Paper:

Baynes, TM, Lenzen, M, Steinberger, JK and Bai, X (2011) *Comparison of Household Consumption and Regional Production Approaches to Assessing Urban Energy Use and Implications for Policy.* Energy Policy, 39 (11). 7298 - 7309.

http://dx.doi.org/10.1016/j.enpol.2011.08.053

Comparison of Consumption and Production Approaches to Assessing Urban Energy Use and Implications for Policy

Timothy Baynes[a, 1], Manfred Lenzen[b, 2], Julia K. Steinberger[c, d, 3], Xuemei Bai[e, 4]

[a] *Ecosystems Science Division, CSIRO, P.O. Box 310, North Ryde NSW 1670, Australia*

[b] *ISA, School of Physics A28, The University of Sydney NSW 2006, Australia*

[c] *Institute of Social Ecology Alpen-Adria University, Schottenfeldg. 29, Vienna A-1070, Austria*

[d] *Sustainability Research Institute, School of Earth and Environment, University of Leeds, LS29JT, UK*

[e] *Ecosystems Science Division, CSIRO, P.O. Box 284, Canberra ACT 2601, Australia*

[1] Corresponding author. Tel.: +61 (0)294 908 824

[2] Tel.: +61 (0)293 515 985

[3] Tel.: +44 (0)113 343 1631

[4] Tel.: +61 (0)262 421 710

E-mail addresses:

Tim.Baynes@csiro.au (T. Baynes), m.lenzen@physics.usyd.edu.au (M. Lenzen),

j.k.steinberger@leeds.ac.uk (J. K. Steinberger), Xuemei.Bai@csiro.au (X. Bai)

ABSTRACT

Assessment of urban energy use may proceed by a number of methods. Here we derive the regional energy use from local statistics, and compare it with the results of an input output (IO) analysis as applied to Melbourne, Australia. Features of both approaches highlight different aspects of urban energy use and they are presented together to compare selected outputs for consistency, to identify complementarities and discuss the insight each approach brings to assessing and understanding urban energy. Melbourne is an established and relatively affluent city with a significant manufacturing and heavy industry sector. The IO method captures the direct and embodied energy requirements of local household expenditure while the regional assessment more directly accounts for local production activity. IO analysis of the geography of Melbourne's 'energy catchment' and sectoral detail on energy consumption demonstrates the difference between the primary energy required by Melbourne's economic structure and that ultimately required through the full supply chain relating to household expenditure. We suggest that the IO and regional approaches have particular relevance to policies aimed at consumption behaviour and economic (re)structuring, respectively. The complementarity of both methods further suggests that simultaneous analyses would be valuable in understanding urban energy futures and economic transitions.

Key words: urban energy, input-output analysis, regional assessment

1 Introduction

With globally growing urban populations and the concentration of economic activities in cities, urban energy supply and demand has become increasingly significant. The intimate part that energy plays in the urban economy means that energy statistics are reasonable indicators of economic activity and concurrently a potential measure of the impact of that activity depending on how energy is sourced and used. Energy use is the single largest source of greenhouse gas emission (GHG) from cities and thus it is a key metric when assessing their global impacts (Bai, 2007; Ramaswami et al., 2008).

Having an accurate urban energy account can provide important information on overall sustainability performance of cities. It provides baseline information for establishing future scenarios of urban energy demand of the city, evaluating the effectiveness of various policy options for energy conservation or GHG emission measures, and provides a useful basis for conducting other analysis that may bear important policy and planning implications, e.g. the relationship between urban energy demand and urban forms and density (Lin et al., 2010). However, it is not always an easy task to perform energy account at city level, and different approaches may render different results.

Although we acknowledge the potential environmental impacts and the links to sustainability in general, in this study we are primarily concerned with energy itself, and we compare and contrast two methods for analysing urban energy consumption in application to the metropolitan area of Melbourne, Australia.

It is important to clarify immediately some energy accounting terms used in this paper. 'Final' energy is that which is ultimately consumed (e.g. petrol used in cars), primary energy is the energy source as extracted from nature (e.g. crude oil) and secondary energy is that transformed or exchanged within the energy sector in any process between the primary and final forms (e.g. natural gas used in district heating).

"Direct energy" in the regional production analysis refers to primary, secondary or final energy consumed directly by any sector of the economy in the metropolitan area. In an Input-Output (IO) consumption analysis, "direct energy" refers only to the primary equivalent of energy purchased and used directly by households (e.g. transport fuels, electricity, fuels for cooking and heating).

