Appendix B

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1. Assessment framework

Technical frameworks to assess the performance of a circular economy have distinct strengths and weaknesses. Process-based Life Cycle Assessment (LCA) excels at assessing the environmental impact at the product level but falls short in capturing the complexities of entire value chains and economies. Economy-wide Material Flow Analysis (MFA) captures the entire domestic economy, offering valuable headline indicators on direct material flows, but obscures information for closing supply-chain loops as it observes the economy as a black box. Lastly, an environmentally extended input-output (IO) approach addresses these gaps by providing an economy-wide perspective, capturing inter-industry flows and lifecycle impacts. While IO data is typically published by governments at the national level, a global IO model connects multiple regions through supply-chain networks, allowing for the tracing of impacts beyond national boundaries. Advanced approaches can combine these methods in a hybrid framework allows for leveraging the distinct strengths of LCA, MFA and IO, offering the most comprehensive approach to circularity assessment at the national and subnational level[1]. These methods are advanced through this research as we move towards a consistent, integrated circular assessment and monitoring framework.

1.1. Material flow analysis

Economy-Wide Material Flow Analysis (EW-MFA) is a statistical mapping an economy's resource inflows and outflows (e.g., thousand tonnes per year). It describes the physical interaction of a broader economy with the environment and the rest of the world. Relevant indicators of material use can be derived from this approach[2] (Figure 1). As EW-MFA measures a region’s socioeconomic metabolism, it can inform policies on circularity, sustainable growth and material efficiencies[3, 4]. This approach is extensively used in the European Union (EU-28) as part of monitoring frameworks to assess the transition towards circular economies and benchmarking progress among member countries[5, 6].

EW-MFA inherently focuses on solid materials rather than water and air flows[7]. A set of indicators derived from EW-MFA and standardised methodological guidelines are available[8-10]. EW-MFA is relied upon to assess the physical scale of economies, energic and material use, emission and waste outflows, and the degree of efficiency of production activites[11].

Although EW-MFA allows for accounting emissions and waste flows, it focuses on quantifying the flow of primary materials. Therefore, recycled flows recirculating into the economy are not represented, which is a limitation of this approach[7]. To address this limitation, extended EW-MFA frameworks have been proposed which account for secondary materials[5].

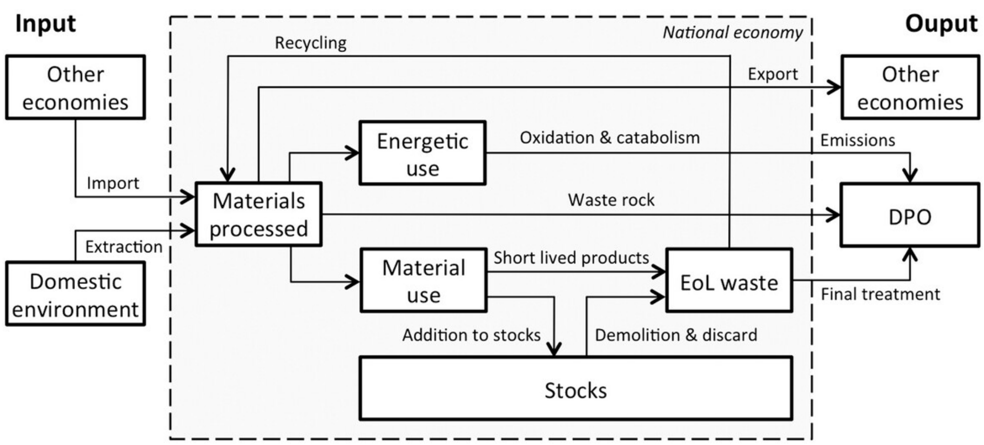

Figure 1. A general model of economy-wide material flows from resource inputs imports and extraction to wastes, emissions and export outputs.
Reproduced under a CC-BY 4.0 licence from Haas et al.[12]

While the EW-MFA framework is crucial for mapping the scale and overall composition of an economic system, one critical limitation is that it treats the economy as a "black box." The lack of intermediate flows between industrial sectors and consumers makes it difficult to understand the structure of an economy, and therefore, challenging to derive comprehensive insights, design appropriate circular response measures and implement effective strategies across sectors and system levels. Another limitation of EW-MFA is its focus on direct, physical flows, in and out of the chosen system boundary. The lack of information on impacts outside the immediate socioeconomic system boundary limits its application for lifecycle assessment. These limitations are addressed in the following sections.

1.2. Material footprints

The physical weight of traded goods offers an incomplete picture, as it overlooks the raw materials originally required to produce them. A more comprehensive view is obtained by considering the total amount of raw materials needed to produce these goods in 'raw material equivalents' (RME). This is particularly relevant for finished and semi-finished products, where the RME significantly exceeds their physical weight.

Material footprints (MFs) are a critical metric for advancing the principles of the circular economy. By quantifying the total raw materials extracted to meet consumption demands, MFs provide a comprehensive measure of resource use and environmental impact. The MF metric encompasses biomass, fossil fuels, metal ores, and non-metal ores, offering a holistic view of the resources embedded in production and consumption cycles. MFs can thus be used to help identify areas where materials can be used more effectively. This aligns with the circular economy's goal of minimizing waste and maximizing the utility of existing resources[13]. By pinpointing inefficiencies, businesses and policymakers can develop strategies to optimize resource use, thereby reducing the overall material footprint[14].

Material footprints are instrumental in waste reduction. By understanding the flow of materials through the economy, stakeholders can implement measures to promote recycling, reuse, and the design of longer-lasting products[15]. This not only reduces the volume of waste generated but also conserves valuable resources, contributing to a more sustainable production system.

