Australia's National Science Agency

Australian material flow analysis to progress to a circular economy

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Citation

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Important disclaimer

Sustainable Communities and Waste

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Essential glossary

Circularity rate: the share of secondary materials used within a national economy against domestic material consumption. This number, mathematically, can vary between 0 and 1. A value of 0 indicates that no recycled materials were present in the economy. Conversely, a value of 1 indicates that the economy functioned using only recycled materials.

Domestic extraction: the mass of materials sourced from Australia's territorial boundaries.

Domestic material consumption: the balance of domestic material extraction plus imports minus exports.

Domestic material input: the sum of domestic extraction and imports.

Domestic processed output: the mass of all the materials that flow from the socioeconomic sphere of a country back to the environment. These flows include greenhouse gas emissions, waste disposed to landfill, seeds and fertilisers used in agriculture, and unregulated emissions to water. Note that, by definition, domestic processed output does not include water flows.

Exports: the mass of materials exported to other countries and territories.

Imports: the mass of materials imported from other countries and territories.

Material footprint exports: exports created by allocating the whole burden of material extraction to the final user, even if part of the burden never physically leaves the country of origin. Material footprint exports are generally larger than physical exports because they allocate the whole extracted mass to the final user, even if resources and products are processed and produced domestically. This category is also called raw material equivalent exports.

Material footprint imports: imports created by allocating the whole burden of material extraction to the final user, even if part of the burden never physically leaves the country of origin. Material footprint imports are generally larger than physical imports because they allocate the whole extracted mass to the final user, even if the products are processed and produced abroad. This category is also called raw material equivalent imports.

Material footprint: an account that attributes the whole burden of material extraction to the final user, regardless of where this happens.

Material intensity: measurement of the rate between material use and gross domestic product. In other words, it measures how many kilograms of materials are necessary to produce one unit of wealth (e.g., kg/AU$). A low material intensity is desirable, as it indicates that wealth is produced with a small volume of materials.

Raw material equivalent domestic material consumption: see material footprint.

Raw material equivalent exports: see material footprint exports.

Raw material equivalent imports: see material footprint imports.

Executive summary

Material flow accounts establish a link between human consumption patterns and the environment. Hence, they are widely used to inform policymakers about the environmental consequences of human activities. These accounts comprehensively measure extracted and traded materials and the related waste and emissions in one accounting framework. Material flow accounts also provide environmental metrics that allow for early assessment of the environmental implications of socioeconomic activities. Consequently, they can inform policies on resource efficiency, waste minimisation, and greenhouse gas abatement.

This report provides the Australian economy-wide material flows for 2019, the latest year for which we have data at the time of writing. In 2019, Australia extracted and harvested 2,587 Mt (million tonnes) of materials from its territory. These virgin materials were supplemented with 119 Mt of imports and 39 Mt of domestically recycled materials. More than half of these materials were exported to other countries (1,459 Mt). Specifically, exports mainly comprised metal ores (880 Mt) and fossil fuels (480 Mt). Australia's domestic material consumption, i.e., the sum of domestic extraction and imports minus exports, was 1,287 Mt. The domestic material consumption was evenly split between materials used for energetic purposes, chiefly biomass and fossil fuels, and materials used for 'physical' (or structural) purposes, primarily metals and non-metallic minerals. A considerable quota of the domestic material consumption (371 Mt) was mining waste. Australia's domestic processed output, which is the sum of all emissions and waste, accounted for 999 Mt. 471 Mt of these materials were liquid and solid waste, which were dominated by mining waste of 371 Mt. 404 Mt of air emissions came at a close second.

In this report, we also present Australia's material footprint. The material footprint allocates the burden of resource extraction to the final user, regardless of where it occurs. Australia's material footprint imports were 297 Mt, and its material footprint exports were 1,926 Mt. Domestic material extraction is unaffected by this allocation and accounted for 2,587 Mt. The raw material equivalent domestic material consumption was 997 Mt. We allocated these materials to seven systems of provision and discovered that mobility used the most, at 273 Mt, closely followed by housing, 251 Mt. Food was also one of the major systems as it accounted for 215 Mt of materials.

We used the material balance to inform the circularity of the Australian economy, i.e., the share of recycled materials against all materials used in a year. We derived a 2019 circularity rate of 3.7%. Note that if we excluded mining waste from the domestic material consumption indicator (as previously done in Mayer et al. [1] and Miatto et al. [2]), we would obtain a circularity rate of 5.1%. This result marks a modest improvement over the circularity rate of 3.5% measured for 2015 [3]. We calculated the theoretical maximum circularity rate achievable with today's technology to be 32.5%. Moreover, Australia's material intensity, measured as material consumption per unit of wealth, increased from 0.56 to 0.61 kg/AU$ between 2015 and 2019, suggesting that Australia needs more materials to produce each unit of wealth.

This report provides a high-level analysis of the Australian physical economy and facilitates the identification of major areas for the role of policy aimed at promoting sustainable materials management. Material flow accounts now feature prominently in the context of the Sustainable Development Goals, and Australia performs well on three of the proposed indicators. Australia has successfully improved its material footprint resource efficiency, increased its circularity rate, and curbed air emissions. It is notable, however, that the Australian economy operates at a material use level four times the world average. This result, on the one hand, reflects the country's economic structure but, on the other, demonstrates how policy can help address the potentially adverse environmental and human health effects of this material-intensive pattern.

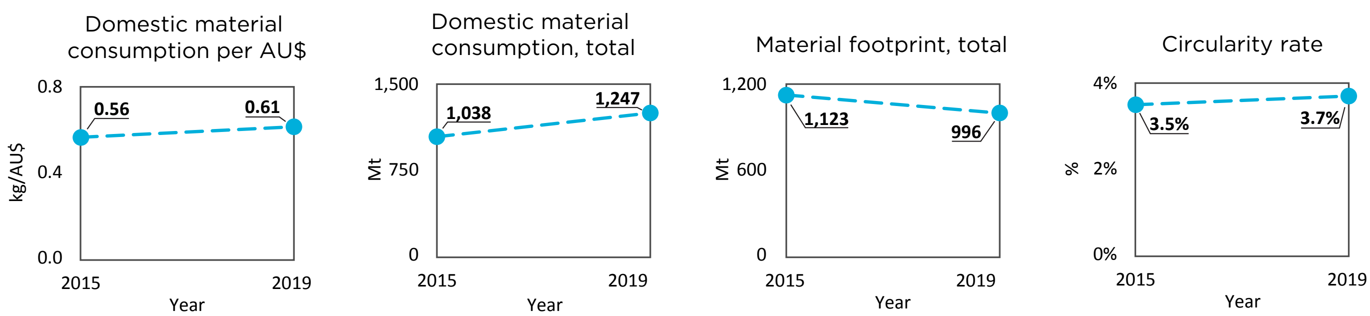


Figure 1 – Domestic material consumption per AU$ (material efficiency), total domestic material consumption, total material footprint, and circularity rate for Australia in 2015 and 2019.

Four key indicators can provide a first assessment of Australia's environmental performance. These headline indicators are used by the United Nations (UN), the Organisation for Economic Co-operation and Development (OECD), the European Commission, and other national and intergovernmental agencies. The four indicators, shown in Figure 1, are Resource Productivity, Domestic Material Consumption, Material Footprint, and the Circularity Rate.

These indicators can be compared over time to show Australia's progress and be compared against other countries to identify best practices and evaluate Australia's performance internationally.

Introduction

The Australian Government is committed to transitioning its national economy toward a more sustainable and resilient system. As part of this commitment, Australia's Environment Ministers have agreed to work in concert with the private sector to foster recycling, design out waste, and aim to achieve a circular economy by 2030 [4]. The circular economy concepts – increasing recycling to offset primary material extraction, material efficiency strategies, 3Rs (Recycle, Reduce, Reuse), and now 10Rs [5] – are not recent discoveries [6]. In fact, they have been around since the 1980s in one form or another [7]. To date, a universal and agreed-upon definition of the circular economy does not exist. In 2017, Kirchherr and colleagues analysed 114 definitions of the circular economy. Interestingly, they found that recycling is commonly cited but appears in only ~80% of the definitions [8]. Kirchherr and colleagues recently revisited these definitions considering the gargantuan number of publications related to the circular economy in the past three years. They now assessed 221 different definitions and found that reuse and recycle remain popular terms in circular economy definitions and that the use of 'macro perspective' has dramatically increased [9].

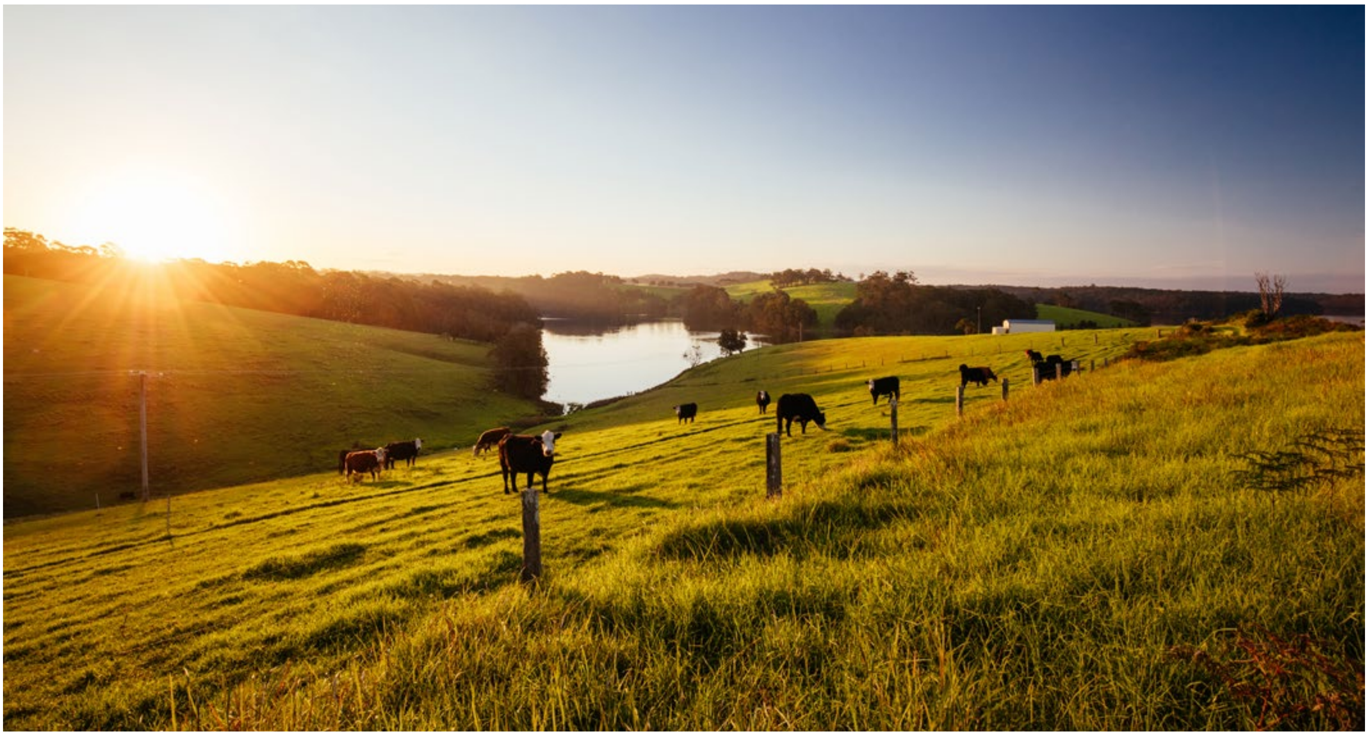
One of the most popular definitions of circular economy is provided by the Ellen MacArthur Foundation, which describes the circular economy with three principles: eliminate waste and pollution, circulate products and materials, and regenerate nature [10]. According to some scientists, despite its qualities, this definition is lacking in terms of economic and social sustainability [11]. Recently, Nobre and Tavares interviewed 44 experts to create a definitive definition of circular economy [12]. The fruit of their work is:

'Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption are efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation.'

Whether this definition will be accepted as the definitive circular economy explanation or whether some other will prevail remains to be seen.

To achieve any circular economy goals, we need, first and foremost, to garner metrics of the current level of circularity. The Circularity Gap Report, issued annually by the Circularity Gap Reporting Initiative, publishes the percentage of secondary materials out of all used annually in the world [13]. In their latest 2023 report, the authors calculated that the current global circularity is 7.2% [14]. In other words, for every 100 kg of resources used, 92.8 kg are virgin materials. This result is a slight improvement over the global circularity of 2005, which was calculated to be 6% [15]. However, the global average tells only one part of the story. Countries significantly differ in their interest and capacity to achieve a circular economy, and national policies can considerably affect a national circularity metric.

Nonetheless, calculating the national circularity metric is a complex feat that needs to consider not only domestic recycling rates but also attempt to estimate the share of secondary materials embedded in imports and exports. Considering this technical challenge, it is unsurprising that national circularity metrics are hard to come by. Of the countries and regions explored by the Circularity Gap Reporting Initiative, the best results have been found in the Netherlands, with a circularity score of 24.5% [16]. At the other end of the spectrum, the Circularity Gap Report Initiative found Scotland, where only 1.3% of materials are recirculated [17]. It is essential to point out that these two countries are the best and worst of a small pool of European countries and are not meant to be interpreted as the extreme cases of the entire world.



The circularity score reported by the Circularity Gap Reporting Initiative measures the secondary materials in an economy, but this is not the only relevant metric in a circular economy. Certain products, such as those used for energy purposes, are inherently linear, as they are irreversibly transformed during their use phase. Such examples include petrol used in vehicles or food used for nourishment. Note that this definition of linearity is based on the material flow analysis framework [18-21]. Other research fields consider biomass a circular material, but if we decided to do so, our account would be incompatible with any other national material flow account so far created, and so would be our circularity metrics. Because of the material flow framework boundaries, some scholars argue that it is essential to create ancillary metrics that focus on those materials that can actually be recovered. The most notable of such metrics is the recycling rate. The recycling rate measures the percentage of end-of-life materials that are recycled. This metric is available for many counties, and the Republic of Korea leads the globe with a domestic rate of 57% [22].

