The Concept of City Carbon Maps

A Case Study of Melbourne, Australia

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Summary

Cities are thought to be associated with most of humanity's consumption of natural resources and impacts on the environment. Cities not only constitute major centers of economic activity, knowledge, innovation, and governance—they are also said to be linked to approximately 70% to 80% of global carbon dioxide emissions. This makes cities primary agents of change in a resource- and carbon-constraint world. In order to set meaningful targets, design successful policies, and implement effective mitigation strategies, it is important that greenhouse gas (GHG) emissions accounting for cities is accurate, comparable, comprehensive, and complete. Despite recent developments in the standardization of city GHG accounting, there is still a lack of consistent guidelines regarding out-of-boundary emissions, thus hampering efforts to identify mitigation priorities and responsibilities. We introduce a new conceptual framework—based on environmental input-output analysis—that allows for a consistent and complete reconciliation of direct and indirect GHG emissions from a city. The "city carbon map" shows local, regional, national, and global origins and destinations of flows of embodied emissions. We test the carbon map concept by applying it to the greater metropolitan area of Melbourne, Australia. We discuss the results and limitations of the approach in the light of possible mitigation strategies and policies by different urban stakeholders.

Introduction

Accounting Frameworks for Decarbonizing Cities

The "decarbonization" of cities is increasingly being seen as a crucial contribution to limiting global warming (IPCC 2014). Cities are not only thought to be linked to approximately 70% to 80% of global carbon dioxide (CO_2) emissions (Hoornweg et al. 2011; IPCC 2014), but they also constitute major centers of economic activity, knowledge, innovation, and governance, making them primary agents of change in a carbon-constraint world (Rauland and Newman 2015b). According to the recent report by the United Nations (UN) Secretary-General's Special Envoy for Cities and Climate Change, cities are well positioned to make a substantial contribution to additional mitigation strategies and policies (UNSECC 2014).

More and more cities sign up to a commitment of addressing climate change as exemplified by the agendas of the C40 Cities Climate Leadership Group (www.c40.org) or ICLEI Local Governments for Sustainability (www.iclei.org), both global networks of cities. As a basis for action on climate change, cities need to quantify and report their greenhouse gas (GHG) emissions (Dodman 2011; Ibrahim et al. 2012; Kennedy et al. 2012; Lin et al. 2013b; Rauland and Newman 2015a; Ramaswami et al. 2012b). In order to set meaningful targets, design successful policies, and implement effective emission reduction strategies, it is important that the reporting of GHGs from cities is

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accurate, comparable, comprehensive, and complete. To support effective climate action planning, city GHG accounting frameworks should:

- include both direct and indirect emissions;
- provide sufficient detail to identify those specific sectors, processes, and supply chains that have the largest potential for reductions;
- clearly identify the origin (location and industry or activity) of emissions;
- ensure that GHG inventories of cities are mutually exclusive and nested within subnational, national, and global inventories;
- allow for consistent benchmarking and comparisons; and
- apply internationally recognized environmental and economic accounting principles.

Several propositions have been made regarding the accounting for GHG emissions from cities, both in the scientific literature and in the form of accounting standards (see the following two sections). However, several open questions remain, in particular, with respect to emissions that occur outside the city boundary, but are linked to production or consumption in the city. Whereas the responsibilities for in-boundary city emissions are well understood (Arup 2014), the lack of consistent guidelines for out-of-boundary emissions is hampering efforts to manage more comprehensive and effective mitigation strategies and policies. It also makes comparisons between cities difficult.

Building on recent developments, this article introduces a conceptual framework that allows for a consistent and complete reconciliation of direct and indirect city GHG emissions from different perspectives and in sufficient accuracy and detail. A particular emphasis is placed on the evaluation of out-of-boundary emissions and on the relationship between a city's territorial carbon emissions and its wider carbon footprint (CF). In this section, we first review the recent literature on urban GHG accounting, including standards for GHG reporting, before proposing and describing the concept of a "city carbon map." We then describe and discuss the results for Melbourne, Australia as a case study, including a discussion on the role of different stakeholders.

Accounting for Greenhouse Gas Emissions from Cities: A Literature Review

The ecological footprint concept developed in the 1990s set the milestone for recognizing and evaluating the resource consumption of cities (Rees and Wackernagel 1996). Around the same time, interest grew in accounting for GHG emissions from cities (Baldasano et al. 1999; Harvey 1993), setting the scene for the next 20 years. Following the ICLEI (2009) Local Government GHG Analysis Protocol, Kennedy and colleagues (2009, 2010, 2011) explored the GHG emissions of many global cities. Examples of national case studies are Bi and colleagues 2011, Feng and colleagues 2014a, Hillman and Ramaswami 2010, and McGraw and colleagues 2010.

Until more recently, however, the components of urban GHG inventories were not compared by a consistent methodology (Ibrahim et al. 2012). What matters most is how emissions are allocated (Satterthwaite 2008). It is generally recognized in the literature that a comprehensive city-scale emission inventory should include both territorial emissions as well as those that occur outside of the city boundary, but can be attributed to activities within the city. Several terms have been used for such indirect emissions, including out-of-boundary, transboundary, supply chain, or Scope 3 emissions (Yetano Roche et al. 2014). Consumption-based accounting (CBA) and CF have been described as the underlying methodology (Baynes and Wiedmann 2012; Chavez and Ramaswami 2011, 2013; Kennedy and Sgouridis 2011; Ramaswami et al. 2012a). Researchers have pointed out the complementarities and synergies of territorial and consumption-based emissions accounting. Whereas, at the global level, both accounting perspectives lead to the same total (Hoekstra and Wiedmann 2014), they can play out very differently for cities, depending on the type of industrialization (Feng et al. 2014b). Chavez and Ramaswami (2013) elegantly summarize the relationship between territory plus transboundary and consumption-based accounting in mathematical terms.

Many cities still do not report indirect emissions comprehensively (Kennedy et al. 2010), most likely because the underlying methodologies and data have only been developed in recent years and have not yet been widely adopted in practice. In the scientific literature, environmental input-output (I-O) analysis (IOA) has emerged as the prevailing method for CBA. Wright and colleagues (2011) and Baynes and Wiedmann (2012) summarized the literature on CBA at city scale up to 2011–2012. Since then, IOA-based CFs and related environmental indicators have been estimated for a number of American, Chinese, and European cities (table 1), all providing new insights into the relationship between urban consumption and lifestyles and teleconnected environmental impacts elsewhere. A typical finding for large cities is that of Feng and colleagues (2014b), who calculated that more than 70% of CO_2 emissions related to the consumption of goods in Beijing, Shanghai, and Tianjin occur outside of the city boundary (at the same time, these cities also have substantial production-based emissions).

So far, city CF studies had two main limitations (see Methodology column in table 1). First, where no city-scale I-O data existed, national interindustry transaction data were commonly used instead, thus assuming that the economic structure of a city and its hinterland is identical. Such a setting does not capture the idiosyncrasies of local production systems, even when locally specific or downscaled consumption data are used for calculating city CFs. Most important, it does not take into account differences in sectoral GHG emissions intensities within and outside of the city. To overcome this limitation, researchers have either used bottom-up data to complement the I-O calculations (e.g., Jones and Kammen 2011, 2014; Ramaswami et al. 2008) or they have regionalized national I-O data to regional or city scale. The three-region model for Glasgow devised by Hermannsson and McIntyre (2014) is one

Table 1 Studies on global cities' GHG emissions based on consumption-based accounting (CBA)

Country: city or metropolitan area	*GHG emissions per capita*	*Year of data*	*Methodology*	*Reference*
Europe				
Finland: Helsinki Metropolitan Area (HMA) and three other types of settlement area/lifestyle	11 t CO_2-eq/cap for HMA	2006	IOA, national IOT (ENVIMAT model), local HH expenditure data	Heinonen et al. 2013
Finland: Helsinki, Vantaa, Espoo, and Kauniainen	13–14 t CO_2-eq/cap	2006	IOA, national IOT (ENVIMAT model), local HH expenditure data	Ala-Mantila et al. 2013; see also Ala-Mantila et al. 2014
Finland: Raahe, Heinavesi, Joensuu, Kaunianien	14–18 t CO_2-eq/cap[a]	2006	Allocating national GHG inventories based on municipal consumption data (not based on IOA)	Paloheimo and Salmi 2013
Luxembourg	60 t CO_2-eq/cap	1995–2009	Two-region IOA, national consumption and GHG data	Caro et al. 2015
Norway: 429 municipalities (CF of municipal services only)	0.4–2.9 t CO_2-eq/cap[a]	2007	IOA, national IOT, municipal expenditure data	Larsen and Hertwich 2010b; see also Larsen and Hertwich 2009, 2010a, 2011
Portugal: Aveiro	9.5 t CO_2-eq/cap[a]	2005	IOA, national IOT, national HH expenditure data downscaled to urban level	Dias et al. 2014
UK: 434 municipalities	10–16 t CO_2/cap	2004	MRIOA, global MRIOT, imputed local HH expenditure data	Minx et al. 2013
UK: Glasgow	2.2 t CO_2/cap[a] (Glasgow households only)	2006	MRIOA, subnational MRIOT, emissions intensities are equal for all three subregions (except for electricity)	Hermannsson and McIntyre 2014
Asia				
China: Beijing	n.a. (only sectorial emission intensities)	2002, 2007	IOA, city-scale IOT	Guo et al. 2012; Zhou et al. 2010
China: Beijing	9 t CO_2/cap	2007	IOA, city-scale IOT, national and global GHG intensities	Chen et al. 2013
China: Beijing	Not calculated	1997–2010	IOA, city-scale IOTs	Wang et al. 2013
China: Beijing-Tianjin GMA	3.8 t CO_2-eq/cap	2007	MRIOA, eight regions, one for Beijing-Tianjin	Yao et al. 2013
China: Beijing, Chongqing, Shanghai, Tianjin	4–11 t CO_2/cap	2007	MRIOA, 30 regions (provinces), study regions corresponding to GMAs	Feng et al. 2014b
China: Beijing, Chongqing, Shanghai, Tianjin	Only embodied energy calculated: 1.8–7.4 tce/cap	2007	MRIOA, 30 regions (provinces), study regions corresponding to GMAs	Zhang et al. 2015
China: Xiamen	9.3 t CO_2/cap	2009	Not CBA, IOA for Scope 3	Lin et al. 2013a
China: Xiamen	6.8 t CO_2/cap[a]	2007	IOA, city-scale IOT	Vause et al. 2013
America				
USA: Atlanta, San Francisco, Seattle	11.5–14.7 t CO_2-eq/cap	2006	IOA, downscaled IOTs (using IMPLAN database)[b]	Choi 2015
USA: Denver	25 t CO_2-eq/cap	2005	Not CBA, MFA with IOA emission factors for Scope 3	Ramaswami et al. 2008
USA: Denver, Routt, Sarasota	29–32 t CO_2-eq/cap	2008	IOA, downscaled IOTs (using IMPLAN database)[b]	Chavez and Ramaswami 2013

