historical Trends scenario grows by $0.014 per year and reaches $1.63 per kilogram in 2050. The Circular Economy Policy scenario, on the other hand, grows by $0.032 per year, delivering a material productivity of $2.11/kg in 2050.

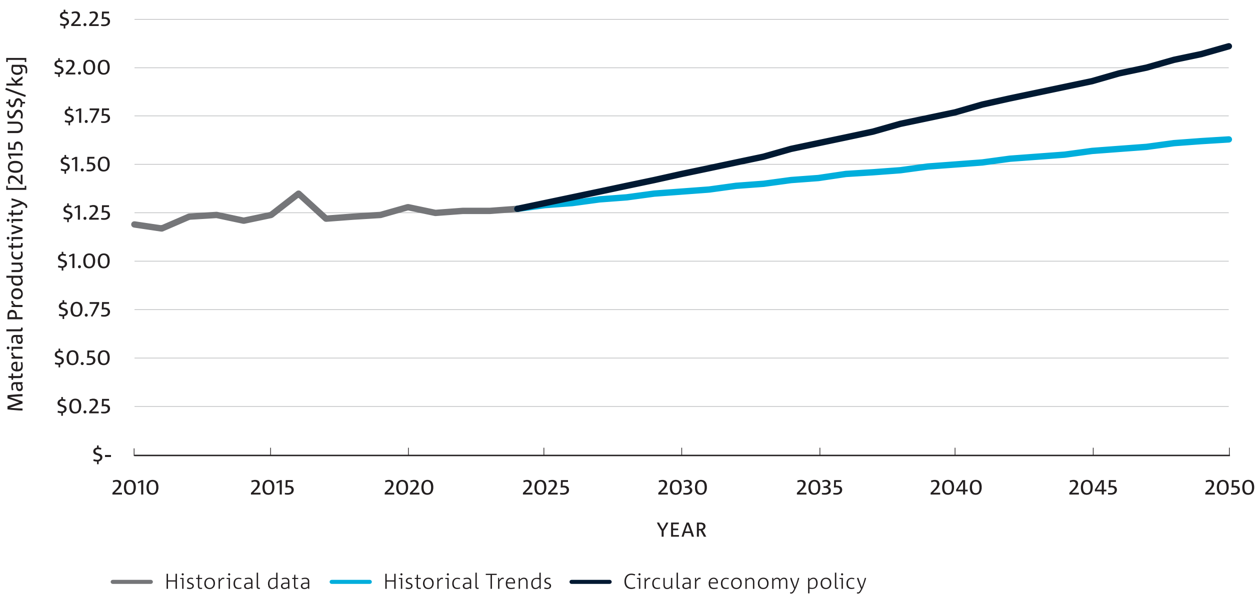


Figure 10 Australia's material productivity 2010-2050.

4.4 Waste generation

Waste is one of the headline indicators present in the Measuring What Matters framework under the "Resource Use and Waste Generation" topic (Australian Treasury, 2024). Currently, this indicator reports the "Proportion of waste recovered for reuse, recycling, or energy." In this and the following sections, we offer additional waste information to better frame our understanding of Australia's waste generation and management.

We present in Figure 11 Australia's total waste generation from 2010 to 2050 (note that with total waste, we include municipal, industrial, and mining waste). Available historical data cover 2010-2021, which are then followed by the two scenarios Historical Trends and Circular Economy Policy. Historical data display that, in 2010, Australia generated 381 million tonnes of waste. Waste generation grew steadily, reaching 696 million tonnes in 2021. There is a dip in waste generation in 2019, likely linked to the global pandemic and appearing in 2019 because of Australia's reporting frame.

While the dip in waste generation has most likely happened in the first half of 2020, the waste generation reported by the Blue Environment report goes from July 1st to June 30th, which aligns with Australia's fiscal year reporting.

Moving forward, the two scenarios show continuous growth of the overall waste generation. The Historical Trends scenario reaches 1,117 million tonnes in 2050, while the Circular Economy Policy scenario reaches 866 million tonnes. In both cases, the average yearly increase in waste production decreases slightly. At the beginning of our projections, the Historical Trends gains over 20 million tonnes in a single year, while at the end, this growth is reduced to 13 million tonnes. The Circular Economy Policy scenario exhibits the same trend at a reduced rate. The initial addition to the generated waste is 12 million tonnes, while the final is 3 million tonnes. This stark reduction in waste generated in the most sustainable of the two scenarios is linked to both dematerialisation efforts and a general extension of product lifetimes.

