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Household Consumption Emissions in the Inner West Local Government Area

INNER WEST COUNCIL

Prepared by

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The University of Sydney
Integrated Sustainability Analysis ™

Household Consumption Emissions in the Inner West Local Government Area

Results of consultancy work undertaken for the Inner West Council

by

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The University of Sydney

The outputs from this report will also be submitted to a journal in the form of a research article with all authors listed above, and delegates from the Council, and other academic experts.

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1 Introduction

The concept of "carbon accounting" has been extensively addressed in the theoretical accounting literature, with the application of social science theories of framing and empirical research methods, for formulating a common, unique and comprehensive understanding of this term (Burritt et al. 2002; Ascui and Lovell 2011; Stechemesser and Guenther 2012). For quantifying and analysing the environmental impacts of organisations, there have been calls for employing integrated environmental accounting tools for effective decision making (Burritt et al. 2002), in particular by taking a 'whole-of-life' cycle approach for evaluating the environmental costs of products and services (Ratnatunga and Balachandran 2009). Two such environmental accounting tools are "life cycle assessment and "input-output analysis". These tools can be applied for carbon accounting of products, businesses, organisations or even to the case of products bought by households.

In the process of "*accounting for the environment*", Gray and Bebbington (2001) emphasise the need for considering the entire life-cycle of a product. They give an example of an everyday product – "a pencil", often perceived as a relatively simple product. The authors describe that a comprehensive life cycle assessment must trace impacts along all backward links (hereon called the "upstream supply chain") from the use of machines for the extraction of raw materials from the biosphere (-and carbon emissions/energy use associated with this step), to the transportation of those raw materials (-and associated emissions/energy use) to the production site, and all subsequent steps that feed into the production of a single product – "a pencil". Each of these stages in turn have a life cycle of their own, for example construction of machines requires the input of raw materials, which in turn requires the input of energy and associated carbon emissions. It quickly becomes evident that lifecycles are intertwined and interconnected, hence needing for a boundary to be drawn for accounting of environmental impacts (e.g. carbon emissions). Collection of detailed and specific data for all lifecycles is a time-consuming and expensive process (Schmidt 2009). Therefore, Gray and Bebbington (2001) explicitly state that "*no LCA can be complete and comprehensive*". The incomplete nature of LCAs often results in so-called truncation errors (Lenzen 2000b). To avoid these errors, the macroeconomic accounting technique called "input-output analysis" becomes useful.

Input-output analysis (IOA) takes into account all upstream supply chains of a product, entity or a nation, thus removing the issue of boundary selection. The technique is based on input-output tables (UNSD 2009) that follow the national accounting guidelines, and are derived from business accounts (UNSD 2000). Input-output tables provide a snapshot of an economy in accounting terms – outputs from one industry sector are used as inputs by another industry sector to produce goods and services. Each country has its own input-output table that shows the interactions between sectors in the respective country's economy. The input-output tables of national economies and additional data on inter-regional trade come together to make multi-regional input-output (MRIO) tables. MRIO tables include intra- and inter-industry transactions for more than one region – the tables can either be at a global level (global MRIO tables feature data on more than one country), or sub-national level (MRIO tables for different regions of a country).

Input-output tables have been widely used for carbon accounting applications (Minx et al. 2009). In particular, for managing corporate carbon performance, IOA serves as a useful screening tool for appraising both the direct and indirect impacts of doing business (Huang et al. 2009). It is important to take both the direct and indirect impacts into account, since lifecycles and supply chains of inputs consumed by a business are long and vastly complex with many upstream supply chain links. This is due to the increasing separation between production and consumption systems. Since these systems are no longer localised, Burritt and Schaltegger (2014) stress the importance of developing quantitative techniques for measuring sustainability performance in supply chains. From a business perspective, an input-output based supply chain assessment offers useful insights on procurement decisions – emissions profile of businesses and their suppliers. A term often used for carbon accounting of the entire supply chain from a consumption-based perspective is “carbon footprint”. Wiedmann and Minx (2008) state that “*the carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.*" For the case of a business, a carbon footprint assessment using input-output analysis would involve the inclusion of all upstream supply chains that feed into the business entity. The business in this sense is considered a “final user”, and all goods and services that the business buys, plus all intermediate transformation stages from raw material extraction to the final product get considered. Both “direct” and “embodied” “indirect” impacts are taken into account. This all-inclusive approach is also termed consumption-based accounting (Mózner 2015).

Accounting for carbon should be undertaken at multiple scales to create awareness of the negative environmental impacts of consumption. Businesses cannot be considered in isolation, hence the application of this technique at various functional scales is important (Csutora and Harangozo 2017). Burritt and Schaltegger (2014) emphasise the need for bringing together transdisciplinary teams to comprehensively address the complexity in supply chains from different perspectives. We address this notion by presenting a transdisciplinary study of consumption-based emissions for a selected community area in Greater Sydney region of Australia. This study brings together specialised knowledge of experts working in accounting, business, sustainability assessment, economics, engineering and corporate sustainability managers. The aim of this study is to undertake a comprehensive consumption-based supply-chain assessment of a community’s emissions, based on their expenditure data. The novelty of this study is as follows:

a) MRIO table construction is a time-consuming and expensive process. These tables are often constructed using a fixed regional and sectoral classification. In this study, we use a comprehensive virtual laboratory platform (Lenzen et al. 2014) for constructing a customised MRIO database, specific to the case study of interest, using a wide-array of statistical data sources, including the Household Expenditure Survey (ABS 2017a).

b) Prior studies on consumption-based carbon accounting of household consumption have primarily been focussed at a national scale (Weber and Matthews 2008; Druckman and Jackson 2009). Here, we use a detailed sub-national regional MRIO table of Australia for assessing the consumption patterns of households in a local council area to undertake a supply chain carbon footprint assessment of the community's emissions.

2 Methods

2.1 Case study

We undertake a consumption-based carbon footprint assessment of households in a Local Government Area of Australia.

Australia is large nation with many states that are divided into Local Government Areas (LGAs). In this study, we focus on the Inner West Council (IWC) area, located in the Greater Sydney region of the state of New South Wales, Australia (Figure 1).

The Council is made up of several suburbs, including Marrickville, Balmain, Ashfield and many others (see Table 1). The consumption-patterns of the residents of the IWC area are included in the Household Expenditure Survey (HES) data that are collected by the Australian Bureau of Statistics (ABS) (ABS 2017a). The survey is undertaken every six years, and the final data that are made available for open-source access contain estimates of expenditure patterns and the socio-demographic-economic composition of households. HES data offer insights on the living standards of people in different regions. The collection of data involves the sampling of about 11,000 households over a year. At the time of writing, the most recent version of the data-set was available for the financial year 2015-16 (ABS 2017a).