(*Continued*)

Table 1 Continued

Country: city or metropolitan area	*GHG emissions per capita*	*Year of data*	*Methodology*	*Reference*
USA: Seattle	25 t CO_2-eq/cap	2008	IOA, downscaled from CBA of King County (Erickson et al. 2012), county final demand data	Lazarus et al. 2013
USA: eight cities	15–26 t CO_2-eq/cap		Not CBA, Scope 1+2+3 based on MFA	Hillman and Ramaswami 2010
USA: Neighborhoods in Maricopa County, Arizona,	6–21 t CO_2/cap	2006	National I-O model and local consumption data by 42 household types	Petsch et al. 2011
USA: Households in 28 metropolitan regions	38–52 t CO_2-eq/HH	2005	IOA and LCA, national IOT, local HH expenditure data	Jones and Kammen 2011
USA: all cities, counties, and GMAs	25–80 t CO_2-eq/HH in the 50 largest GMAs (~40 tCO_2-eq/HH in urban core cities)	2007	IOA and LCA, national IOT, local HH expenditure data	Jones and Kammen 2014
Oceania				
Australia: Households in Melbourne and Sydney	77–91 t CO_2-eq/HH	2007	MRIOA, state-level MRIOT, only selected urban HH expenditure data	Lenzen and Peters 2010
Australia: Melbourne	25.1 t CO_2-eq/cap	2009	MRIOA, four-region MRIOT of city, region, nation and world	This study

[a]Calculated from other data provided in the original article.
[b]http://implan.com.
Note: CF = carbon footprint; GHG = greenhouse gas; GMA = greater metropolitan area; HH = household; IO = input-output; IOA/IOT = input-output analysis/table; LCA = life cycle assessment; MFA = material flow analysis; MRIOA/MRIOT = multiregion input-output (analysis/table); n.a. = not applicable; tce = tonnes of coal equivalent; t CO_2-eq/cap = tonnes of carbon dioxide equivalent per capita.

such example; however, the same sectoral GHG intensity still had to be assumed in that model.

In the last few years, researchers have increased efforts in obtaining higher quality city-scale I-O data. In China, I-O tables (IOTs) and GHG emissions data are available at the level of provincial administrations. In the case of four Chinese megacities—Beijing, Chongqing, Shanghai, and Tianjin—provincial boundaries coincide with city boundaries, thus providing a good basis for city-specific production and CBA (table 1). Increasingly, subnational multiregion input-output (MRIO) tables are used for city CF calculations (Feng et al. 2014b; Hermannsson and McIntyre 2014; Lenzen and Peters 2010; Yao et al. 2013; Zhang et al. 2015). Liu and Zhang 2012 derive a physical IOT to study the material metabolism of Beijing.

The second main limitation in most previous studies was that GHG emissions was directly linked to final demand without showing the flows along supply chains (intermediate demand), thus hiding detail helpful for the analysis of different emission scopes and paths. One notable exception is the work by Lenzen and Peters (2010), who explicitly identify the location of GHG emissions linked to final household demand in Melbourne and Sydney, albeit not by economic sector or product group.

The original and novel contribution in this study is to conceptualize a detailed representation of emissions embodied in city-specific interindustry transactions and supply chains by way of a city carbon map. A similar presentation of GHG emissions in I-O format was presented by Paloheimo and Salmi (2013); however, the allocation was not done by means of environmentally extended economic IOA, but rather through reassigning national GHG inventories based on municipal consumption data. Dias and colleagues (2014) present a table showing the contributions of emitting sectors to the CF of goods and services consumed by households in Aveiro (Portugal).

We present a four-region carbon map for the greater Melbourne metropolitan area. This is achieved through the derivation of specific city-scale, MRIO data with environmental extensions using the Australian Industrial Ecology Virtual Laboratory (IELab) (Lenzen et al. 2014). All types of final demand are included. We point out the connection between territorial, out-of-boundary, and consumption-based accounting in the carbon map and suggest mitigation pathways based on embodied carbon flows.

Standards for Reporting Greenhouse Gas Emissions from Cities

Since ICLEI (2009) published the first version of the Local Government GHG Analysis Protocol, several other guidelines and standards have been developed to help cities to account for their GHG emissions (e.g., Rauland and Newman 2015a; World Bank 2010; lists can also be found in WRI et al. 2014,

Table A.2 and in Bertoldi et al. 2010). The most advanced and recent standards to date are the PAS 2070 Specification for the Assessment of Greenhouse Gas Emissions of a City (BSI 2013) initiated by the Greater London Authority, and the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) (WRI et al. 2014), which has been developed by the World Resources Institute (WRI), C40 Cities Climate Leadership Group, and ICLEI–Local Governments for Sustainability. Inventory methods vary with respect to the sources and number of GHGs included and how out-of-boundary and transboundary emissions are accounted for. PAS 2070 emphasizes indirect emissions.

The GPC standard follows the well-established format introduced by the GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard (WRI and WBCSD 2011) and distinguishes three scopes (WRI et al. 2014, page 11, Table 2):

> Scope 1: GHG emissions from sources located within the city boundary
> Scope 2: GHG emissions occurring as a consequence of the use of grid-supplied electricity, heating, and/or cooling within the city boundary
> Scope 3: All other GHG emissions that occur outside the city boundary as a result of activities within the city boundary

The GPC only provides guidance for a limited number of Scope 3 emission sources (losses associated with grid-supplied energy, out-of-boundary waste disposal and treatment, and transboundary transportation). Consumption-based accounting is mentioned as a more comprehensive option (WRI et al. 2014, 33); a more detailed guidance document for Scope 3 emissions is planned for 2016. As part of city-scale GHG accounting, the GPC standard also describes a separate Local Government Operations (LGO) inventory that can be compiled to identify emission sources that can be directly controlled by local authorities.

PAS 2070 (initiated by the Greater London Authority) describes two methodologies to account for both direct and indirect GHG emissions of a city:

- Direct plus supply chain (DPSC) accounting "captures territorial GHG emissions and those associated with the largest supply chains serving cities, many of which are associated with city infrastructures" (BSI 2013, 1). It largely follows the three scopes defined by the GHG Protocol and GPC standards (WRI et al. 2014; WRI and WBCSD 2011).
- The consumption-based (CB) methodology captures direct and life cycle GHG emissions for all goods and services consumed by residents of a city, that is, GHG emissions are allocated to the final consumers of goods and services, rather than to the original producers of those GHG emissions (BSI 2013, 1). It is equivalent to a city's CF (Minx et al. 2013) and does not include emissions that are associated with goods and services exported from the city for consumption elsewhere.

Despite intense consultation of experts and stakeholders and detailed accounting guidelines, the existing standards are still partly incomplete or inconsistent with respect to indirect emissions. Incompleteness applies because not all indirect emissions of cities are accounted for. Both GPC and PAS 2070 recommend the inclusion of Scope 3 or supply-chain emissions from certain products or services only. These "are either of exceptional importance to life in cities (e.g. water), or are known to make a material contribution to the GHG emissions of cities . . . " (BSI 2013, 17). Explicitly mentioned in the PAS 2070 are water provision, food and drink, and construction materials (p. 11). The GPC covers similar areas and allows for the inclusion of "Other indirect emissions" as well; however, the guidelines for these Scope 3 emissions are yet to be written.

The definition of what constitutes a "material contribution" is vague and contentious. As has been shown previously in the context of CF accounting for industry sectors and organizations (Wiedmann 2009), the consumption of large amounts of goods and services that each, by themselves, might only emit small amounts of emissions can add up to significant contributions. Depending on the economic sector, a materiality threshold of only 1% can cut off between 5% and 70% of indirect emissions (Huang et al. 2009). Estimating the full extent of Scope 3 (supply chain) emissions is only possible by employing a top-down method such as IOA.

Inconsistency applies because of nonexclusivity and the potential for double counting. Out-of-boundary emissions may also be reported by regional GHG inventories, and national inventories will not be consistent with the sum of regional inventories and those from a country's cities that include out-of-boundary supply-chain emissions. Care must also be taken to not double count supply-chain emissions of materials with emissions from industrial processes given that these might overlap (the PAS 2070 recommends subtraction or separate reporting; BSI 2013, 14)

The inclusion of the CB methodology in the PAS 2070 is an encouraging development. It avoids incompleteness given that it is based on economy-wide IOA and avoids inconsistency because it allocates emissions to final demand only, without double counting. The dichotomy with extended territorial accounting, however, remains (Wiedmann 2012), and it is obvious that existing city GHG accounting standards are struggling to deal with the ensuing ambivalence.

The city carbon map we propose here constitutes a consistent accounting framework that allows for the unambiguous identification of direct and indirect GHG emissions. It clearly identifies all different scopes described in the standards (Scope 1, 2, and 3, DPSC, and CB) and introduces additional consistency with national and regional accounting frameworks.

The City Carbon Map: An Accounting Framework Based on Input-Output Tables

The Concept of a City Carbon Map

The ideal accounting framework for city CFs should show the type and location of emission source (origin), the type of product consumed in the city (destination), and whether emissions belong to Scope 1, 2, or 3. Most importantly, a consistent framework should set city CFs in context with national GHG accounting. Categorization of emissions should be done in a mutually exclusive and collectively exhaustive way in order to avoid over, under, or double counting of emissions. City GHG accounts and CFs must be consistent with regional, national, and global emissions accounts.