“Indirect energy” can also be defined two ways depending on the context. In a regional analysis, it refers to any primary, secondary or final energy consumed outside the boundary of the metropolitan area in order to produce energy, goods or services consumed by any entity, public or private, inside the metropolitan area. In an IO consumption analysis, indirect energy refers to energy embodied in the production, storage and transport of goods and services consumed by households in the metropolitan area. To allay confusion we will usually refer to the latter as “embodied energy”. Elsewhere there may be other definitions for embodied energy.

The regional energy assessment draws on a top-down energy account which records direct energy production and use across all sectors. Such an assessment has much in common with “production approaches” similar to those used to generate national energy accounts. Here we refer to ‘regional energy assessment’ as synonymous with the production approach. Separately, an IO approach is used which involves a bottom-up derivation of direct and embodied energy using data on household expenditure for the same metropolitan area. This is classed as a “consumption approach” as in Refsgaard et al. (1998)

The main purpose of this study is to assess the consistency across the results of these two approaches and the source and meaning of any differences. Results appear in tabulated totals of residential energy use and also in the per-capita measures that total energy use across all sectors. We also present an analysis of the ‘energy catchment’ relating to Melbourne's household expenditure. The energy catchment is essentially the geography of where primary energy is used initially in the full chain of supply to final household demand. This is compared with the primary energy needs of the local economy within the metropolitan area. The use of energy in the urban area by households and industry categories illuminates the relationship between energy consumption due to household expenditure and that due to the local economic structure.

There are some data common to both methods but very different techniques are used for arriving at measures of urban energy consumption. The extent to which they agree or disagree is of practical and academic interest on urban energy accounting and reporting. We demonstrate that these approaches reveal different aspects of the energy characteristics of Melbourne with different implications for policy and decision making about urban energy. These two approaches are complementary, and consideration of both is recommended to better understand the energy impacts of changes in economic production and consumption.

2 Accounting for Urban or Regional Energy

Energy accounts at state or national levels usually attribute direct energy production or use to sectors of the economy, including "residential" and "transportation" categories (ABARE, 2008a; USEIA, 2010). It makes sense that, within a state or country, regional energy accounting uses the same categories and definitions and is internally consistent to allow comparisons and benchmarking. These forms of energy accounting predominantly deal with direct energy and usually do not provide separate statistics of primary, secondary and final energy use, (although the International Energy Agency separates these in national energy balances (OECD/IEA, 2010;

OECD/IEA and Eurostat, 2004)). Detail on those energy measures may have to be derived through some form of additional analysis, for example, using reported losses in conversion processes as in Baynes and Bai (2009)[1]. Furthermore, energy data are not always collected at a regional resolution. In these instances, regional energy data have to be modelled or inferred from higher level energy accounts using relevant regional statistics, for example, the proportion of state or national population within a region.

Hypothetically, if a city, or any region, was entirely self-sufficient in energy, goods and services then the direct energy would account for all energy needed by sectors in the production processes upstream of final consumption. Such self-sufficiency is rarely the case and so direct energy accounting generally presents a limited view of energy use. The inclusion of primary or secondary energy required to produce the final energy is one remedy. This upstream energy may be estimated using life-cycle analysis (LCA) factors for fuels as in Kennedy et al. (2010). However, direct and upstream energy accounting does not include energy embodied in imported goods and services. At an urban level, embodied emissions have been reported (Hillman and Ramaswami, 2010; Lenzen et al., 2004; Lenzen and Peters, 2010; Lenzen et al., 2008a; Ramaswami et al., 2008). The technique of Ramaswami et al. (2008) is notable as they produced a GHG inventory using a hybrid approach that included both direct energy consumption and embodied emissions in food, water, fuel and concrete imported into Denver, Colorado U.S.A. (again using LCA factors).

Recently, Ramaswami et al 2011 have compared the total production-base and consumption-based GHG emissions of two US cities (Denver and Routt), with the production emissions of the later being far higher than its consumption-based emissions, due to a high concentration of commercial activity. A similar phenomenon is seen in London City, as opposed to the Greater London Area (Kennedy, personal communication).

Transport is a difficult sector to account for, as there needs to be a formalism to attribute energy to origin and/or destination. The main boundary condition with urban transport energy accounting is that it should at least be consistent with the next highest level of reporting i.e. the aggregate of inter-regional transport energy use should concur with national totals. Both Ramaswami et al. (2008) and Kennedy et al. (2010) respond to this condition and provide examples of how to attribute energy use for transport within and across regional boundaries.

2.1 Energy Accounts for Cities

Previous international studies have investigated the ecological footprint or greenhouse gas (GHG) emission profile of different cities and may have considered the wider topic of urban metabolism but few have concentrated on urban energy alone. Naturally, urban energy figures prominently in those investigations but often with a more aggregate treatment than we use here.