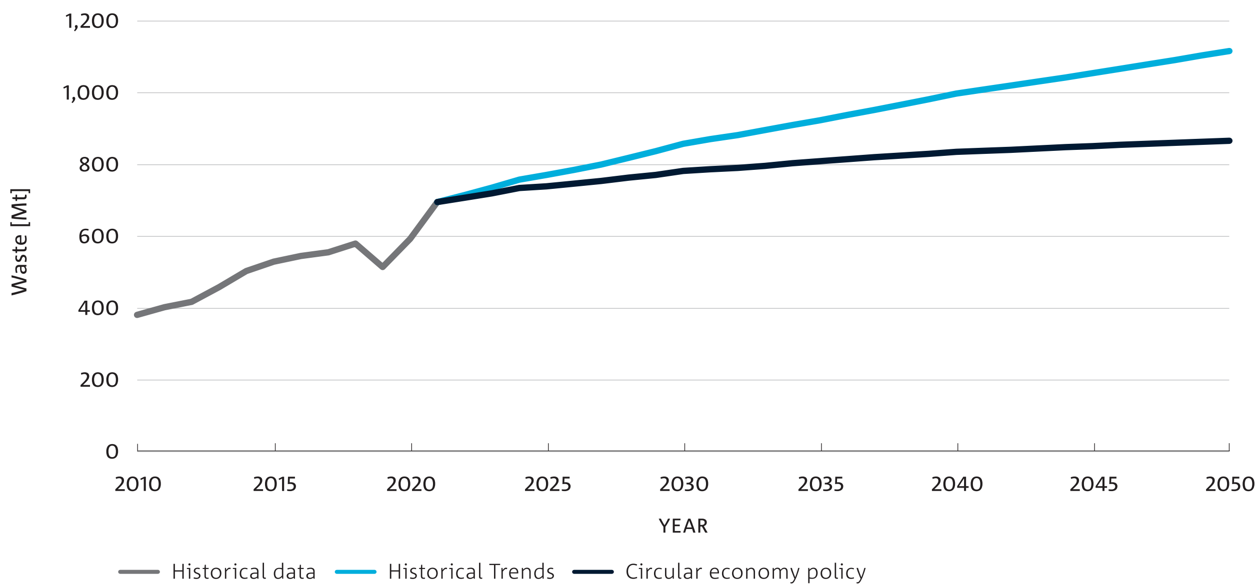


Figure 11 Australia's total waste generation from 2010 to 2050.

It is interesting to observe the opposing trends in waste generation between the two scenarios when we normalise them by population (Figure 12). Historically, per capita waste generation has increased from 17 t/cap in 2010 to 27 t/cap in 2021. These values correspond to a compound annual growth rate of 4.2% over 11 years. Moving forward, the two scenarios envision two diverging trajectories. The Historical Trends scenario displays a continuous growth in the waste generated by each Australian person, reaching 32 tonnes in 2050. The Circular Economy Policy scenario, on the other hand, foresees a slow but progressive reduction, with waste production decreasing below 25 t/cap by 2050. Once again, this result is linked to dematerialisation policies and increased product lifetimes, which include reuse.

In Figure 13, we compare the waste composition between the two scenarios, similar to what we reported for the domestic material consumption in Figure 8. It is important to keep in mind that this figure shows the split of solid waste into four material categories. Thus, it does not include other outputs such as air or water emissions.

It is evident that mining waste makes up most of Australia's overall solid waste. It is 88% of all the waste generated in the Historical Trends scenario and 87% in the Circular Economy Policy. The other three waste categories are evenly split, at least when compared with waste derived from mining activities. In both scenarios, non-metallic minerals make up 5-6% of all waste, biomass is around 4%, and fossil fuels make up some 3%. This result clearly indicates that, in terms of sheer mass, mining waste is where most of the waste reduction efforts might be concentrated.

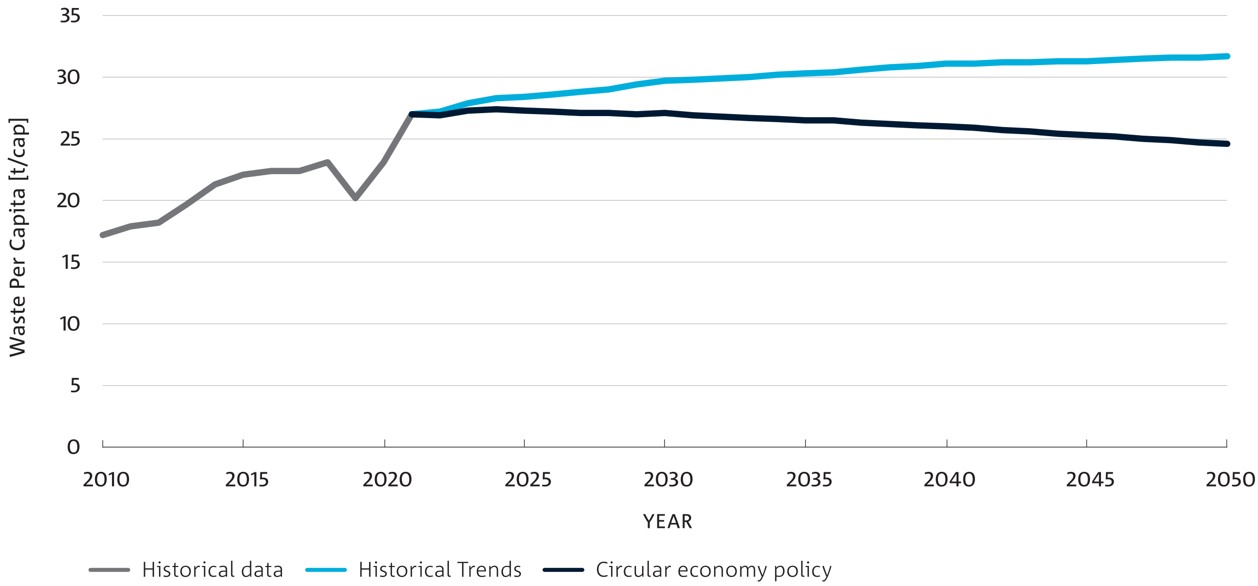


Figure 12 Australia's total waste generation per capita from 2010 to 2050.