A consistent way of reporting territorial and embodied emissions simultaneously is to show the origin and destination in one table, or carbon map. Whereas the origin can be interpreted as the physical source of emissions, for example, one particular industry sector in a particular region, the word destination has no equivalent physical meaning. It is simply the allocation of supply-chain emissions to final products that are consumed within the city. In that sense, city CF accounting is analogous to its national counterpart where emissions embodied in international imports and exports are often depicted as "carbon flows" between countries, whereas the physical emissions always occur in the country of origin (see, e.g., Davis et al. 2011).

The rest of this section explains how to compile and read a city carbon map before the example of a carbon map for Melbourne is described in detail.

Compilation of the Carbon Map

Based on standard Leontief-inverse demand-pull I-O calculus (Miller and Blair 2009), the carbon map is simply a two-dimensional decomposition of the CF of a city's final demand. It splits up the total CF into the industry sectors from which the GHG emissions originate as well as into the product groups in which the emissions become embodied. A third dimension can be introduced by splitting up final demand into its constituents. In aggregated form, the calculations can be denoted as follows (equation 1).

$$\mathbf{C} = \widehat{\boldsymbol{Ex}^{-1}}\,(\boldsymbol{I} - \mathbf{A})^{-1}\,\hat{\mathbf{y}} \tag{1}$$

In an I-O system with n sectors:

- $\mathbf{C}$ is a carbon map of dimensions n×n.
- $\widehat{\boldsymbol{Ex}^{-1}}$ is the diagonalized vector (n×n) of direct industry emission intensities, calculated as the product of a vector (1×n) of industry emissions $\boldsymbol{E}$ and the inverse matrix $\boldsymbol{x}^{-1}$ of diagonalized total industry output (n×n). The hat symbol (^) indicates that the resulting 1×n vector has been placed onto the diagonal of an n×n matrix with all off-diagonal matrix elements being zero.
- $\boldsymbol{I}$ is an n×n identity matrix with ones on the diagonal and zeroes elsewhere.
- $\boldsymbol{A}$ is the technology coefficient matrix (n×n), calculated as the product of the I-O transaction matrix $\boldsymbol{T}$ (n×n) and the inverse matrix $\boldsymbol{x}^{-1}$ of diagonalized total industry output (n×n).
- $\hat{\mathbf{y}}$ is an n×1 vector of final demand which has been diagonalized.

Note that only one column of final demand (n×1) can be turned into a carbon map at a time. If the final demand of a city is split in different subcategories, a carbon map can be produced for each of these categories.

IOTs can be compiled as symmetric tables (in industry-by-industry or product-by-product format) or in a supply and use table (SUT) framework (Eurostat 2008). Any of these can be used to produce a city carbon map; however, we regard the SUT format as most useful because the data are closer to original information, can more readily be aligned with environmental statistics, and the resulting carbon map distinguishes products and industries, which is easier to interpret and more intuitive (see also Lenzen and Rueda-Cantuche 2012; Rueda-Cantuche 2011). The number of sectors in a SUT framework is 2n, the vector x contains both industry and product outputs, emissions are allocated to industry sectors, and final demand is for products. Ideally, the city's tables should be nested in a multiregional framework that contains the city's region and/or nation as well as other countries and/or the rest of the world (figure 1).

The carbon map (figure 2 and figure 3) shows the allocation of emissions from industries (vertical labels on the left side) to products (horizontal labels along the top). Industries can be thought of as the origin of emissions and products as the final destination, in terms of cradle-to-shelf embodied emissions. Direct household emissions, for example from heating homes or driving cars, are not included in the map (E_f in figure 1).

Case Study Illustration: The Carbon Map of Melbourne

Case Study Data

For the purpose of demonstrating a real carbon map, we chose Greater Melbourne, Australia, as a case study, adopting the Greater Capital City Statistical Area (GCCSA) published by the Australian Bureau of Statistics (ABS 2011) as the metropolitan's boundary definition (figure 1A in supporting information S1 on the Journal's website). The GCCSA is designed to provide a stable and consistent boundary that reflects the functional extent of a capital city. It includes those living within the urban area of the city as well as people who regularly socialize, shop, or work within the city, but live in small towns and rural areas surrounding the city. In 2009—our reporting period—Greater Melbourne's population (3,998,022 people) made up 73.4% of the population of the state of Victoria and 3.4% (7,693 square kilometers) of its area (ABS 2014).

Multiregion SUTs and GHG data for Melbourne, Rest of Victoria (RoV), and Rest of Australia (RoA) for the year 2009 were taken from the IELab (www.ielab.info). The IELab compilation has been described elsewhere (Lenzen et al. 2014); it uses GHG data at the state level from the Australian Greenhouse Emissions Information System (AGEIS) database (AGEIS 2014). For the present analysis, three GHGs were considered: CO_2, methane, and nitrous oxide. To achieve global closure, a Rest of World (RoW) region derived from the global Eora database (Lenzen et al. 2012, 2013) was added as the fourth region in the MRIO model. This procedure is described in supporting information S1 on the Web.

	City industries	City products	Region industries	Region products	Nation industries	Nation products	World industries	World products	C FD	R FD	N FD	W FD	Total output
City industries		V^{CC}											x^{C}
City products	U^{CC}		U^{CR}		U^{CN}		U^{CW}		y^{CC}	y^{CR}	y^{CN}	y^{CW}	q^{C}
Region industries				V^{RR}									x^{R}
Region products	U^{RC}		U^{RR}		U^{RN}		U^{RW}		y^{RC}	y^{RR}	y^{RN}	y^{RW}	q^{R}
Nation industries						V^{NN}							x^{N}
Nation products	U^{NC}		U^{NR}		U^{NN}		U^{NW}		y^{NC}	y^{NR}	y^{NN}	y^{NW}	q^{N}
World industries								V^{WW}					x^{W}
World products	U^{WC}		U^{WR}		U^{WN}		U^{WW}		y^{WC}	y^{WR}	y^{WN}	y^{WW}	q^{W}
Primary inputs	v^{C}		v^{R}		v^{N}		v^{W}						
Total input	$x^{C'}$	$q^{C'}$	$x^{R'}$	$q^{R'}$	$x^{N'}$	$q^{N'}$	$x^{W'}$	$q^{W'}$					
Emissions	E_i^{C}		E_i^{R}		E_i^{N}		E_i^{W}		E_f^{C}	E_f^{R}	E_f^{N}	E_f^{W}	

Figure 1 Multiregional supply (V) and use table (U) framework for a city (C), its region (R), nation (N), and rest of the world (W). Data sections related to the city are shaded, with imports and exports in a lighter shade of gray. y = final demand for products; x = total industry outputs; q = total product outputs; v = value added; E = emissions.

Melbourne Carbon Map

Figure 2 shows a schematic overview of a city carbon map and the associated virtual carbon flows. In its simplest and most aggregated form, we distinguish six segments that represent emissions from industries in and outside of the city, embodied in products produced and consumed in and outside of the city.

The actual carbon map of Melbourne is shown in figure 3, which resolves the segments I to IV into ten industry sectors and product groups. To make the map legible, all regions outside of Melbourne have been aggregated to one World-outside-of-Melbourne (WooM) region.

Industries and products from outside of the city can be further disaggregated into region, nation, and rest of the world. Figure 2A in supporting information S2 on the Web shows a schematic of this breakdown. The full four-region carbon map of Melbourne can be found in supporting information S2 on the Web.

How to Read the Carbon Map?

The carbon map identifies the origin of emissions from industries (rows) and the destination of their embodiment in (allocation to) products (columns). One important point to notice is that industry and product labels are transposed in the carbon map, compared to a use table.

Segment I shows the emissions of city industries that produce city products. As an example, the number at the intersection of the first row and the third column represents the emissions from agriculture in the city that are embodied in city food products. The seventh row of that column shows the emissions from transporting the food within the city. City industries may also produce intermediate products that are exported and subsequently used to produce goods and services from outside of the region, which are consumed by city residents. These intermediate embodied emissions are shown in segment II and constitute a decomposition of a supply chain (see also dotted lines in figure 2 and compare to the "streams" of embodied emissions mentioned in Wiedmann et al. 2010).

Industries outside of the city are listed further below in segments III and IV. Again, the map lists industry emissions that are embodied in products produced in the city (III) or produced in the region, nation, or world (IV). Note that *all* these products are consumed in the city because the table has been generated using the city's final demand. Hence, in these sections, the map shows all emissions outside of the city (Scope 3 emissions) that have become embodied in products consumed by the city. For example, the number at the intersection of "WooM-Ind-Elec" and "WooM-Prod-Goods" may include emissions from a regional power plant supplying electricity to a regional aluminum smelter, which exports aluminum to Japan for the construction of cars that are bought by city residents.

A column in the carbon map shows the CF of the product group consumed in the city. For example, the column "Melb-Prod-Constr" shows the embodied emissions of new buildings and infrastructure in the city. The rows show the industries where these embodied emissions come from.