In a survey of 10 cities from North America, South Africa, Europe and Asia, Kennedy et al. (2009) accounted for the direct consumption of electricity, transport, heating and industrial fuel energy in a broader inventory of GHG emissions. The study was founded on direct energy use data or derived data for example using vehicle-kilometres travelled (VKT) or fuel sales to estimate urban energy use by ground transportation (Kennedy et al., 2010). GHG emissions for New York City (New York City, 2007) were calculated from data on final energy use obtained directly from metered data and detail on characteristics of generation and losses of energy forms e.g. electricity and steam.

Again, GHG emissions were the focus of Dhakal (2009) who used gross regional product (GRP) as a proxy scale with which to estimate regional energy use. In lieu of specific regional energy data, the energy intensity per unit of GDP was used to infer primary energy use in 34 provinces and subsequently the GHG intensity associated with urban economic activity. How much of that primary energy was lost in transformations and how much was finally consumed is unknown.

In a review of the urban metabolism of the world’s 25 largest cities, Decker at al.(2000) presented a great deal of information on the primary energy needs of urban areas and energy balance tables for Bangalore, India and Mexico City. These tables were in the form of relative (%) consumption, by sector, of energy by fuel types, including firewood and coal and transformed fuels like liquefied petroleum gas (LPG) and electricity. Urban metabolism studies as in Kennedy et al. (2007) are data intensive and rare. Some efforts such as for London (Chartered Institute of Waste Management, 2002) or Cape Town (Gasson, 2002) are phrased in terms of ecological footprint analysis. Urban metabolism studies report material, water and energy flows but they do not automatically account for embodied energy and often energy flows are presented as aggregates. While there may be some detail on the sectors that use energy directly as in Newman et al. (1996), there is seldom a distinction between primary, secondary or final energy consumption. In Melbourne there has been a metabolism-style study on the energy required for water supply (Kenway et al., 2008) but to the best knowledge of the authors there has been no complete urban metabolism study for Melbourne for comparison with the results presented here.

The Greater London Authority (2006) has produced a methodology manual for an energy and emissions inventory and a recent World Bank report (Bose, 2010) concentrates on carbon accounting and urban energy modelling but not benchmarking energy accounting. At the household and district scale Troy et al (2003) looked at direct and indirect residential energy use in characteristic suburbs of Adelaide, Australia, which is indicative of the sort of Australian urban energy assessment studies in the literature.

The international experience is to be contrasted with the notable difficulty in accessing urban energy data in Australia where energy statistics are most commonly reported at a national or state level. The fact that there is only one major metropolitan area in each state means that any urban statistics are dominated by data from those cities although there will be some contribution from smaller urban centres. Since the IO method relies on data at the regional level for energy, and local data for household expenditures, it does not suffer from the lack of local energy data, which is why Lenzen et al. in Droege (2008a) are able provide an IO assessment of urban energy use for metropolitan Sydney at postal district resolution.

3 Methodology and Data

Urban energy studies generally do not compare or contrast the results from different methodologies. However, two recent, independent studies have assessed similar metrics of energy use, with different techniques for the one city: Melbourne, Australia. Dey et al. (2007) have used an Environmentally-Extended Input-Output table coupled with a household expenditure survey in order to map GHG emissions related, directly and indirectly, to household consumption. This method was adapted to provide results in terms of direct and embodied energy for Melbourne. Baynes and Bai (2009) have scaled regional data down to the urban level, focusing on Melbourne's primary and final energy use.

3.1 Input Output Analysis of Energy Use in Melbourne

The IO approach uses national IO tables and localized household expenditure surveys to capture the energy embodied in resources, materials, goods and services traded in a region. IO tables are based on monetary transactions but can be extended to track energy use, in different forms, through all sectors from production to final consumption. The IO method has been applied to embodied energy accounting numerous times over the past decades, without major changes in methodology, so we refer the reader to the literature (Bullard and Herendeen, 1975a; Bullard and Herendeen, 1975b; Cohen et al., 2005; Herendeen et al., 1981; Herendeen and Tanaka, 1976; Lenzen, 1998a; Lenzen et al., 2004; Lenzen et al., 2006).

Like its predecessors, this study draws from a national household survey at a sub-urban geographical resolution. The sampling rate was the same across urban areas and rural areas, and nationally so urban areas were sampled at relatively high spatial detail proportionally to their population. The IO method applies the perspective of full consumer responsibility and thus allocates energy expended throughout the supply chains of consumption bundles to the household that purchased them. Different spending patterns can then be visualised in maps of household locations colour-coded according to their total energy footprint (Lenzen et al., 2008b). The inverse of this is a map of the location of industries that first use the energy in the chain of supply to household demand. As cities tend to be net energy consumers; energy sinks rather than sources, we term this an ‘energy catchment’ map. In this work, we produced an energy catchment map which shows the proportion of primary energy attributed to a typical Melbourne household broken down by the location of supply chain industries across Australia. The methodology for this approach is described in (Lenzen and Peters, 2010).