Measuring the circularity gap as a percentage suggests that an economy can be 100% circular. In reality, the economic structure of a country determines the circularity potential, i.e., the total amount of materials that can be expected to be organised in a closed loop, and this potential is well below 100% in all cases. We, therefore, define the circularity gap as the distance between the circularity potential and achieved circularity within a certain economic structure. Countries can engage in two strategies to become more circular: first, to transition their economy to raise the circularity potential through, for instance, investing in renewable energy, long-lived infrastructure, and active mobility. Second, they can also aim to reach the circularity potential by ensuring materials are recovered and reintroduced into the economic process once their first life has been completed.

The challenges of a linear economy

The circular economy agenda can be advanced only through the concerted effort of policymakers, industry partners, and consumers. But why, in the first place, should we aim to achieve a circular economy? Studies that have tracked historical material extraction highlight how the material consumption rate has been increasing over the past decades [23]. Not only material extraction, but the physical accumulation and permanence of materials in our societies grew 20-fold during the 20th century [24]. The current rate of material exploitation appears unsustainable, especially considering that the citizens of many emerging economies are still improving their living standards [25].

Resources are finite. While this notion is generally well understood, traditional economic models treat resources as unlimited. Materials are extracted, processed, and combined to achieve desired set characteristics [26]. Once a product breaks or the owner decides to replace it, the product enters the waste stream, where it is usually landfilled or incinerated. Because of the paucity of secondary materials due to economic and technical complexities, virgin resources are needed to create new products [27]. Resource depletion is not only a source of concern for future resource availability, as it was for fossil fuels [28] and is now for rare earths [29], but is also related to geopolitical tensions [30, 31].

The general tendency to dispose of waste rather than focusing on repair, reuse, and repurpose is responsible for generating substantial waste and pollution [32]. Landfill area progressively increases [33], incineration contributes to greenhouse gas emissions [33], and informal waste disposal poses severe threats to both people and the environment [34]. One of the goals of the Circular Economy is to prevent waste disposal by fostering recycling, which in turn would decrease the mass of materials that ends up being landfilled or incinerated, with obvious benefits to the environment.

Multiple reasons can cause the final disposal of products. The cost of recycling a product might be uneconomical compared with the cost of its virgin counterpart; technical limitations might impede recycling; users cannot or are unwilling to make the effort to properly sort waste or transport it to a suitable recycling location [35]. This squandering of potentially reusable resources can be evaluated as lost economic value, a missed opportunity for cost savings, and a failure to create local jobs. By contrast, a Circular Economy can create positive externalities by creating jobs and cost-saving opportunities for manufacturing companies [36].

In addition, linear economies rely on complex global supply chains. While different materials exhibit different levels of resilience to supply chain disruptions, the heavy interdependence of the current linear economic system exposes the manufacturing sector to raw material shortages [37]. These shortages can sprout from unexpected geopolitical conflicts (e.g., Wen et al., 2021 [38] and Gulley, 2022 [39]), natural disasters (e.g., Wenxin et al., 2022 [40]), or artificial ones, such as was the case with the ship that ran aground in the Suez Canal in 2021 [41, 42]. As a result, significant months-long shortages at an international scale can happen, as seen during the years of the COVID-19 emergency [43]. By retaining resources locally, economies can become more resilient to supply chain shocks.

One additional externality exacerbated by a linear economic model is that second-hand goods availability is scarce because of the large reliance on new products, and opportunities for reuse, repair, and refurbishment are lacklustre. Consequently, access to affordable goods is hindered, and the most affected people are marginalised communities and low-income citizens [44]. By shifting the paradigm and creating more opportunities for a second life for products, it is possible to realise more just societies that allow equitable access to resources.

Material flows in the Australian economy

We present the results of the material flow calculations in Figure 2. In 2019, Australia extracted 2,587 Mt of natural resources from the environment. Of these, about half were metal ores. Fossil fuels represent one-quarter of all domestically sourced materials, which indicates the importance these materials have in the Australian economy. The domestic extraction of materials was supplemented by a modest quantity of imports, about 119 Mt. Imports are only 5% of the volume of domestic extraction, demonstrating the vast abundance of domestic resources and the relative independence from foreign materials. Of all imported materials, about 40% were fossil fuels, and about one-third were semifinished and manufactured products, such as automobiles and laptops. Australian exports are substantial and tallied 1,459 Mt. About two-thirds of these exports are metal ores, and the remaining third are fossil fuels. Exports of biomass, non-metallic minerals, and intermediate and finished products are a minor component of exports, at least when ordered by mass – proportions would undoubtedly look different in monetary terms.

The balance of domestic extraction, imports, and exports results in domestic material consumption. Australia's domestic material consumption was 1,287 Mt or about 49 metric tons per capita. The composition of the domestic material consumption favoured metals (34%), which include their gangue and tailings. Biomass (26%) and non-metallic minerals (25%) were roughly evenly split. Fossil energy carriers account for 14% of Australian domestic material use. We then split material use into energetic uses, material uses, and mining gangue[a] and tailings. Of the four major categories, only biomass and fossil fuels are used for energetic purposes. Biomass is chiefly used for nutrition and, to a minor extent, to produce heat (325 Mt). Fossil energy carriers are extensively used to generate electricity and heat (174 Mt). To these two material categories, we add balancing items. These items account for physiochemical changes that happen to biomass and fossil fuels during energetic use. On the input side, 531 Mt of oxygen and nitrogen are taken from the atmosphere for combustion, respiration, and fertiliser production. On the output side, the balancing items accounted for 477 Mt of water vapour emitted during combustion, and gases expelled during respiration (these gases are not accounted for in the final emissions to air, as the category 'emissions to air' refers to gases emitted from industrial processes).

During the 'material use' phase, the Australian people use materials and the products into which they are transformed to fulfil their needs and wishes. Some products, such as newspapers or packaging, are consumed promptly and directly become part of the domestic processed output. Others, like concrete and timber, are used in long-lived products (e.g., houses). In 2019, Australia used 418 Mt of materials and products, of which 375 Mt were added to material stocks. Meanwhile, 33 Mt of materials were removed from the stock, resulting in a net positive addition of 343 Mt.

The domestic processed output comprises all kinds of emissions from the Australian economic sphere. The balance of materials accruing in 2019 in the domestic processed output was 999 Mt. The primary component of this category is waste derived from ore refining processes (371 Mt). The other two important components are biomass (173 Mt) and fossil fuels (396 Mt). The domestic processed output is then distributed according to its final destination: back to the environment or reinputted into the economy through recycling processes. Recycling flows were 39 Mt, resulting in a recycling rate of 51.1% [45]. The official national Australian waste report indicates a higher recycling rate of 58.7% [46]. We have relied on the Australian Bureau of Statistics' 'Experimental Waste Accounts' to establish the material flow account because of the input-output structure of the datasets available therein. In other words, the 'Experimental Waste Accounts' lend themselves to seamless integration into the material flow accounting framework.

The primary destination of the domestic processed output is land, as the very considerable mass of mineral waste lifts this flow to 471 Mt. In close second come atmospheric emissions, 404 Mt, which mainly consist of carbon dioxide generated during the combustion of fossil fuels. Around 85 Mt of materials, i.e., seeds and fertiliser, are intentionally dissipated into the environment.

a Gangue: the worthless rock or vein matter in which valuable metals or minerals occur. (From https://www.merriam-webster.com/dictionary/gangue)

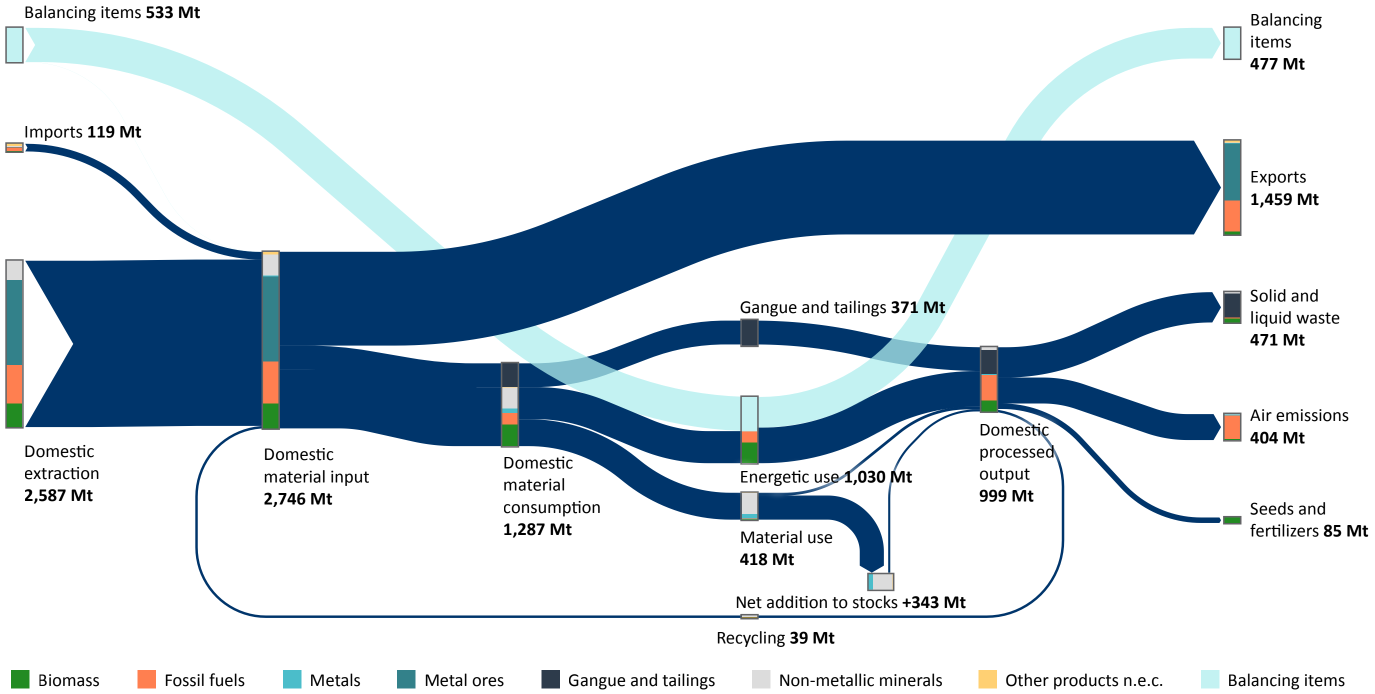


Figure 2 – Material flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

The following figures show a breakdown of the Australian material cycle displayed in Figure 2 into its four principal constituents. Biomass is reported in Figure 3, fossil energy carriers in Figure 4, metal ores and metals in Figure 5, and non-metallic minerals in Figure 6. The most evident characteristic of Figure 3 is that the vast majority of biomass is used within one year and is then converted into environmental emissions. Biomass imports (10 Mt) are tiny compared with domestic biomass extraction (367 Mt). Biomass exports are relevant (49 Mt) but represent only 13% of the domestically extracted biomass. A small flow of biomass (3 Mt) enters the Australian material stocks in the form of timber used in construction. The large difference between the inflow (325 Mt) and outflow (159 Mt) of biomass in energetic use is due to the conversion of part of food into water vapour and carbon dioxide emissions from living animals. The outflow of biomass, which is the timber present in demolished buildings, is nearly identical: ~2 Mt. Because of its large share of energetic use, the flow of recycled biomass is minimal: 9 Mt against a domestic biomass use of 339 Mt, which represents 3% of total domestic biomass use.

Figure 4 displays the flows of fossil energy carriers across the Australian economy. Australia is a major coal exporter, as evident from the considerable mass of exports (480 Mt). Exports equal 73% of the domestic material input (656 Mt). The domestic use of fossil energy carriers accounts for 177 Mt, of which 98% are used to generate energy and the remainder for creating plastics. These plastics are either used in durable products such as polyvinyl chloride (PVC) pipes in buildings or short-lived products such as pens. The flow of fossil fuels seems to augment during energetic use. Of course, fossil fuels are not produced out of thin air. During combustion, fossil fuel takes oxygen from the atmosphere, generating carbon dioxide, water vapour, and ash. Traditional material flow accounts calculate carbon dioxide from combustion processes and ash as part of the system, while water vapour is part of the balancing items. This methodological norm explains the difference between fossil fuels before and after the 'energetic use' node. The recycling rate of plastics in Australia is 9% [45]. When considering the recycling rate for the entirety of fossil fuel flows (i.e., including coal and petrol used for energetic purpose), the end-of-life recycling rate is much lower: 2%. The circularity rate for fossil fuels is about 5%.