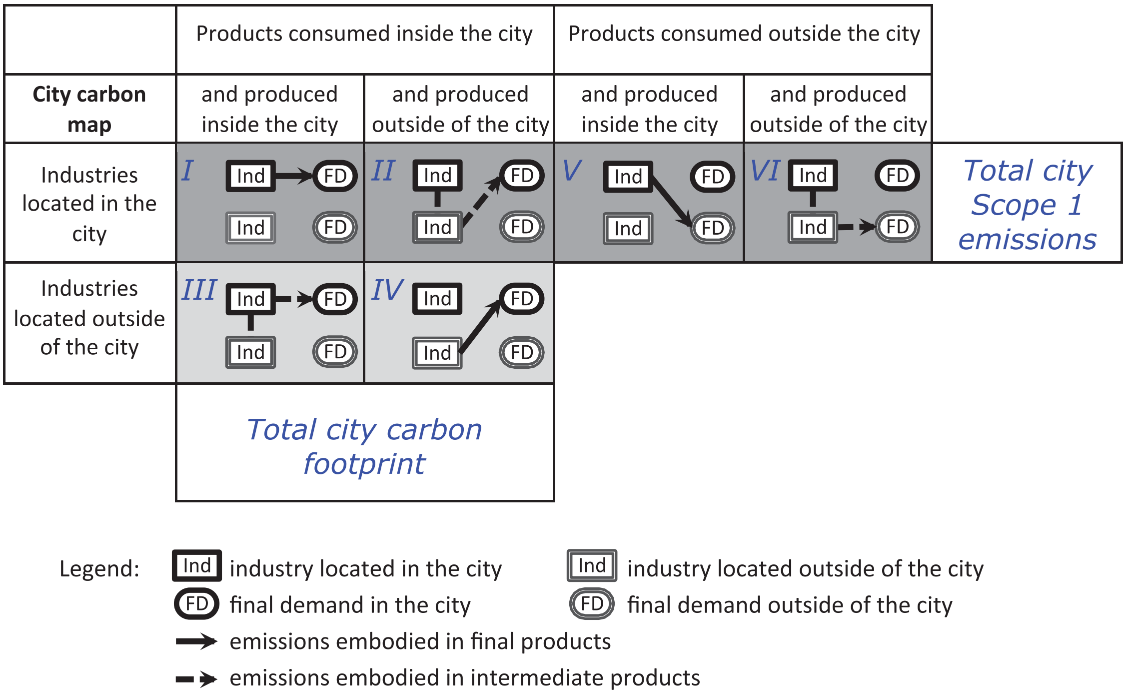

Figure 2 Overview schematic of a city carbon map and flows of embodied emissions. Emissions from the city's industries (Scope 1, and partly Scope 2) are located in the map's sections I, II, V, and VI (shaded in dark gray). Segments III and IV represent emissions from industries outside of the city that are associated with (embodied in) the city's final demand (lightly shaded, Scope 3). The sum of segments I to IV is the total carbon footprint of the city (see also figure 1 in Choi 2015).

Emissions are embodied in > / Origin of emissions v	GHG Emissions (kt CO_2-eq)	Mel-Prod Agric	Mel-Prod Ind	Mel-Prod Food	Mel-Prod Goods	Mel-Prod Elec	Mel-Prod W/W	Mel-Prod Transp	Mel-Prod Constr	Mel-Prod Govt	Mel-Prod Biz	WooM-Prod Agric	WooM-Prod Ind	WooM-Prod Food	WooM-Prod Goods	WooM-Prod Elec	WooM-Prod W/W	WooM-Prod Transp	WooM-Prod Constr	WooM-Prod Govt	WooM-Prod Biz
Melb-Ind	Agric	217.9	0.2	279.0	29.8	0.5	0.9	6.2	82.8	38.1	121.6	0.11	0.05	0.07	0.04	0.01	0.02	0.003	0.08	0.22	0.003
Melb-Ind	Ind	2.1	674.6	87.0	532	84.2	21.3	43.1	477.5	147.8	542.6	1.34	1.08	0.33	4.47	0.37	0.32	0.11	1.05	2.31	0.06
Melb-Ind	Food	0.7	0.2	676.1	13.6	0.6	0.8	6.0	62.5	47.9	156.5	0.14	0.05	0.10	0.02	0.01	0.02	0.00	0.07	0.28	0.002
Melb-Ind	Goods	3.8	3.4	125.4	1,268	8.9	17.5	74.1	850.7	247.3	690.9	2.37	1.34	0.44	0.50	0.34	0.57	0.03	1.99	4.37	0.011
Melb-Ind	Elec	20.6	23.7	972	1,368	10,686	109.1	418.5	6,532	1,646	4,009	3.62	2.06	0.76	0.80	1.37	0.96	0.07	3.20	6.98	0.023
Melb-Ind	W/W	1.2	1.3	28.8	151.6	4.1	283.6	17.2	433.1	74.0	179.6	0.38	0.21	0.07	0.09	0.07	0.14	0.01	0.38	0.70	0.002
Melb-Ind	Transp	5.5	3.4	228.2	222.8	10.0	9.9	1,495	740.8	358.4	1,138	0.77	0.39	0.17	0.33	0.11	0.18	0.13	0.60	1.40	0.015
Melb-Ind	Constr	0.4	0.5	15.8	15.2	1.2	2.2	10.6	1,204	56.1	136.0	0.08	0.06	0.02	0.01	0.02	0.03	0.002	0.13	0.21	0.000
Melb-Ind	Govt	0.04	0.04	1.8	2.2	0.1	0.2	1.8	11.4	588.8	20.9	0.01	0.005	0.002	0.003	0.001	0.002	0.000	0.01	0.02	0.000
Melb-Ind	Biz	1.6	1.1	72.5	62.5	3.1	4.4	39.2	376.8	157.7	1,301	0.35	0.20	0.07	0.06	0.06	0.09	0.01	0.32	0.79	0.003
WooM-Ind	Agric	85.2	2.8	3,044	411.5	10.1	13.3	78.3	778.0	513.7	1,492	4,677	28.9	776.7	487.0	8.6	14.8	22.2	64.9	174.9	26.5
WooM-Ind	Ind	5.6	15.4	199.2	1,124	100.4	22.5	88.4	849	311.7	854	53.7	1,587	23.5	507.2	98.6	30.1	14.3	54.1	102.5	6.9
WooM-Ind	Food	0.6	0.1	62.7	11.6	0.7	0.5	3.2	28.7	24.2	55.7	17.1	4.3	261.2	29.2	1.5	2.1	2.1	7.4	33.5	3.9
WooM-Ind	Goods	15.9	8.3	392.4	781	28.6	37.2	183.2	1,584	760.9	1,444	220.3	124.5	128.1	5,432	35.8	60.8	109.8	182.8	391.8	49.4
WooM-Ind	Elec	19.3	13.7	680.6	1,139	812.8	58.8	251.2	2,223	1,005	2,241	272.1	232.6	253.6	3,135	5,775	124.6	178.4	351.4	572.4	94.9
WooM-Ind	W/W	0.9	0.4	23.3	26.4	2.1	2.8	6.3	77.3	25.8	58.6	20.3	12.9	7.3	67.0	6.3	188.6	3.6	36.0	37.5	1.9
WooM-Ind	Transp	5.1	2.7	164.7	253.8	10.8	11.3	93.7	469.3	303.8	567.6	103.3	58.5	108.8	987	17.9	22.5	1,427	72.6	217.3	45.3
WooM-Ind	Constr	0.2	0.1	7.0	9.5	0.8	0.4	1.8	20.7	8.0	17.4	6.3	7.1	3.3	24.5	1.9	3.5	3.3	86.5	23.1	2.3
WooM-Ind	Govt	0.05	0.03	1.5	2.5	0.1	0.1	0.7	5.0	3.9	6.3	0.7	0.5	1.0	10.3	0.1	0.3	1.0	0.7	135.9	0.9
WooM-Ind	Biz	1.3	0.6	41.1	47.3	3.1	2.0	10.7	94.2	47.7	109.9	38.5	23.5	23.7	178.4	7.3	11.2	16.4	41.9	103.3	49.5

Legend: Scope 1 (excl. exports); Scope 2; Scope 3; Scope 3 emissions of electricity use; Scope 3 emissions of electricity use already accounted for under Scope 1

Figure 3 Two-region, ten-sector carbon map of Melbourne (GHG values in kt CO_2-eq) (green bars symbolize relative size of values. GHG = greenhouse gas; kt CO2-eq = kilotonnes carbon dioxide equivalent; WooM = world outside of Melbourne; Agric = agriculture; Ind = industrial products; Elec = electricity, W/W = water and waste; Transp = transport services; Constr = construction and estate services; Govt = government services; Biz = business and private services.

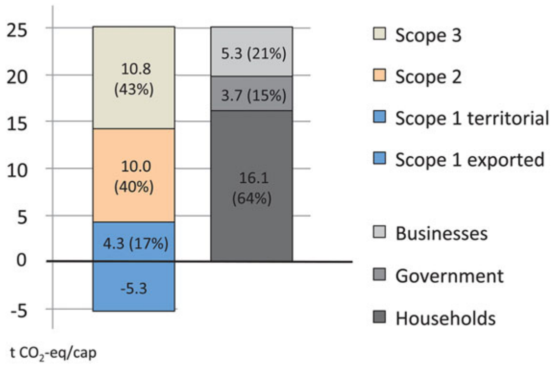

Figure 4 Breakdown of Melbourne's carbon footprint by scopes and type of final demand (percentages of the total carbon footprint are shown).

Results and Discussion

Standard Greenhouse Gas Accounting Using the City Carbon Map

The city carbon map is particularly well suited to account consistently for all standard emission scopes because these can be identified unambiguously in the map. We demonstrate this by showing results for our Melbourne case study.

Melbourne's CF amounts to 100 megatonnes (Mt) carbon dioxide equivalent (CO_2-eq) or 25.1 tonnes (t) carbon dioxide equivalent per capita (CO_2-eq/cap), most of which falls under Scope 2 and 3 (figure 4).

Direct emissions from city industries (Scope 1) are located in the first set of rows of the map (figure 3). They have become embodied in products consumed by the city (segments I and II) or consumed elsewhere (V and VI). The latter are considered exported emissions and are not included in a CBA. However, when fully accounting for Scope 1 emissions from a territorial perspective, these exported emissions can be calculated separately, using the final demand of other regions (see also figure 2A in S2). Total Scope 1 emissions for Melbourne are 38.4 Mt CO_2-eq (9.6 t CO_2-eq/cap), of which 4.3 t CO_2-eq/cap are embodied in the city's final demand and 5.3 t CO_2-eq/cap are exported (figure 4 and figure 5).