Before unpacking the HES data made available by the ABS, it is worth noting the different classification structures that are used by the ABS for the release of statistical information. The smallest geographical area defined by the ABS are so-called "mesh blocks", which come together to make "Statistical Area Level 1 (SA1s)", which in turn are aggregated into "Statistical Area Level 2 (SA2s)" with an average population of 10,000 persons. Many ABS statistics are released at the SA2 level. SA2s join to form SA3s, which in turn join to form SA4s. The HES data are released at the SA4 level, with an aggregation of areas totalling over 100,000 persons (ABS 2018). The suburbs that make up the Council fall under two SA4 categories – "Sydney – City and Inner South" and "Sydney – Inner West". There is a misalignment between these two SA4 boundaries and the IWC's boundaries. After comparing the SA4 boundaries with the IWC area map, we found that the Council covers a majority of the suburbs that come under the "Sydney – Inner West" SA4 and only a small portion of the "Sydney – City and Inner South" area (Table 1).

Table 1. A comparison of Inner West Council's area with the geographical areas defined under the two ABS structures – Statistical Area Level 2 (SA2) and Statistical Area Level 4 (SA4) (ABS 2018) . The regions that are included in the Council area are marked with a tick (✓), and a cross otherwise (X).

SA4 regions	SA2 regions	Inner West Council area
Sydney – City and Inner South	Newtown - Camperdown - Darlington	Only part of Newtown and
	Marrickville	✓
	Petersham - Stanmore	✓
	Sydenham - Tempe - St Peters	✓
Sydney - Inner West	Concord - Mortlake - Cabarita	X
	Concord West - North Strathfield	X
	Drummoyne - Rodd Point	X
	Five Dock - Abbotsford	X
	Balmain	✓
	Leichhardt - Annandale	✓
	Lilyfield - Rozelle	✓
	Ashfield	✓
	Burwood - Croydon	X Only part of Croydon
	Canterbury (North) - Ashbury	X Only part of Ashbury
	Croydon Park - Enfield	X Only part of Croydon Park
	Dulwich Hill - Lewisham	✓
	Haberfield - Summer Hill	✓
	Homebush	X
	Strathfield	X

2.2 Economic accounting database – multi-regional input-output database

To quantify emissions embodied in the goods and services bought by households in the IWC area, as a first step we constructed a customised multi-regional input-output (MRIO) economic accounting database. We used the Australian Industrial Ecology Virtual Laboratory (Aus IELab; (Lenzen et al. 2014)) for this step. As mentioned above, MRIO tables contain data on more than one region. For this study, we constructed a customised table with 10 selected regions – Inner West Council, Rest of Greater Sydney, Rest of New South Wales, and all other Australian states (Figure 1). For populating these regions with intra-regional and inter-regional trade data, we used a range of accounting data-sets from the ABS, for example data on National Income and Expenditure (ABS 2016e), Australian National Accounts – Input-output tables (ABS 2017b, 2016a), Australian National Accounts – State Accounts (ABS 2016d), Business register (ABS 2016c), Value of agricultural commodities produced (ABS 2016b), Census (ABS 2012), Household Expenditure Survey (ABS 2017a), and others. The HES data are represented at the SA4 level, whereas the input-output data are at SA2 level. We selected a total of 344 sectors for each region. These sectors are listed elsewhere (Foran et al. 2005), and provide a detailed mix of primary, secondary and tertiary industries.

We subjected the aforementioned data-sets through a series of harmonisation and optimisation steps in the Australian IELab for constructing a MRIO table featuring 10 regions and 344 sectors for each region (Figure 1). In order to construct a reliable and accurate MRIO such as the one used in this study, different source data sets must be considered. In most cases, data from different sources are to a certain degree misaligned and even contradictive. However, the information from each data source should be adequately represented in the final MRIO. In order to achieve this, the different data sources must be reconciled by means of mathematical optimisation. Mathematical optimisation smoothens out any discrepancies stemming from different primary data sources in the final MRIO. The AusIELab offers a data reconciliation routine based on a least-squares approach (van der Ploeg 1982). The basic concept of this approach is to consider the reliability of each primary data source, and in cases where conflicting information exists, to find a final solution that reflects all available information according to their reliability. In many cases, different primary data sets are available at different levels of detail. In this case, the AusIELab processes economic data for each SA2 region. The reconciliation routine ensures that the sum of all SA2 regions accurately reflects the information provided in the national statistical data source.

The AusIELab carries out the complete building process from assessing the source data to the final MRIO in a multi-step process, as explained by Geschke and Hadjikakou (2017).

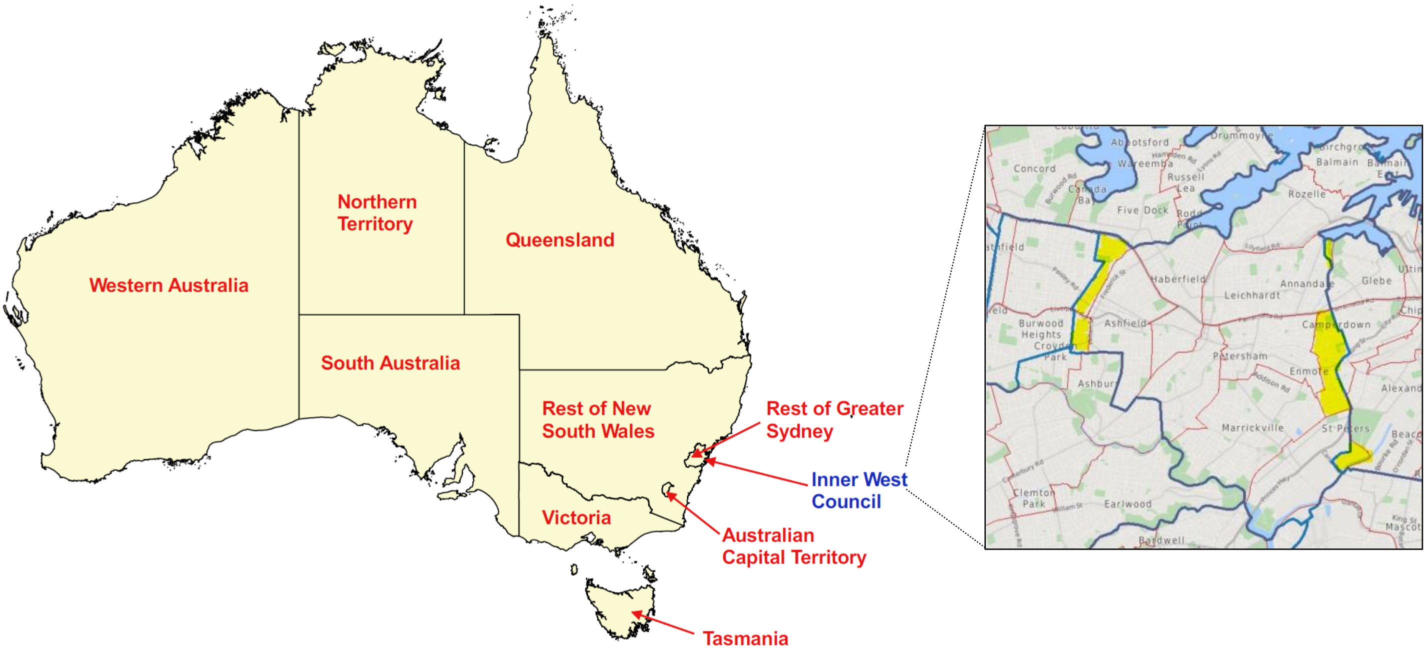


Figure 1. Australian map showing ten distinct regions, including the Inner West Council region that we nested in a MRIO database containing nine other regions.