Furthermore, material footprints provide insights into the environmental impact of production processes[16]. This information is crucial for driving the adoption of sustainable practices, such as the use of renewable resources and the reduction of dependency on non-renewable materials. By highlighting the environmental costs associated with different production methods, material footprints encourage the shift towards greener alternatives[17].

From a policy perspective, material footprint data is invaluable for developing regulations and incentives that support the circular economy[15]. Governments can use this data to create policies that encourage companies to reduce their material use and invest in technologies that facilitate recycling and reuse. Such policies can drive systemic changes that align economic activities with environmental sustainability.

The method described here quantifies the material (minerals, ores, biomass, fuels, and water) inflows – the material footprints within political-administrative boundaries[18]. Alongside material flows, this accounts for embodied environmental flows generated along the supply chain during the production of all goods and services.

The methods utilise Environmentally-Extended Input-Output Analysis (EE-IOA) – a method to quantify the life-cycle of products and services and the associated environmental impacts[19] – together with local activity data to estimate the material and GHG emission footprints of state, Greater Capital and local government regions, taking into account the consumption and investment activity of governments (e.g., procurement, subsidisation) and households, and the total supply required to meet final demand.

2. Environmentally extended input-output model

Material footprints are generally calculated by use of environmentally extended input-output (EEIO) models or material-flow analysis (MFA)[20, 21]. The advantage of EEIO models are that they are comprehensive in nature and can adhere to official economic statistics. In comparison, MFA models are better able to trace individual materials through processing steps, but lack capacity to treat complex product groups and supply-chains. IO data are a core part of economic national accounts and provide the basis for the calculation of derived and aggregate economic indicators such as gross domestic product (GDP) and gross national expenditure (GNE). IO models utilise trade data directly and are based on surveys on economic activity and expenditure by industry and households, as well as other collected data.

EEIO models have been used for many years to calculate energy and environmental impacts embodied in final demand of a country. More recently, as globalisation increased and issues around carbon leakage and border tax adjustments became important, EEIO models have been linked to form multi-regional input-output (MRIO) models. MRIO models are considered the base standard to which to calculate consumption-based accounts in current times. Several MRIO models now exist, with EXIOBASE, GTAP, WIOD, Eora, Gloria originating from academic research projects, and the OECD ICIO and Eurostat FIGARO being developed by government agencies.

MRIO models are born from compromise however, and the ability to link data from different jurisdictions around the world means that data that is reported in one country that is reported differently in a different country must be reconciled. This can lead to deviation from official statistics for a certain country of interest. Early efforts to provide a more robust picture at the country level included the SNAC approach developed by Statistics Netherlands[22] and the UK-MRIO model , both of which nested a domestic table in a global MRIO model. Both these approaches were relatively complex however, with the need to rebalance the global tables around the domestic data of either the Netherlands or the UK. They also provide estimates for the final demand of a country but cannot extract the carbon footprints of actual goods traded. There is a difference between the “environmental impacts embodied in imports” which allocate emissions to final good (like a car) in a conventional consumption-based approach, in comparison to the “environmental impacts embodied in imports” which can be allocated to the actual good being imported (such as steel)[23]. It is non-trivial to be able to both account for the environmental impact of the good at the border and allocate that impact to a “final good” such as a car which may be used domestically or exported for consumption in another country. There is the risk of double counting such emission flows in a MRIO framework[24].

To circumvent these issues, the model used in this work is a so-called “coupled model” approach as documented[25, 26]. Instead of the approach described by Edens et al., which requires a full rebalance of the MRIO tables, it uses a relaxation of the widely used domestic technology assumption with MRIO data on technology used to produce imports. As such the coupled model uses Australian data for the Australian input-output tables and environmental pressures, while import related emissions are calculated using an environmentally extended multiregional input-output (EE-MRIO) database.

One significant advance of the work in WATCH has been the integration of sub-national tables into the coupled model. As the main focus of interest was at the state level and lower, a multi-regional model for Australia was developed in order to have resolution on production processes at the state level, and a novel disaggregation of demand into state, greater capital and LGA level was undertaken to give better insight into local and regional drivers of material footprints.

2.1. Nesting a sub-regional Australian model in a MRIO model

A critical advancement of the work in this project is both the linking of Australian specific IO and other data into a MRIO model, and the disaggregation of the national level IO data to provide state and LGA level insights. The approach taken to nest the Australian IO model in a MRIO model is a multi-step process (see Figure 2). A coupled model is created between the Australian IO data and the MRIO data, from which the Australian IO data is broken down to provide insights at the regional level.

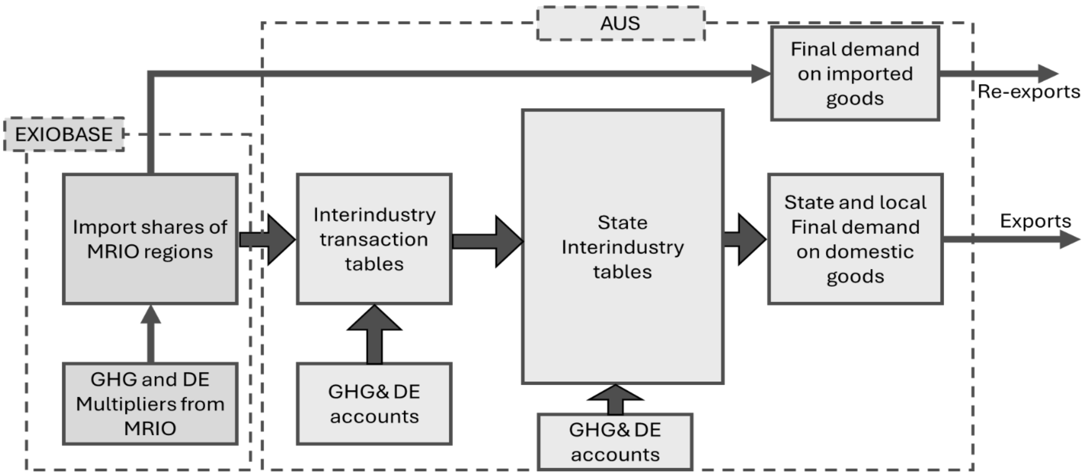

Figure 2. Model structure for the calculation of material footprints linking global impacts through to Australian and state level production and state and local level demand (DE = domestic extraction, GHG = greenhouse gas emissions, MRIO = multi-regional input-output.