Emissions from electricity generation can be distinguished by scope in the carbon map. Emissions from power plants within the city are in row Melb-Ind-Elec (fifth row in figure 3, orange shaded). These Scope 2 emissions are either associated with the final demand of electricity (column Melb-Prod-Elec) or with the use of electricity by city companies that produce goods and services consumed by the city. For example, the emissions from electricity for public transport are located at the intersection of row Melb-Ind-Elec and column Melb-Prod-Transp. A small amount of electricity generated in the city may be exported to regions outside of the city, for example, during times of excess supply. In segment II of the carbon map, we distinguish whether the associated emissions are embodied in regional products (Scope 1) or in regional electricity (Scope 2) consumed in the city (figure 3).

Both residents and businesses in a city may buy electricity from providers outside of the city, either as part of a conscious decision to choose a particular supplier or unknowingly, when the city power grid is supplied with out-of-boundary electricity, for example, in times of high demand. These imported Scope 2 emissions can be found in row WooM-Ind-Elec. In the case of transport, for example, these include out-of-boundary emissions from regional power stations used for transboundary railway travel. Total Scope 2 emissions for Melbourne are 40.0 Mt CO_2-eq (10.0 t CO_2-eq/cap), of which 14.2 Mt are embodied in out-of-boundary electricity (row 15 in figure 3).

In addition to emissions from transmission and distribution losses included in the GPC standard (WRI et al. 2014, 56), the carbon map identifies other Scope 3 emissions from electricity, for example, from building and maintaining the transmission network (optional in the standard). These emissions are shown in the columns of electricity products consumed in the city (bordered cells in figure 3) and include emissions embodied in a diverse range of products, for example, power pylons, cables, and transformers (manufacturing industries) or buildings and insurance (banking and real estate industries). In segments I and II, these emissions have already been accounted for under Scope 1 (double border line).

All other parts of the carbon map represent Scope 3 emissions of the city, produced by industries outside of the city (segments III and IV). For example, a city ticketing agency is likely to use office equipment that has been produced outside of the city, maybe even abroad. The associated Scope 3 emissions can be found at the intersection of WooM-Ind-Goods and Melb-Prod-Biz. Melbourne's Scope 3 emissions make up 43% of the city's CF (43.3 Mt CO_2-eq, 10.8 t CO_2-eq/cap). More than half of these, 58%, are embodied in imported products (figure 5 and figure 6).

Standard emissions accounting is organized by categories, such as Stationary energy, Transportation, Waste, Industrial processes, and product use (IPPU), Agriculture, forestry, and other land use (AFOLU), and Other indirect emissions (WRI et al. 2014, page 10, Table 1). With the city carbon map depicting all origins and destinations of emissions related to urban final demand, it is straightforward to account for Scopes 1, 2, and 3 just by adding up the correct parts of the table. The ten-sector map for Melbourne shown in figure 3 is a very aggregated version; summary results are shown in figure 6. For practical use, the map can be disaggregated to many detailed industries and products, including, for example, specific materials, waste and recycling plants, modes of transport, and so on. For example, emissions embodied in steel for new buildings can then be found at the intersection of steel manufacturing and construction services in all segments I to IV, depending on where the steel comes from. The Australian IElab platform allows for a disaggregation of up to 1,284 separate sectors (Lenzen et al. 2014), providing a level of detail that is more than sufficient for accurate GHG accounting.

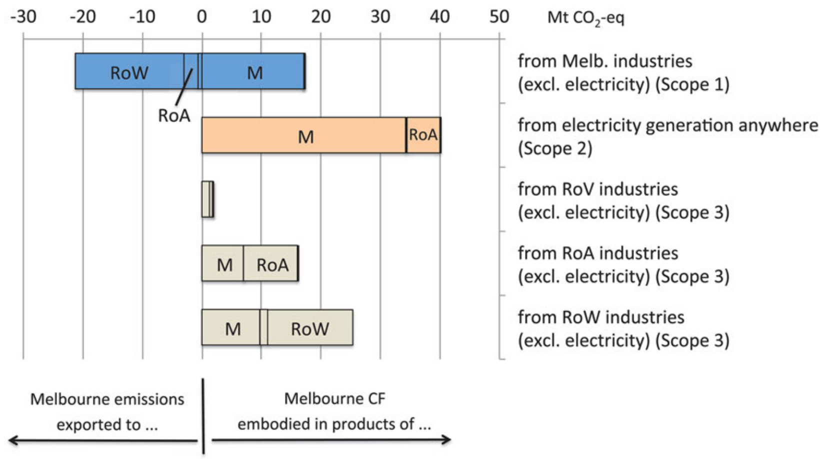

Figure 5 Origin and destination of Melbourne's GHG emissions. All positive values add up to Melbourne's carbon footprint; negative values represent emissions embodied in final demand elsewhere. GHG = greenhouse gas.

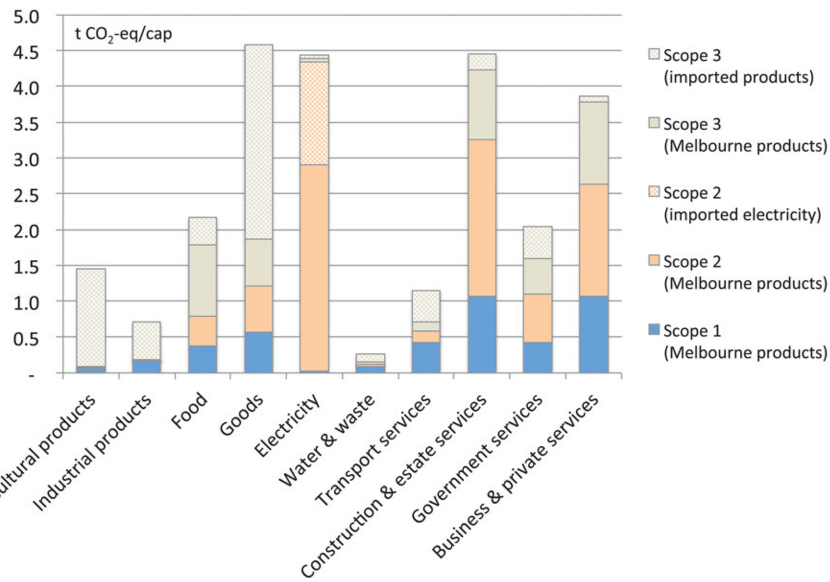

Figure 6 Per capita carbon footprint of Melbourne's total final demand by broad product category and scope.

The Carbon Footprint of Different Actors in a City: Decomposing Final Demand

IOTs from national statistical offices distinguish different types of final demand (UN 2009; Eurostat 2008), which usually include household and government consumption, investments, and other categories; the exact breakdown can vary between countries. We aggregate the six final demand categories from the IELab into three main groups, representing main actors in a city: households, government, and businesses. Whereas households are responsible for the majority of Melbourne's CF (64%, 16.1 t CO2-eq/cap), both government (15%), and business demand (21%) also contribute significantly (figure 4; see supporting information S1 and S2 on the Web for further details). The CF of local government spending in Melbourne is 3.7 t CO_2-eq/cap—this compares to 0.4 to 2.9 t CO_2-eq/cap for the CF of municipal services in Norway reported by Larsen and Hertwich (2010b).

The division between public and private sector, as well as households provides information to cities for additional policies and strategies to help mitigate global emissions. The influence of cities combines both the ability to affect territorial emissions of households, businesses, and government, such as transport and building emissions, but also the indirect emissions covering their consumption and procurement patterns (Erickson et al. 2013; Lazarus et al. 2013).

One of the reasons for inaction related to indirect emissions is a lack of knowledge and data, a gap that could, in part, be covered by the availability of emissions data at a high level of sectoral and spatial resolution. Most of the evidence related to the application of such data relates to local authorities (Calcott and Bull 2008; WWF 2007). For local governments, this information can help steer energy demand reduction strategies for a number of sectors and go beyond merely identifying the high emitting sectors. There is considerable evidence that appropriate implementation is at the city level to deal with the large-dispersed changes required (DECC 2014; GEA 2012; IEA 2014; Roelich and Knoeri 2014). For example, spatial emissions data give insights into prioritizing retrofit programs and rollout of microgeneration to ensure the greatest return on evidence. In addition, for local transport issues, such data informs spatial planning decisions, the sighting of public transport and cycle networks, and where to establish individualized and social marketing campaigns (Barrett et al. 2007; Erickson et al. 2013; Haq et al. 2013; Nye and Rydin 2008). There is evidence from U.S. and UK cities, such as Seattle and London, who have employed similar data to explore the areas of influence for different actors across a city, identifying many more additional options for climate-change mitigation (Erickson et al. 2013; James and Dessai 2003; Owen et al. 2008).

Related specifically to indirect emissions, a number of local authorities in Scotland have employed the information to shape sustainable food campaigns, the location of allotments and waste management plans (Barrett et al. 2007). The common pattern is that carbon data are not used in isolation, but contribute to a body of evidence to achieve multiple local ambitions to address emission reduction alongside poverty alleviation, environmental improvement, and growth to the local economy (Seyfang et al. 2013).

Although more evidence exists related to local government applications, increasingly, both private and public sector organizations are applying local carbon to procurement and investment decisions. Local authorities, universities, and businesses have applied spatial carbon data to map the emissions associated with procurement patterns (Townsend and Barrett 2015). However, further investigation and the development of case studies is required to provide further support on the application at the local level.

Characteristics and Limitations of the Approach

The word carbon map is imprecise insofar as it only shows the flows of GHG emissions, not the flows or stocks of the element carbon. Carbon in Carbon map is used in the same way as in carbon footprint, where also only the embodied flows of GHGs are accounted for.