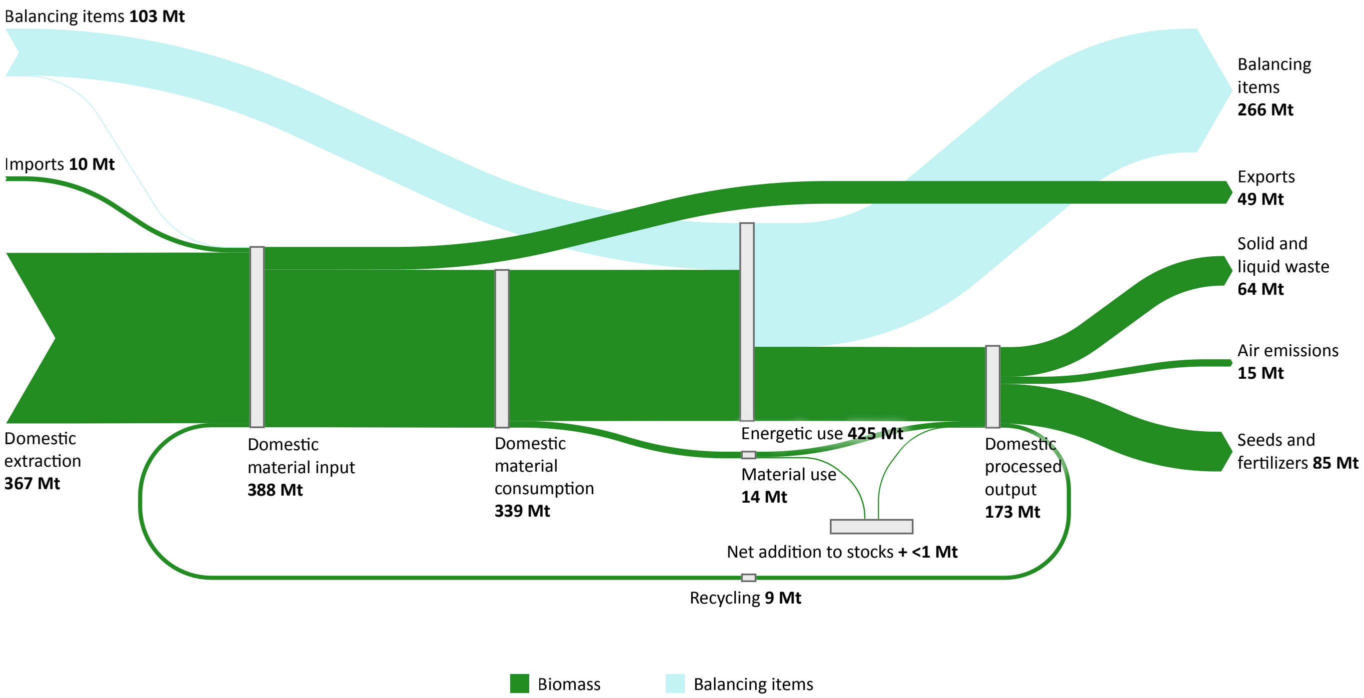


Figure 3 – Biomass flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

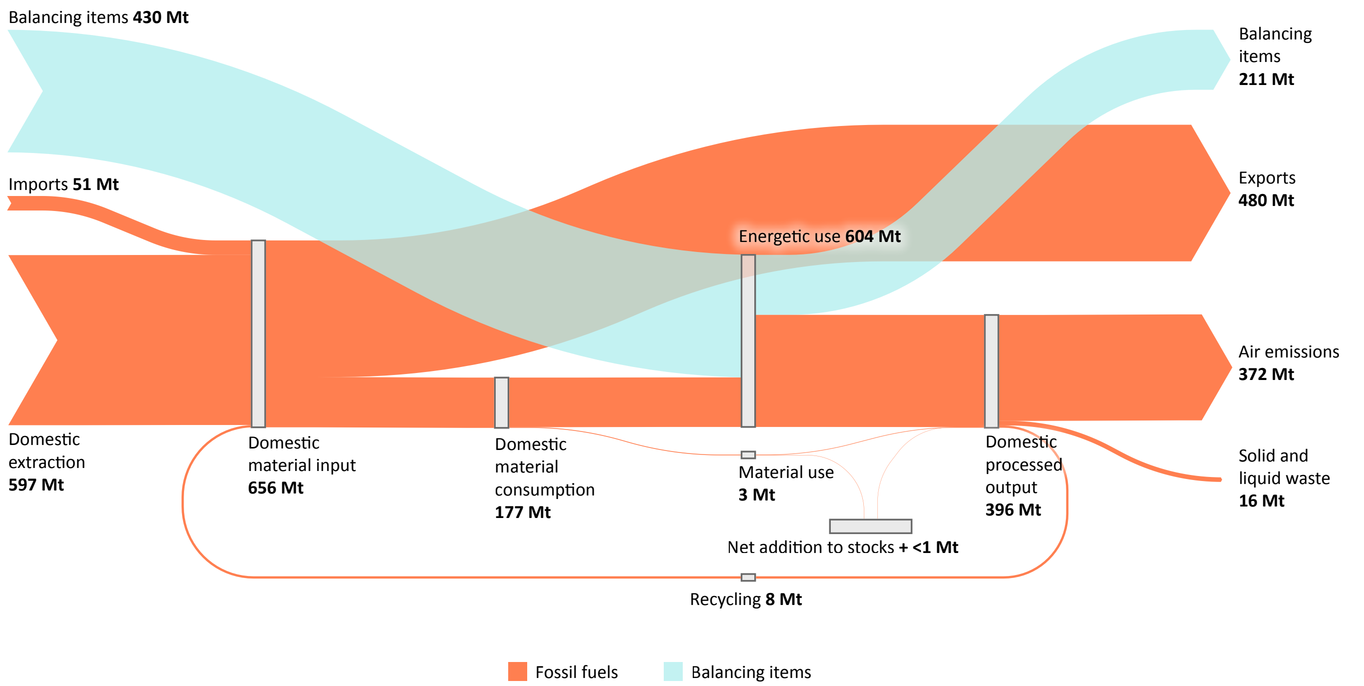


Figure 4 – Fossil fuel flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

Australia's primary exports are metal ores, which can be easily spotted in Figure 5. Of the 1,325 Mt of domestically extracted ores – and a tiny import of 8 Mt – 896 Mt are exported. The remaining ores (437 Mt + 2 Mt of recycled metals) are then processed and refined into metals (69 Mt). The gangue and tailings that derive from refining processes account for 371 Mt. Nearly all the refined metals, 62 Mt, become part of the Australian material stocks because of their extensive use in buildings, vehicles, and machinery, all of which are durable goods. The 11 Mt of emissions to air refer to those emissions generated during domestic steel production. The end-of-life recycling rate of metals is 82%, but in this case, it is confounded by the presence of mineral refining waste, which makes it seem that the end-of-life recycling rate is below 1%.

Non-metallic minerals are ubiquitous and, because of their abundance and low economic value, are rarely traded between countries [47]. Australia makes no exception, and non-metallic mineral inflows (15 Mt) and outflows (4 Mt) are minute compared with their domestic extraction counterparts (297 Mt). Most non-metallic minerals, about 90% of domestic material consumption, are used in construction and end up being part of the Australian material stocks (304 Mt). Around 23 Mt comes out of the built environment stock. Recycled flows account for 19 Mt, which equates to an end-of-life recycling rate of 42%. The overall input of secondary non-metallic materials in the system is 6%.

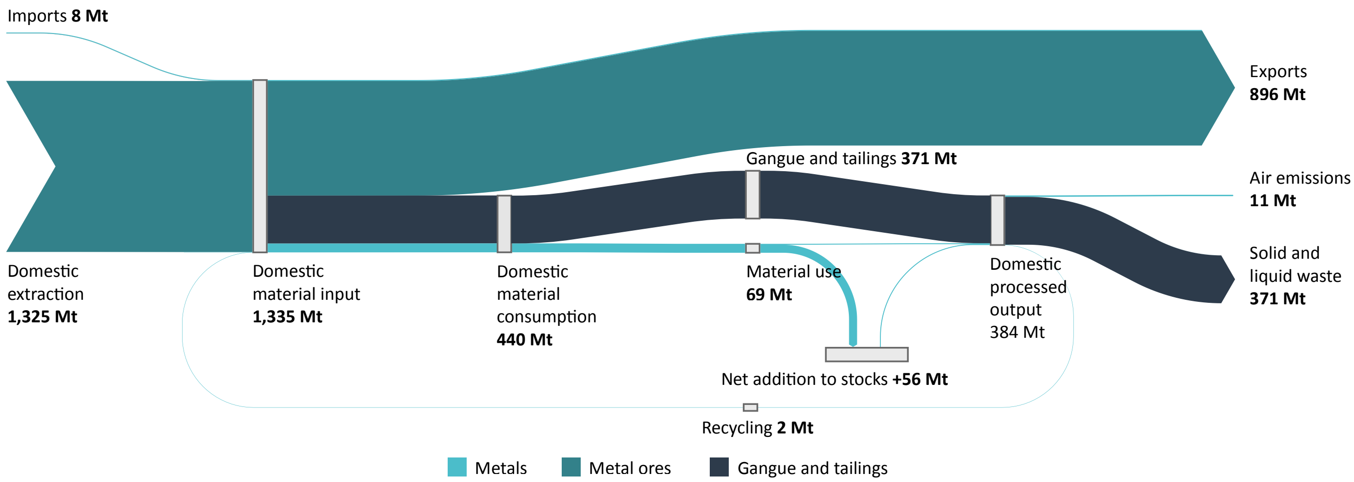


Figure 5 – Metal ore flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

It is interesting to replot Figure 5 in terms of metal content rather than the actual mass of ores, metals, and tailings. We do this in Figure 7. The mass of domestically extracted metals is 440 Mt, which is then augmented by 7 Mt of imports. Most of these metals are then exported (380 Mt). The remainder, i.e., the domestic material use of metals, accounts for 69 Mt. Around 62 Mt of metals flow into material stocks, while the output from them is 7 Mt. Of the resulting 11 Mt of domestic processed output, 2 Mt are recycled (21%), and the rest are returned to the environment.

In Figure 8, we plot all the materials components of the physical Australian economy shown earlier, but in this case, we display them using a constant scale. While some smaller flows become difficult to appreciate, we can easily compare the magnitude of the overall material use across categories. In this case, we can see the predominance of the metallurgical sector and the large flow of mining waste generated by mineral processing.

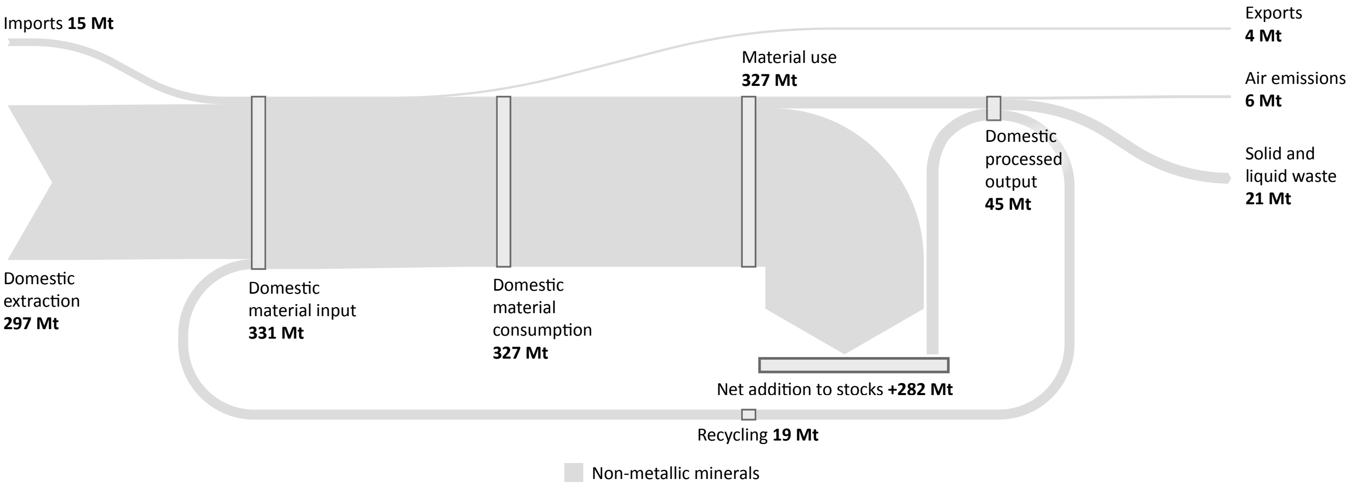


Figure 6 – Non-metallic mineral flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

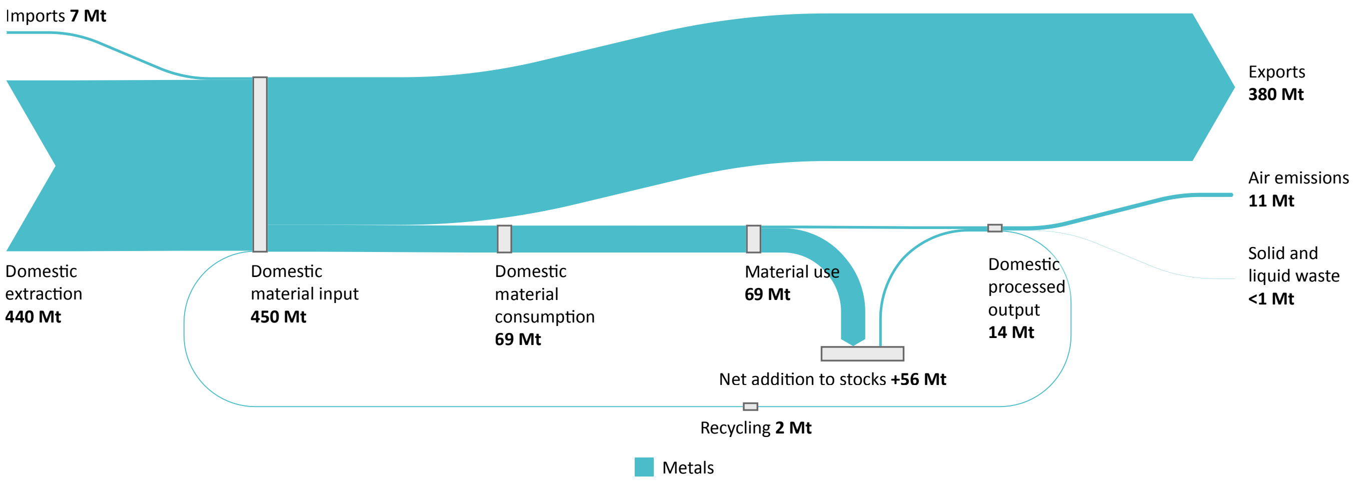


Figure 7 – Metal content equivalent flows through the Australian economy in 2019. The displayed units are million metric tons (Mt).