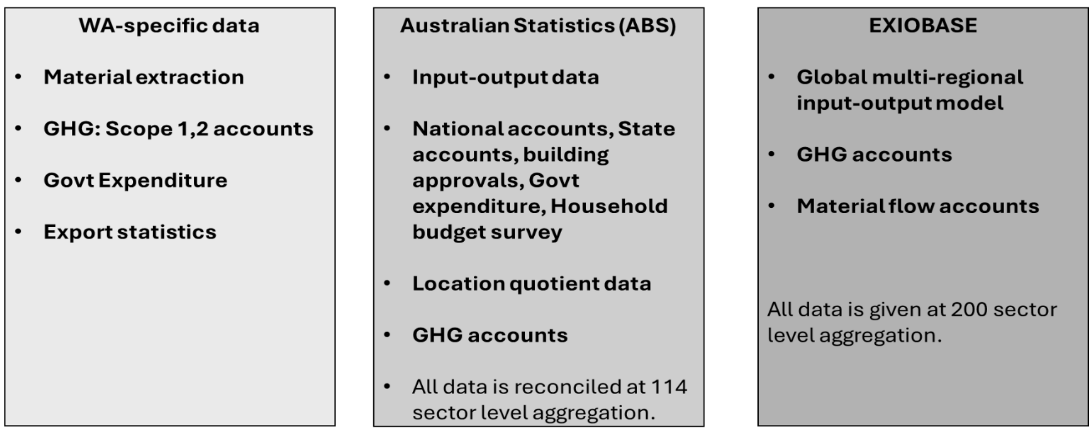

Figure 3. Data sources for the calculation of material footprints linking global impacts through to Australian and state level production and state and local level demand.

The calculation in the coupled model can be broken down into three principal parts:

1. The allocation of Australian production from industrial sources to final products produced in Australia, and the disaggregation of production to state level. This is essentially the allocation of the Australian production (and associated energy, emissions and materials) through the Australian input-output table (representing Australian supply-chains) to Australian final demand. The disaggregation of domestic production to state level production processes based on location quotient data to estimate volume of production by industry and state.

2. The estimation of environmental impacts embodied in imports used in intermediate production of the Australian economy; and the impacts embodied in imports imported directly to final consumers. This is the environmental impacts embodied in the import of goods/services used by Australian industry and households. For example, material footprint associated with foreign feed production used by the Australian agricultural industry would be included here.
3. The disaggregation of Australian final demand into state levels, greater capital and residual levels and further into LGA level. Environmental impacts embodied in exports are included in the calculation.

Some prior knowledge is required for the understanding of the background to the model and of input-output in general. A more detailed write-up behind the concept of the coupled model for linking national and international data is available at: https://doi.org/10.5281/zenodo.1489942. A list of variables is included in the section "Notation" below.

2.2. Australian domestic impacts

The Australian IO model is the mechanism for the allocation of Australian production to final goods, as well as for the allocation to final demand of the environmental impacts embodied in imports which are used in intermediate production of the Australian economy.

The impacts from the domestic model in domestic final demand at the national level are calculated as:

$$\boldsymbol{D^d} = \boldsymbol{s^d}\left(\boldsymbol{I} - \widehat{(\boldsymbol{A^d})}\right)^{-1}\boldsymbol{Y^d} \qquad \text{Equation 1}$$

Where $\boldsymbol{D^d}$ is the domestic component of the Australian footprint, $\boldsymbol{s^d}$ is the environmental impact intensity of Australian production (Australian emissions by sector divided by output by sector), $\boldsymbol{I}$ is an identity matrix (a matrix of ones along the diagonal), $\boldsymbol{A^d}$ is the technical coefficients of the domestically produced output used by Australian industries, $\boldsymbol{Y^d}$ is the final demand of Australian produced output.

The domestic coefficients are calculated as:

$$\boldsymbol{A^d}_{.,j} = \frac{\boldsymbol{Z}_{.,j}}{\boldsymbol{x_j}} \qquad \text{Equation 2}$$

Where $\boldsymbol{A^d}_{.,j}$ are the coefficients of each intermediate input, by sector j, $\boldsymbol{Z}_{.,j}$ are the actual Australian intermediate inputs (domestically sourced), by sector j and $\boldsymbol{x_j}$ is the industrial output by sector j.

Define the Leontief inverse matrix and shows the amount of Domestic production required to fulfill a unit of Australian final demand.

$$\boldsymbol{L^d} = \left(\boldsymbol{I} - \left(\boldsymbol{A^d}\right)\right)^{\boldsymbol{-1}} \qquad \text{Equation 3}$$

and with a diagonal hat shows diagonalisation to keep the sector dimension of the calculation:

$$\boldsymbol{D^d} = (\widehat{\boldsymbol{s^d L^d}})\boldsymbol{Y^d} \qquad \text{Equation 4}$$

Gives the domestic environmental footprints for each product.