The Melbourne carbon map example presented in this study is based on a purely monetary IOT, but could equally be based on physical or mixed-units tables. Using monetary tables for assigning embodied GHG emissions to the different parts of the carbon map means that implicitly the process of economic allocation as known in life cycle assessment (LCA) is employed. Carbon flows follow the economic transactions among industry sectors and between industry sectors and final demand. In some cases, this mechanism of allocation might be counterintuitive to the perception of physical flows. For example, in standard national accounting (UN 2009), there is no final demand for construction materials; instead, construction materials are bought by builders or construction companies who, in turn, provide the service of construction to final consumers or investors. Including this service provision into the flow of processes for construction is in line with life cycle thinking. However, it is not consistent with existing LCA standards. International Organization for Standardization (ISO) 14040 (ISO 2006) and PAS 2050 (BSI 2008) give preference to physical allocation, that is, the embodied carbon emissions of a building, for example, would be determined by the quantity of building materials used, not by the price paid to the builder. In physical allocation, flows of embodied environmental impacts and physical flows are proportional; in economic allocation, impacts are assigned in proportion to the value that an economy places on goods and services. Both methods are equally justifiable and the analyst has a choice by using the respective type of IOT. Mixed-unit IOTs are often used to overcome price inhomogeneity (e.g., Lindner and Guan 2014). Purely physical IOTs could be used to generate city carbon maps in exactly the same way as described in this article (see, e.g., Liu and Zhang 2012); the reality, however, is that physical data are more difficult to collect and compile.

One main limitation in practice might be the lack of city-scale IOTs. They are rarely available from official statistics, making it necessary to estimate the data. For more than 60 years, researchers have developed methods to estimate subnational IOTs based on nonsurvey methods (see, e.g., Leontief 1953), and the same methods can, in principle, be applied to the city level. The IELab, for example, utilizes several nonsurvey methods and local census and industry data for the regionalization of national and state-level IOTs (Lenzen et al. 2014). Hermannsson and McIntyre (2014) used a similar approach for Glasgow. Thus, derived localized IOTs represent a reasonable approximation of local economies, though results may differ depending on the method chosen. Top-down derived data in the carbon map should therefore be viewed as a "tier 1" or "initial estimate" of city GHG flows that can and should be augmented with bottom-up data collected from locally specific activities (including energy use data), if available. Further, the engagement of local governments and other stakeholders is important for the actual implementation of emission reduction strategies and actions. The fundamental purpose of the carbon map is to provide the *framework* to aid standard city GHG accounting, and subsequent mitigation.

Finally, we reiterate that direct emissions from households are not included in the carbon map because they do not have an (industry) origin and (product) destination as such. Emissions from heating residential homes fall under Scope 1, whereas the use of private motor vehicles leads to both territorial and transboundary emissions. Even though the purchase of fuels is captured by final demand in IOTs, bespoke transport modeling is likely to be the most suitable way of accounting for GHG emissions from private commuting.

Conclusions

We present the concept of a city carbon map based on environmental IOA. The carbon map:

- is a consistent carbon accounting framework at various spatial scales, providing the ability to nest city, regional, national, and global GHG inventories;

- unambiguously identifies territorial and out-of-boundary emissions of cities as well as standard Scope 1, 2, and 3 emissions;
- allows for meaningful comparisons between cities and their contribution to regional and national GHG mitigation strategies.

Using Greater Melbourne, Australia, as a case study, we demonstrate how the carbon map can be interpreted and used in practice. The results also confirm the importance of comprehensive Scope 3 accounting, with this scope making up the largest part of Melbourne's CF (43%).

Ramaswami and Chavez (2013) point out that there is no one-fits-all GHG metric for the carbon intensity of cities—different accounting perspectives lead to complementary indicators that should be considered alongside one another and with different denominators. The carbon map concept presented here offers the opportunity to accomplish multiperspective accounting in one coherent framework. There is no double counting or ambiguity in the carbon map given that all emissions have been allocated to clearly defined and standardized sectors, representing either industry or product groups, collectively covering all economies from the urban, via the regional and national to the global scale. The framework can be extended to a multicity, multiregion map that shows the interlinkages of GHG emissions between multiple cities and regions.

Often, large geographical maps of urban areas can be see hanging on the wall of city planning offices. Why should not large, detailed city carbon maps be posted there as well, showing hundreds of industries and dozens of areas within a city, color coded to highlight the hotspots that need priority attention? Updated annually, this system could become one key tool in planning and managing the decarbonization of cities.

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References

ABS (Australian Bureau of Statistics). 2011. Australian Statistical Geography Standard (ASGS): Volume 1—Main structure and greater capital city statistical areas. In *ABS catalogue number 1270.0.55.001*. Canberra, ACT, Australia: Australian Bureau of Statistics.

ABS (Australian Bureau of Statistics). 2014. Regional population growth, Australia, 2012–13 In *ABS catalogue number 3218.0*. Canberra, ACT, Australia: Australian Bureau of Statistics. www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02012-13?OpenDocument. Accessed 14 April 2015.

AGEIS. 2014. Australian Greenhouse Emissions Information System (AGEIS). Australian Government, Department of the Environment. www.environment.gov.au/climate-change/greenhouse-gas-measurement/ageis. Accessed July 2014.

Ala-Mantila, S., J. Heinonen, and S. Junnila. 2013. Greenhouse gas implications of urban sprawl in the Helsinki metropolitan area. *Sustainability* 5(10): 4461–4478. http://dx.doi.org/10.3390/su5104461.

Ala-Mantila, S., J. Heinonen, and S. Junnila. 2014. Relationship between urbanization, direct and indirect greenhouse gas emissions, and expenditures: A multivariate analysis. *Ecological Economics* 104: 129–139. http://dx.doi.org/10.1016/j.ecolecon.2014.04.019.

Arup. 2014. *Climate action in megacities version 2.0*. A report by Arup for C40 cities, February 2014. http://issuu.com/c40cities/docs/c40_climate_action_in_megacities/1?e=10643095/6541335. Accessed 14 April 2015.

Baldasano, J. M., C. Soriano, and L. S. Boada. 1999. Emission inventory for greenhouse gases in the City of Barcelona, 1987–1996. *Atmospheric Environment* 33(23): 3765–3775.

Barrett, J., J. Minx, A. Paul, and S. D. Frey. 2007. *Towards a low footprint Scotland—Living well, within our ecological limits*. A report to Scotland's Global Footprint project. York, UK: Stockholm Environment Institute, March 2007.

Baynes, T. M. and T. Wiedmann. 2012. General approaches for assessing urban environmental sustainability. *Current Opinion in Environmental Sustainability* 4(4): 458–464. http://dx.doi.org/10.1016/j.cosust.2012.09.003.

Bertoldi, P., D. B. Cayuela, S. Monni, and R. Piers de Raveschoot. 2010. *Existing methodologies and tools for the development and implementation of Sustainable Energy Action Plans (SEAP). Summary report II: Methodologies and tools for CO_2 inventories in cities*. JRC European Commission, IES, IE, Covenant of Mayors. www.covenantofmayors.eu/IMG/pdf/003_Report_II.pdf. Accessed 14 April 2015.

Bi, J., R. Zhang, H. Wang, M. Liu, and Y. Wu. 2011. The benchmarks of carbon emissions and policy implications for China's cities: Case of Nanjing. *Energy Policy* 39(9): 4785–4794. http://dx.doi.org/10.1016/j.enpol.2011.06.045.

BSI (British Standards Institute). 2008. *PAS 2050:2008—Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*. London: British Standards Institution, October 2008. www.bsigroup.com/en/Standards-and-Publications/Industry-Sectors/Energy/PAS-2050/. Accessed 14 April 2015.

BSI (British Standards Institute). 2013. *PAS 2070:2013 specification for the assessment of greenhouse gas emissions of a city—Direct plus supply chain and consumption-based methodologies*. L ondon: The British Standards Institution. http://shop.bsigroup.com/Browse-By-Subject/Environmental-Management-and-Sustainability/PAS-2070-2013/. Accessed 14 April 2015.

Calcott, A. and J. Bull. 2008. *The ecological footprint of British city residents*. Godalming, UK: World Wide Fund for Nature. www.wwf.org.uk/filelibrary/pdf/city_footprint2.pdf. Accessed 14 April 2015.

Caro, D., B. Rugani, F. M. Pulselli, and E. Benetto. 2015. Implications of a consumer-based perspective for the estimation of GHG emissions. The illustrative case of Luxembourg. *Science of the Total Environment* 508: 67–75. http://dx.doi.org/10.1016/j.scitotenv.2014.11.053.

Chavez, A. and A. Ramaswami. 2011. Progress toward low carbon cities: Approaches for transboundary GHG emissions' footprinting. *Carbon Management* 2(4): 471–482. http://dx.doi.org/10.4155/cmt.11.38.

Chavez, A. and A. Ramaswami. 2013. Articulating a transboundary infrastructure supply chain greenhouse gas emission footprint for cities: Mathematical relationships and policy relevance. *Energy Policy* 54: 376–384. http://dx.doi.org/10.1016/j.enpol.2012.10.037.

Chen, G. Q., S. Guo, L. Shao, J. S. Li, and Z.-M. Chen. 2013. Three-scale input-output modeling for urban economy: Carbon emission by Beijing 2007. *Communications in Nonlinear Science and Numerical Simulation* 18(9): 2493–2506. http://dx.doi.org/10.1016/j.cnsns.2012.12.029.

Choi, T. 2015. Understanding environmental responsibilities of cities and emissions embodied in trade. *Economic Systems Research* 27(2): 133–153. http://dx.doi.org/10.1080/09535314.2015.1012638.

Davis, S. J., G. P. Peters, and K. Caldeira. 2011. The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* 108(45): 18554–18559. http://dx.doi.org/10.1073/pnas.1107409108.

DECC (UK Department of Energy and Climate Change). 2014. *Community energy strategy*. Lo ndon: UK Department of Energy and Climate Change, 17 April 2014. www.gov.uk/government/publications/community-energy-strategy. Accessed 14 April 2015.

Dias, A. C., D. Lemos, X. Gabarrell, and L. Arroja. 2014. Environmentally extended input-output analysis on a city scale—Application to Aveiro (Portugal). *Journal of Cleaner Production* 75: 118–129. http://dx.doi.org/10.1016/j.jclepro.2014.04.012.

Dodman, D. 2011. Forces driving urban greenhouse gas emissions. *Current Opinion in Environmental Sustainability* 3(3): 121–125. http://dx.doi.org/10.1016/j.cosust.2010.12.013.

Erickson, P., M. Lazarus, C. Chandler, and S. Schultz. 2013. Technologies, policies and measures for GHG abatement at the urban scale. *Greenhouse Gas Measurement and Management* 3(1–2): 37–54. http://dx.doi.org/10.1080/20430779.2013.806866.