Metropolitan industrial activity is not directly represented, but instead a state-level characteristic is attributed to the production of commodities purchased by metropolitan households. The question of the representativeness of state or national IO tables for specific urban areas with different economic structures and prices is an acknowledged limitation. Given the mobility of resources, labour and capital in Australia it may be reasonable to assume that different urban areas have a similar mix of factors of production, similar production structures and efficiencies. However, it is worth noting that regional specifics are important: Melbourne is unique in Australia, in its dependence on brown coal (lignite) for its electricity generation. In this study we have resolved elements of the production chain to statistical local areas (SLA) of Australia which enables the construction of a national map of where industry sectors have initially used primary energy (the ‘energy catchment’) in the chain of supply to household demand.

IO analysis that uses only household expenditure will not include the energy associated with government expenditure on public goods and services. However, in this work we did account for government services (administration, defence, medical care, etc) and common infrastructure no matter whether private or public (roads, railways, public buildings, livestock, plant and machinery, etc) by converting the national accounts data on government final consumption and gross fixed capital expenditure into embodied energy using IO multipliers, just as with the household expenditures.

Accounting for the energy demand for transport (within and between the system boundaries under consideration) represents a particular challenge in this approach although Lenzen at al. (1999) attempted at least one IO study of transport GHG and energy requirements in Australia (see also Munksgaard et al. (2005) for Denmark).

Whilst the single-region IO analysis used here does not capture the country-specific origin of energy embodied in internationally traded commodities and goods, Multi-Region IO (MRIO) models are able to trace all inter-country trade connections and feedback loops (Lenzen et al., 2010; Rueda-Cantuche et al., 2009; Tukker et al., 2009; Wiedmann et al., 2010). MRIO models have recently received considerable attention in evaluating trade-corrected national carbon footprints (Hertwich and Peters, 2009; Peters and Hertwich, 2008)[2].

3.2 Regional Energy Assessment for Melbourne

The approach to energy accounting used in the regional assessment involves aggregate statistics about the production, conversion and distribution of energy and similarly aggregate accounts for final energy consumed by households, commerce, industry and other sectors.

We obtained or derived metropolitan level energy information from raw data on Melbourne such as regional transport statistics (BITRE, 2008); state or regional data including those from the Energy Supply Association of Australia (2002, 2005) and the Australian Bureau of Agricultural and Resource Economics' data Tables B, C, F, G and L (ABARE, 2006, 2008a, b, c, d); and local knowledge such as the petroleum refining capacity in Melbourne and the location of some energy intensive industries such as aluminium smelting (which is entirely outside of Melbourne). An energy account was constructed from these sources and presents the primary energy required, and direct energy used, by residents[3] and locally represented sectors of the economy – refer to Table 5 in the Appendix. Data on energy supply were also disaggregated by fuel type: brown coal, brown coal briquettes, oil, oil products (including LPG), gas (natural gas), hydropower and electricity.

Many of the data sources on sectoral energy demands were in common with the IO consumption analysis but several data sets were only available at the state level. Consequently, much of the data for Melbourne have been derived and in Table 4 of the Appendix is a more detailed explanation of the data calculations used. Many of the data derivation techniques employ the same methods as in Kennedy et al. (2010). For example, the fraction of state level employment (in a given sector) that occurs in the metropolitan area is used to deduce the direct energy used by Melbourne's construction, commercial and services sectors. The derivation of some data on energy use by different sectors in Melbourne used spatial methods. Energy use in agriculture and mining was derived by using data on land use for 2004.

4 Results

Table 1 presents results showing the elements of direct, indirect and total primary residential energy consumption and also the totals for metropolitan Melbourne including non-residential sectors. Only the "Total Primary" column of both methods can be compared, since the "direct" and "indirect" terms correspond to different units of investigation and steps along the energy chain.

The difference between the two approaches is amplified when comparing total primary energy for the metropolitan economy. The total for all sectors from the regional method is explicitly covers local energy consumption. The IO method only represents energy consumed by local industry to the extent that Melbourne households consume locally produced goods and services. Hence these calculations in the lower half of Table 1 are designated non-comparable.

The results for residential heating fuels exhibit a large difference (21.1 and 12 GJ/cap for regional and IO approaches, respectively) but the sources of that may well be in the derivation and processing of the data used in both methods. The regional analysis used the Melbourne fraction of state population applied to Victoria’s total residential gas consumption, and this may incorrectly attribute higher per capita consumption. In the IO approach, there may also be under-reporting of gas consumption in expenditure surveys (e.g. if respondents did not count gas used for hot water heating).