2.3 Commodities bought by households – Household Expenditure Survey

We sourced data on household expenditure for all Australian states. The household expenditure survey (HES) is conducted by the ABS every six years, and the data are presented at a household rather than at a per-capita level (ABS 2017a). We compared the HES data for the "Sydney – Inner West" and "Sydney – City and Inner South" SA4s to determine the expenditure profile for the two regions. The HES data provide information on the mean weekly expenditure profile, average household size, and the estimated number of households in different regions. We added the expenditure profiles for the two SA4s and aggregated the 500+ expenditure categories into 15 broad groups. Figure 2 presents a snapshot of the different commodities bought, and services acquired by a typical household in the Inner West Council area.

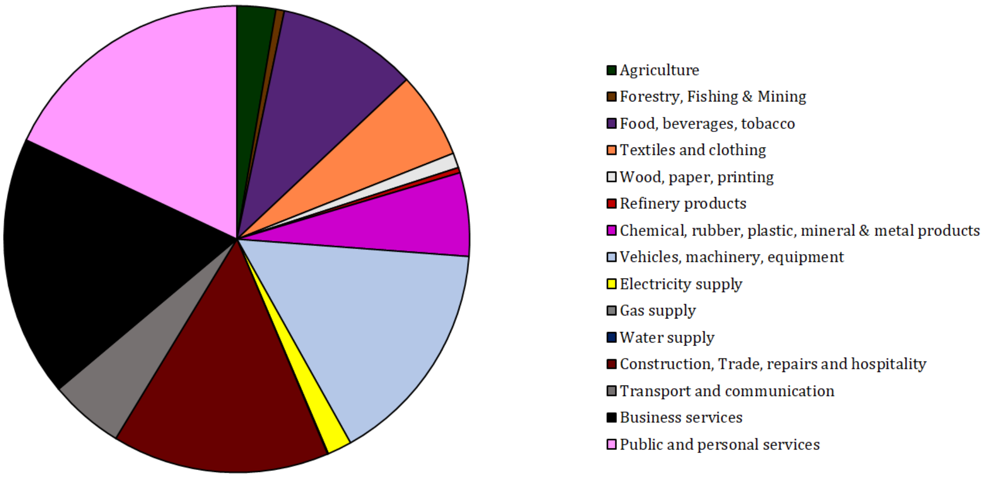


Figure 2. Typical expenditure profile for a household in the Inner West Council.

2.4 Accounting frameworks for tracing carbon flows

The most comprehensive compilation of greenhouse gas (GHG) emissions data for Australia, is provided by the AGEIS (Australian Greenhouse Emissions Inventory System) database (AGEIS 2018), compiled by the Commonwealth Government as part of meeting its international GHG reporting obligations.

The AGEIS provides annual emission estimates since the year 1990, for a range of substances. The coverage includes the three most important substances on a global scale (CO_2, CH_4 and N_2O), and a selection of other substances. Each inventory is reported as kilo-tonnes of the substance involved (i.e. methane emissions are reported as kt-CH_4). A subset of the substances are also reported as CO_2-equivalent mass flows, using 100-year Global Warming Potential equivalency factors taken from the 2007 IPCC Fourth Assessment Report (IPCC 2007), excluding any accounting for indirect radiative forcing effects.

Emission estimates are reported at the national and state-levels, using three different sectoral classification systems: (i) activity-based accounts using the Kyoto Protocol classification; (ii) activity based accounts using the UNFCCC classification; and (iii) sectoral-based accounts using an aggregated form of the 2006 Australian and New Zealand Standard Industrial Classification (ANZSIC) system (ABS 2013).

The AGEIS estimates are compiled from a mix of empirical data and estimates based on emissions factors, with the data contributed by industry sectors and government agencies, using standardised estimation methodologies. The AGEIS specified methods conform to the international guidelines prepared by the Intergovernmental Panel on Climate Change (IPCC) and adopted by the UNFCCC – the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006)* and the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (IPCC 2014)*. The 2016 release contains net emissions for 2016 compiled using reporting rules applicable to the Kyoto Protocol second commitment period (CP2).

The data collection and emission estimation methodologies are described in more detail in the *National Inventory Report 2016 Volume 1, Commonwealth of Australia (Department of the Environment & Energy 2016)* . The full AGEIS database is revised and updated annually, to provide a revised historical time-series as international practice evolves.

The Australian IELab generates satellite rows for three (CO_2, CH_4, N_2O) substances, as well as the aggregate CO_2 equivalent (CO_2e), which is a sum of gas-specific emissions weighted by so-called Global Warming Potentials: $CO_2 = 1$, $CH_4 = 21$, $N_2O = 310$). The GHG results for this study reflect the national- and state-level estimates from the ANZSIC-classified accounts of the National Inventory Report (Department of the Environment & Energy 2016). The sectoral correspondence between the national- and state-level data is shown in Table 2. Since the MRIO sectors and regions are more disaggregated than the source data, the GHG results are disaggregated using two datasets from the ABS as proxies – a total sectoral output dataset used for splitting data into more detailed sectors; and a total wages dataset used for splitting data into more detailed regions.

Table 2. A comparison of sectoral correspondence between national- and state-level AGEIS accounts.