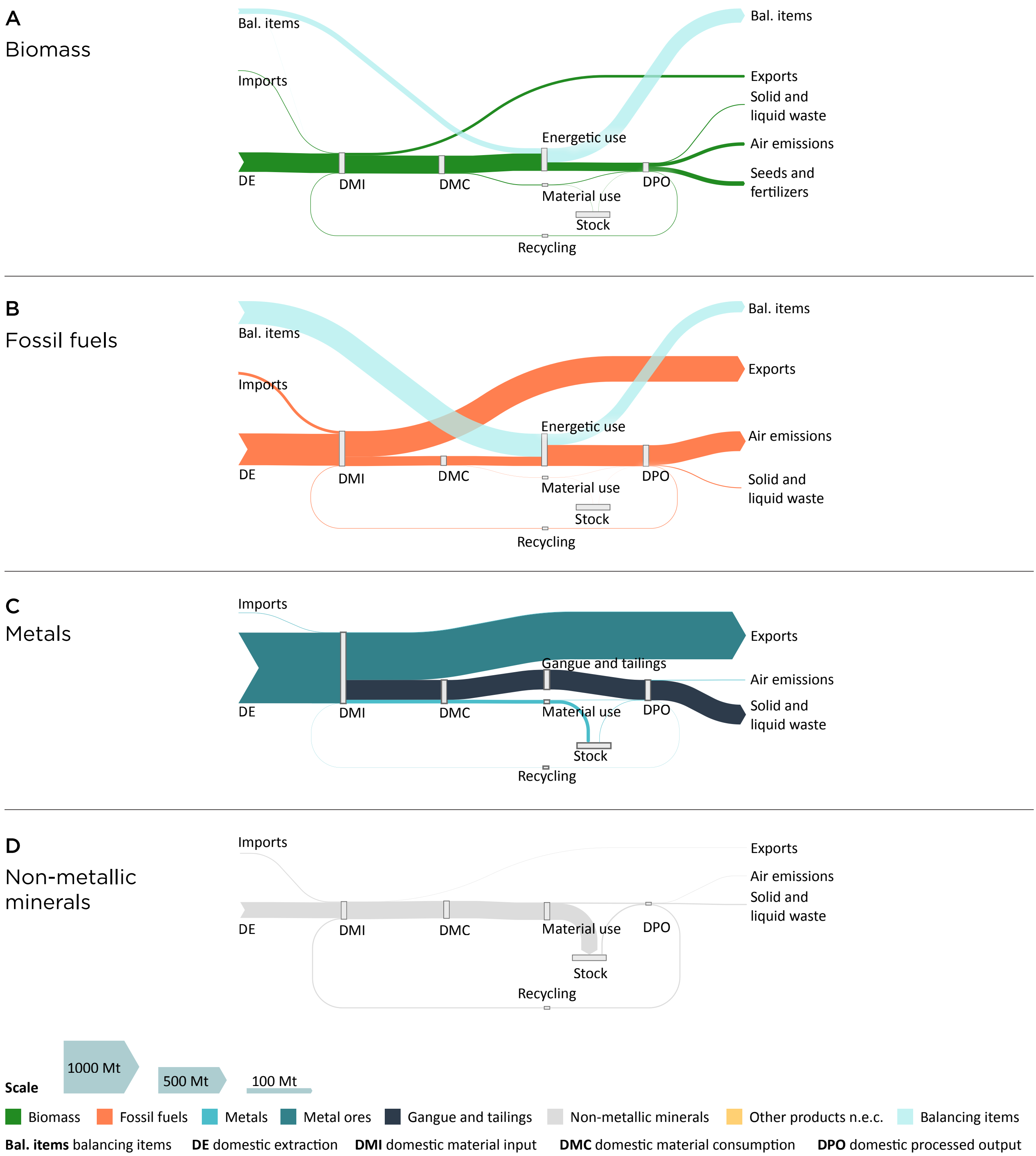


Figure 8 – A comparison of the material components of the Australian economy in 2019. A) Biomass. B) Fossil fuels. C) Metals. D) Non-metallic minerals. The components are plotted using a constant scale among them, facilitating comparison.

Domestic extraction at the subnational level

The results we reported in the previous section refer to Australia as a whole. We investigate domestic extraction at the subnational level in Figure 9. Biomass is produced in each state and territory, albeit at hugely different rates. Most biomass is harvested in New South Wales (99 Mt), while the Australian Capital Territory collects around 0.1 Mt. Normalising these results by the population of each state and territory, we find that South Australia has the highest per capita biomass production (37 t cap^{-1}) and the Australian Capital Territory has the lowest (0.3 t cap^{-1}). Australia's three most populous states (New South Wales, Victoria, and Queensland) see biomass extraction of ~11 t cap^{-1}, while South Australia, Western Australia, and Tasmania collect biomass at about 27 t cap^{-1}.

Metal ores dominate Australia's extractive industry. This behaviour is reflected in Figure 9, which shows Western Australia extracting 838 Mt of ores in 2019. Distant second and third are South Australia and the Northern Territory, with 252 and 141 Mt, respectively. All other states present modest ore extraction, especially when compared to the first three. The only area in Australia that does not extract metal ores is the Australian Capital Territory. Because of its relatively small population, the Northern Territory leads the list of per capita metal ore extraction (577 t cap^{-1}). Western Australia (317 t cap^{-1}) and South Australia (143 t cap^{-1}) follow in this list – all other states' ore extraction averages around 6 t cap^{-1}.

The extraction of non-metallic minerals is somewhat evenly distributed among all states and territories, at least when compared to the pattern of metal ores. The state that reports the highest extraction of non-metallic minerals is Victoria (118 Mt), while neither Tasmania nor the Australian Capital Territory reports any such extraction. While we consider it plausible for the Australian Capital Territory to source its sand and gravel from surrounding areas in New South Wales, we believe that we encountered a data gap when researching the extractive industry in Tasmania. A 2008 governmental report indicates that Tasmania extracted around 1 Mt of sand and gravel in 2007 [48]. While this mass is certainly not enough to significantly alter the results we present herein, it is a gap we consider worth mentioning. On a per capita level, South Australia sees the highest extraction (52 t cap^{-1}), while the aggregated average of all other states is 9 t cap^{-1}.

Fossil fuels are the other major category of materials exported from Australia in vast quantities (cf. Figure 8). In 2019, these materials were primarily collected in New South Wales (321 Mt) and Queensland (232 Mt). Minor quantities were reported by Western Australia (27 Mt), Victoria (15 Mt), and South Australia (1 Mt). Tasmania, the Australian Capital Territory, and the Northern Territory did not report any extraction of fossil fuels. The per capita extraction of fossil fuels is highest in Queensland (45 t cap^{-1}), closely followed by that of New South Wales (39 t cap^{-1}). The other extracting states average around 4 t cap^{-1}.

It is important to remember that domestic extraction in each state and territory does not correspond to the actual use of materials (i.e., the domestic material consumption) in those locales. Not only does international trade significantly change what ends up being used domestically, but national trade shifts consumption. If that were not the case, people in the Australian Capital Territory would live off a handful of biomass and nothing else. Unfortunately, trade among states and territories is not reported in any official statistics, so it is impossible for us to map the domestic material consumption at the subnational level. While impossible to achieve with material flows, we can estimate the end use of materials at the subnational level through material footprinting, which we report in section 3.1.

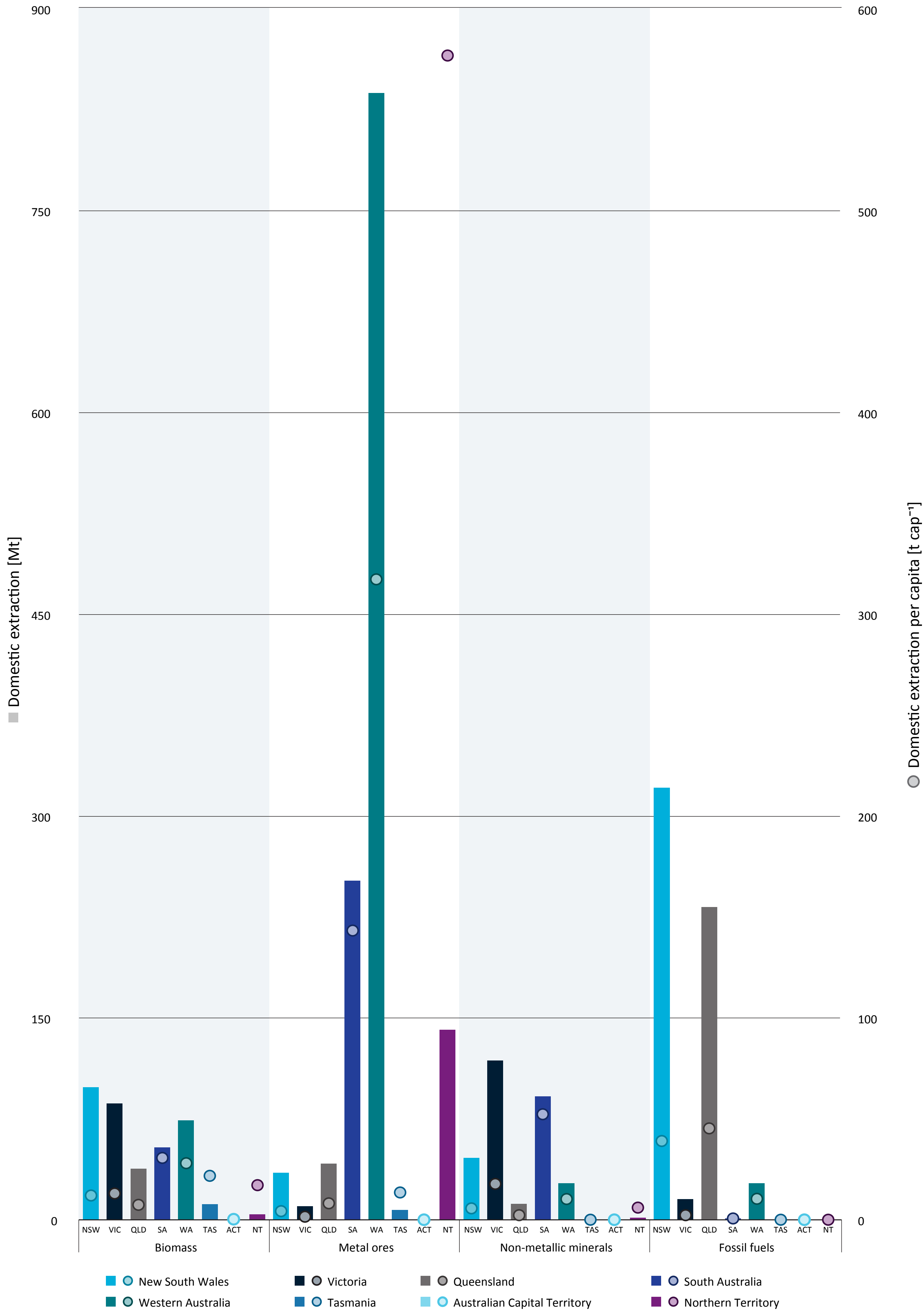


Figure 9 – Domestic extraction by state and territory in Australia in 2019. The bars refer to the mass of domestic extraction; the dots refer to the mass of domestic extraction per capita.

Material footprint of the Australian economy

We present the material footprint for the 2019 Australian economy in Figure 10. As defined in the glossary, the material footprint is a type of environmental account that attributes the overall burden of material extraction to the final user, regardless of where the material extraction or processing happens [49]. In the material footprint account, domestic extraction coincides with that of the material flow analysis, as these materials enter the economy domestically so there are no additional equivalent flows for which to account. We then move our attention to raw material equivalent imports and exports, which are flows that attribute the entire burden of material extraction to the final user. Please refer to the glossary and the Eurostat manual [20] for further details.
The raw material equivalent imports are 297 Mt, 178 Mt more than their physical counterparts. On the export side, Australia exports 1,926 Mt of raw material equivalents compared with 1,459 Mt of physical exports, which tallies to a net difference of 467 Mt. The cluster node, 'material input', sums together the domestic extraction and the raw material equivalent imports. All materials are segregated into macro categories that are then processed. Ferrous ores are the largest flow in the 'processing' cluster (978 Mt), followed by coal (525 Mt) and non-ferrous ores (419 Mt). At this stage, materials either continue their journey through the Australian economy or are shipped abroad. The 'production' cluster totals 996 Mt and is dominated by non-metallic minerals used in construction (226 Mt). Materials are then aggregated according to the four major material categories in the 'provision' cluster. The four material groups are similar in size, with biomass being the largest (300 Mt) and metals the smallest (174 Mt).

We then rearrange these materials into seven systems of provision in the 'societal needs' cluster, similar to the work of Yin et al. [50]. These systems of provision are macro-groups that represent seven major economic sectors: housing (i.e., all buildings), mobility (i.e., vehicles, infrastructure), food, energy (i.e., power plants, distribution lines), communication (i.e., phones, telephone lines, antenna towers), waste management (i.e., landfills, water treatment sites), and other, which is a catch-all category that includes things like healthcare, education, government, research, etc. We see that the system of provision that uses most materials is mobility (273 Mt). In this node, 52% of materials are attributed to fossil fuels. The second largest node is housing, which uses 251 Mt of materials. Unsurprisingly, 54% of this node is primarily comprised of non-metallic minerals. The 'food' node occupies the third spot, using 215 Mt of materials. Once again, without much surprise, the primary material category used in this system of provision is biomass. Other systems of provision consume far less materials: energy uses 46 Mt, communication employs 31 Mt, and waste management only 3 Mt. All other systems of provision are aggregated in the 'other' category and tallies 176 Mt.