Erickson, P., E. A. Stanton, C. Chandler, M. Lazarus, R. Bueno, C. Munitz, J. Cegan, M. Daudon, and S. Donegan. 2012. *Greenhouse gas emissions in King County*. Somerville, MA, USA: Stockholm Environment Institute U.S. Center for King County, Washington. http://sei-us.org/publications/id/432S. Accessed 14 April 2015.

Eurostat. 2008. *Eurostat manual of supply, use and input-output tables, 2008 edition*. Luxembourg: Office for Official Publications of the European Communities. http://ec.europa.eu/eurostat. Accessed 14 April 2015.

Feng, C., X. Gao, J. Wu, Y. Tang, J. He, Y. Qi, and Y. Zhang. 2014a. Greenhouse gas emissions investigation for towns in China: A case study of Xiaolan. *Journal of Cleaner Production* 103: 130–139. http://dx.doi.org/10.1016/j.jclepro.2014.01.013.

Feng, K., K. Hubacek, L. Sun, and Z. Liu. 2014b. Consumption-based CO_2 accounting of China's megacities: The case of Beijing, Tianjin, Shanghai and Chongqing. *Ecological Indicators* 47: 26–31. http://dx.doi.org/10.1016/j.ecolind.2014.04.045.

GEA. 2012. *Global energy assessment—Toward a sustainable future*. Cambridge, UK; New York: Cambridge University Press, and the International Institute for Applied Systems Analysis, Laxenburg, Austria. www.globalenergyassessment.org, http://dx.doi.org/10.1017/CBO9780511793677. Accessed 14 April 2015.

Guo, S., L. Shao, H. Chen, Z. Li, J. B. Liu, F. X. Xu, J. S. Li, et al. 2012. Inventory and input-output analysis of CO_2 emissions by fossil fuel consumption in Beijing 2007. *Ecological Informatics* 12: 93–100. http://dx.doi.org/10.1016/j.ecoinf.2012.05.005.

Haq, G., H. Cambridge, and A. Owen. 2013. A targeted social marketing approach for community pro-environmental behavioural change. *Local Environment* 18(10): 1134–1152. http://dx.doi.org/10.1080/13549839.2013.787974.

Harvey, L. D. 1993. Tackling urban CO_2 emissions in Toronto. *Environment: Science and Policy for Sustainable Development* 35(7): 16–44.

Heinonen, J., M. Jalas, J. K. Juntunen, S. Ala-Mantila, and S. Junnila. 2013. Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—A study of Finland. *Environmental Research Letters* 8(2): 025003. http://stacks.iop.org/1748-9326/8/i=2/a=025003.

Hermannsson, K. and S. G. McIntyre. 2014. Local consumption and territorial based accounting for CO_2 emissions. *Ecological Economics* 104: 1–11. http://dx.doi.org/10.1016/j.ecolecon.2014.04.020.

Hillman, T. and A. Ramaswami. 2010. Greenhouse gas emission footprints and energy use benchmarks for eight U.S. cities. *Environmental Science & Technology* 44(6): 1902–1910. http://dx.doi.org/10.1021/es9024194.

Hoekstra, A. Y. and T. O. Wiedmann. 2014. Humanity's unsustainable environmental footprint. *Science* 344(6188): 1114–1117. http://dx.doi.org/10.1126/science.1248365.

Hoornweg, D., L. Sugar, and C. L. Trejos Gómez. 2011. Cities and greenhouse gas emissions: Moving forward. *Environment and Urbanization* 23(1): 207–227. http://eau.sagepub.com/content/23/1/207.abstract.

Huang, Y. A., M. Lenzen, C. L. Weber, J. Murray, and H. S. Matthews. 2009. The role of input-output analysis for the screening of corporate carbon footprints. *Economic Systems Research* 21(3): 217–242. http://dx.doi.org/10.1080/09535310903541348.

Ibrahim, N., L. Sugar, D. Hoornweg, and C. Kennedy. 2012. Greenhouse gas emissions from cities: comparison of international inventory frameworks. *Local Environment* 17(2): 223–241. http://dx.doi.org/10.1080/13549839.2012.660909.

ICLEI. 2009. *International Local Government GHG Emissions Analysis Protocol (IEAP)*. Version 1.0. Bonn, Germany: ICLEI—Local Governments for Sustainability, October 2009. www.iclei.org/index.php?id=ghgprotocol. Accessed 14 April 2015.

IEA (International Energy Agency). 2014. *Capturing the multiple benefits of energy efficiency*. Paris: International Energy Agency. www.iea.org/w/bookshop/475-Capturing_the_Multiple_Benefits_of_Energy_Efficiency. Accessed 14 April 2015.

IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change—Summary for policymakers*. Geneva, Switzerland: IPCC. http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf. Accessed 14 April 2015.

ISO (International Organization for Standardization). 2006. *International Standard ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO 14040:2006(E). Geneva, Switzerland: International Organization for Standardization. Second edition 2006-07-01. www.iso.org. Accessed 14 April 2015.

James, N. and P. Dessai. 2003. *One planet living in the Thames gateway*. Godalming, UK: World Wide Fund for Nature. www.wwf.org.uk/filelibrary/pdf/thamesgateway.pdf. Accessed 14 April 2015.

Jones, C. and D. M. Kammen. 2014. Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science and Technology* 48(2): 895–902. http://dx.doi.org/10.1021/es4034364.

Jones, C. M. and D. M. Kammen. 2011. Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environmental Science & Technology* 45(9): 4088–4095. http://pubs.acs.org/doi/abs/10.1021/es102221h.

Kennedy, C., S. Demoullin, and E. Mohareb. 2012. Cities reducing their greenhouse gas emissions. *Energy Policy* 49: 774–777. http://dx.doi.org/10.1016/j.enpol.2012.07.030.

Kennedy, C., A. Ramaswami, S. Carney, and S. Dhakal. 2010. Greenhouse gas emission baselines for global cities and metropolitan regions. In *Cities and climate change: Responding to an urgent agenda*, edited by D. Hoornweg et al. Washington, DC: World Bank. http://hdl.handle.net/10986/17381. Accessed 14 April 2015.

Kennedy, C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havránek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G. V. Mendez. 2009. Greenhouse gas emissions from global cities. *Environmental Science & Technology* 43(19): 7297–7302. http://dx.doi.org/10.1021/es900213p.

Kennedy, C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havránek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G. V. Mendez. 2011. Greenhouse gas emissions from global cities (corrigendum). *Environmental Science & Technology* 45(8): 3816–3817. http://dx.doi.org/10.1021/es200849z.

Kennedy, S. and S. Sgouridis. 2011. Rigorous classification and carbon accounting principles for low and zero carbon cities. *Energy Policy* 39(9): 5259–5268. http://dx.doi.org/10.1016/j.enpol.2011.05.038.

Larsen, H. N. and E. G. Hertwich. 2009. The case for consumption-based accounting of greenhouse gas emissions to promote local climate action. *Environmental Science & Policy* 12(7): 791–798. http://dx.doi.org/10.1016/j.envsci.2009.07.010.

Larsen, H. N. and E. G. Hertwich. 2010a. Implementing carbon-footprint-based calculation tools in municipal greenhouse gas inventories. *Journal of Industrial Ecology* 14(6): 965–977. http://dx.doi.org/10.1111/j.1530-9290.2010.00295.x.

Larsen, H. N. and E. G. Hertwich. 2010b. Identifying important characteristics of municipal carbon footprints. *Ecological Economics* 70(1): 60–66. http://dx.doi.org/10.1016/j.ecolecon.2010.05.001.

Larsen, H. N. and E. G. Hertwich. 2011. Analyzing the carbon footprint from public services provided by counties. *Journal of Cleaner Production* 19(17–18): 1975–1981. http://dx.doi.org/10.1016/j.jclepro.2011.06.014.

Lazarus, M., C. Chandler, and P. Erickson. 2013. A core framework and scenario for deep GHG reductions at the city scale. *Energy Policy* 57(6): 563–574. http://dx.doi.org/10.1016/j.enpol.2013.02.031.

Lenzen, M. and G. M. Peters. 2010. How city dwellers affect their resource hinterland—A spatial impact study of Australian households. *Journal of Industrial Ecology* 14(1): 73–90. http://dx.doi.org/10.1111/j.1530-9290.2009.00190.x.

Lenzen, M. and J. M. Rueda-Cantuche. 2012. A note on the use of supply-use tables in impact analyses. *Statistics and Operations Research Transactions* 36(2): 139–152. http://www.idescat.cat/sort/sort362/36.2.2.lenzen-cantuche.pdf.

Lenzen, M., K. Kanemoto, D. Moran, and A. Geschke. 2012. Mapping the structure of the world economy. *Environmental Science & Technology* 46(15): 8374–8381. http://dx.doi.org/10.1021/es300171x.

Lenzen, M., D. Moran, K. Kanemoto, and A. Geschke. 2013. Building Eora: A global multi-region input-output database at high country and sector resolution. *Economic Systems Research* 25(1): 20–49. http://dx.doi.org/10.1080/09535314.2013.769938.

Lenzen, M., A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, et al. 2014. Compiling and using input-output frameworks through collaborative virtual laboratories. *Science of the Total Environment* 485–486: 241–251. http://dx.doi.org/10.1016/j.scitotenv.2014.03.062.

Leontief, W. 1953. Interregional theory. In *Studies in the structure of the American economy*, edited by W. Leontief. New York: Oxford University Press.

Lin, J., Y. Liu, F. Meng, S. Cui, and L. Xu. 2013a. Using hybrid method to evaluate carbon footprint of Xiamen City, China. *Energy Policy* 58: 220–227. http://dx.doi.org/10.1016/j.enpol.2013.03.007.

Lin, T., Y. Yu, X. Bai, L. Feng, and J. Wang. 2013b. Greenhouse gas emissions accounting of urban residential consumption: A household survey based approach. *PLoS ONE* 8(2): e55642. http://dx.doi.org/10.1371/journal.pone.0055642.