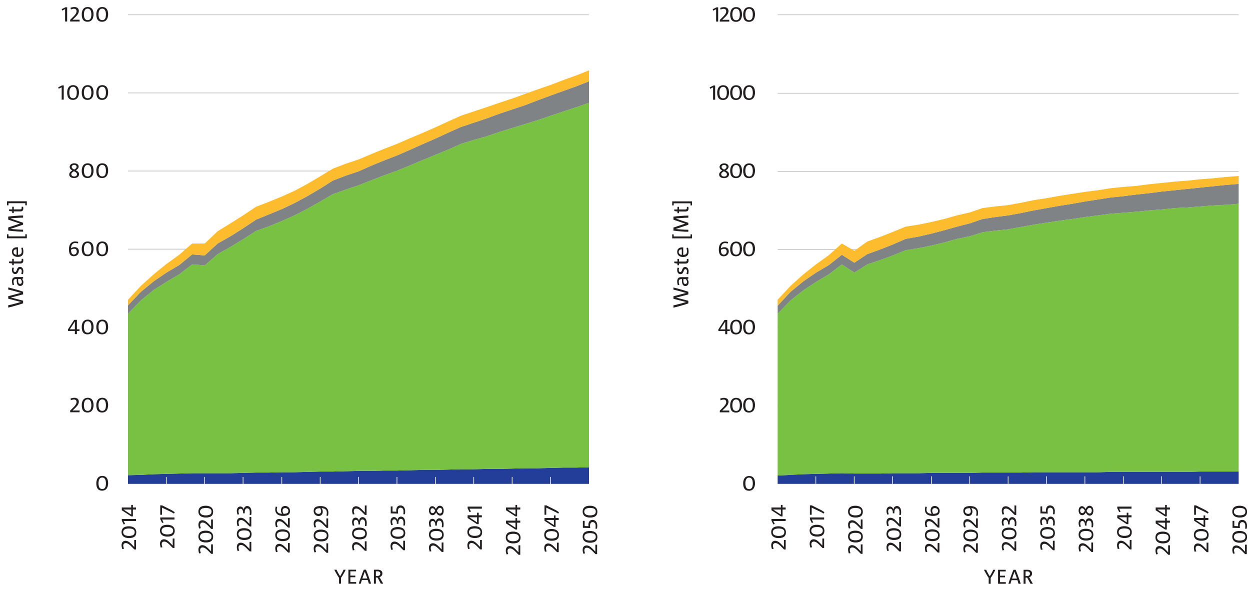


Figure 13 Australia's waste generation by material type for two scenarios from 2014 to 2050. A: Historical Trends; B: Circular Economy Policy.

Because mining waste is so dominant in the overall waste generation figures (cf. Figure 13), we replot data on waste generation, excluding it (Figure 14). In other words, we show here the sum of municipal, industrial, construction and demolition waste (the sum of which is labelled "core waste"), and ash recovered from power plants. Looking at historical data, core waste and ash tallied between 65 and 76 million tonnes and, after an initial plateau, exhibited a generally growing trend. The Historical Trends scenario grows steadily from 76 million tonnes in 2021 to 100 million tonnes in 2050, adding, on average, an additional 800 thousand tonnes every year over the projection period. The Circular Economy Policy scenario is flat. It starts at 76 million tonnes in 2021 and ends at 78 million tonnes in 2050, with an average annual increase in waste generation of only 100 thousand tonnes, or 92% less than the Historical Trends scenario. We see, once again, that circular economy policies that foster material reuse and reduction can greatly contribute to minimising core waste generation.

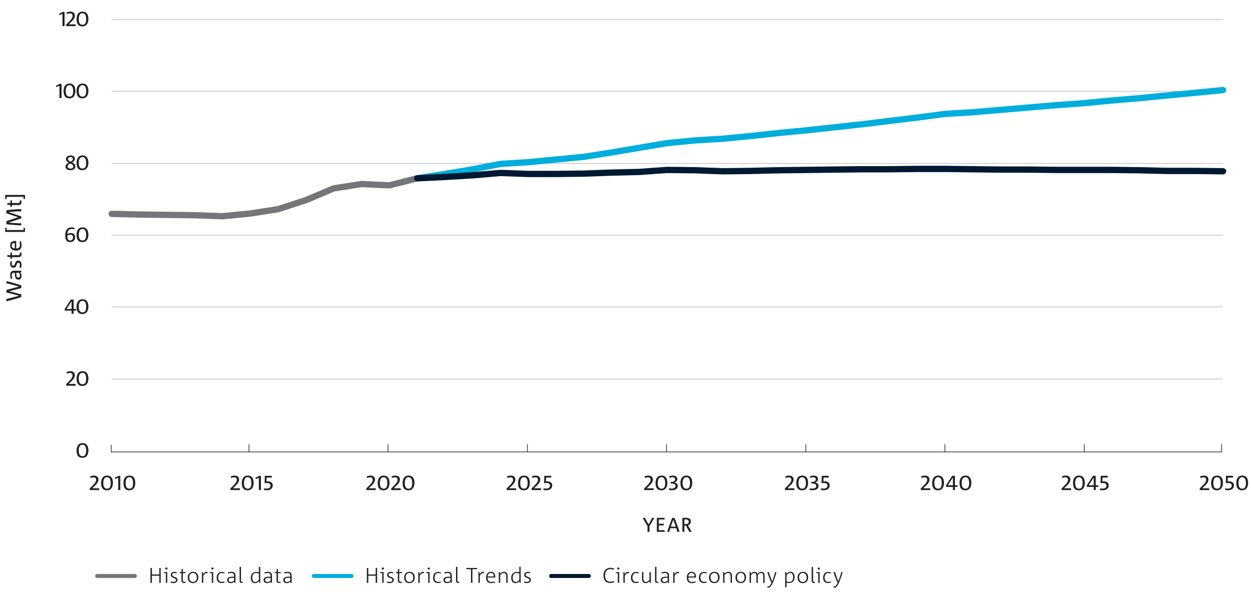


Figure 14 Australia's core waste plus ash generation 2010-2050.