2.3. Disaggregation of production to state level

Location quotient approach

The Location Quotient (LQ) is a measure used to analyse the concentration of a particular industry in a region compared to a larger reference area. The LQ is defined as:

$$LQ_{rj} = \frac{\left(\frac{E_{rj}}{E_r}\right)}{\left(\frac{E_j}{E}\right)} \qquad \text{Equation 5}$$

where:

E_{rj} = Employment in industry j in region r

E_r = Total employment in region r

E_j = Employment in industry j in the reference area

E = Total employment in the reference area

A normalised LQ (NLQ) to give the size relative to total Australian production by industry is then:

$$NLQ_{rj} = \frac{LQ_{rj}}{\sum_r LQ_{rj}} \qquad \text{Equation 6}$$

Estimating regional input-output tables

The calculation of state-based input-output tables proceeds in two steps:

Firstly, we adjust the national domestic input-output table using the LQs to estimate state-level tables.

$$A_{ij}^{r,s} = NLQ_{rj} * A_{ij}^{d} \qquad \text{Equation 7}$$

where:

- $A_{ij}^{r,s}$ = Regional input-output coefficient of demand for domestically produced goods
- A_{ij}^{d} = National input-output coefficient of demand for domestically produced goods

Note that the disaggregation of the domestic IO table proportionally allocates production to the state of production based on the LQ data, but is the same for all states so that the summation of the IO coefficients directly adds up to the national IO coefficients for all states.

As no data is available for the import of international goods differentiated by state, it is assumed that the import coefficients of each state are identical:

$$A_{ij}^{m,r} = A_{ij}^{m} \qquad \text{Equation 8}$$

Where:

- $A_{ij}^{m,r}$ = Regional input-output coefficient of demand for imported goods
- A_{ij}^{m} = National input-output coefficient of demand for imported goods

The Leontief inverse of domestically produced goods proceeds as per normal:

$$L_{ij}^{r,s} = \left(I - A_{ij}^{r,s}\right)^{-1} \qquad \text{Equation 9}$$

Where I is the identity matrix.

Note that the approach is short of a full multi-regional input-output table at the state level, as it does not explicitly model inter-state trade. Instead, production processes are broken down into the relative quantity of production from the domestic state versus other states.

The final demand by state is taken from the disaggregation of national final demand as described below to give Y_i^r, but then split into domestic and imported shares based on national data:

$$Y_i^{d,r} = Y_i^r * \frac{Y_i^d}{(Y_i^d + Y_i^m)}$$ Equation 10

$$Y_i^{m,r} = Y_i^r * \frac{Y_i^m}{\left(Y_i^d + Y_i^m\right)}$$ Equation 11

This allows for the estimation of production volumes endogenously by the model, to facilitate the use of input-output balances in the allocation of environmental stressors:

$$x_i^r = L_{ij}^{r,s} * Y_i^r$$ Equation 12

By default, the environmental stressors by state in coefficient form are assumed to be the same as the national average (e.g. to produce 1 million AUD of iron ore, the same extraction of iron ore is undertaken).

$$s_j^r = s_j^d$$ Equation 13

where:

- s_j^r = Regional environmental stressor coefficients
- s_j^d = National environmental stressor coefficients

In the case of material extraction, we have state specific data, so that s_j^{WA} is based on data on material extraction, divided by estimated output of the state.

The state-based table then replaces the national data in equation 4:

$$D_{i,j}^{d,r} = \left(\widehat{s_j^s L_{ij}^{r,s}}\right) Y_i^{d,r}$$ Equation 14

Or in matrix form:

$$\boldsymbol{D}^{d,r} = \left(\widehat{\boldsymbol{s}^{s} \boldsymbol{L}^{r,s}}\right) \boldsymbol{Y}^{d,r}$$ Equation 15

2.4. Environmental impacts embodied in imports – coupled approach

For the impacts embodied in imports, the calculation stems from the basic economic balance where total imports into Australia $\boldsymbol{m}$ is the sum of intermediate imports $\boldsymbol{A^m x}$ and the sum over the k categories (columns) of final imports $\boldsymbol{Y^m}$:

$$\boldsymbol{m} = \boldsymbol{A^m x} + \sum_{\boldsymbol{k}} \boldsymbol{Y_{.,k}}^{\boldsymbol{m}} \qquad \text{Equation 16}$$

Note that $\boldsymbol{A^m x}$ is imports to Australian producer and $\boldsymbol{Y^m}$ is import of products purchased directy by the final consumer. Further note that the calculation of impacts embodied in imports into Australia is done at the Australian level, before being pro-rated to state demand.

To calculate the environmental impacts embodied in imports, we need to know the environmental impacts embodied in imports per unit of import. This information comes from the EXIOABSE model, and is referred to as the MRIO multiplier, denoted $\boldsymbol{Q^{imp}}$. There are a few steps involved in arriving at the multiplier relevant for Australian imports, and in the Australian industry classification – further notes are provided on this topic below in the section, “Multipliers for impacts embodied in imports”.

The multiplier $\boldsymbol{Q^{imp}}$ shows the emissions per unit of imported goods/services and can simply be multiplied by the economic value of the imports, which gives $\boldsymbol{D^m}$

$$\boldsymbol{D^m} = \boldsymbol{Q^{imp} m} \qquad \text{Equation 17}$$

Of note, the environmental impacts embodied in imports corresponds to the goods/services imported into Australia, regardless of who imports the goods/services. For example, the environmental impacts embodied in imports corresponding to the agricultural sector would include feed import to the agricultural sector, as well as agricultural production such as grains used directly by households, the food manufacturing sector, and other industries.