Lindner, S. and D. Guan. 2014. A hybrid-unit energy input-output model to evaluate embodied energy and life cycle emissions for China's economy. *Journal of Industrial Ecology* 18(2): 201–211. http://dx.doi.org/10.1111/jiec.12119.

Liu, H. and Y. Zhang. 2012. Ecological network analysis of urban metabolism based on input-output table. *Procedia Environmental Sciences* 13: 1616–1623. http://dx.doi.org/10.1016/j.proenv.2012.01.154.

McGraw, J., P. Haas, L. Young, and A. Evens. 2010. Greenhouse gas emissions in Chicago: Emissions inventories and reduction strategies for Chicago and its metropolitan region. *Journal of Great Lakes Research* 36(sp2): 106–114.

Miller, R. E. and P. D. Blair. 2009. *Input-output analysis: Foundations and extensions*, 2nd ed. Cambridge, UK: Cambridge University Press. www.cambridge.org/millerandblair.

Minx, J., G. Baiocchi, T. Wiedmann, J. Barrett, F. Creutzig, K. Feng, M. Förster, P.-P. Pichler, H. Weisz, and K. Hubacek. 2013. Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters* 8(3): 035039. http://dx.doi.org/10.1088/1748-9326/8/3/035039.

Nye, M. and Y. Rydin. 2008. The contribution of ecological footprinting to planning policy development: Using REAP to evaluate policies for sustainable housing construction. *Environment and Planning B: Planning and Design* 35(2): 227–247. http://dx.doi.org/10.1068/b3379.

Owen, A., A. Paul, and J. Barrett. 2008. *Ashford's footprint—Now and in the future*. York, UK: Stockholm Environment Institute, University of York.

Paloheimo, E. and O. Salmi. 2013. Evaluating the carbon emissions of the low carbon city: A novel approach for consumer based allocation. *Cities* 30: 233–239. http://dx.doi.org/10.1016/j.cities.2012.04.003.

Petsch, S., S. Guhathakurta, L. Heischbourg, K. Müller, and H. Hagen. 2011. Modeling, monitoring, and visualizing carbon footprints at the urban neighborhood scale. *Journal of Urban Technology* 18(4): 81–96. http://dx.doi.org/10.1080/10630732.2011.648436.

Ramaswami, A. and A. Chavez. 2013. What metrics best reflect the energy and carbon intensity of cities? Insights from theory and modeling of 20 US cities. *Environmental Research Letters* 8(3): 035011. http://stacks.iop.org/1748-9326/8/i=3/a=035011.

Ramaswami, A., A. Chavez, and M. Chertow. 2012a. Carbon footprinting of cities and implications for analysis of urban material and energy flows. *Journal of Industrial Ecology* 16(6): 783–785. http://dx.doi.org/10.1111/j.1530-9290.2012.00569.x.

Ramaswami, A., T. Hillman, B. Janson, M. Reiner, and G. Thomas. 2008. A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories. *Environmental Science & Technology* 42(17): 6455–6461. http://dx.doi.org/10.1021/es702992q.

Ramaswami, A., M. Bernard, A. Chavez, T. Hillman, M. Whitaker, G. Thomas, and M. Marshall. 2012b. Quantifying carbon mitigation wedges in U.S. cities: Near-term strategy analysis and critical review. *Environmental Science & Technology* 46(7): 3629–3642. http://dx.doi.org/10.1021/es203503a.

Rauland, V. and P. Newman. 2015a. Counting carbon in cities. In *Decarbonising Cities*, 8: 117–130. Basel, Switzerland: Springer International. http://dx.doi.org/10.1007/978-3-319-15506-7_8.

Rauland, V. and P. Newman. 2015b. Why cities? In *Decarbonising cities*, 3: 19–35. Basel, Switzerland: Springer International. http://dx.doi.org/10.1007/978-3-319-15506-7_3.

Rees, W. and M. Wackernagel. 1996. Urban ecological footprints: Why cities cannot be sustainable—And why they are a key to sustainability. *Environmental Impact Assessment Review* 16(4–6): 223–248. www.sciencedirect.com/science/article/B6V9G-3VWNJWM-2/2/065f7b8a857f0831f84f8b6e7141b50d.

Roelich, K. and C. Knoeri. 2014. Community energy projects: Why are they constrained by liberalised markets and how can cities help them overcome these constraints? In *Workshop on Sustainable Heating Provisions and Cities: Theory, practice and future implications*. www.heatandthecity.org.uk/resources/workshop_on_research_findings_on_sustainable_heating_provisions_and_cities_theory,_practice_and_future_implications. Accessed 14 April 2015.

Rueda-Cantuche, J. M. 2011. The choice of type of input-output table revisited: Moving towards the use of supply-use tables in impact analysis. *Statistics and Operations Research Transactions* 35(1): 21–38.

Satterthwaite, D. 2008. Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and Urbanization* 20(2): 539–549. http://eau.sagepub.com/content/20/2/539.abstract.

Seyfang, G., J. J. Park, and A. Smith. 2013. A thousand flowers blooming? An examination of community energy in the UK. *Energy Policy* 61: 977–989. http://dx.doi.org/10.1016/j.enpol.2013.06.030.

Townsend, J. and J. Barrett. 2015. Exploring the applications of carbon footprinting towards sustainability at a UK university: Reporting and decision making. *Journal of Cleaner Production*. In press. http://dx.doi.org/10.1016/j.jclepro.2013.11.004.

UN (United Nations). 2009. *System of National Accounts 2008*. New York: European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations and World Bank. http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf. Accessed 14 April 2015.

UNSECC. 2014. *Advancing climate ambition: Cities as partners in global climate action—A report to the UN Secretary-General from the UN Secretary General's Special Envoy for Cities and Climate Change, in partnership with the C40 Cities Climate Leadership Group*. September 2014. http://c40-production-images.s3.amazonaws.com/researches/images/25_Advancing_Climate_Ambition.original.pdf?1412878084. Accessed 14 April 2015.

Vause, J., L. Gao, L. Shi, and J. Zhao. 2013. Production and consumption accounting of CO_2 emissions for Xiamen, China. *Energy Policy* 60: 697–704. http://dx.doi.org/10.1016/j.enpol.2013.04.069.

Wang, Y., H. Zhao, L. Li, Z. Liu, and S. Liang. 2013. Carbon dioxide emission drivers for a typical metropolis using input-output structural decomposition analysis. *Energy Policy* 58: 312–318. http://dx.doi.org/10.1016/j.enpol.2013.03.022.

Wiedmann, T. 2009. Carbon footprint and input-output analysis—An introduction. *Economic Systems Research* 21(3): 175–186. http://dx.doi.org/10.1080/09535310903541256.

Wiedmann, T., R. Wood, J. Minx, M. Lenzen, D. Guan, and R. Harris. 2010. A carbon footprint time series of the UK—Results from a multi-region input-output model. *Economic Systems Research* 22(1): 19–42. http://dx.doi.org/10.1080/09535311003612591.

Wiedmann, T. O. 2012. Defining (urban) producer and consumer sinks. *Journal of Industrial Ecology* 16(3): 317–321. http://dx.doi.org/10.1111/j.1530-9290.2011.00436.x.

World Bank. 2010. *UN standard for GHG emissions of cities V2.1*. Washington, DC: The World Bank. http://siteresources.worldbank.org/INTUWM/Resources/GreenhouseGasStandard.pdf. Accessed 14 April 2015.

WRI (World Resources Institute) and WBCSD (World Business Council for Sustainable Development). 2011. *Greenhouse Gas Protocol corporate value chain (Scope 3) accounting and reporting standard*. World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). www.wri.org/publication/greenhouse-gas-protocol-corporate-value-chain-accounting-and-reporting-standard. Accessed 14 April 2015.

WRI, C40, and ICLEI. 2014. *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC)—An accounting and reporting standard for cities*. World Resources Institute, C40 Cities Climate Leadership Group, and ICLEI Local Governments for Sustainability, December 2014. http://ghgprotocol.org/city-accounting. Accessed 14 April 2015.

Wright, L. A., J. Coello, S. Kemp, and I. Williams. 2011. Carbon footprinting for climate change management in cities. *Carbon Management* 2(1): 49–60. http://dx.doi.org/10.4155/cmt.10.41.

WWF (World Wide Fund for Nature). 2007. *The right climate for change—Using the carbon footprint to reduce CO_2 emission—A guide for local authorities*. Godalming, UK: World Wide Fund for Nature,

Yao, L., J. Liu, R. Wang, and K. Yin. 2013. Carbon footprint accounting of regional household consumption in China through multi-regional input-output model. *Huanjing Kexue Xuebao/Acta Scientiae Circumstantiae* 33(7): 2050–2058. www.scopus.com/inward/record.url?eid=2-s2.0-84880341503&partnerID=40&md5=e539c0d5683e6b3d40f412a3ce6747b7.

Yetano Roche, M., S. Lechtenböhmer, M. Fischedick, M.-C. Gröne, C. Xia, and C. Dienst. 2014. Concepts and methodologies for measuring the sustainability of cities. *Annual Review of Environment and Resources* 39(1): 519–547. http://dx.doi.org/10.1146/annurev-environ-012913-101223.

Zhang, B., H. Qiao, and B. Chen. 2015. Embodied energy uses by China's four municipalities: A study based on multi-regional input-output model. *Ecological Modelling*. In press. http://dx.doi.org/10.1016/j.ecolmodel.2014.10.007. Accessed 14 April 2015.

Zhou, S. Y., H. Chen, and S. C. Li. 2010. Resources use and greenhouse gas emissions in urban economy: Ecological input-output modeling for Beijing 2002. *Communications in Nonlinear Science and Numerical Simulation* 15(10): 3201–3231. http://dx.doi.org/10.1016/j.cnsns.2009.11.026.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information includes a map of the greater Melbourne statistical area, full regional presentation of a city carbon map, instructions on adding a Rest-of-World region to IELab MRIO data, and final demand categories in the Industrial Ecology Virtual Laboratory.

Supporting Information S2: This supporting information includes two spreadsheets: The first one is a summary map of Melbourne with ten sectors and two regions. The second one is a breakdown of Melbourne carbon maps by ten sectors, four regions, and three final demand categories.