4.5 Recycling rates and recycled waste

In this section, we explore how two different recycling rates affect the mass of recycling waste and the flow of materials to landfills. Figure 15 displays past and modelled recycling rates. The historical rate indicates a slow increase over 2010-2021. In fact, it went from 49% to 60%. Moving forward, the Historical Trends scenario projects the historical data forward. It envisions slow but steady progress, which will reach 63% by 2050. In the Circular Economy Policy scenario, we adopt the ambitious recycling targets of Australia's National Waste Policy Action Plan, which aims to recycle or reuse 80% of its waste by 2030 (Australian Department of Climate Change, 2019). We then taper off this increase to a recycling rate of 90%, which is reached around 2035. The Circular Economy Policy recycling rate is very ambitious, but we chose it to explore how such a high recycling rate influences all subsequent indicators: recycled waste, waste-to-landfill, and the circularity rate.

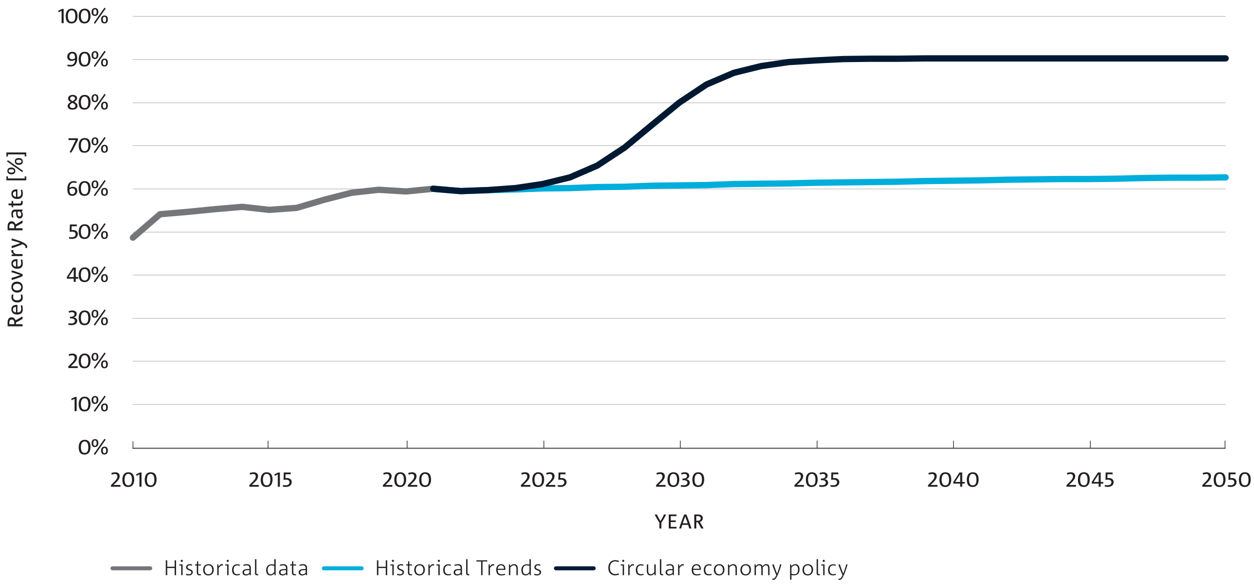


Figure 15 Australia's core waste and ash recycling rates 2010-2050 for two scenarios.

The dramatic change in recycling displayed in Figure 15 results in vastly different amounts of waste sent to landfills (Figure 16). From a historical perspective, we found a steep decrease in the waste sent to landfill between 2010 (34 million tonnes) and 2011 (30 million tonnes). Since then, this number has stayed stable around the 30 million tonnes mark. Moving forward, the Historical Trends scenario sees a progressive increase in waste sent to landfill, mostly because a fairly steady recycling rate (see Figure 15) is paired with an increasing waste generation (cf. Figure 14). The Circular Economy Policy scenario envisions a very different future, where waste sent to landfill dramatically decreases to 8 million tonnes around 2040. The practically constant line between 2040 and 2050 happens because the constant recycling rate is paired with an almost constant total waste generation. It is important to emphasise that this result stems from our choice of the recycling rate curve, which, in the case of the Circular Economy Policy scenario, matches the target of 80% end-of-life recycling rate by 2030.