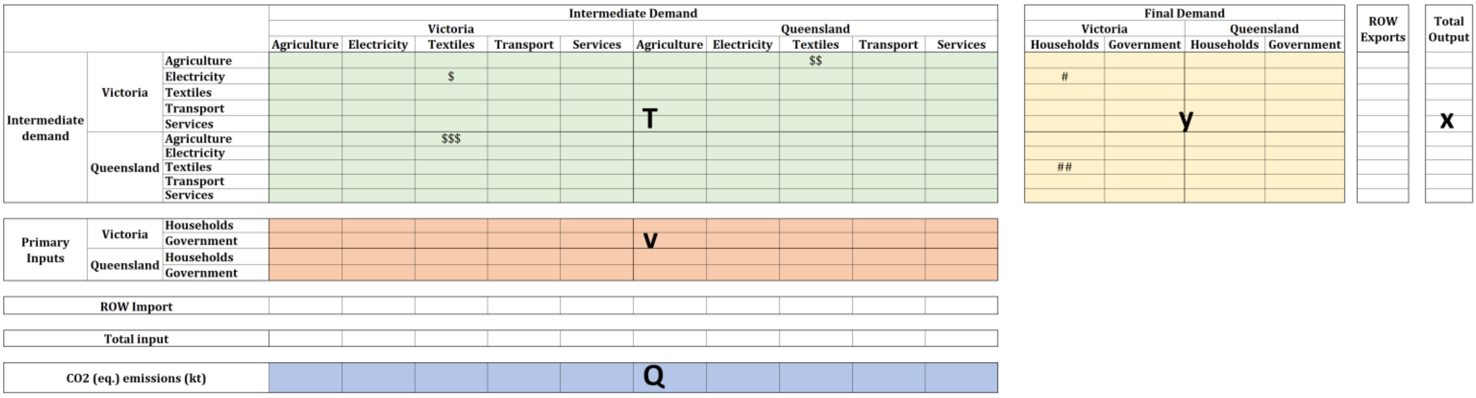
ANZSIC division	State-level sectors	National-level sectors
Div. A Agriculture, Forestry and Fishing	Div. A Agriculture, Forestry and Fishing	Div. A Agriculture, Forestry and Fishing
Div. B Mining	Div. B Mining	06 Coal Mining
		07 Oil and Gas Extraction
		08-10 Metal Ore and Non-Metallic Mineral Mining and Quarrying
Div. C Manufacturing	Div. C Manufacturing	11-12 Food, Beverages and Tobacco Product Manufacturing
		13 Textile, Leather, Clothing and Footwear Manufacturing
		14-16 Wood and Paper Manufacturing and Printing Services
		1701 Petroleum Refining and Petroleum Fuel Manufacturing
		1709 Other Petroleum and Coal Product Manufacturing
		18-19 Basic Chemical and Chemical, Polymer and Rubber Product Manufacturing
		201 Glass and Glass Product Manufacturing
		202 Ceramic Product Manufacturing
		203 Cement, Lime, Plaster and Concrete Product Manufacturing
		209 Other Non-Metallic Mineral Product Manufacturing
		211-212 Basic Ferrous Metal Manufacturing
		213-214 Basic Non-Ferrous Metal Manufacturing
		22 Fabricated Metal Product Manufacturing
		24 Machinery and Equipment Manufacturing
		25 Furniture and Other Manufacturing
Div. D Electricity, Gas and Water Supply	Div. D Electricity, Gas and Water Supply	26 Electricity Supply
		27 Gas Supply
		28 Water Supply, Sewerage and Drainage
Div. E Construction	Div. E Construction	Div. E Construction
Div. F-H, J-Q Commercial Services	Div. F-H, J-Q Commercial Services	Div. F,G Wholesale and Retail Trade
		Div. H,P,Q Accommodation, Food Services, Education and Health Services
		Div. J Information Media and Telecommunications
		Div. K,L Finance, Insurance, Rental, Hiring and Real Estate
		Div. M Professional, Scientific and Technical Services
		Div. N,O Administration, Public Administration and Services
Div. I Transport, Postal and Warehousing	46 Road Transport	46 Road Transport
	47 Railway Transport	47 Railway Transport
	48 Domestic Water Transport	48 Domestic Water Transport
	49 Domestic Air and Space Transport	49 Domestic Air and Space Transport
	50-53 Other Transport, Services and Storage	50-53 Other Transport, Services and Storage

2.5 Application of economic theory to carbon accounting

We integrated the custom-built MRIO economic database (Section 2.2) with the carbon dioxide (equivalent, CO_2e) satellite account (Section 2.4) to undertake a consumption-based footprint calculation for the households in the IWC area.

The input-output economic accounting system consists of three key matrices – Intermediate demand **T**, Final demand **y** and Primary inputs **v**. The structure of these matrices is explained in detail elsewhere (ABS 2017b, 2016a). In essence, the intermediate demand matrix **T** (highlighted in green, Figure 3) contains information on intra- and inter-industry transactions. For example, the symbol $ in Figure 3 represents the input of ‘Electricity’ into the ‘Textiles’ sector (for the region ‘Victoria’). In other words, money ($) spent by the ‘Textiles’ sector of Victoria for buying ‘Electricity’ that is produced in Victoria. The value $$ represents the money spent by the ‘Textiles’ sector of Queensland for buying ‘Agriculture’ – related products produced in Victoria. Similarly, the value $$$ shows the input of ‘Agriculture’ - related products from Queensland to Victoria’s ‘Textiles’ sector. Note that the values $, $$ and $$$ are merely for illustration purposes, and by no means indicate that $ is less than $$ and $$$. Applying this analogy of inputs going from one sector to next, we can deduce the value (#) as referring to the money spent by ‘Households’ in Victoria on ‘Electricity’ produced in Victoria, and (##) as the input of goods from Queensland’s ‘Textiles’ sector. The final demand matrix **y** shows the final consumption of goods, and acquisition of services. The primary inputs (also called the value added) matrix **v** contains information on primary inputs needed for the production of goods and services (e.g. labour input). For illustration, only two final demand and value added categories are shown in Figure 3. The data sources and procedure described in Section 2.2 refer to the construction of the T, y and v matrices, and the Rest of the World (RoW) import and export vectors. These vectors contain data on imports and exports from regions that do not explicitly feature in the MRIO table.

The data sources and procedure explained in Section 2.4 refer to the construction of the CO_2e satellite account **Q**. The satellite account holds information on physical accounts that are not necessarily in dollars (hence **Q** is also called the physical account), and are external to the economic input-output accounting system. This account is critical for integrating data on a range of indicators, such as environmental (e.g. greenhouse gas emissions, water use), social (e.g. employment, poverty) and economic (e.g. profit, stimulus), into the economic database (Leontief 1970).



			Intermediate Demand										Final Demand				ROW Exports	Total Output
			Victoria					Queensland					Victoria		Queensland			
			Agriculture	Electricity	Textiles	Transport	Services	Agriculture	Electricity	Textiles	Transport	Services	Households	Government	Households	Government		
Intermediate demand	Victoria	Agriculture								$$								
		Electricity			$								#					
		Textiles																
		Transport																
		Services						T						y				x
	Queensland	Agriculture			$$$													
		Electricity																
		Textiles											##					
		Transport																
		Services																
Primary Inputs	Victoria	Households																
		Government						v										
	Queensland	Households																
		Government																
ROW Import																		
Total input																		
CO2 (eq.) emissions (kt)								Q										

Figure 3. A schematic of a multi-regional input-output (MRIO) table, showing two regions (Victoria and Queensland) with five sectors in each region. Intermediate demand **T**, Final demand **y**, Primary inputs **v**, Total output **x**, Satellite account **Q**. Note that for illustration purposes, we have shown symmetrical IO tables within the MRIO table, however our MRIO table follows a supply-use structure.

We subjected the integrated (economic MRIO tables and satellite account) database to input-output algebra as follows:

First, we calculate the total output **x** (Figure 3) using two row summation operators (for summing all elements in a row, for getting a column vector) as $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathrm{T}} + \mathbf{y}\mathbf{1}^{\mathrm{y}}$, where $\mathbf{1}^{\mathrm{T}}$ is the row summation operator (all elements being 1) for the matrix **T**, and $\mathbf{1}^{\mathrm{y}}$ the row summation operator for matrix **y**. Next, we calculate the direct coefficients matrix **A** (inputs needed to produce 1$ of output of a sector) using $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$, where $\hat{\mathbf{x}}^{-1}$ is the inverse of the diagonal matrix of vector **x**. Using a similar process, we calculate the coefficients of the matrix **Q** – we determine the carbon dioxide (eq.) emissions (e.g. in kg CO_2e) produced for every dollar of output of an industry sector (direct intensities, **q**), as $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$. As mentioned in the introduction, input-output analysis takes into account all upstream supply chains. This is made possible by deriving the total coefficients matrix (**L**), as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$. The matrix **L** holds information on all upstream supply chains, which can be used to calculate the total intensities **m**, using $\mathbf{m} = \mathbf{qL}$. The total intensities hold information on both the direct and indirect emissions (e.g. in kg CO_2e) embodied in 1$ of final demand (also known as final consumption) of a commodity. The total (direct and indirect) emissions embodied in the products bought and services acquired by the households of the IWC area can then be calculated by taking the 'Households' final demand column vector ($\mathbf{y}_\mathrm{H}$) as, $\mathbf{f} = \mathbf{m} \otimes \mathbf{y}_\mathrm{H}$, where $\otimes$ denotes element-wise multiplication.