Melbourne is predominantly served by a natural gas network for heating but this fuel may also be used for cooking and this could confound the results e.g. where some households only use gas for cooking. A survey of end-use might reveal the split of natural gas usage and enable a more accurate comparison but to the authors’ knowledge there is no gas end-use study for Melbourne in 2001. It is worth noting that both measures of indirect energy scale similarly to their respective direct energy estimates. In this case the different approaches probably use common calculations because of the short production chain between Melbourne and natural gas reserves off the south coast of Victoria.

The closest agreement between the methods can be found for total primary energy due to residential electricity use, at 28.1 and 29.5 GJ/cap for the regional and IO approaches, respectively. While a national electricity grid can theoretically supply Melbourne's electricity from a number of sources, in practice supply is dominated by the brown coal power stations to the north-west of the metropolitan area. Again, the energy supply chain is relatively local and uncomplicated and it might be expected that the two methods would concur on this metric.

The range of values in the transportation final energy estimation derives from two different calculations of urban transport. Vehicle-kilometres travelled (VKT) figures published by the International Association of Public Transport (UITP, 2006) and passenger-kilometres travelled (PKT) from the Australian Transport Statistics Yearbook (BITRE, 2008) were used with corresponding per-kilometre energy efficiencies to produce the lower and higher estimates respectively. There is a substantial difference between either of these and the IO results which may be caused by a number of sources of error. Per-kilometre efficiencies applied to PKT or VKT figures averaged for a large area may not be realistic (and these efficiencies may vary over time with transport construction schedules). Both statistics sources relate to private transport use but in the regional statistics this may include some automobile use by small businesses in addition to residents. The regional calculations from macro-statistics are perhaps more remote from actual consumption than the IO expenditure surveys but there may be systematic errors and stochastic uncertainty in each approach and it is possible the compound effect of these errors could explain the differences in the results (refer also to the Discussion section).

The regional primary energy per capita result for the entire city of Melbourne are 258.1 GJ/cap – larger than the household-expenditure related primary energy consumption of 235.8 GJ/cap given by the energy IO method. Notwithstanding the potential uncertainties involved, one conclusion would be that Melbourne is using more energy for local production activities than for consumption – directly or indirectly. Its local energy consumption across all sectors is higher than the energy consumption induced by the spending of its households. This fits with Melbourne's economic structure which has historically been connected to manufacturing and currently located within the metropolitan area there is an oil refinery, petrochemical plant, steel works, automobile manufacturing and other heavy industries as well as light manufacturing and recycling plant.

The inclusion of government expenditure adds significantly to the primary energy impact of household expenditure. Using household expenditure alone would account for 183.5 GJ/cap of the 235.8 GJ/cap total in Table 1. Apportioning the energy requirements for government services and infrastructure, on a per-capita basis across the Australian population, adds another 17.3 GJ/cap and 35 GJ/cap respectively. Even though monetary spending on government services and infrastructure are about equal, government services require less energy because they involve less energy-intensive industries compared with infrastructure.

Energy use by government is included in the regional analysis within the 'Commercial and Services' category of Table 2 (and Table 5 in the Appendix). This only covers the intermediate demand of government to supply output (administration, defence etc.), but not its final demand[4]. Consequently, the regional assessment for energy consumption by government is approximately one quarter of that for the IO analysis.

In Figure 1 we present an energy catchment map of the total energy footprint of a Melbourne household (235.8 GJ/cap) broken down by locations of industries throughout the regional supply chains that lead to the household's consumption bundle. Thus, the energy catchment map could be said to visualise the "energy hinterland" of that household.

About 17% of the household's energy footprint comes from just three power generators: Morwell, Traralgon and Moe, in the Latrobe Valley. These power plants generate electricity not necessarily for the household alone, but for industries that produce commodities for the household's supply chain.

Further prominent energy requirements are found in Wyndham (iron and steel semi-manufactures, 2.6%), Wellington (natural gas processing, 1.2%), Corio (petrol refining, 1.1%), and Maribyrnong (basic chemicals manufacturing, 1.1%). All locations mentioned so far are located in Melbourne's home state, Victoria.

The most important inter-state embodied-energy supply chains originate from Ashburton and Roebourne in Western Australia (natural gas, 0.3%, dark SLAs in north-western Australia), Port Kembla in New South Wales (iron and steel semi-manufactures, 0.2%), the Gladstone and Nanango power plants in Queensland (inter-state grid power, 0.11% each), and the Wallerawang power plant near Lithgow in New South Wales (0.06%).