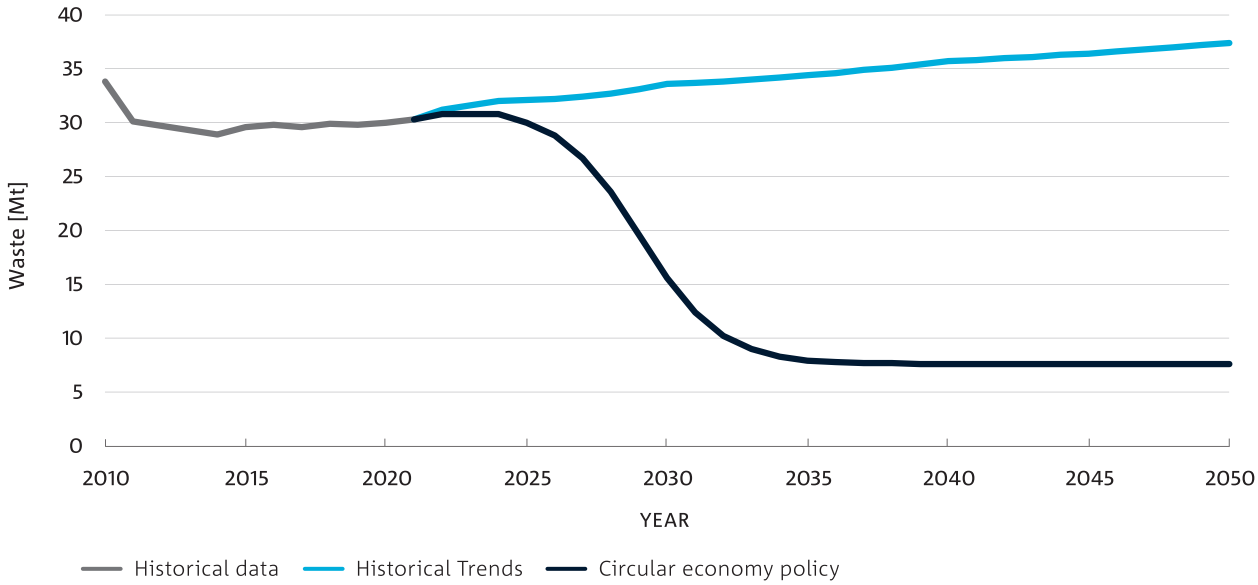


Figure 16 Australia's core waste and ash sent to landfill 2010-2050.

We show in Figure 17 the mass of recycled waste, which is complementary to Figure 16, in the sense that the sum of these two figures results in Figure 14. Historical data show a general upward trend. In 2010, Australia recycled 32 million tonnes of materials. Eleven years later, this number was 45 million tonnes. From there, both scenarios indicate a growth in the mass of recycled waste. From 2026 onwards, the Circular Economy Policy scenario outpaces the Historical Trends. In fact, the Circular Economy Policy scenario reaches 71 million tonnes of recycled materials in 2037 and plateaus around that level. The Historical Trends scenario has slow but constant growth for the whole duration of our analysis. In fact, it reaches 63 million tonnes of recycled materials in 2050. This growth happens because, in spite of a nearly constant end-of-life recycling rate of 63%, the overall generate waste increases, thus resulting in a constantly increasing flow of recycled materials.

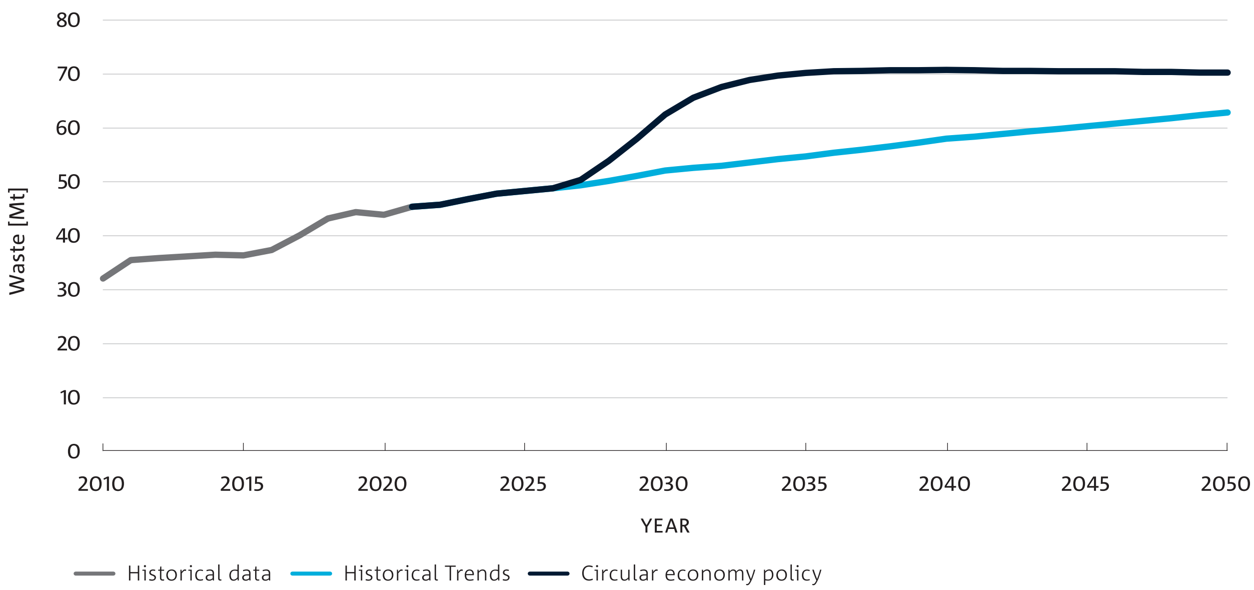


Figure 17 Australia's recycled waste from core waste and ash 2010-2050.

4.6 Circularity rate

The circularity rate is a high-level measure of how much of the material we manage in a year is returned to another use in the economy; in other words, it accounts for the share of secondary materials in overall materials management (Figure 18). It measures recycling as a share of DMC. Over the last decade, Australia's circularity rate has been persistently at around 4%. Continuing Historical Trends with no additional policy ambition would maintain this low level of circularity all the way to 2050. This unwavering circularity rate happens because of a combination of trends, which include an increasing DMC and the recycling rate plateauing under 65%.