Input-output accounting can also be used for unravelling different upstream layers of production, e.g. for quantifying the amount of emissions at various upstream layers in a so-called supply chain tree, initiated by a consumer spending a certain amount of money for buying a commodity. The technique called Production Layer Decomposition (PLD) can unravel production layers from the extraction of raw materials, to the transportation and processing of those materials to the production of the commodity that the consumer eventually buys at a shop. The PLD calculation relies on the series expansion (Waugh 1950) of the matrix **L** into different production layers: $\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{A}^4 + \mathbf{A}^5 + \mathbf{A}^6 + \ldots$, followed by the calculation of impacts at each layer of production: $\mathbf{q} \otimes (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{A}^4 + \mathbf{A}^5 + \mathbf{A}^6 + \ldots)\mathbf{y}_\mathrm{H}$ (for an application of PLD to companies see Wiedmann et al. (2009).

2.6 Uncertainty and limitations

The calculation of scope-3 emission entails a range of uncertainties. First of all, specifying the household consumption of the IWC relies on data from the HES (ABS 2017a). However, the area of the Council is not distinguished in the HES but only the SA4 – "Sydney -Inner West", thus representing the first uncertainty due to imperfect regional delineation. Then, the HES is a survey and not a census, covering about 10,000 households out of a total of about 9 million, a coverage of about 0.1%. The second source of uncertainty therefore results from the potential unrepresentativeness of the sample for the population. Third, the survey was taken at a particular time of the year, meaning that the survey period may not be representative for the entire annual consumption pattern. The second and third sources of uncertainty are reflected in the ABS' standard deviation estimates, which can be as high as 50% for many individual items. Fourth, scope-3 emissions need regional input-output tables, and these carry their own uncertainties, which are due to the underlying data sources only representing about a few % of the table data, being misaligned in their classification, and recorded for different not matching years, amongst other deficiencies. Standard deviations of input-output table elements can range between 3% and more than

100%, with generally smaller transactions (for example for less populated regions) being associated with larger uncertainties, because these transactions are the sum of fewer raw data items, and hence error propagation leads to less error cancellation (Imbeault-Tétreault et al. 2013; Heijungs and Lenzen 2014). This is shown in the so-called rocket plot in Figure 4, where transactions smaller than $100,000 are afflicted by standard deviation of more than 100%. Fortunately, in the calculation of input-output multipliers, many of these large uncertainties cancel out due to error propagation (Jensen 1980). Fifth and finally, scope-3 emissions require greenhouse gas inventories (Section 2.4). Like any other source, these inventories carry measurement and classification errors. For example, systematic errors exist in that emissions from international air and water transport are excluded in official statistics. Our conservative estimate for the results provided in this work is that the totals for the Inner West Council are accurate to about 20%, and the individual commodity and production layer estimates accurate to about 50% or less.

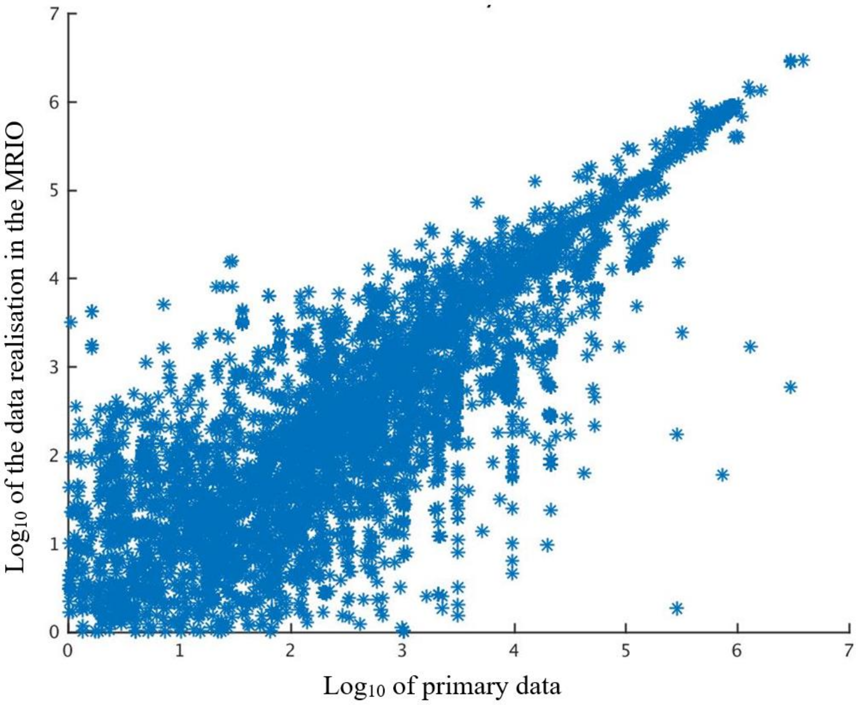


Figure 4. A rocket plot of our MRIO table for the year 2014, showing the variability of input-output table elements. The diagonal represents perfect representation of primary data in the table; any departure from the table reflects a primary data violation. The smaller data items are often not accurately represented in IO tables, however this circumstance does not impact aggregate footprint measures.

3 Results and Discussion

3.1 Per-capita consumption-based emissions

For determining per-capita consumption-based emissions, we divided the CO_2e footprint (**f**, see Section 2.5) for each region by the respective population data (ABS 2017c). The population data are provided at both SA2 and SA4 levels. According to the ABS publication *3235.0 Population by Age and Sex, Regions of Australia*, the total population of SA4 "Sydney-Inner West" was 278,364 persons in 2016. We calculated the total number of persons residing in the Inner West Council area, by adding the population of SA2s that make up the Inner West Council area, and SA2s that partly come under the Council (Section 2.1 and Table 1) to be 272,640. The conversion factor from SA4 "Sydney – Inner West" to the Inner West Council area comes out as 0.9794.