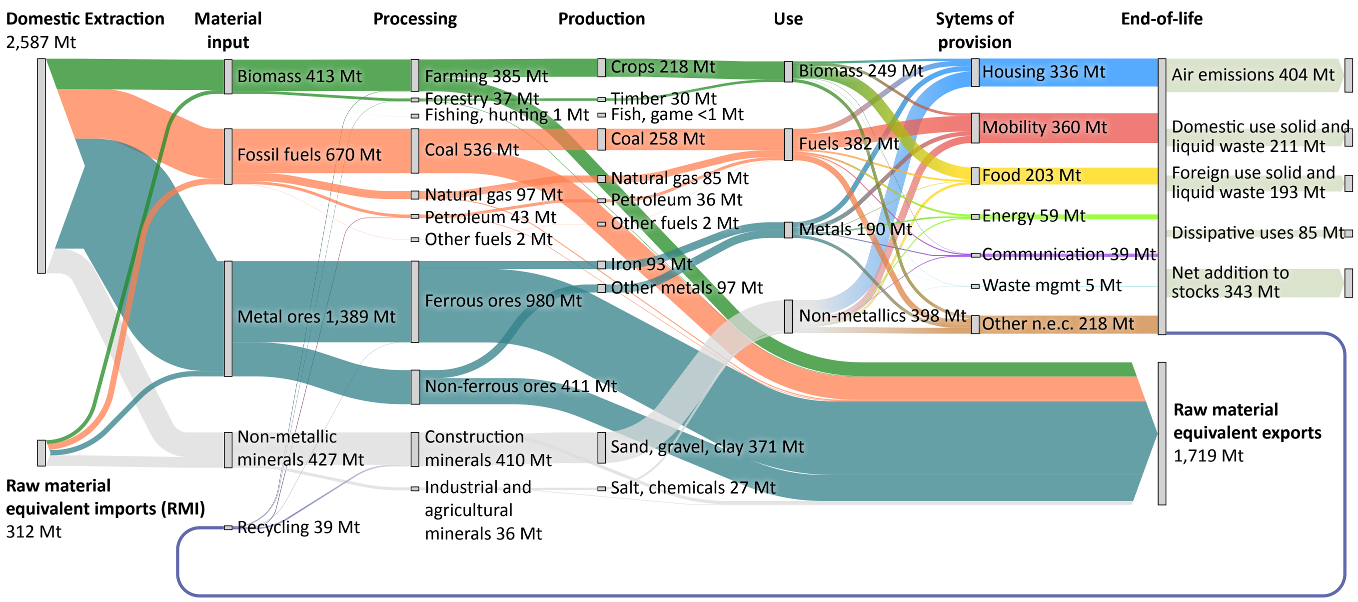


Figure 10 – Australia's material footprint for 2019, including a breakdown of the material use according to seven systems of provision.

Material footprint at the subnational level

Leveraging data on monetary flows at the subnational level, we can plot the material footprint for each Australian state and territory (Figure 11). Housing and mobility are the two systems of provision that show the highest material footprint. New South Wales has the highest footprint in both these systems, tallying 77 Mt for housing and 88 Mt for mobility. The lowest material footprint for housing appears in the Northern Territory (4 Mt), while the lowest for mobility is recorded for the Australian Capital Territory (3 Mt). Regarding per capita use, housing tends to use around 9 t cap^{-1} across the country, where Tasmania occupies the lowest place with 8 t cap^{-1} and the Northern Territory the highest with 15 t cap^{-1}. Mobility uses slightly more materials, 10 t cap^{-1}, with the Australian Capital Territory consuming the least (8 t cap^{-1}) and the Northern Territory consuming the most (19 t cap^{-1}).

The third most prominent system of provision is food. In absolute terms, New South Wales has the highest food footprint (73 Mt) and the Northern Territory the lowest (5 Mt). These values should not come as a surprise as New South Wales is the most populous state in the country and the Northern Territory the least populous. Things look drastically different when results are normalised by population. The Northern Territory has the highest food footprint of all states and territories (20 t cap^{-1}), while all others account for about 10 t cap^{-1}. The lowest material footprint related to food was recorded in Victoria, at 9 t cap^{-1}.

Energy and communication use comparable amounts of materials, 44 Mt and 30 Mt, respectively. New South Wales, being the most populous Australian state, leads in both systems of provision with 14 Mt and 13 Mt, respectively. The Australian Capital Territory uses the least materials in both of these systems. Analysing the material footprint per capita for these two systems of provision, the Northern Territory is once again the highest material user. In fact, it used about 4 t cap^{-1} for energy and 3 t cap^{-1} for communication. All other states and territories recorded similar material footprints in these two systems, specifically around 2 t cap^{-1} for energy and 1 t cap^{-1} for communication.

The material footprint for waste management appears low across all states and territories. We want to clarify that these materials are those used to manage waste (e.g., trucks, municipal recovery facilities), not the amount of waste generated. The highest material footprint for waste management happens in New South Wales (1 Mt) and the lowest in the Australian Capital Territory (0.1 Mt). In terms of per capita footprint, most states and territories account for 0.1 t cap^{-1}, while the Northern Territory accounts for 0.4 t cap^{-1}.

The final category, labelled 'other,' refers to all those systems of provision that we did not previously classify, such as healthcare, education, governance, etc. This final system of provision shows considerable amounts of materials. New South Wales uses 53 Mt of materials, while Victoria and Queensland use 39 Mt and 34 Mt, respectively. When normalised by population, the material footprint appears the highest in the Northern Territory (13 t cap^{-1}), followed by the Australian Capital Territory (11 t cap^{-1}). All other states use around 6 t cap^{-1}.

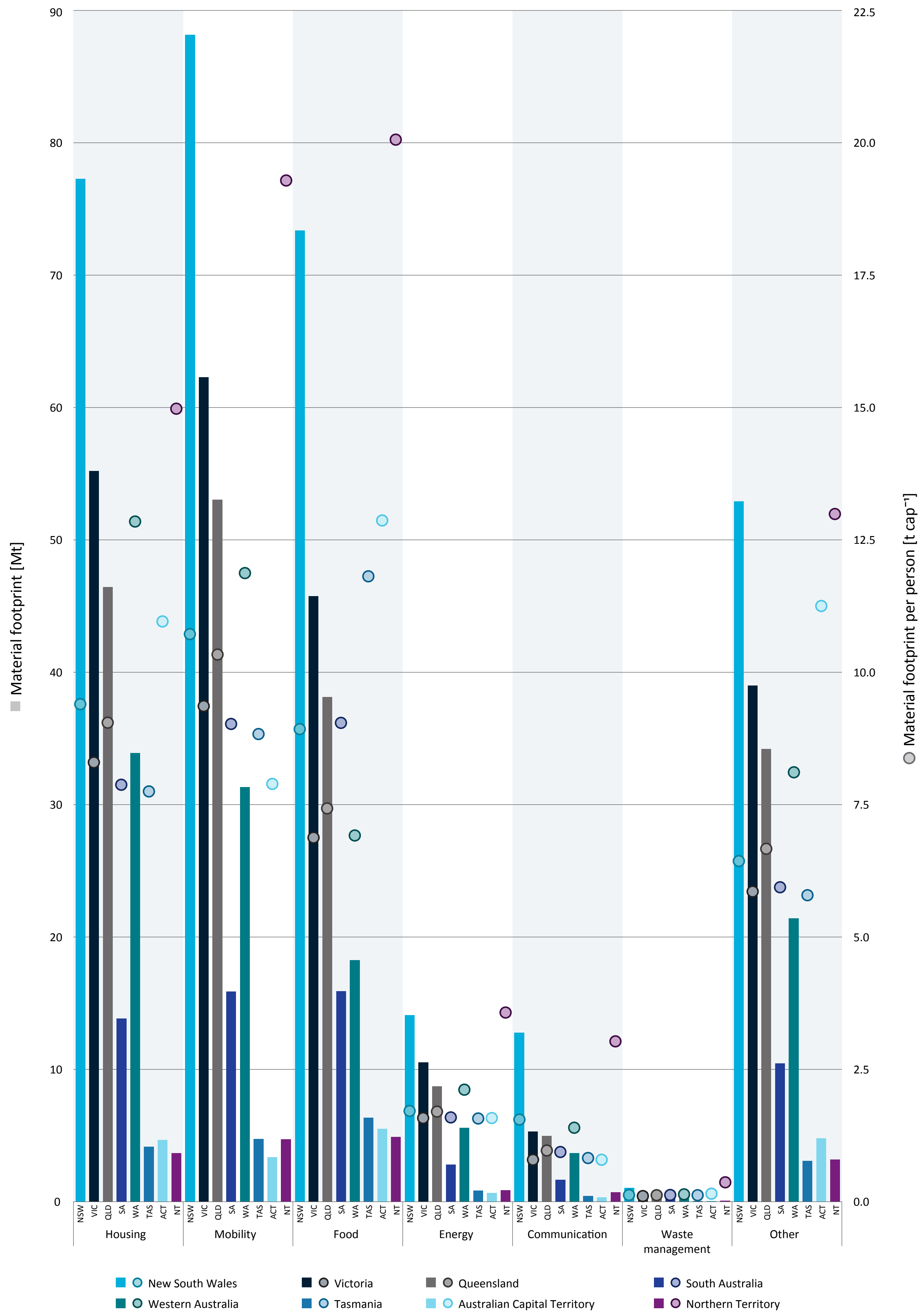


Figure 11 – Material footprint by system of provision for each Australian state and territory in 2019.

Australia's circularity indicators

We report several circularity metrics for Australia in Figure 12. The end-of-life recycling rate measures the share of recycled materials against the total mass of waste that reached municipal recovery facilities in 2019. Australia recycled just over half of its municipal solid waste when considering all materials. Note that this metric excludes mineral wastes, which are not generally 'recycled' per se. Mineral tailings are sometimes reprocessed, either to extract different minerals to those targeted initially or because market prices or extractive technology have sufficiently improved that it is profitable to extract the remaining metal content [51]. However, mineral tailings cannot be recycled per se, as it is impossible, or at the very least purposeless, to reinsert metals into the ore. Looking at specific material groups, about two-thirds of all biomass was recycled (mostly timber), four-fifths of all metals (they have high monetary value), and two-fifths of all non-metallic minerals (they are mostly crushed and used in road beddings, building drainage, and backfill). Fossil fuels are a special case, as they appear to have the highest share of recycling. Most fossil fuels are used for energetic purposes, with a small fraction used to produce plastics. However, the vast majority of the recycled mass of fossil fuels comes from fly ash (5.9 Mt) that is captured and used to produce cement (Australia's national waste report indicates total production of 12.5 Mt of ash [46], indicating that roughly half of all ash is recycled).

The circularity rate is measured as the share of secondary materials against the total use of materials. In practice, the circularity rate for all materials in 2019 was measured as the mass of recycled materials in Australia plus an assumed 7.2% of secondary materials in imported products (based on the global circularity rate [14]) divided by the total mass of materials used. We calculated that the Australian circularity rate for 2019 for all materials was 3.7%. When looking at the material subcategories, we notice that all materials perform similarly, with non-metallic minerals leading at 6.2% and metals tailing at 0.6% (this very low percentage stems from the vast mass of tailings and gangue).

However, a circularity rate of 100% is not achievable because several materials are irreversibly transformed during their use, such as biomass used as food or fossil fuels used for energy. We measure the theoretical circularity maximum as the highest possible circularity rate under today's economic and technical structure. At most, Australia could supply its economy with 32.5% of secondary materials, which are all the materials that are used for non-energetic purposes. Realistically, this number would be lower, as a recycling rate of 100% is impossible when considering entropic processes. CSIRO's 2015 report on Australia's circular economy estimated that a circularity rate of 20% could be more realistically achievable [3]. As for the material subgroups, only metals could theoretically achieve circularity of 100%. Non-metallic minerals are, in part, used as fertiliser, which is deliberately dispersed on the soil and hence unrecyclable according to the material flow framework. Fossil fuels and biomass are extensively used for energetic purposes and are, once again, not recyclable. We note that some scholars consider the natural cycle of biomass a circular strategy [52]. While this argument is undoubtedly valid, in this research, we consider 'recyclable materials', and hence materials that contribute to the circularity metric, only those that can be recycled and reused in the economy without leaving the economic sphere [53].

The circularity gap is measured as the remainder of the ratio between the circularity rate and the theoretical circularity maximum. In other words, how much more can the circularity rate grow relative to the circularity maximum? We see that the overall circularity cap is relatively high, at 88.6%. This high percentage is driven by three material subgroups: biomass, metals, and non-metallic minerals. All these material subgroups make use of large quantities of virgin materials. Even in the case of metals, which are largely routinely recycled, the circularity gap accounted for 96.2%. This surprisingly large value was achieved because of the large need for metals, which can only be marginally supplemented by recycled metals.