The Circular Economy Policy scenario, because of its more ambitious recycling targets—assuming they can be achieved—takes Australia's circularity rate to 6%. It plateaus around this mark because the waste streams that are targeted by the recycling effort are only the core waste and ash, which are relatively small compared with the overall waste, i.e., including mining waste. As an example, if we were progressively to reuse 10% of mining waste to replace virgin construction aggregates, it would take the circularity rate to 12%. While reusing 10% of mining waste as construction aggregates might seem like a modest goal, it may be difficult to achieve. First, the low unit value of construction aggregates makes long-distance transportation costly, rendering them uncompetitive with locally sourced materials. Additionally, construction aggregates typically need to be chemically stable and physically durable, which is often not the case for most mining wastes, especially metalliferous mine tailings. In-depth, case-by-case analysis will be needed to assess the potential for reusing mining waste and to identify economically viable opportunities.

There are similar opportunities for biological end-of-life materials that would further improve Australia's circularity rate. These opportunities can include composting and organic waste recycling, biogas and bioenergy production, and, more generally, circular agriculture practices. For example, implementing regenerative farming practices that prioritise waste reduction, soil health, and nutrient cycling can enhance the sustainability of Australia's agricultural sector.

It is useful to compare the circularity rate to circularity potential, which denotes the share of materials that can circulate assuming all technological options are realised. The potential was evaluated at 20% circularity in a previous study (Schandl et al., 2019).

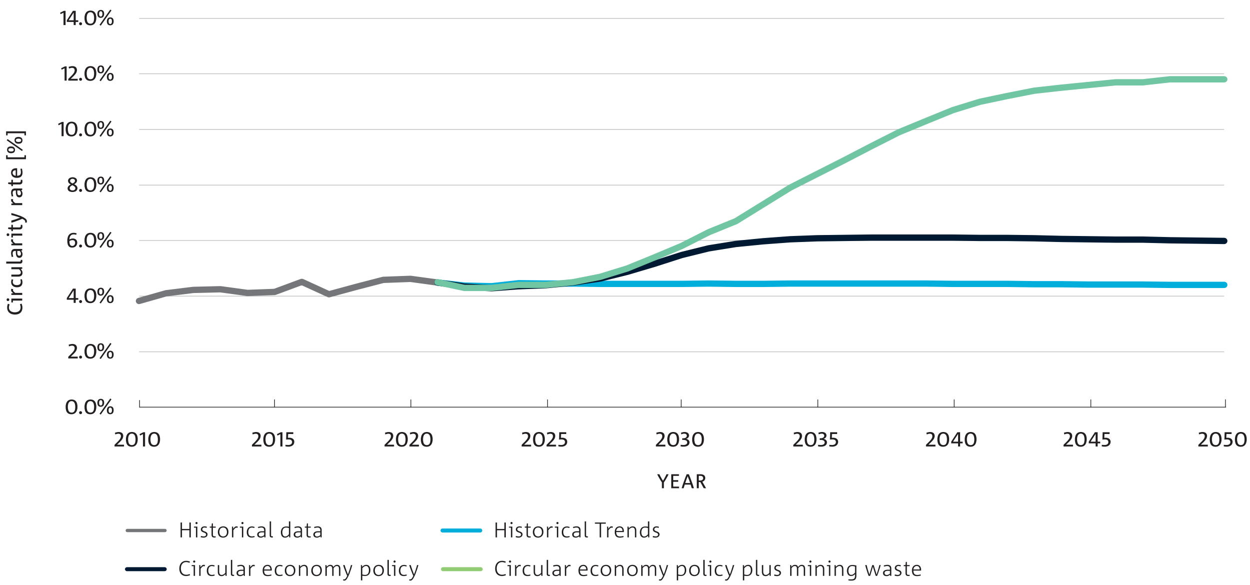


Figure 18 Australia's historical circularity rate (2010-2021) plus three alternative circularity rates (2021-2050).

4.7 Greenhouse gas abatement and economic implications

Several international studies have demonstrated that resource efficiency and circular economy initiatives can significantly contribute to greenhouse gas (GHG) abatement, leading many countries to include circular economy strategies in their net zero pathways and Nationally Determined Contributions' for GHG emission reduction (UNEP, 2017). The resource efficiency package highlighted in the Global Resources Outlook suggests that by 2050 23% of GHG emission reductions could stem from circular economy policy initiatives, with supply-side improvements in resource extraction and manufacturing contributing 16% and demand-side changes accounting for 7% of these reductions respectively. This result underscores the potential for circular economy policy to play a critical role in achieving Australia's net zero goals.

Moreover, resource efficiency and circular economy measures appear to be economically advantageous, with projections indicating that the resource efficiency scenario could generate an additional US$9 billion in 2015 prices (corresponding to US$315 per capita) by 2030 and an additional US$48 billion in 2015 prices (US$1,357 per capita) by 2050, compared to a continuation of historical trends.

In the short term, for the decade to 2035, doubling Australia's circularity has a potential economic payoff of $15 billion, reduces greenhouse gas emissions by 14%, and allows diversion of 26 million tonnes of materials from landfill (or pollution) each year.

The effectiveness and economic impacts of these measures, however, depend heavily on the calibration of price changes in the model and the detailed design and implementation of the corresponding policies. Nonetheless, the current results offer a reasonable estimate of the potential abatement and economic benefits based on internationally recognised benchmarks.