In order to allocate the environmental impacts embodied in imports to the final goods and services consumed by Australian residents, we must apply the import balance of Equation 16 to break down information about which intermediate user $\boldsymbol{A^m x}$ or final user $\boldsymbol{Y^m}$ imports the goods/services.

That is,

$$\boldsymbol{D^m} = \boldsymbol{Q^{imp} m} = \boldsymbol{Q^{imp}}(\boldsymbol{A^m x} + \boldsymbol{Y^m}) \qquad \text{Equation 18}$$

$\boldsymbol{Q^{imp} A^m}$ shows the total imported emissions per unit of Australian production for intermediate use of imports. It is a matrix multiplication between the variable $\boldsymbol{Q^{imp}}$ specified in Equation 27 and the intermediate import component of the coefficient matrix “A”.

Now, as $\boldsymbol{x} = \left(\boldsymbol{I} - \left(\boldsymbol{A^d}\right)\right)^{-1} \boldsymbol{Y^d}$ (from basic input-output relationships), we can substitute to get:

$$\boldsymbol{D^{m}} = \boldsymbol{Q^{imp}m} = \boldsymbol{Q^{imp}}\left(\boldsymbol{A^{m}}\left(\boldsymbol{I} - \left(\boldsymbol{A^{d}}\right)\right)^{-1}\boldsymbol{Y^{d}} + \boldsymbol{Y^{m}}\right)$$ Equation 19

And simplifying using the notation for the Leontief inverse as above:

$$\boldsymbol{D^{m}} = \boldsymbol{Q^{imp}A^{m}L^{d}Y^{d}} + \boldsymbol{Q^{imp}Y^{m}}$$ Equation 20

$\boldsymbol{Q^{imp}A^{m}L^{d}}$ is a matrix multiplication between the matrix $\boldsymbol{Q^{imp}A^{m}}$ (which shows imported emissions per unit of Australian production) and $\boldsymbol{L^{d}}$ (which shows the total Australian production required per unit of final demand).

Equation 13 is thus allocating the environmental impacts embodied in imports $\boldsymbol{D^{m}}$ (on the left hand side) to the final goods/services of Australian finally produced goods ($\boldsymbol{Y^{d}}$) and imports direct to final demand ($\boldsymbol{Y^{m}}$) – on the right hand side.

Given that we need to allocate the impacts embodied in imports to the state level rather than the national level, we substitute in the earlier state-based equations for the national counterparts

$$\boldsymbol{D^{m,r}} = \boldsymbol{Q^{imp}A^{m,r}}\boldsymbol{L}^{r,s}\boldsymbol{Y^{d,r}} + \boldsymbol{Q^{imp}Y^{m,r}}$$ Equation 21

2.5. Total environmental footprints

The total environmental footprint from industrial sources is the summation of Equation 7 and 13, and make the total Australian footprint for goods and services as:

$$\boldsymbol{D^{d+m,r}} = \left(\widehat{\boldsymbol{s}^{s}\boldsymbol{L}^{r,s}}\right)\boldsymbol{Y}^{d,r} + \boldsymbol{Q^{imp}}\boldsymbol{A}^{m,r}\boldsymbol{L}^{r,s}\boldsymbol{Y^{d,r}} + \boldsymbol{Q^{imp}Y^{m,r}}$$ Equation 22

2.6. Disaggregating national and state final demand

The ultimate driver of the input-output models described above is the final demand of each region modelled. The final demand includes the demand of households, government, capital formation and exports, i.e. the demand for goods or services that are no longer used in production processes in the year and region of interest. Household final demand is the main component of final demand, but there are also significant contributions from government consumption and capital formation. For some commodity groups, exports are also highly important.

Whilst the input-output model developed above models production processes to the state level – allowing for the consideration of quantity of production produced locally versus in other states or internationally, there is no further resolution on production beyond the state. An approach to fill the gap for footprint-based approaches is to disaggregate the national or state demand to higher regional resolutions. This allows insight into drivers of material footprints at high levels of resolution, whilst still using the assumption of production processes in each industry being identical at the state (or national) level.

A multi-faceted approach is taken to disaggregate final demand.

Household expenditure data is integrated in COICOP classification. A balancing (RAS) based approach is used to reconcile the consumption by input-output industry group (IOIG) and COICOP data. COICOP data is available at state, greater capital and rest of state levels. Further disaggregation to LGA level is done by population.

Government consumption is first broken down to state level by use of state accounts and data on government consumption by category (COFOG) data. As part of this process, the national data is split into consumption by National, State and Local government based on state accounts. Due to the incompatibility of classifications and concepts in COFOG data to IO data, rather than reconciling both datasets simultaneously, COFOG data was used to provide spatial insights into the IO data and state accounts. Further disaggregation to LGA level for local government expenditure was undertaken by use of local government expenditure accounts by COFOG category.

Capital formation is broken down into government, public corporation and private investments. State accounts provide the initial breakdown of this data to the state level. Further disaggregation was undertaken for the construction sector, the key driver of material and other environmental impacts, and the main component (in economic terms) of capital formation. Building approval data was used for the disaggregation, which high provides high spatial resolution (including at LGA level) for a range of building types and for different (private vs public) investment types. As building approval data does not equate to actual investments, the data was only used for spatial distribution, and a two-year time lag was assumed to occur between approval and actual investment[a].

Export data for WA by product group was included explicitly. For all other states, state account aggregates were used to disaggregate national exports.

[a] https://www.planning.nsw.gov.au/policy-and-legislation/housing/housing-supply-insights/quarterly-insights-monitor-q1/trends-in-housing-supply#:~:text=Historically%2C%20there%20is%20a%20lag,significantly%20delayed%2C%20changed%20or%20discontinued.