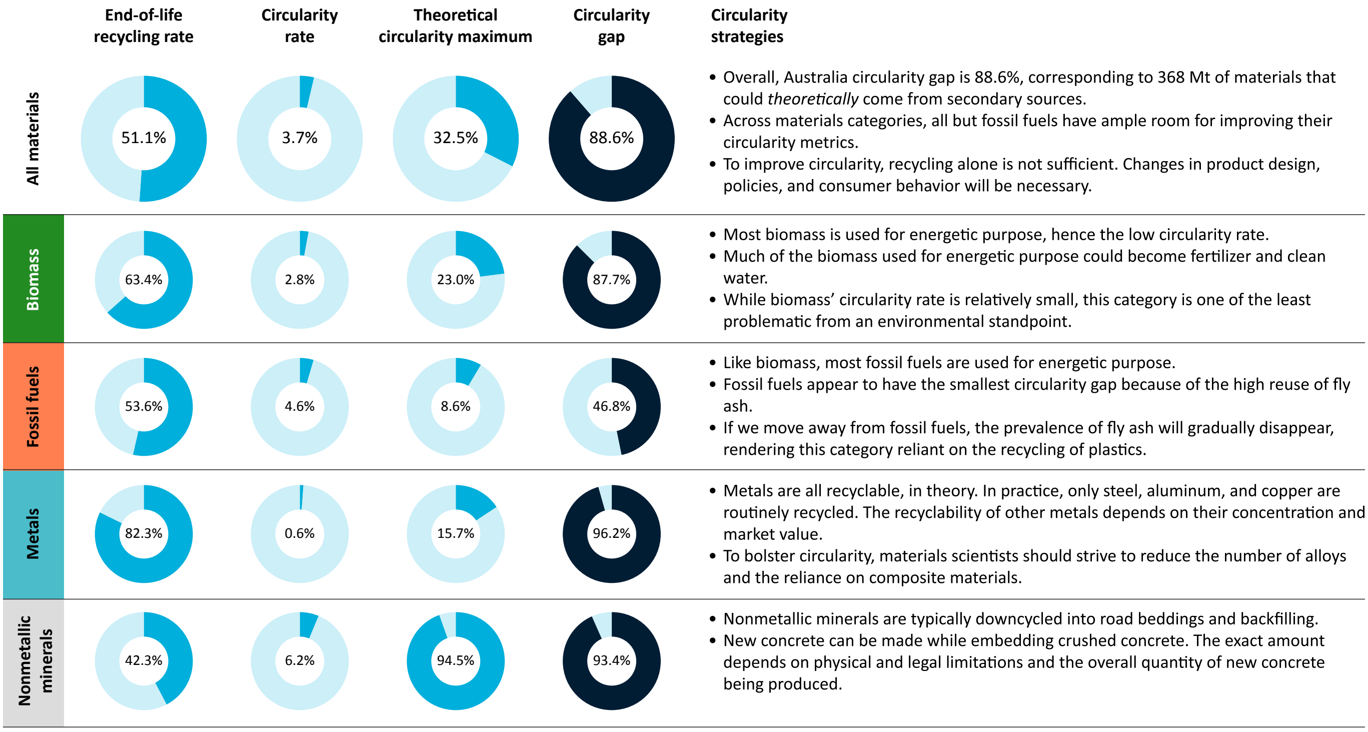


Figure 12 – Circularity indicators for all materials and four material subcategories for Australia in 2019.

Finally, the right side of Figure 12 reports some strategies to bolster circularity in Australia. It would be repetitive to rehash what is already present in the figure, so we invite readers to peruse these strategies directly in Figure 12.

Thanks to similar work on Australia's material flows for 2015 [3], we can evaluate the temporal changes between those results and the ones calculated for this report concerning different Sustainable Development Goal (SDG) targets. We do so in Figure 13.

The first goal this research can inform is #8, 'Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.' Specifically, target 8.4 aims to 'Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead.' In other words, it measures resource productivity. Between 2015 and 2019, the domestic material consumption per Australian dollar increased from 0.56 to 0.61 kg/AU$. In practice, more materials were needed to produce a unit of GDP in 2019 than in 2015. On the other hand, the material footprint per unit of wealth decreased from 0.61 to 0.49 kg/AU$. This second result suggests that, when considering what materials are ultimately used by its citizens, Australia has improved its efficiency as it can create a dollar of wealth with 0.49 kg of materials.

Goal #12 is the goal we can most inform with material flow analysis and material footprinting. This goal is focused on 'Ensur[ing] sustainable consumption and production patterns.' Target 12.2 focuses on 'By 2030, achieve the sustainable management and efficient use of natural resources', and measurement of domestic material consumption and the material footprint are two ways to measure this progress. We found that Australia's domestic material consumption (DMC) grew from 1,038 to 1,287 Mt, corresponding to a modest increase in per capita consumption. In fact, the DMC per capita grew from 45.1 to 49.2 t/cap. Conversely, the material footprint decreased: it was 1,123 Mt in 2015 and became 996 Mt in 2019. This decrement, combined with population growth, resulted in a distinct decrease in the material footprint per capita: it went from 46.9 to 39.3 t/cap. Domestic mining activities explain the opposing trends exhibited by the DMC and the material footprint. The DMC measures what physically happens in Australia, and because Australia's mining activities grew (i.e., generating more mining waste), so did the DMC. The material footprint allocates the total burden of material extraction to the final user. Because much of the extracted metal ended up in products used by people outside of Australia, the material footprint attributed the burden of these materials abroad.

Target 12.5 strives to 'substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030.' Part of this target includes measurement of solid waste generation, recycling rates, and circularity rates. Solid waste generation increased in absolute terms, growing from 64 to 75.3 Mt. Despite population growth, waste generation outpaced it, resulting in an average per capita waste production that went from 2.7 to 3.0 t/cap. The recycling rate decreased slightly, going from 59.4% to 51.1%. On the other hand, the circularity rate grew modestly from 3.5% to 3.7%.

The last SDG we can inform is #13: 'Take urgent action to combat climate change and its impacts.' As part of our assessment includes air emissions, we can evaluate how these have changed. We discovered a moderate absolute decrement in emissions, which went from 412 to 404 Mt. This result is encouraging, especially when evaluated in per capita terms: they were 17.2 t/cap in 2015 and 15.9 t/cap in 2019.

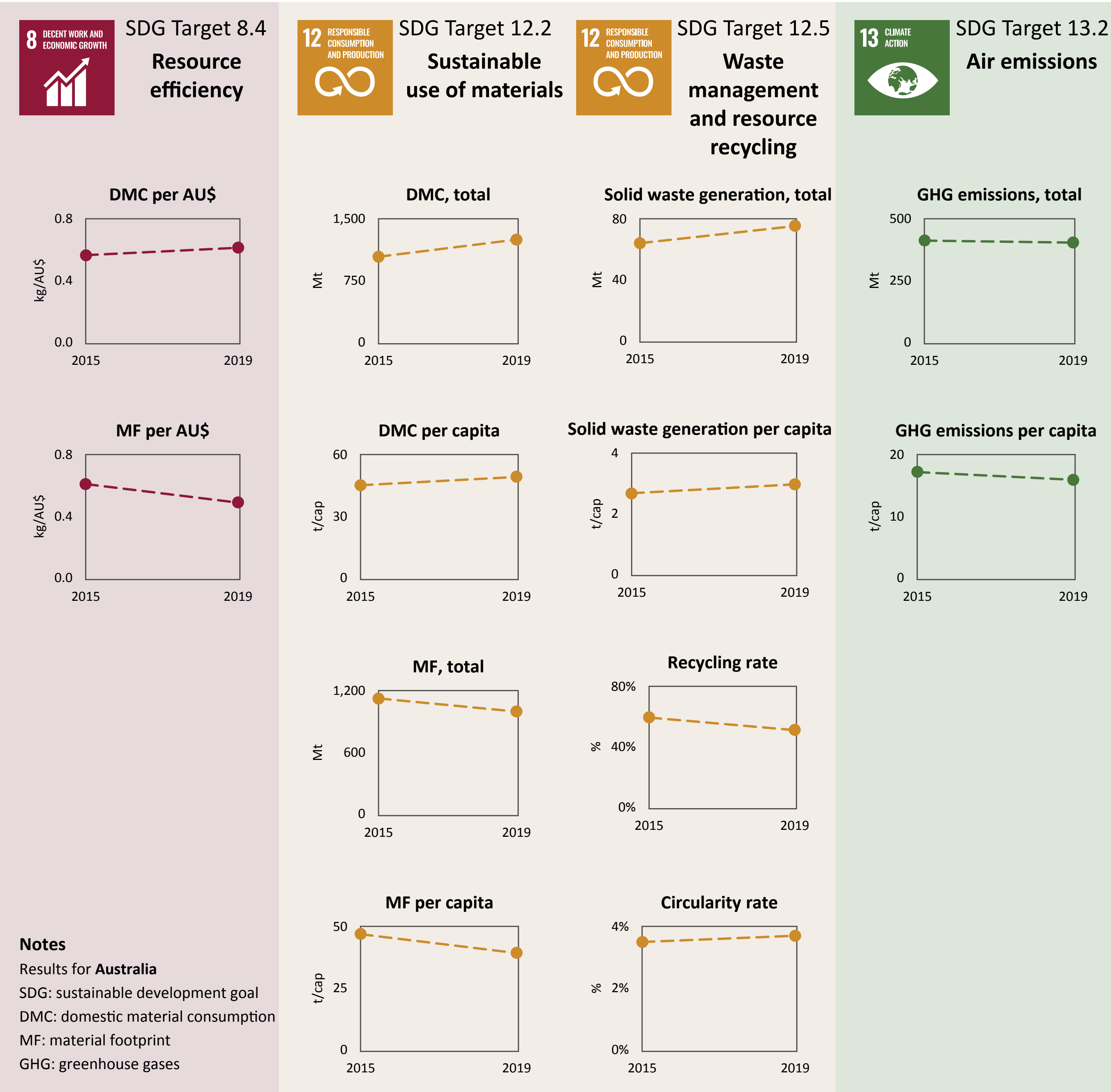


Figure 13 – Comparison of various Sustainable Development Goal targets for Australia between 2015 and 2019.

Discussion

Australia's extractive industry

Figure 2 groups all materials flowing through the Australian economy. It is evident that physical imports (119 Mt) are marginal when compared to the mass of exports (1,459 Mt) and domestically extracted materials (2,587 Mt). In other words, Australia is a major global supplier of natural resources. The only things Australia imports in considerable quantities are semifinished and finished products, as exemplified by the 36 Mt of such imports, close to a third of all imports. Concurrently, Australia exports 30 Mt of these products. It is unlikely that the exported products are taken from the pool of imported ones; they likely stem from domestically manufactured items. Nonetheless, given the current resolution available in material flow databases, we can only speculate on the origin of such products.

Metal ores make up 61% of all physical exports. In 2019, Australia exported 896 Mt of metal ores, of which 838 Mt were iron ores. About three-quarters of Australian ores go to China for further processing, distantly followed in second place by Japan with about 10% [54]. The second most exported material category is fossil fuels (33% of all 2019 exports). Of the 480 Mt of exported fossil fuels, 393 Mt are coal, and 72 Mt are natural gas. These massive exports are enabled by significant reserves of metal ores and fossil fuels, which often leave the country without any significant value-adding. As Australia and the world transition to a renewable energy system, Australian exports may shift to an even higher share of metal ores and potentially refined metals, which will have economic and policy implications that will need to be managed.

Crops, livestock, and dairy exports are another vital aspect of Australia's economic structure. While much smaller in volume compared to metal ores and fossil fuels, these exports add to the Australia's economic prosperity and require well-managed agricultural, forest, and marine ecosystems to align economic benefits with environmental objectives.

The National Reconstruction Fund [55] policy priorities aimed at diversifying and transforming Australia's industry and economy. These policies can support a reinvigorated manufacturing sector in areas of renewables and low-emission technologies and allow added value in the agriculture, forestry, fishery, and extractive sectors, which would, in all likelihood, improve Australia's economic complexity [56] and the sustainability credentials of its export industries.

Australia's emissions to the environment

The total mass of output flows from the Australian socioeconomic system in 2019 was 999 Mt or 39 metric tons per capita. The two primary sinks for the end-of-life flows were air emissions (404 Mt) and solid and liquid waste (471 Mt). Air emissions derive from a multitude of activities, but the combustion of fossil fuels predominantly causes them. Solid and liquid waste flows are inflated by the large mass of gangue and tailings derived from the Australian metallurgical industry (371 Mt). If we were to exclude minerals production waste, the mass of solid and liquid waste would be 101 Mt. Biomass would be the dominant flow (64 Mt), followed by non-metallic minerals that stem from construction and demolition waste (21 Mt).

Australia intentionally disperses 85 Mt of seeds and fertilisers into the natural environment. This flow, officially termed 'dissipative uses of products', is one of the material outputs classified in both the Eurostat Material Flow Manual [20] and the UNEP Global Economy-Wide Material Flow Accounting Manual [21]. Seeds and fertilisers are used deliberately to foster the growth of edible vegetables and fruits; they are not an accidental and uncontrolled spill of resources into nature. This flow might thus seem of less concern when compared with the issues caused by greenhouse gas emissions or landfill. Fertilisers, however, have been the object of studies as they can trickle into groundwater and cause environmental and health issues [57]. Today, Australia sits low in the global rankings of fertiliser use, but it is nonetheless an outflow worth attention.

The 39 metric tons per capita of domestic processed output in Australia is strikingly high when compared with Europe. In 2019, Europe's average domestic processed output was 9 metric tons per capita (the highest country was Iceland, with 19 metric tons per capita, and the lowest was Malta, with 4 metric tons per capita). The considerable Australian mining activities cause part of this difference. Nevertheless, direct comparison is still not possible. The methodology to account for the domestic processed output presented in this report differs from the reporting of the European Union. The European Union considers only illegal dumping into water and land as part of its solid and liquid waste accounted for in domestic processed output. All legal landfills and wastewater reaching a water treatment plant are considered part of the economy and not part of the domestic processed output. We believe it is essential to show these flows, and we thus include them in our report. Moreover, it is nearly impossible to properly quantify the mass of illegal dumping on land and water, and we could not find any data in this regard. While certainly not zero, we believe Australian illegal dumping flows to be negligible compared with their regulated counterparts.

Opportunities for improving resource efficiency and circularity

Australia's current circularity rate is 3.7%. This measurement is calculated as the share of secondary materials against Australia's domestic material consumption in 2019. Considering that materials used for energetic purposes cannot be recycled, we can estimate that the highest possible circularity rate is around 32.5%. The stark gap, 89%, between the calculated circularity rate and the theoretical circularity optimum, which we term the circularity gap, indicates that there are ample opportunities for improvement. These metrics are summarised in Table 1.

Non-metallic minerals are the dominant constituents of secondary materials (19 Mt), followed by biomass (9 Mt) and fossil fuels (8 Mt). Metals occupy the last spot at 2 Mt. Most secondary non-metallic minerals are used as crushed aggregate in roadbeds, building drainage layers, ballast, and backfill. While certainly better than relying on virgin rocks and gravel, these applications for secondary non-metallic minerals are a far cry from concrete, from which most of the secondary non-metallic minerals come. Small quotas of secondary non-metallic minerals can be reintegrated into fresh concrete, but they cannot entirely replace virgin aggregate under today's technology without compromising its strength [58]. Much research is being conducted to improve concrete recycling, so we can hope that, in the future, there will be margins to improve the circularity of this stream of materials [59].