Table 1. A comparison of two urban energy accounting methods applied to Melbourne (Statistical Division) for the year 2001. The direct, indirect and total values (in GJ/capita) are shown for each method: note that only the total primary energy can be compared, since direct and indirect flows are measured differently in the two methods. Some small accounting discrepancies appear due to rounding.

	Regional Energy Assessment Source: Baynes & Bai (2009) – see notes			**Energy Input-Output method** Source: Lenzen 2009		
	Direct *Final energy*	Indirect *Primary upstream*	Total *Primary*	Direct *Primary direct expenditure*	Indirect *Primary indirect expenditure*	Total *Primary*
Comparable						
Residential: heating fuels	18.6[a]	2.5[b]	21.1	10.6	1.4	12.0
Residential: electricity	8.5	19.6[c]	28.1	0.0	29.5	29.5
Transportation (private)	31.1[d]-39.9[e]	1.5[f]	32.7-41.4	22.6	3.9	26.5
Total residential + private transport	58.2-67.0	23.7	81.9-90.7	33.2	34.8	68.0
Non-comparable						
Total Melbourne Household Expenditures				68.0	150.3	235.8
Total Melbourne (including non-residential)	147.3[g]	110.8	258.1			

[a] residential use of natural gas (also includes gas for cooking)

[b] for Victoria in 2001, total primary energy was 13.5% more than final consumption for gas (Collins and Powell, 2002)

[c] a factor of 2.3 times the final electricity consumption derived from the quotient of primary energy (of all fuel types) used to generate electricity in Victoria and the total reported electricity generated (ABARE, 2006)

[d] using VKT and fuel efficiency data from UITP (2006) and census data on the number of private vehicles

[e] using BITRE (2008) values for PKT and UITP (2006) values for passenger-km fuel consumption

[f] An average for the range 1.3-1.7GJ/capita corresponding to the direct energy consumption figures. Based on a nationally reported loss fraction for the petroleum industry which was 4% for 2001 (ABARE, 2008d).

[g] This uses an aggregate of *all* transport energy from Baynes and Bai (2009) and does not distinguish the possible residential transport range.

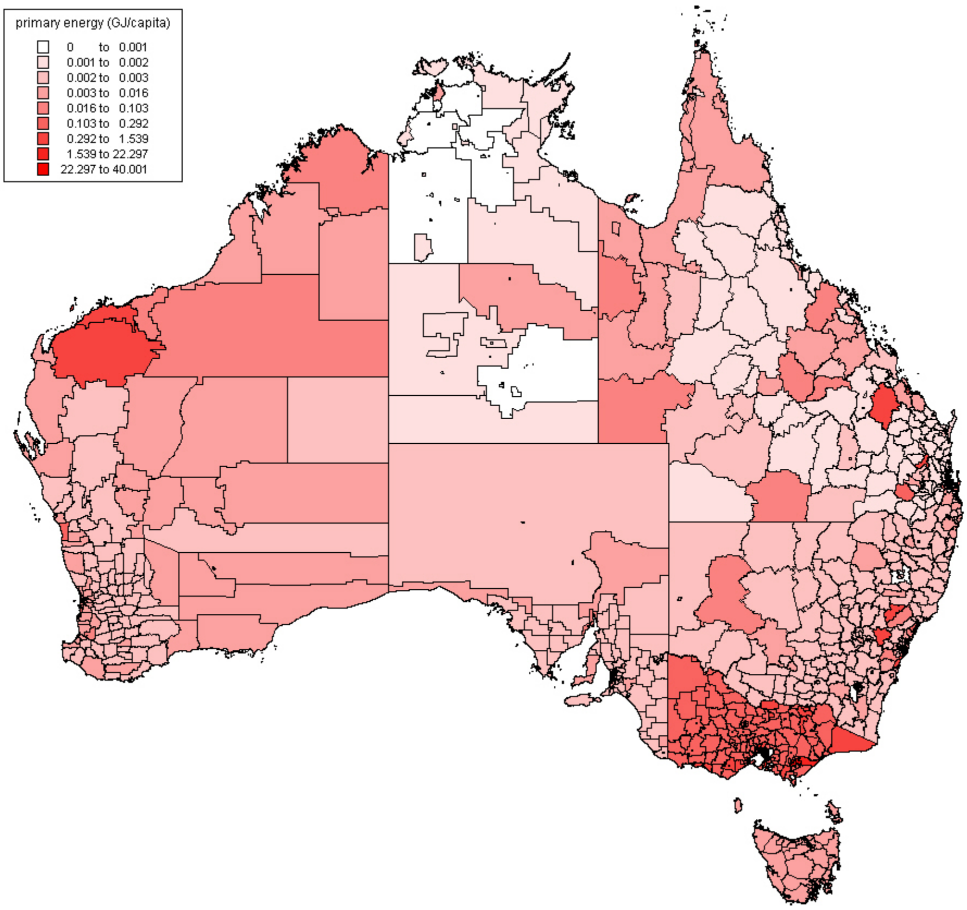

Figure 1. The "energy catchment" of Melbourne's households. Shown is the primary energy equivalent (direct and embodied) consumed per capita by all industries that supply Melbourne households with goods and services. Boundaries are statistical local areas.