2.7. Multipliers for impacts embodied in imports

For the calculation of environmental footprints embodied in imports, environmental impact “multipliers” $\boldsymbol{Q}^{imp}$ are required, which show the upstream life-cycle emissions per unit of imports. These multipliers are extracted from the EXIOBASE dataset but require reclassification (due to differing industry classifications between EXIOBASE and the Australian IO table) before implementation in the Coupled model (Equation 10 and onwards).

The re-classified multipliers (in Australian IO classification) are generated by the division of absolute values of environmental impacts embodied in imports by the economic value of imports in order to obtain multipliers per unit of imports. This division is done on derived accounts in absolute terms, as the reclassification involves aggregation across multiple industries. Aggregation can be performed directly for values in absolute terms, but not for intensity values such as multipliers.

Two sets of data are needed from the MRIO:

1) Environmental impacts embodied in imports – these are the full supply chain emissions to point of purchase (i.e. total upstream life-cycle emissions) of sector imports as calculated via the EXIOBASE MRIO. Hence, the value in "Cattle farming" will include all supply chain emissions of cattle farming imports, including the emissions released in cattle farming imports directly, and any emissions associated with feed production used in cattle farming.

2) Value of imports. Reported in million Euro in the EXIOBASE database - these are the total imports into Australia as reported in EXIOBASE. Please note, that the import into Australia from EXIOBASE does not necessarily equal the import into Australia according to Statistics Australia. This is due to the fact that global import = global export in a global MRIO as EXIOBASE, and to make sure this is the case the trade data in EXIOBASE is re-balanced. In addition, re-exports (imports that are directly exported without any transformation by Australian producers are excluded from a MRIO calculation). As the import-value from EXIOBASE is used only as a weight in the calculation of the multipliers from EXIOBASE, the re-balancing is not seen as an issue that affects the carbon footprint in the coupled model. For full details on the handling of trade data in EXIOBASE, the reader is referred to Stadler et al 2018.

These two sets of data are then aggregated to the 115 sector classification for Australia. In the case of one EXIOBASE sector linking to many Australian sectors, the Australian sectors will each be assigned the same EXIOBASE multiplier – for example “Hotels and restaurants” is one sector in EXIOBASE, whilst it is split in the Australian IO table. As EXIOBASE does not provide any more detail on differences in emissions intensity between Hotels and Restaurants, the best we can do is assign the aggregate emissions multiplier to both sectors.

In the case of many EXIOBASE sectors linking to one Australian sector. This occurs for agriculture, where EXIOBASE has 15 agricultural industries, and Australian one. As the Australian IO model can only treat the aggregate import of agricultural goods, the EXIOBASE data must be aggregated. Hence a simple aggregation of EXIOBASE environmental impacts embodied in imports and import value is taken to give a single multiplier for the Australian model. Note that the multiplier is a “weighted” multiplier of the 15 EXIOBASE sectors based on import value.

In the case of many EXIOBASE sectors linking to many Australian sectors, both the above steps are implemented together – all EXIOBASE environmental impacts embodied in imports for the relevant sectors are aggregated, and the same is done for import value. The emission multiplier is calculated as the division of the aggregated environmental impacts embodied in imports by the aggregated imports; then the emission multiplier is assigned to all relevant Australian industry sectors.

When there are one-to-many or many-to-many linkages, the intermediate steps of calculating aggregate “environmental impacts embodied in imports” and “imports” will show double counting of values such that if you sum the value of the aggregated imports over the whole economy, it will be larger than known imports. However, this double counting occurs consistently for both imports and footprints, such that the calculation of multipliers cancels the double counting out.

Mathematically we can express this as:

$\mathbf{Q^{imp}}$ – the multipliers in EXIOBASE classification; dimension 163 industries. Note these multipliers are calculated explicitly for Australian imports.

$\mathbf{D^{imp}}$ – the value of environmental impacts embodied in imports, as extracted from EXIOBASE; dimension 163 industries.

$\boldsymbol{m}$ – the value of imports to Australia, as extracted from EXIOBASE; dimension 163 industries. $\hat{\mathbf{m}}$ signifies diagonalisation

Now, using a ′ to signify matrix transposition,

$$\boldsymbol{D^{imp'}} = \boldsymbol{Q^{imp}}\hat{\boldsymbol{m}} \qquad \text{Equation 23}$$

Or alternatively,

$$\boldsymbol{Q^{imp'}} = \boldsymbol{D^{imp'}}\hat{\boldsymbol{m}}^{\boldsymbol{-1}} \qquad \text{Equation 24}$$

As this data is in EXIOBASE classification, we introduce a concordance matrix as discussed above:

G – the relationship between EXIOBASE 163 and Australian 115 industries. Dimension 163 EXIOBASE industries by 115 Australian industries.

Now we aggregate environmental impacts embodied in imports and imports separately:

$$\boldsymbol{D^{imp,agg}} = [\![(\boldsymbol{D}]\!]^{\boldsymbol{imp'}} * \boldsymbol{G}\big)' \qquad \text{Equation 25}$$

$$\boldsymbol{m^{agg}} = [\![(\boldsymbol{m}]\!]' * \boldsymbol{G})' \qquad \text{Equation 26}$$

And calculate the aggregated multipliers, the same as in equation 19:

$$\boldsymbol{Q^{imp,agg}} = \big(\boldsymbol{D^{imp,agg'}} * (\widehat{\boldsymbol{m}^{agg}})^{\boldsymbol{-1}}\big)' \qquad \text{Equation 27}$$

Gives us the multipliers in Australian classification. The «import» multipliers cover the supply chain to the point of import into Australia.