Recycled biomass comprises paper (2.4 Mt), timber (1.1 Mt), and other organic materials (5.4 Mt). Paper recycling is well established, and albeit being an intense activity from the viewpoint of using chemicals and energy [60], it allows paper to remain in use within the system multiple times. However, paper can be recycled about seven times before

Table 1 – Summary of different circularity index metrics for Australia in 2019.

INDICATOR	MEASUREMENT	RESULTS
Sustainable material management (SDG 12.2)	Domestic material consumption (DMC) per capita; material footprint (MF) per capita.	DMC: 49 t/cap MF: 39 t/cap
Material efficiency (SDG 8.4)	DMC per gross domestic product (GDP); MF per GDP.	DMC/GDP: 0.61 kg/A$ MF/GDP: 0.49 kg/A$
Waste disposal	Mass of disposed waste per capita (excl. mining waste).	3 t/cap
End-of-life recycling rate of municipal solid waste (SDG 12.5)	Recycled material/end-of-life solid and liquid waste (excl. gangue and tailings).	51.1%
End-of-life recycling rate incl. mining	Recycled material/end-of-life solid and liquid waste (incl. gangue and tailings).	8.6%
Circularity rate	Recycled materials/DMC.	3.7%
Theoretical circularity optimum	Level of circularity achievable in theory, i.e., secondary physical use of materials/DMC.	~33%
Current circularity potential	Detailed analysis of Schandl et al. [3]	~20%
Circularity gap	One minus the ratio between circularity rate and theoretical circularity optimum.	~89%

Note: Australia's end-of-life recycling rate calculated by Blue Environment is 58.7% [46]. This rate does not include mining waste.

the pulp fibres become too short to produce usable paper [61]. Timber can be reused for producing furniture, door and window frames, and floor slats [62]. In some cases, it can be used for structural components [63]. All other organic materials can be turned into compost and used as fertiliser [64].

Recycled fossil fuel flows are considerable (8 Mt). While plastics account for only 0.2 Mt, most of this category comprises ash (5.9 Mt). Recycled ashes from coal power plants are mostly recycled into building materials (chiefly cement, bricks, and cinder blocks), but they also find applications in adsorbents, the synthesis of zeolite and geopolymers, and more [65]. Finally, vehicle tyres are recycled into a myriad of civil engineering applications, from whole-tyre embankments to concrete fillers [66].

Australia's end-of-life metal recycling rate is very high, around 90%, according to a report by the Australian Department of the Environment and Energy [67]. This high recycling rate is unsurprising, especially when considered against the price of metals, the financial and environmental convenience of recycling, and the ease with which metals can be sorted in municipal recycling facilities. One important caveat to point out is that out of the three score of metals routinely used in modern economies, only three are routinely recycled: steel, aluminium, and copper [68]. All other metals have varying degrees of recycling but come nowhere near the recycling rates of those three metals.

Differences between material flows and material footprint

When comparing the results of the material flow analysis and those of the material footprint, we see that the material footprint has higher imports by 178 Mt and higher exports by 467 Mt. Perhaps more interesting is to calculate these differences in relative terms. The raw material equivalent imports are 2.5 times larger than the physical imports, while the raw material equivalent exports are 1.3 times larger than their physical counterparts. These results suggest two considerations: first, most of the physical extraction related to the import of products for the Australian economy happens abroad. Second, because the relative difference between exports and raw material equivalent exports is minute, Australia's exports predominantly comprise raw materials. This intuition is further supported by Australia's low ranking in the Atlas of Economic Complexity [56].

Dematerialisation and circularity strategies for sustainable systems of provision

The material footprint allows for the identification of the material intensity of sectors and products and helps in setting priorities for policy efforts. In such a way, the material requirements of key provision systems such as housing, mobility, food, and energy can be established. This approach identifies mobility as the primary system in which materials are used. The whole life cycle material requirements of the 'mobility' system of provision refer to two things, primarily: the vehicles used for mobility and the infrastructure required to operate these vehicles. From a circularity perspective, significant improvements in the dematerialisation of this sector appear challenging. Roads are already the primary recipients of the majority of crushed concrete [69], so curtailing road construction would also reduce the capacity to absorb construction and demolition waste. Moreover, historical analyses of road construction have demonstrated how roads themselves have become heavier over time because of the implementation of safety features such as wider lanes, guardrails, and longer turning radii [70]. Chasing a material reduction in road construction while accepting a consequent reduction in safety standards does not seem to be the most sensible way forward. On the other hand, material flows into the mobility sector can be slowed with better construction quality that leads to less frequent maintenance. From the viewpoint of vehicles, components are getting lighter [71], but the overall mass of vehicles has been increasing in recent years due to ever-larger vehicle sizes offered by manufacturers [72]. From a dematerialisation perspective, the only way to reduce vehicle mass would be to introduce limits to vehicle dimensions and weights, but this strategy would likely be met with pushback from automakers and consumers alike. Thus, the literature recommends better end-of-life disassembly and separation to enable higher recycling rates [73]. While this strategy would have little effect on dematerialisation strategies, it would enable better circularity rates, reduce primary material extraction, and consequently reduce Australia's material footprint (all Australian cars are imported). One additional strategy to limit the use of materials for vehicles is the extension of mass transit. If more people can rely on public transport and live without a personal vehicle, material flows into this system of provision will almost certainly decrease.

The second system of provision that uses most materials is housing, which, as a reminder, encompasses all residential buildings. Buildings, even those made with a timber structure, are predominantly composed of concrete, a product that belongs in the non-metallic mineral category [74]. Similar to vehicles, there are two ways to attempt to dematerialise the housing sector. One would be to build smaller houses, which would require fewer materials. Considering that the average size of dwellings has increased over time and that Australian homes are the largest in the world [75], the market seems to be of a different opinion. The other option is then to use materials more efficiently. Engineers have already indicated how concrete is largely overutilised in construction and that more complex beam geometry would lead to material savings. Unfortunately, these physical savings are not met by economic gains. Complex beam geometries require additional labour, specialised mouldings and tools, and designs that require further work from the engineers [76]. Nevertheless, material efficiency does not solely mean using less material. It also considers strategies to elongate building lifespans, substituting polluting and scarce materials with less problematic alternatives, and reusing building components [77]. One of the most significant limiting factors in material reuse is the lack of space to store second-hand building components and the difficulty in creating a live inventory [78]. Moving forward, one strategy to improve the circularity of housing would be to have policies and interventions in support of the creation of these secondary construction materials hubs.

The food sector is the third largest consumer of materials from a material footprint perspective. If we were only to focus on receiving the same level of nutrition with fewer materials, a straightforward suggestion would be to focus on consuming more calorie-intensive food. This solution is probably not feasible, as calories are only one aspect of nutrition (macro and micronutrients play a vital role, along with dietary preferences and restrictions). Moving forward, we see it as more important to focus on promoting food that is healthy, part of a balanced diet, and that has lower environmental impacts than other alternatives, rather than focusing on lowering the mass of the food we eat [79].

Socioeconomic considerations

In Figure 14, we compare the results of the material footprint calculated for seven provision systems with three socioeconomic statistics: energy use [80], total work hours [81], and gross domestic product [82]. The most striking feature of this figure is that housing, mobility, and food account for some three-quarters of the material footprint, but they together require only 26% of the labour force and produce 23% of the Australian gross domestic product. In terms of energy use, mobility alone is responsible for 28% of overall Australian energy consumption. What is perhaps more surprising is that the energy sector uses one-quarter of all energy used domestically. From this figure, we can infer that decoupling efforts are most effective in those sectors that have high employment, contribute significantly to the gross domestic product, and do not require as many materials as other sectors: services (we have them lumped in the 'other' category of Figure 14). On the other hand, sectors such as construction and transportation are tightly tied to the use of materials and energy. As such, decarbonisation and dematerialisation efforts are uphill battles that focus on material reduction, efficiency gains, and technological advancements to reduce environmental impact. Moving forward, to explore decarbonisation scenarios and the impact of policy decision, we identify integrated assessment models and scenario analysis as two key tools to explore the complex interrelations between material use, economic growth, and productivity.

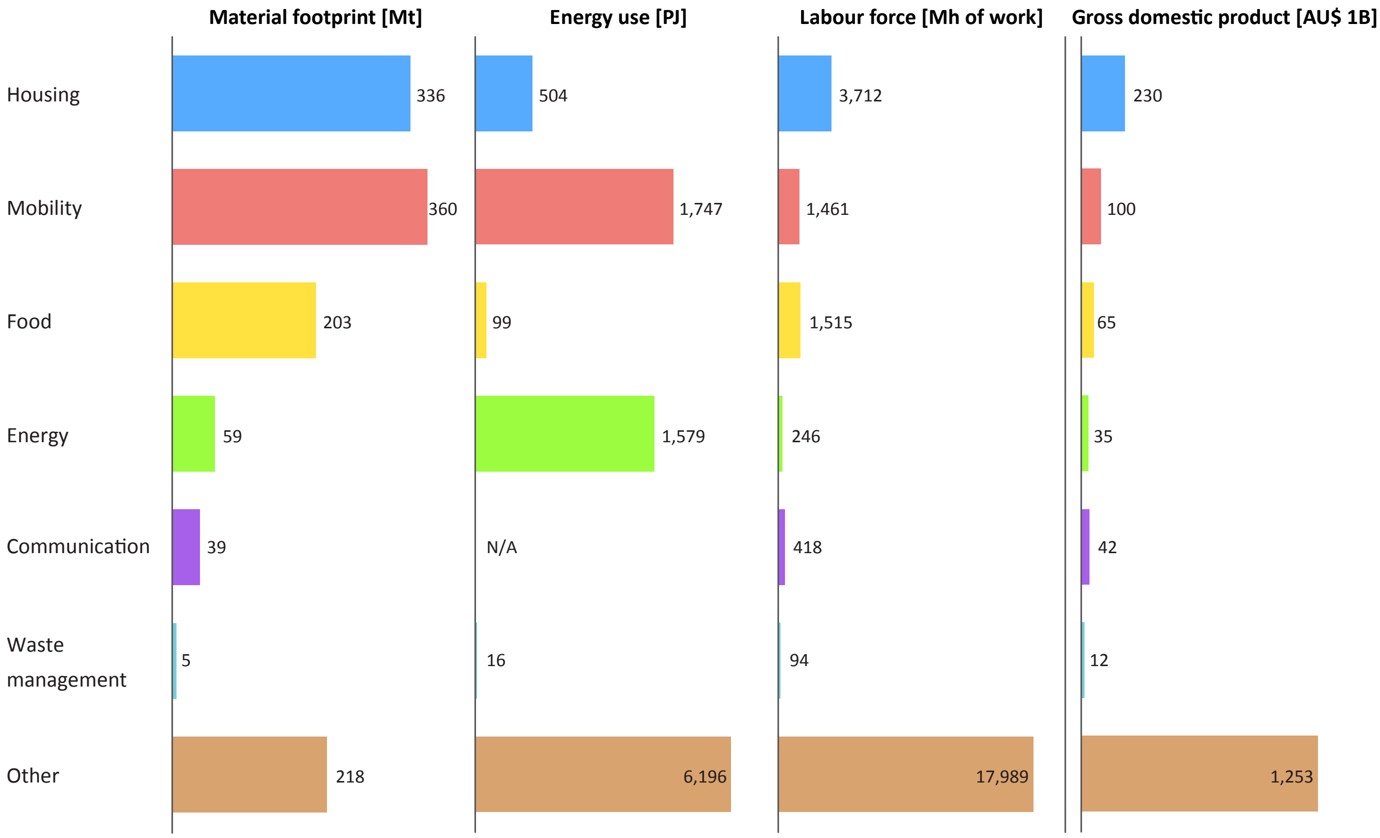


Figure 14 – Material footprint, energy use, number of hours worked in a year, and gross domestic products for seven systems of provision in Australia in 2019.

Conclusions

In this report, we explore the physical aspects of the Australian economy in 2019. From the viewpoint of physical flows, we find that Australia extracted 2,587 Mt, imported 119 Mt, and exported 1,459 Mt of material. These flows resulted in a domestic material consumption of 1,287 Mt. These materials were roughly evenly split between energetic use and material use, plus a considerable quota of mining waste. The net addition to stocks accounted for 343 Mt, most of which went into buildings and infrastructure. The overall domestic processed output was just shy of 1 billion metric tons. 371 Mt of these materials were gangue and mineral tailings, while greenhouse gas emissions were 404 Mt. The overall flow of recycled materials was 39 Mt, which is equivalent to an end-of-life recycling rate of 51.1% (this number does not consider mining waste). The overall circularity, measured as the rate of secondary materials against domestic material consumption, was 3.7%.

We also measured the Australian material footprint. The raw material equivalent imports were 297 Mt, 2.5 times more than physical imports, and the raw material equivalent exports were 1,926 Mt, 1.3 times more than their physical counterparts. These very different ratios indicate that Australia imports semifinished and finished products and exports raw and minimally processed materials. From a footprint perspective, we also found that mobility uses most materials (273 Mt), closely followed by housing (251 Mt). These two sectors, together with food, are responsible for three-quarters of all material needs but contribute to only one-quarter of the gross domestic product.

Efforts to dematerialise the economy can target the mobility and housing sectors, as even marginal gains can translate into substantial reductions in primary material extraction. Moreover, we see ample margins to improve end-of-life recycling rates. Future research should investigate ways to reuse construction and demolition waste, create material hubs to stock and trade these materials, and discover potential uses for mining gangue and tailings, which alone contribute to almost 40% of all Australian domestic processed output.

Method: calculating physical material inputs and outputs

We rely on material flow analysis (MFA) to calculate the physical inputs and outputs from the Australian economy. MFA is a well-established method used to create physical balances of national economies, among other systems [19]. It is based on the principle of mass permanence, and its application to a national economy is standardised in the economy-wide MFA manual developed by the European statistical agency [20]. The economy-wide MFA manual identifies five main constituents to national physical accounts: domestic extraction, physical imports and exports, domestic processed output, and balancing items. In the following sections, we provide brief descriptions of these components.