It becomes apparent that the per-capita CO_2e footprints of regions with comparatively small populations – such the Inner West Council, the Northern Territory, or the Australian Capital Territory – fluctuate more than those for larger regions or the nation (Table 3). This is due to the larger uncertainty and the smaller amount of data for smaller regions (see Section 2.6). Whether variability is due to error must be examined for the 25% increase in the IWC's footprint between 2009 and 2014, based on an appraisal of HES data for the Inner West SA4 region. Between 2009 and 2015, average weekly household expenditure in the Inner West SA4 increased by 33% from $1,382 to $1,833. This increase is well above the Australian average increase of 15% (from $1,236 in 2009 to $1,425 in 2015), thus explaining why the CO_2e footprint figures for the IWC reported in Table 3 also increase above the average. The question arises whether the expenditure increase of the Inner West SA4 area over time is representative, given the sample coverage of only 0.08%. The Australian Bureau of Statistics provides 2009 and 2015 total expenditure standard errors of 7.6% and 26.0%, for sample populations of 85 and 117, respectively. Subjecting these standard errors and sample sizes to a regression analysis and Student's t test of the apparent expenditure increase yields a positive coefficient of +75±10 $/year, and this increase is statistically significant at the 99%-level of confidence.

Second, there are significant regional deviations from the national average of around 21 tonnes per capita. In 2014, total Australian emissions were about 524 tonnes CO_2e (Department of the Environment and Energy 2015), which, for a population of 23.5 million (ABS 2014), gives 22.6 t/cap. This compares with our footprint estimate of 21.0 t/cap, and estimates of 20-25 t/cap in Lenzen (1988a), around 18.9 t/cap in Table 9.1 in Dey et al. (2007), 25 t/cap in Wood and Dey (2009), and 19.9 t/cap excluding imports and 27.7 t/cap including imports in Lenzen (1988b). In our findings, the footprints of the rest of Greater Sydney and Tasmania are significantly below the national average, which is due to their smaller overall expenditure, and lower CO_2e intensity, respectively.

Further checks against aggregated data showed that our regional estimates are largely in line with territorial per-capita emissions (right column in Table 3). Discrepancies between footprints and territorial emissions are obviously due to embodied emissions being traded in and out of regions. For example, Tasmania and the ACT do not emit significantly territorially (for example because of Tasmania's hydro-electricity and the absence of major power plants in the ACT), but import embodied emissions from elsewhere. In contrast, Queensland and Western Australia are clear embodied emissions exporters. The reason for these discrepancies have not only to do with the fact that the simple ratios are territorial per-capita emissions and not footprints, but are also due to a number of technical issues, for example whether process emissions of non-CO_2 greenhouse gases and emissions from land use change are included, whether requirements from capital infrastructure are considered (Lenzen 2001), how international imports are dealt with (for example using single- or multi-regional databases; (Lenzen et al. 2004b)), whether (non-Kyoto) emissions from the combustion of international bunker fuels are counted, and many more.

Table 3. Per-capita consumption-based emissions for all regions, from years 2009-2014 (in tonnes CO_2e per capita).

Regions	2009	2010	2011	2012	2013	2014	Territorial
Inner West Council	17.5	17.5	21.3	23.8	21.8	21.8	-
Rest of Greater Sydney	15.3	15.2	15.7	16.0	16.0	16.2	-
Rest of New South Wales	25.6	25.6	26.8	27.4	27.6	27.6	17.7
Victoria	19.4	19.3	18.7	18.5	18.7	18.7	20.2
Queensland	23.2	23.5	23.3	23.3	23.4	23.2	31.1
South Australia	19.4	19.3	19.2	18.5	18.5	18.5	16.4
Western Australia	23.9	24.3	23.8	23.4	23.5	23.4	33.5
Tasmania	19.1	20.2	16.8	18.6	17.7	17.9	3.1
Australian Capital Territory	15.7	15.8	17.1	17.4	17.2	19.4	3.9
Northern Territory	37.2	37.9	43.0	46.2	47.1	47.3	50.6
Australia - all regions	20.8	20.8	20.9	20.9	21.0	21.0	22.3

So far, in order to demonstrate consistency with national accounting, we have quantified regions' CO_2e footprint by considering their entire final demand. The Australian Bureau of Statistics defines "final demand" as including household final consumption, government final consumption, expenditure on fixed capital, and increases in stocks. In the following, we concentrate on the Inner West Council's CO_2e footprint, and as such we only consider household final consumption. Whilst this consumption is indirectly supported by capital infrastructure such as buildings and roads, and government at all levels, these categories are largely beyond the reach of household decisions, and it is practice in population footprinting to exclude them.

3.2 Breakdown into scope-1, -2 and -3 emissions

We carried out a production layer decomposition analysis to break down the 2014 emissions from the purchase and usage of goods, and acquisition of services. Here, we break down the cumulative emissions according to 12 layers of production. Layer 1 represents direct, or scope-1 emissions (see the red oval), for example from the combustion of petrol (red band in Figure 5) and gas (light grey). Layer 2 represents indirect emissions, occurring at the site of a direct supplier, for example at the power plant supplying electricity (yellow, scope 2, see green oval), or the bus transporting people to work (dark grey). Figure 5 shows that Scope-1 emissions (from the combustion of petrol, LPG and town gas) coincide with layer 1, that Scope-2 emissions (purchase of electricity) form part of layer 2, and that Scope-3 emissions (purchase of all other goods and services) represent the remainder.

Proceeding in an upstream direction into the supply-chain network, we find that the IWC's CO_2e footprint increases as we include more and more higher-order production layers. Interestingly, we find that only when we include layers up to 12th order and higher does the cumulative sum of these layers converges to a more or less stable total. It is intriguing to illustrate what this means in terms of supply chains. Assume that a household buys 100 different items from 100 producers included in production layer 1. Assume that each of these 100 producers require 100 inputs to manufacture their products. Then, we would have 100×100 = 10,000 supply chains originating from production layer 2. If we assumed now that each of the suppliers of our producers has 100 suppliers in turn, production layer 3 would count 1 million supply chains. It is clearly impossible in terms of human resources to evaluate that many supply-chain contributions to an entity's footprint using bottom-up methods but yet, counting only up to layer 3, we would be ignoring more than 50% of the footprint. This convergence behaviour is not untypical for organisational and population carbon footprints, and demonstrates clearly the necessity to include input-output techniques into any footprint assessment (Lenzen 2000a).

Figure 5 shows two production layer decompositions. The coloured bands in the right panel distinguish the CO_2e footprint by purchased commodity, grouped into 15 broad categories. In this representation, each band contains upstream supply-chain contributions to a particular type of commodity. For example, the red band, including the IWC's petrol purchases, includes emissions from road transport to petrol stations, process energy at refineries, CH_4 emitted during venting and flaring at the rig, emissions from aluminium smelting for making parts of the rig, and so on. The yellow band, the IWC's electricity consumption, includes emissions from constructing and maintaining the power plants around Sydney, mining and transporting the coal, seam gas emissions, and so on.

The right-hand edge of this production layer decomposition is the ultimate commodity breakdown of the IWC's CO_2e footprint. About 8% of this CO_2e footprint is exerted by the petrol and diesel combusted in the IWC resident's vehicles, and the upstream emissions that enable this petrol and diesel consumption. A further 3% are embodied in combusted gas, and 13% is embodied in electricity use (compare with similar values in Fig. 9.2 of Dey et al. 2007). This means that, according to this calculation, and based on HES information, the Scope-1 and -2 emissions of the IWC represent just about 24% of its total CO_2e footprint. The remainder of 76% is embodied in purchases of food, services such as education, health, and entertainment, or public transport. Of this, about 29% are sourced directly from businesses in the Inner West (entertainment, hospitality, education, food, personal services, etc), 29% from Australian regions outside the Inner West, and another 18% directly imported from outside Australia. This result is significant in that it means that if policy addressed only energy-related consumption, it would be missing 76% of the population's CO_2e footprint.