It is important to note that the current scenario modelling does not capture the full potential of circular economy policies, including more ambitious resource recovery and recycling efforts, which could result in even greater reductions in resource use compared to historical trends. Future modelling and outlooks should incorporate the contribution of circular economy policies to Australia's achievement of its Nationally Determined Contribution targets.

5 Discussion

In this report, we explored two alternative futures for Australia's material flows: waste generation, recycling, and circularity. One is a continuation of current trends without additional policy effort, and the other is based on implementing ambitious circular economy policies. The core results of these two scenarios can be summarised as follows:

The **Historical Trends** scenario shows:

- A steady increase in domestic material consumption
- A similarly steady growth in the material footprint
- A moderate increase in material productivity
- Steady growth in waste generation
- Increasing amounts of waste sent to landfill
- A constant circularity rate of around 4.4%

The **Circular Economy Policy** scenario indicates:

- Plateauing domestic material consumption
- A steady material footprint
- High growth in material productivity
- Slow growth in waste generation
- A substantial decrease in waste sent to landfill
- A circularity rate that caps around 6%

Given that large flows of mining waste dominate Australia's waste profile, we propose further exploring the potential for progressive adoption of mining waste as loose aggregate in construction projects. This initiative could boost the circularity rate to nearly 12%. The diversion of biological materials from landfills and the utilisation of agricultural waste are other high-impact pathways that can improve Australia's circularity.

In addition, the circular economy also contributes to Greenhouse Gas (GHG) abatement and creates positive economic outcomes. One-fifth of Australia's GHG abatement can be achieved by circular economy measures, which will add US$ 48 billion in 2015 prices to Australia's GDP by 2050.

5.1 Evaluation of Australia's circular economy goals and targets

The two scenarios can inform a set of ambitious targets for Australia's circular economy. The modelling explored if **doubling Australia's circularity rate** by 2035 would be an ambitious but achievable objective. The modelling shows that achieving this will require substantial investment beyond traditional recycling practices, extending to the recycling of mining waste and biological end-of-life materials such as biosolids. As an overarching long-term target, maintaining the goal of doubling circularity is recommended despite its ambitious nature.

Modelling suggests **reducing the material footprint** in absolute terms is unfeasible given the growing population and the current economic and trade settings. A realistic target could focus on reducing the per capita material footprint, aiming for a 10% reduction by 2035, which our modelling suggests will be achievable. This reduction in Australia's material footprint will mean that our average environmental pressure and impact will be reduced, creating a more responsible economic pathway focussing on long-term economic and environmental objectives.

Modelling suggests that an ambitious but achievable target for **increasing material productivity** could be a 30% improvement by 2035. Such a rise in material productivity will have positive economic impacts and contribute to Australia's economic growth.

Achieving an 80% **reduction in waste to landfill**, which involves the safe recovery of core waste, presents significant difficulties due to diminishing returns. This goal would require considerable additional investment in sorting and recovery facilities and the development of strong domestic and export markets for secondary materials. While achieving very high recycling rates and reducing landfills to minimal levels is theoretically possible, the eco-efficiency of such efforts can quickly become negative. This negative result is due to the significant material and energy inputs that may be needed to make the recovered materials economically viable. Determining which recycling activities are truly eco-efficient often requires detailed, location- and material-specific life cycle assessments (LCA).

Table 2 Summary of five policy goals and their likelihood of being achieved by 2030.

POLICY GOAL	2020	2030 HISTORICAL TRENDS	2030 CIRCULAR ECONOMY POLICY	GOAL LIKELIHOOD
Double the circularity of the economy	4.6%	4.5%	5.5% - 5.8%	Unlikely
Shrink material footprint	802.6 million tonnes	909.1 million tonnes +13.3%	848 million tonnes +5.7%	Unachievable, replace by stabilise material footprint
Shrink per-capita material footprint	31.5 tonnes	31.3 tonnes -0.6%	29.2 tonnes -7.3%	Achievable
Lift material productivity	1.28 US$/kg	1.36 US$/kg +6.3%	1.45 US$/kg +13.3%	Achievable
Safely recover 80% of materials	59%	61%	80% (modelled based on target)	Hard to achieve and requires additional investment into recovery facilities and end markets

We here report two additional tables similar to Table 2 for 2035 and 2050.

Table 3 Summary of five policy goals and their likelihood of being achieved by 2035.

POLICY GOAL	2020	2035 HISTORICAL TRENDS	2035 CIRCULAR ECONOMY POLICY	GOAL LIKELIHOOD
Double the circularity of the economy	4.6%	4.5%	6.1% - 8.4%	Achievable with additional effort beyond recycling of core waste
Shrink material footprint	802.6 million tonnes	958.4 million tonnes +19.4%	848.8 million tonnes +5.8%	Unachievable, replace by stabilise material footprint
Shrink per-capita material footprint	31.5 tonnes	31.3 tonnes -0.6%	27.7 tonnes -12.1%	Achievable
Lift material productivity	1.28 US$/kg	1.43 US$/kg +11.7%	1.61 US$/kg +25.8%	Achievable
Safely recover 80% of materials	59%	61%	80% (modelled based on target)	Hard to achieve and requires additional investment into recovery facilities and end markets

Table 4 Summary of five policy goals and their likelihood of being achieved by 2050.