Domestic extraction

One of the main components of large economies, domestic extraction (DE), indicates all materials sourced within a nation's political boundaries. Some primary materials that constitute DE are agricultural products (e.g., corn, wheat), forestry, wild fishery, ores and quarries, and oil and gas. DE is generally reported in mass per year, where the typical reporting units are metric tons and their derivative units (e.g., megatons, gigatons). While these units do not belong to the international system of units, they appear to be generally accepted by the scientific community.

DE accounts only for domestically sourced materials that are then supplied to some economic activity, either for processing (e.g., mining ores that become concentrates) or immediate consumption (e.g., apples). Materials mobilised but not part of any economic process are termed 'unused extraction' and are not part of material flow accounts. An example of unused extraction is soil stripped away to access a mineral vein. This segregation is done in the spirit of keeping parallelism between physical and economic accounts, thus considering primary materials that are part of the System of National Accounts. DE considers 57 distinct categories, which are then aggregated into four main categories: biomass, fossil energy carriers, metal ores, and non-metallic minerals. Items that are derivative products, such as alloyed metals or refined fuels, are not included as these are not directly extracted from the environment.

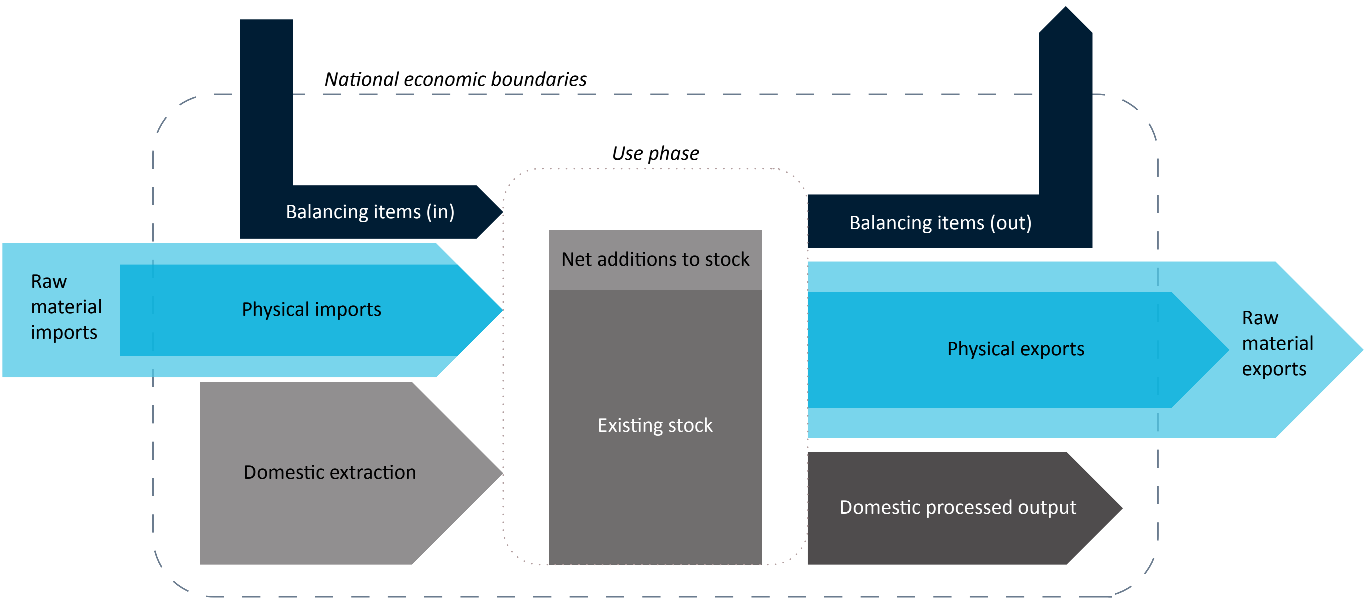


Figure 15 – Material flow analysis conceptual framework. The raw material equivalents are used in the calculation of the material footprint.

Physical imports and exports of materials

The second most crucial component in creating a physical account of national material use is trade. Trade accounts for imports and exports of primary materials, semifinished products, and final goods. Imports and exports are accounted for in metric tons per year, similarly to how DE is calculated. Trade categories cover all the basic categories present in DE accounting and add additional ones for intermediate and final products that cannot be sourced from the environment, such as automobiles.

An attentive reader might wonder why products such as automobiles are present in trade accounts but not DE accounts. Were we to include intermediate and final products in DE accounts, we would count the same material multiple times: a first time after the material extraction from the environment and a second time after its industrial processing. Conversely, the issue of multiple counting does not exist with traded products. On the other hand, were we to ignore the existence of semifinished and finished goods in traded products, the resulting account would miss a considerable mass of inputs and outputs and thus invalidate any material balance.

Domestic processed output

Domestic processed output (DPO) accounts for all emissions from a national economy to the environment at all stages of the physical supply chain of products. DPO comprises five distinct categories, according to the mode through which items are emitted: emissions to air, emissions to land, emissions to water, dissipative use of products, and dissipative loss of products. Emissions to air account for all gaseous emissions that derive from economic activities. The chief component of this category is carbon dioxide (CO_2), but it also comprises all other gaseous emissions, such as methane (CH_4) and carbon monoxide (CO). All gases are reported according to their mass and not their global warming potential, which tends to be reported in carbon dioxide equivalent units (CO_2e).

According to the economy-wide MFA methodology described in the Eurostat manual [20], emissions to land account solely for the illegal dumping of materials on land. Thus, landfilled items are not part of the emissions to land balance. In this regard, we differ from the Eurostat methodology in this report, as we include all landfilled materials as part of the domestic processed output. Emissions to water account solely for the final disposal of material in water, and because most wastewater is opportunely conducted to water treatment plants, this category includes only the illegal dumping of items in rivers and seas. The Australian National Pollutant inventory reports that, in 2019, the mass of substances that was discharged in water was 0.002 Mt [83]. While some of these substances might be highly problematic, they are several orders of magnitude smaller than the typical Australian material flows, and as such negligible from the standpoint of an economy-wide material flow analysis. We do not advocate disregarding these flows, but rather that they should be part of dedicated studies of emissions to water.

The dissipative use of products accounts for those products deliberately dispersed to the environment. Chief examples are seeds and fertilisers, but products like fireworks also belong to this category. Dissipative loss of products accounts for those products unintentionally but inevitably dispersed to the environment during a product lifecycle. The most notorious examples of products that fall into this category are car tyres, brake pads, and lubricants.

Balancing items

Balancing items are necessary on both the input and output side of the economy to consider the fact that several materials undergo physical reactions with the environment. On the input side, balancing items are dominated by oxygen, which is taken from the atmosphere and used in combustion processes. One other example is nitrogenous fertilisers, whose production process sources most materials from the environment prior to their dissipation on the output side. One minor contributor to the balancing items on the input side is water used to produce beverages that are then traded. On the output side, balancing items tend to be dominated by the moisture content of fuels, which is released during the combustion of such fuels as lignite and wood, and that are not separately accounted for in the manner of CO_2, for example.

The existence of balancing items stems from the fact that main material accounts are designed to track the flow of all materials that go from the environment to the economy, with the exclusion of bulk water and atmospheric gases (on the input side). The decision to exclude these items is purely practical: including items like bulk water would render the volumes of all other materials insignificant. Note that this decision conforms with international economy-wide material flow analysis standards. For reference, the Australian Bureau of Statistics reported that, in 2019, the total Australian water use was 78,675 Mt [84], or roughly two orders of magnitude larger than the sum of all materials used in the Australian economy (917 Mt).

Data sources

The data we used to compile the Australian economy-wide material cycle were sourced from various datasets and publications. In general, we opted for domestic data sources whenever possible. These domestically sourced data were: solid and liquid waste and recycling data, which come from the Australian Bureau of Statistics waste account [45]. Furthermore, air emissions data were taken from the Australian national inventory report to the United Nations Framework Convention on Climate Change (UNFCCC) [85].

For those data that were not available in domestically compiled datasets, we relied on established international datasets. We retrieved domestic extraction and trade data from the Global Material Flows Database of the International Resource Panel [86]. We calculated balancing items flows and seed and fertiliser use by applying the method listed in the Eurostat MFA manual [20]. This method requires knowledge of the number of people [87] and animals [88], farmland area [88], fertiliser use [89], energy use [85], and trade of beverages [86].

We could not provide any estimates related to the uncertainty of these results as all of the data sources we encountered do not provide any quantitative or qualitative information related to the uncertainty of their datasets. Broadly speaking, economic and population data tend to be very accurate, extractive information and trade information have varying degrees of accuracy depending on the economic value and strategic importance of the extracted materials, and waste data tend to be the least reliable.

Recycling rate and circularity rate

The recycling rate is measured as the mass of materials that are recycled against all the waste generated (note that this waste data excludes mining waste). This relation is expressed in Equation 1.

$$recycling\ rate = \frac{mass\ of\ recycled\ materials}{mass\ of\ produced\ waste\ (excl.\ mining)} \quad (1)$$

The circularity rate considers the mass of secondary materials against all materials used within the economy. This rate is reported in Equation 2.

$$circularity\ rate = \frac{mass\ of\ domestically\ rcl\ mat +\ mass\ of\ rcl\ mat\ in\ imports}{domestic\ material\ consumption} \quad (2)$$

These formulas adhere to international standards and allow for the comparison of Australia's rates with those of other countries.

Method: calculating raw material equivalents and material footprint

The results created using the material flow method illustrated in section 6 measure the mass of materials effectively used within a national economy. These results do not consider that many semifinished and imported materials weigh much less than their raw material counterparts, as much of the initial mass is discarded during refining and manufacturing. For example, a modern laptop might weigh some 2 kg, but excavating several dozen kilograms of ores is often necessary to obtain enough metals for its production. This disparity between the mass of traded products and their raw material counterparts is valid for most products, but it is especially remarkable in the case of metals, whose typical ore grade concentration is in the single-digit percentages [90]. To consider this disparity, researchers have envisioned a method to allocate to the final user the total mass of raw materials needed to produce the products they employ: the material footprint [49]. The material footprint uses raw material extraction data and allocates it to final users leveraging multi-regional economic input-output tables. This method is used today to measure progress towards sustainable development goals 8 and 12 [91]. Further, it provides a clear linkage between material extraction and final use, regardless of the geographical boundaries in which resources undergo intermediate processing. In other words, countries cannot artificially decrease their domestic material use by simply relocating production abroad [92].

The calculation of the origin of material footprints by Australian states and territories and material types was based on a carbon map approach [93]. This approach splits the total material footprint into the industry sectors from which the material usage originates, as well as into the product groups in which the materials become embodied, thus enabling a more accurate calculation of imports vs domestic sourced material usage.

Data sources

We used Release 057 of the GLORIA global environmentally-extended multi-region input-output (MRIO) database [91], constructed in the Global MRIO Lab [94] to generate global economic and material flow data. Australian economic data was sourced from the Australian IE Lab, using the economic data feeds listed in Table 2.

Australian economic data was then nested into the global economic data according to the methodology developed by Fry et al. [101].

The state-by-state breakdown of material flows was downscaled from the Australian material flow data in GLORIA on the basis of total Australian production, using nested Australian financial data.

Table 2 – Summary of input-output data sources used for creating the Australian multi-regional input-output tables for the analysis of Australian states and territories' material footprints.

TITLE	SOURCE	LATEST RELEASE / YEAR USED	REFERENCE
Australian System of National Accounts	ABS Catalogue Number 5204.0, Australian Bureau of Statistics.	2019–20	[95]
Australian National Accounts: National Income, Expenditure and Product	ABS Catalogue Number 5206.0, Australian Bureau of Statistics.	2020	[96]
Australian National Accounts: Input-Output Tables	ABS Catalogue Number 5209.0, Australian Bureau of Statistics.	2017–18	[97]
Australian National Accounts, Input-Output Tables (Product Details)	ABS Catalogue Number 5215.0, Australian Bureau of Statistics.	2017–18	[98]
Australian National Accounts: Supply Use Tables	ABS Catalogue Number 5217.0, Australian Bureau of Statistics.	2018–19	[99]
Australian National Accounts: State Accounts	ABS Catalogue Number 5220.0, Australian Bureau of Statistics.	2019–20	[100]

Limitations of this analysis

When compiling material flow data and material footprint data it is common to encounter data gaps and inconsistencies that need to be harmonised to compile consistent results. In our case, we had to infer the material outflows from the stocks by balancing the overall waste mass reported in official waste statistics [45] with the share of materials discarded in one year (e.g., newspapers). In practice, this formula is indicated in Equation 3:

$$waste\ from\ stock = total\ waste - one\ year\ lived\ items \quad (3)$$

One other limitation that we always encounter in economy-wide material flow analysis is the lack of uncertainty in our results. Almost all of the data we used to create this report come from national statistics (see sections 6.5 and 7.1 for details), which never report their associated uncertainty. For this reason, we are unable to quantify the uncertainty associated with our results. There is good confidence around production and import data, especially because of their financial importance [19]. Slightly less so on exports (at times discrepancies can be encountered between the mass of an exported product X between countries A and B, and the mass for the same product X imported to country B from country A). Waste data are notoriously affected by high uncertainty [102, 103], but we have no reason to label the Australian official data on waste as unreliable. As such, besides this qualitative assessment, we cannot quantify the uncertainty associated with our results.

We also note that we do not quantify reuse within the Australian economy. The reason is twofold: first, reuse is part of the use phase. Flows do not leave the socioeconomic sphere and are thus not reported in waste statistics. Note that, with extensive reuse, we should see a reduction in waste generation (because people use things for longer) and/or a reduction in material demand, as people opt for an existing product rather than a new one. Unfortunately, neither seems to be the case, as both domestic material consumption and waste generation increased compared with 2015 data (cf. Figure 13). Second, data on reuse do not exist, and we cannot thus include them in our work.

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