2.8. Disaggregation of Scope 1, 2 and 3 emissions

The default setup of the coupled model calculates consumption-based accounts that aggregates Scope 2 and 3 emissions together. Scope 1 emissions are reported separately. Scope 1 emissions in a consumption-based carbon accounting approach are the direct emissions associated with activity by final demand entities (e.g., heating or cooking by households using natural gas, vehicle use of households using internal combustion engines).

Scope 2 emissions comprise emissions from the generation of electricity. The upstream emissions associated with the potential extraction of energy carriers or the consumption of other resources in the power plant for operational purposes, as well as transmission and distribution losses, are however included as part of Scope 3. Yet, all of these air releases are part of the same supply chain and integrated in the Australian and EXIOBASE IO tables.

Scope 2 emissions can be extracted from the IO model as the direct purchase of electricity going to final demand. Electricity is assumed to be sourced only from domestic suppliers. Only direct emissions due to electricity production are included, and not emissions upstream (e.g., due to coal mining).

Scope 3 emissions are calculated as the full supply-chain impact ("environmental footprint") minus the scope 2 emissions. Scope 1 emissions as mentioned above are treated separately.

3. Compiling environmental accounts

3.1. Global accounts

The EXIOBASE model has been used for MRIO data[27]. EXIOBASE has coverage from 1995 to 2019 in v3.8.2 and a preliminary version 3.9 has been used in this work that has a new release of data until 2021 including updated material, energy and emission accounts. EXIOBASE is a global EE-MRIO database developed by a consortium of a range of European research institutions and financed by European research framework programs. The tables include 44 countries and 5 "rest-of-the-world" regions and offer a great level of detail with 163 sectors. Emission data covers all GHGs included in the project (CO2, CH4, N2O, SF6, HFCs and PFCs). The emissions cover all sources except the IPCC category Land use, land use change and forestry due to the difficulty in assigning emissions of indirect land use change. Material accounts are consistent with the UNEP material flow data[28].

3.2. Emission accounts

Regional and local emission accounts were compiled using a bottom-up and top-down approach. Supply chain emissions are taken from the EEIO model and State and Territory Greenhouse Gas Inventories[29]. Direct emission related to transport and stationary combustion (i.e., scope 1), and indirect emission related to electricity consumption (i.e., scope 2) are compiled using physical activity data acquired from utilities and energy statistics.

On-road transport emissions are quantified using the same consistent method adopted by the European Commission in the compilation of EDGAR (Emissions Database for Global Atmospheric Research)[30]. This approach considers the registered vehicle fleet, vehicle technology, fuel consumption, and on-road activity. Emission factors are derived from the Australian National Greenhouse Gas Accounts[31]. Local accounts are balanced against Australian petroleum statistics[32] at the state and national level to ensure consistency.

Stationary combustion includes emissions related to natural gas and LPG consumption. Emission factors from the National Greenhouse Gas Accounts[31] are applied to activity data sourced from utilities providers. Where primary data is not available, a gas consumption model is used, which considers building/dwelling composition, gas service points, alternative technology availability, and seasonal variability[b]. Local accounts are balanced at the state and national level to ensure consistency.

Emissions related to electricity consumption are estimated based on facility-level information, sourced from the Australian Energy Market Operator (AEMO), and aggregated consumption activity sourced from utility providers. Emission factors are derived from facility energy sources and cross-checked against State and Territory Greenhouse Gas Inventories. Regional accounts are balanced to the grid and state-level to ensure consistency.

3.3. Material accounts

Regional and local material accounts are compiled using commodity-level statistics from state and national government agencies, scientific publications, and industry bodies. Material accounts cover domestic extraction, physical trade, and solid and liquid waste. A python program was developed to extract, transform and load (ETL) raw datasets, generate clean data feeds, and compile consistent material accounts as per the UNEP Material Flow Accounting classification. Where overlapping primary data or conflicts exist (temporal or spatial), a hierarchical data criterion (Figure 4) and reconciliation process is applied[b].

Physical quantities related to the domestic extraction of metal ores, non-metallic minerals, fossil fuels, and biomass are compiled at the state, and if available, local level based on production and sales data primarily sourced from state government royalty information systems. Physical quantities related to international trade is compiled based on port-level commodity trade information, provided by the Australian Bureau of Statistics (ABS) and Department of Home Affairs. Where physical information is not available, physical quantities are estimated based on commodity-level material intensities (i.e., per unit of monetary value).

Waste accounts are compiled by harmonising data from the ABS Waste Account[33], the National Waste Database[34], and waste collection and treatment data sourced from state agencies and local government authorities. Due to limited information of waste generating and recovery activates at the local level, detailed in the main report[39], waste production and material content are estimated using top-down approaches[b]. See Fry and Baynes, 2021[35] for more information.

3.4. Built stocks

The built stock is quantified using a bottom-up approach. We use a set of different building archetypes that represent typical construction typologies in Greater Perth and the rest of WA. Given the lack of spatialised data building-by-building, we use average material intensities for a total of five building archetypes. Material intensities are derived from using averages of 13,760 individual buildings in the City of Melbourne, Australia[36]. The material intensities of the different building archetypes, used to quantify the in-use building stock and the net-addition to stock are presented in Table 1. These material intensities are multiplied by the gross floor areas of buildings derived from building attribute data to obtain the material stock. For the net addition to stock, we apply the same multipliers to the gross floor area of new buildings in 2021 received from building approval data[37] and remove the materials resulting from demolition for the same year[38].

Limitations of the current approach and expected future research has been detailed in the main report[39].