The coloured bands in the left-hand panel of the production layer decomposition distinguish the CO_2e footprint by emitting industry, again grouped into 15 broad categories. In this representation, each band contains upstream supply-chain contributions originating from a particular type of industry. For example, the red band, including the IWC's petrol purchases, includes emissions from petrol refining. Some of these emissions occur to support transport services, or food deliveries. The yellow band, including the IWC's electricity consumption, also includes power plant emissions for generating electricity for lighting schools, restaurants and pubs, propelling trains, and so on.

Some interesting items in the production layer decomposition warrant some explanation. First, the dark green and brown bands in the emitting-industry breakdown (left) represent emissions in agriculture and mining. Note how these emissions only become important at layer 3 and above, and that they are not represented in the purchased-commodity breakdown (right). This is because households do not buy a significant amount of food directly off farms, and nothing off mines. However, in a supply-chain sense, agriculture and mining sit behind virtually every product. Therefore, these two sectors have very different importance in the two PLD graphs. Second, and vice versa, business, personal and public services do not appear to be significant in the emitting-industry breakdown (left), but in the purchased-commodity breakdown (right), where they become significant only at layer 5 and beyond. This is because whilst households buy a significant amount of services, these are not emissions-intensive. On one hand, services do not cause significant supply-chain inputs into other products, but services have themselves very material inputs sitting in their own supply chains. Therefore, again, these two sectors have very different importance in the two PLD graphs. Third, the bands for electricity and transport are larger in the emitting-industry breakdown (left) than in the purchased-commodity breakdown (right). This is because on one hand, transport has its main emissions in layers proximate to the consumer, that is through actual vehicle emissions, and their own supply chains add relatively little (right). On the other hand, electricity and transport are needed to produce virtually every product, which is reflected in the broader emitting-industry band (left).

In the following we report in detail on particularly important footprint components, starting with scope-1 items, followed by electricity (scope 2), and then remaining purchases. We examine scope-1 and -2 components in detail because this enables the comparison with bottom-up calculations of the same quantities. We also examine regions other than the IWC to be able to put our results in perspective.

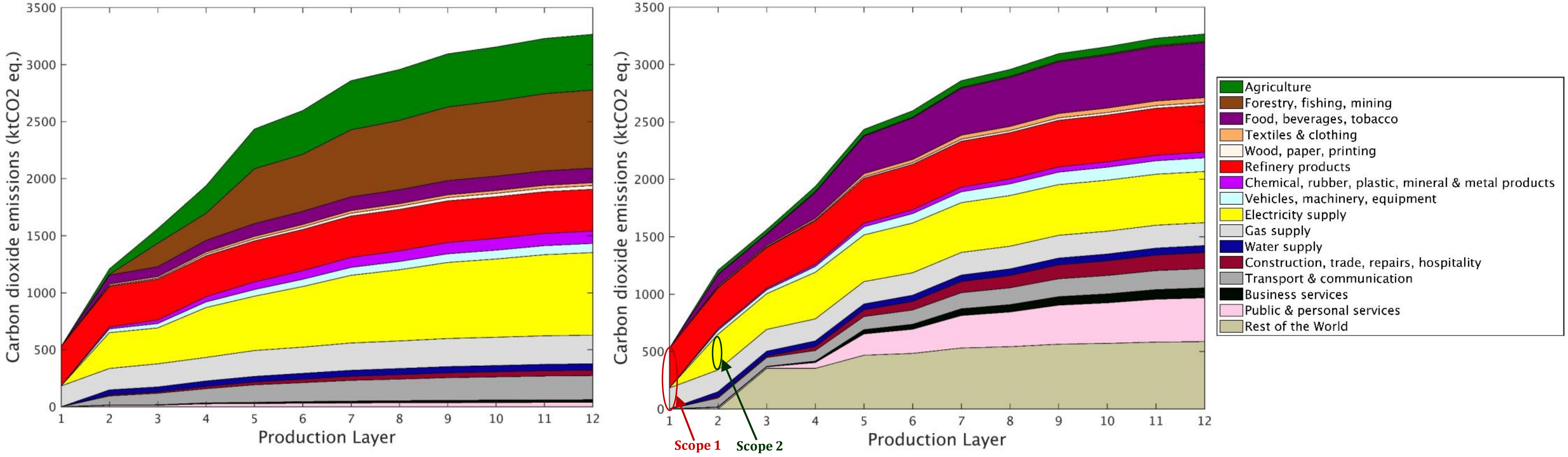


Figure 5. Breakdown of 2014 cumulative emissions according to upstream layers of production. "Cumulative" means that each successive layer includes emissions from lower-order layers. Emissions converge towards a total only after including 12 layers. Left panel: the bands refer to the CO_2e footprint by emitting industry. Right panel: the bands refer to the CO_2e footprint by purchased commodity. 15 categories plus the Rest of the World are presented in the diagram.

3.2.1 Scope 1 (petrol and gas)

We calculated the Scope-1 emissions associated with the combustion of petrol by dividing the value for the combustion of 1L of petrol (2.4kg CO_2e; Department of the Environment & Energy (2017)) by the average price of a litre of petrol over the year 2009 – 2014 ($1.37; AIP (2018)), and then multiplying the resulting emission factor by the total money spent on 'Petrol' by households in the SA4 "Sydney – Inner West" region. In 2015, an average household in SA4 "Sydney - Inner West" spent $26.43 per week (= $1374.36 per year) on petrol. Considering 146,500 households, yields a spending of $m 201.3 (ABS 2017a). The Scope-1 emissions for SA4 "Sydney – Inner West" therefore amount to 353kt (2.4/1.37*201.3). Applying the conversion from SA4 "Sydney – Inner West" to Inner West Council (Section 3.1), yields 346kt.

Table 4 shows that whilst these emissions represent about 8% of the IWC's CO_2e footprint, the corresponding percentage values for other regions are higher. This is to be expected, as people in inner-city suburbs are less reliant on motor vehicles than people in rural areas (Kenworthy and Laube 1996; Troy *et al.* 2003). As a consequence, the IWC's CO_2e footprint in terms of public transport (bus and rail) is higher than that of other regions. Similar results were obtained by Lenzen et al. (2004a) for the components of energy footprints of Greater Sydney Statistical Subdivisions.

For the combustion of town gas, we took the average residential gas price (2.90 ¢/MJ;COA (2017)) and the emission factor for the burning of town gas (60.2kg/GJ; Department of the Environment & Energy (2017)), times the expenditure data ($11.77 per week per household, or $m 89.7 for 146,500 households) to calculate the Scope-1 emissions from burning gas to be 186kt for SA4 "Sydney – Inner West" or 182kt for IWC (see Section 3.1 for the conversion factor). Again, as Table 4 shows, CO_2e footprint from gas combustion is relatively high in more densely populated areas with a piped-gas network. The ACT appears anomalous, which is due to an unusually high, and perhaps unrepresentative HES record ($20.97 for mains gas in the ACT instead of an Australian average of $8.89).