POLICY GOAL	2020	2050 HISTORICAL TRENDS	2050 CIRCULAR ECONOMY POLICY	GOAL LIKELIHOOD
Double the circularity of the economy	4.6%	4.4%	6.0% - 11.8%	Achievable with effort from the mining waste
Shrink material footprint	802.6 million tonnes	1,159.4 million tonnes +44.4%	890.2 million tonnes +10.9%	Unachievable, replace by stabilise material footprint
Shrink per-capita material footprint	31.5 tonnes	32.8 tonnes +4.1%	25.2 tonnes -20.0%	Achievable
Lift material productivity	1.28 US$/kg	1.63 US$/kg +27.3%	2.11 US$/kg +64.8%	Achievable
Safely recover 80% of materials	59%	63%	80% (modelled based on target)	Hard to achieve and requires additional investment into recovery facilities and end markets

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Appendix: Sectoral circular economy opportunities

Australia's current circularity rate of 3.7% (Miatto et al., 2024) appears low compared with the global average of 7.2%. However, there are four main areas of improvement: manufacturing, food and agriculture, the built environment, and the mineral resources industries.

Manufacturing plays a pivotal role in enabling the circular economy because it can alter the quality and quantity of materials it chooses to use as inputs, thus promoting resource efficiency. It is important to highlight that remanufacturing, a subset of all manufacturing processes, falls within this domain. The design stage of a product determines up to 80% of its environmental impact. Therefore, manufacturing designed for waste minimisation and material recovery creates a solid foundation where products are fabricated with circular economy principles in mind. This approach ensures that production waste materials can be easily reclaimed, repurposed, or reprocessed, thereby reducing both waste disposal and the need for primary materials. Remanufacturing extends the lifecycle of products by restoring worn items to near-new condition, preserving the materials embedded in the original manufacturing process. It reduces the materials needed for new products and, in most cases, cuts down energy use and emissions associated with producing brand-new products. In a circular economy, (re)manufacturing fosters a more tightly looped system that emphasises longevity, reduces environmental pressures, and supports sustainable resource use.

The food and agriculture sector is responsible for about a quarter of Australia's material footprint (Miatto et al., 2024). Additionally, Australia generates approximately 7.6 million tonnes of food waste annually. Food packaging, largely reliant on single-use plastics, has a global recycling rate of around 6%. For these reasons, focusing on food and agriculture can generate significant gains in achieving a circular economy. This vast sector covers everything from crop production to animal husbandry, food processing, distribution, and disposal, each with different challenges and opportunities to close material loops, enhance resource efficiency, and minimise waste. Waste can be reduced in the food and agriculture sector through various activities, such as precision farming, which uses advanced technology like drones to collect real-time information on crop health and soil conditions or selective harvesting. Additionally, organic waste composting can reduce the need for synthetic fertilisers.

The built environment uses over 50% of all materials extracted annually and is responsible for over one-quarter of all global greenhouse gas emissions (Krausmann et al., 2017; Su et al., 2023). In the Australian context, housing and mobility use 53% of its overall material footprint (Miatto et al., 2024). Because of these large material and carbon shares, they are often the target of analysis by scholars, as even small percentage reductions can make quite a big difference. Moreover, in 2020–21, construction and demolition activities generated 29 Mt of waste, making it the largest and fastest-growing source of materials processed in waste management systems (Blue Environment, 2022).

There are several strategies one can employ to reduce the impact of the built environment on material extraction, energy use, and emissions. First and foremost, there is better design, in the sense that it is possible to create buildings that use less material, energy, and make a better use of space (González-Torres et al., 2022). The average floorspace of Australian homes is the world's largest, which translates to high material demand and more energy needed to heat/cool the building (Miatto et al., 2023). Second is the inclusion of secondary materials, which can offset the demand for virgin resources and often have lower environmental impacts than primary materials (Nicholson & Miatto, 2024). A third option is to facilitate building refurbishment rather than demolish-and-rebuild, as in almost all cases, the former has smaller impacts than the latter (Pittau et al., 2020; Power, 2008).

The mining sector is critical in supplying metals in increasingly high demand globally (Schandl et al., 2018). Metals are essential for myriad applications and often lack viable substitutes (Kosai & Yamasue, 2019). In Australia, in particular, the mining sector is responsible for large waste flows. Past research has estimated that, in 2019, the Australian mining sector generated 371 Mt of gangue and tailings (Miatto et al., 2024). Addressing the environmental impacts associated with the extraction of virgin resources requires exploring several mitigation strategies.

First, the mining sector could more broadly adopt the Environmental, Social, and Governance (ESG) framework. ESG principles guide responsible investment by prioritising projects that minimise environmental impact while maximising social benefits (Roca & Searcy, 2012). This approach can lead to more sustainable mining practices. Second, repurposing spent electric vehicle (EV) batteries for stationary domestic energy storage represents a promising avenue. Modelling by CSIRO has indicated that in the Australian context, large scale adoption of EVs would lead over time to being able to meet grid storage requirements of renewables-based electricity grid from second-life EV batteries alone (West et al., 2021).

Many EVs are now reaching their end of life, and batteries are often processed in recycling facilities to extract critical minerals such as cobalt and nickel (Gaines, 2014; Harper et al., 2019). Although the performance of these batteries might be unsuitable for such a demanding application as moving a vehicle, they often remain suitable for less demanding applications, such as home energy storage (Shahjalal et al., 2022). Third, much of the mining waste sits unutilised near mining sites. When managed in an environmentally sound manner, this waste could be repurposed as loose aggregate or ballast in civil engineering projects, contributing to resource efficiency and waste reduction. We explore this third option in our circularity rate assessment in §4.6.

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