The primary energy catchment geography exhibits a sharp boundary at the border of Melbourne's host state, Victoria, in the south-east of mainland Australia. A very high percentage (93.6%) of Melbourne's direct and embodied primary energy is first used in Victoria and some 30% of this is located within the Melbourne metropolitan area itself. This reflects local economic independence and probably also parochial state policies that, for example, ensure the demand for agricultural products like fresh milk and meat is supplied from Victoria.

The regional analysis has no greater geographical resolution than the metropolitan area but, to enable some comparison with the energy catchment, Table 2 presents the non-residential shares of primary energy consumption. The Melbourne-only part of the IO energy catchment results have also been extracted and disaggregated by the same non-residential categories. The first column of Table 2 represents a breakdown of energy used by industry sectors residing in Melbourne, whilst the second column represents the energy catchment occurring within Melbourne.

The purpose of Table 2 is to examine the industrial energy character of Melbourne, as derived from final household demand, in contrast to the actual industrial energy character of Melbourne’s economy revealed through the regional data. The greater the disparity between the relative energy use, by the various sectors in Table 2, the greater the difference between Melbourne as a consumer, and Melbourne as a producer.

The proportion of energy consumption by the Residential and Road sectoral categories are both large and Residential is dominated by direct energy consumption in the IO analysis and the regional assessment. Due to the large residential population, Residential energy consumption in the Melbourne part of the energy catchment is so high (67% of the IO total), that it distorts the results for all other categories. Since this comparison is about comparing territorial versus supply-chain industry structure, energy for private transport and residences has been excluded. It is important to remember a couple of key things: that the direct and embodied figures are ultimately based on characteristics of household expenditure and that the energy catchment of Melbourne’s household expenditure is mostly outside of the metropolitan area. We observe a close agreement between the two approaches for industry as a whole and particularly the Commercial and Services sector.

Table 2. Relative contribution of different sectors to primary energy consumption in Melbourne for 2001. Note that for the regional data, the primary energy used to generate electricity has been distributed to sectors based on their final consumption of electrical energy. Entries in bold indicate totals or data for sectors that have not been disaggregated

	Regional primary energy	**Direct and embodied primary energy**
Agriculture and Forestry	**0.12%**	**2%**
Mining	**6%**	**3%**
Industry total	**50%**	**65%**
Petroleum, Coal and Chemical	11%	22%
Machinery and Metal Processing	18%	28%
Textile and Clothing	1%	1%
Wood, paper and printing	12%	8%
Food and Beverages	5%	5%
Other manufacturing	3%	1%
Construction	**1%**	**0.13%**
Commercial and Services	**23%**	**20%**
Transport total (excl. Int. travel and bunkers)	**6%**	**3%**
Road		
Railway	1%	0.08%
Water	2%	1%
Domestic Air	3%	2%
Residential		
Water and Gas Utilities	**2%**	**4%**
Electricity Generation	**14%**	**3%**

5 Discussion

The analysis reveals two main differences between the regional and IO methods: First, and interestingly, Melbourne's total energy use is larger from a regional production rather than from a consumption perspective. The second difference is that the regional energy assessment systematically yields larger estimates for Melbourne's residential and private transport energy than the IO results. In the following we discuss the possible sources and meaning of the differences.

The fact that Melbourne's total regional energy is greater than the total energy related to its household expenditures is a somewhat unexpected result, because in most developed countries territorial emissions are smaller than their consumption-corrected emissions (Peters and Hertwich, 2008). It would be expected that this effect be even more pronounced in urbanized areas. However, as a large fossil fuel and primary resource exporter, Australia is unlike most developed, industrialized countries, in that it is a net exporter of carbon emissions through trade (Lenzen, 1998b). Unlike many major cities in developed countries, Melbourne has maintained a large presence of heavy industrial activity. This makes Melbourne more akin to industrial urban centres in developing countries than their counterparts in developed nations: more like Beijing than Tokyo.

Whilst regional analysis measures the territorial energy metabolism of Melbourne, irrespective of who consumes the commodities generated as a consequence, IO measures the energy attribution to the consumption of commodities by Melbourne households, irrespective of where these commodities were produced, and the energy for their production expended. In other words, the difference between the total regional and IO figures reflects the characteristic of Melbourne as a net energy exporter.