Table 4. Breakdown of the total 2014 CO_2e footprint for selected energy, transport and trade sectors (% of total). Due to inherent uncertainties in the calculation of Scope-3 emissions (Section 2.6), we write values <0.05% as 0.

	Petrol	Gas supply	Electricity supply	Bus Transport	Rail Transport	Air Transport	Inter-region imports	RoW imports
Inner West Council	8.3%	2.8%	13%	0.4%	0.1%	0.1%	29%	18%
Rest of Greater Sydney	9.9%	1.5%	16%	0	0	0	27%	20%
Rest of New South Wales	17%	3.5%	20%	0.2%	0.1%	0.4%	7.2%	11%
Victoria	12%	3.7%	17%	0	0	0	5.0%	21%
Queensland	11%	0.69%	14%	0.3%	0.1%	0. %	2.8%	20%
South Australia	9.5%	2.8%	7.6%	0.2%	0	0	18%	17%
Western Australia	10%	2.4%	9.6%	0.2%	0.1%	0.1%	12%	17%
Tasmania	12%	0.96%	1.7%	0.6%	0.1%	0.1%	10%	28%
Australian Capital Territory	11%	4.3%	13%	0.2%	0	0	40%	27%
Northern Territory	5.3%	0.36%	4.8%	0.1%	0	0	20%	15%

3.2.2 Scope 2 (electricity)

It is difficult to calculate Scope-2 emissions from household expenditure data, because of the multitude of existing tariff structures. The total money spent on 'Electricity' by households in the SA4 "Sydney – Inner West" is \$22.98 per week per household, or \$1,194 per year per household. Assuming an average electricity price of 25 ¢/kWh (CME 2012; AEMC 2017) yields a consumption of 4,780 kWh per year per household. However, in reality, expenditure will be made up of a fixed supply tariff and a per-kWh usage tariff. Assuming \$0.93/day, and 32.285 ¢/kWh, respectively (EnergyAustralia 2018) and an emissions factor of 0.8kg CO_2e/kWh (Department of the Environment & Energy (2017)), and then applying these to the HES data yields 305kt CO_2 annual emissions for the SA4 region, and 299kt for the IWC (see Section 3.1 for the conversion factor). For comparison, a bottom-up evaluation of 2017 Ausgrid data (Ausgrid 2018) gives a daily consumption of 11.9 kWh per customer in the Inner West Local Government Area (LGA), which translates into 4,359 kWh per year and household, and 291kt CO_2 for the entire LGA. Our MRIO calculation includes gases other than CO_2, and yields 314 kt CO_2-e just for Scope 2 (see oval in Fig. 5). The three estimates are in reasonable agreement.

A comparison with other regions reveals that the proportion of the CO_2e footprint taken up by electricity is high where either overall expenditure is low and necessities play a greater role (for example rest of New South Wales), or emission coefficients are high because of generation focused on coal combustion (Queensland and Victoria). Vice versa, this proportion is low where renewable energy is widespread (Tasmania and South Australia). Our results are in agreement with previous research in this area (Dey et al. 2007; State of the Environment 2017).

3.2.3 Scope 3

As explained above, 76% of the IWC's resident's CO_2e footprint is represented by embodiments in consumer purchases, spanning a wide range of consumer needs, from food, to clothing, to manufactured items such as furniture, vehicles, electronics, and appliances, to personal services such as transport, entertainment, health, and education. This finding agrees with national figures of 70% in Figure 9.1 in (Dey et al. 2007), and 77% in (Wood and Dey 2009). This high percentage is also not unusual by international standards (Mélanie et al. 1994; Hamilton and Turton 2002). IWC residents, like those of Greater Sydney and Canberra, cause a significant amount (47%) of their embodied emissions through directly imported purchases, either inter-region or international (compare with Lenzen and Peters (2010).

Note that air travel comes out surprisingly low in our analysis. This is first because international aviation bunker fuels are not included in the AGEIS database. In reality, burgeoning overseas travel expenditure ($ 28.89 per week in 2009 and $ 92.00 per week in 2015 in the SA4 "Sydney - Inner West") is causing tourism to emerge as one of the most significantly growing contributors to global emissions (Lenzen et al. 2018). The second reason is that domestic air travel (which is included) represents only about 1.6% of Australia's emissions. For the purposes of footprinting of Australian residents, we have to subtract freight, business travel, and travel by foreign tourists, which may bring this percentage close to 1%. Still, our results are significantly below even 1%. We believe that this could be because households may have purchased domestic flights, but that some of these purchases have been missed because of the limited survey period. Similarly, bus and train travel contributions range near the level of uncertainty, however a similar result can be found in Lenzen (1988a). The three travel items in Table 4 may need to be followed up in a future bottom-up analysis, however we do not expect these to significantly influence the total.

Interestingly, the purchase of clothing items by IWC residents does not register a high CO2e footprint (Figure 5), owing to the origin of these supply chains (i.e. production of clothing items) at international locations (e.g. China for clothing manufacturing, Bangladesh and India for weaving and spinning, and Uzbekistan for cotton growing). The emission factors for these purchases is not represented in the MRIO used for this study, because at the time of writing, there exists no MRIO database for linking an Australian database with regional detail into a global MRIO database with country detail. Therefore, it is not possible to trace the upstream supply chains for the consumption by IWC residents to international hot-spots of CO2e emissions. Further research into the construction of nested MRIO databases containing both sub-national and international detail would open avenues for tracing international supply chains that feed into the consumption of IWC residents.

There is abundant empirical evidence for indirect, scope-3 emissions being strongly accelerated by affluence and weakly accelerated by decreasing household sizes (Wiedenhofer et al. 2011, 2013; Pachauri and Spreng 2002; Pachauri 2004; Lenzen et al.

2006; Munksgaard et al. 2000; Munksgaard et al. 2001; Wier et al. 2001; Hertwich 2010; Minx et al. 2013; Druckman and Jackson 2009; Lenzen et al. 2008; Jackson and Papathanasopoulou 2008; Guan et al. 2008; Bin and Dowlatabadi 2005; Weber and Perrels 2000; Dietz and Rosa 1997). These results point at the importance of affluent urbanised lifestyles for the persistence of high per-capita emissions levels (Lenzen et al. 2008), and to the challenge in addressing these trends (Whitmarsh et al. 2011; Hamilton and Denniss 2005; Jackson 2005, 2009; Jackson and Papathanasopoulou 2008; Trainer 1997; Trainer 1995; Lenzen et al. 2016). In order to unlock this dilemma, research needs to increase its focus on investigating psychological dimensions of consumption (Costanza 1987; Costanza et al. 2017; Norgaard 2006, 2009, 2011). and examine the decoupling of subjective wellbeing and happiness from affluence. Preliminary findings show that despite being strongly coupled with growing affluence, growing emissions are only weakly coupled with growing subjective wellbeing (Lenzen and Cummins 2013), thus opening up opportunities for win-win situations involving reducing emissions whilst increasing wellbeing.

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