[b] Manuscript under preparation

Table 1: Material intensities of various building archetypes, based on Stephan and Athanassiadis (2017)[36]

Building class	Apartment block		House						
Num storeys	1--2	3	4+	House	1--3	4--7	8--35	1 storey	2
Concrete (kg/m²(GFA))	2,299.83	1,524.02	1,095.02	360.20	1,905.21	1,324.51	1,051.95	577.12	280.28
Steel (kg/m²(GFA))	78.65	53.20	51.94	16.32	52.48	35.12	48.19	66.50	34.35
Timber (kg/m²(GFA))	19.88	19.13	10.05	79.78	13.07	7.06	5.30	8.48	4.02
Glass (kg/m²(GFA))	2.69	2.55	3.10	1.07	6.64	2.40	1.96	1.38	0.53
Carpet (kg/m²(GFA))	1.07	1.12	2.07	0.29			0.35		0.18
Insulation (kg/m²(GFA))	0.24	0.23	0.11	1.32	0.14	0.03	0.03	0.23	0.25
Ceramics (kg/m²(GFA))	188.25	158.43	7.89	195.57	90.86	94.66	23.30	138.62	35.69
Plastics (kg/m²(GFA))	1.64	1.24	0.35	1.33	0.63	0.22	0.13	1.30	0.65
Plasterboard (kg/m²(GFA))	3.55	3.98	10.84	32.11	12.01	6.76	4.79	0.99	0.40
Aluminium (kg/m²(GFA))	0.83	0.67	1.14	0.39	0.78	0.60	1.27	0.46	0.32

4. Data stocktake

To ensure accurate, consistent, timely and relevant results, we conducted a comprehensive data stocktake across WA using a structured evaluation framework aligned with best data sourcing practices.

The methodology involved systematically assessing datasets against six key criteria (Figure 4): data reliability, determined by source credibility and methodological rigor; completeness, ensuring datasets encompassed all necessary variables with minimal gaps; temporal correlation, evaluating alignment with the study's timeframe; geographical correlation, assessing relevance to the specific spatial scales of analysis; other correlation, considering compatibility with complementary datasets and sectoral classifications; and expert judgment, leveraging domain expertise to validate data quality and resolve uncertainties. Where multiple data sources existed, we prioritized those with the highest score across all dimensions. This process ensured that only the most robust and relevant data informed the circular economy assessment, enhancing the accuracy and credibility of the findings.

The results of the data stocktake process are expected to be published in future research stages.

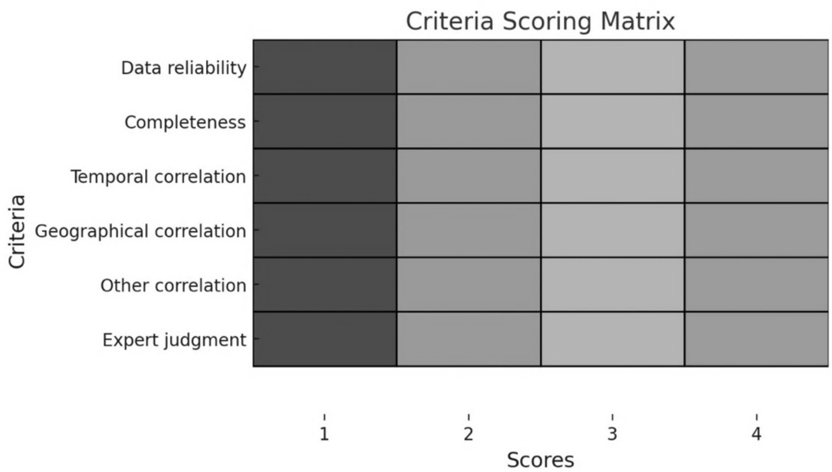

Figure 4. Data source criteria scoring matrix employed in this research.

5. Notation

Variables used in the derivation are defined as:

Variable	Name	Description
$\boldsymbol{I}$	The identity matrix	The Matrix "I" has "1" in the diagonal and the number 0 outside the diagonal and it is only used in the calculation of the Leontief Inverse
$\boldsymbol{A}^{\boldsymbol{d}}$	Coefficient matrix - domestic	Inter-industry coefficients of domestic transactions (direct requirements matrix), dimension n x n
$\boldsymbol{A}^{\boldsymbol{m}}$	Coefficient matrix - imports	Inter-industry coefficients of import transactions (direct requirements matrix), dimension n x n
$\mathbf{L}^{\boldsymbol{d}}$	Leontief inverse	Leontief inverse (total requirements matrix), Domestic transactions only, dimension n x n
$\mathbf{Y}^{\boldsymbol{d}}$	Final demand, domestic	Final demand matrix of domestically produced goods (sectors and final demand categories), dimension n x r
$\mathbf{Y}^{\boldsymbol{m}}$	Final demand, imports	Final demand matrix of imported goods (sectors and final demand categories), dimension n x r
$\mathbf{x}$	Gross output	Total output of industries, dimension n
$\mathbf{m}$	imports	Monetary imports, dimension n x n
$\boldsymbol{s}^{\boldsymbol{d}}$	Emission coefficients	Emissions per unit output of production sectors, domestic sectors only, data made available as a matrix of air emissions, but only 1 category of air emission modelled at a time, hence dimension 1 x n.
$\mathbf{D}$	footprints	Footprint of final demand
$\boldsymbol{Q}^{\boldsymbol{imp},\mathbf{agg}}$	multipliers	Emissions per unit of final demand, superscript signifies that they relate to Australian imports, in 115 sector classification
i,j		Industries, 115 sectors in the Australian model
r		Region of demand
s		Region of supply

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Unless otherwise noted, the methodologies and data models included in this report are licensed from Open Corridor, © 2024. All rights reserved. Open Corridor is a non-profit organisation and custodian of open-source technologies for a more collaborative and sustainable world.

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