The second discrepancy between the IO and regional residential and private transportation energy may be due to a number of factors. First, the parameters used by each of the methods are affected by (presumably stochastic) measurement uncertainty. For example, average Australian occupancy rates of private vehicles have been reported to lie between 1.2 and 1.65[5], which has a major bearing on the conversion between PKT and VKT measures. Total vehicle kilometres driven in Melbourne by passenger cars are reported for the same year (2001) as 34.5×10^{9}, (BITRE, 2008) and 28.5×10^{9} (DPCD, 2005). IO transactions and household expenditure data are affected by stochastic errors due to survey sample variations. Further, there may be systematic errors. For example, when reported by different sources, population, travel distance, and fuel price figures may not refer to the same geographical entity, or vehicle type. Similarly, respondents may have systematically under-reported expenditures on fuels. These and more factors can compound to produce uncertainty around figures and yield the discrepancies visible in Table 1.

The regional assessment involves less modelling and has a more direct link to relevant local statistics than the IO method, which relies on proxy monetary expenditures and has some sampling error. However, in the regional assessment produced here, a number of assumptions and data derivations are used which also introduce uncertainties (see Appendix for details) and thus its proximity to reported data does not necessarily confer greater reliability than the IO outputs.

Regional-type methods are not able to determine embodied energy values. Hence, this work shows that the integration of top-down methods, such as the regional assessment, and bottom-up methods, such as IO, brings about the benefit of combining the top-down accuracy for direct energy with the bottom-up completeness for embodied energy. This conclusion is in line with recent trends of LCA analysts to move to hybrid methods, as described in detail for example by (Bullard et al., 1978; Lenzen and Crawford, 2009; Suh et al., 2004; Suh and Nakamura, 2007).

Notwithstanding the above qualifications, and perhaps surprisingly given the starkly different natures of the two methods, both assessments arrive at total energy metabolisms of around 250 GJ/cap, which agrees well with previous IO studies (Lenzen, 1998a, b; Lenzen et al., 2004).

The fact that nearly 30% of Melbourne's direct and embodied energy requirements is sourced from within the metropolitan boundary suggests that a direct comparison with the non-residential characteristics of the regional assessment is valid. Eliminating the residential sector we find that both approaches show a significant (≥5%) *and similar* contribution from these industry categories:

- Petroleum, Coal and Chemical
- Machinery and Metal Processing
- Wood, paper and printing
- Commercial and Services
- Food and Beverages

This indicates that the actual production characteristics of the region match loosely with the production chain characteristics behind Melbourne's household consumption. This is perhaps least surprising with the 'Commercial and Services' category as Melbourne is a major location of both the production and consumption of this industry's outputs. In an unusual contrast with most cities, Melbourne exhibits some local economic and energy independence because of significant light and heavy manufacturing and a petroleum industry (and possibly also due to protective state policies for Victorian industry e.g. government purchases of locally made cars).

5.1 Important differences

The difference between the two accounting approaches becomes particularly pronounced in trade-intensive open urban economies and when considering industrial versus service-sector and residentially oriented urban economies. For consumers of the outputs of these analyses in the policy sphere it is important to be aware of the relative advantages and limitations.

The regional energy assessment is relevant to local activities and policies. The quality of the built environment, especially residences and commercial buildings, as well as transportation infrastructure, are thus best addressed through this method. In policy terms, regional energy assessments are likely to be of most use for local authorities, urban and transportation planners.

A specific advantage of the regional energy assessment is that local knowledge on specific industries and their location informs the energy use by that sector's activity in a given area. This may be of particular importance in representing the role of the city in the national or international economy, and benchmarking its industries with other similar industries.

However, regional data do not necessarily provide a link to the drivers of affluence and lifestyle that influence indirect energy consumption. The regional assessment does not show the extent of the total ‘energy footprint’ outside the boundary of a city. While much detail on what is contained within the city boundary can be understood, the final results have no greater geographical scope than the metropolitan area.

In comparison, the IO consumption approach has a more comprehensive system boundary, providing a more realistic picture of the energy footprint of an urban area that imports from national and global hinterland (Lenzen and Peters, 2010). Furthermore, it has a detailed link to household expenditure and the geography of consumption. There is the disadvantage that the calculation of direct and embodied energy is associated with a production chain that assumes state or national characteristics which may or may not represent local production.

The IO method can account for energy use associated with public good urban infrastructure investments (e.g. defence, road construction) which are not included in household expenditure statistics, by simply feeding government expenditure statistics through the embodied-energy calculus. However, value judgments arise when deciding how to allocate energy expended and embodied for public purposes across households. A number of options exist, such as per-capita, per-household, and proportional to income tax paid, and obviously the energy requirements of households would depend on such choices.

In urban areas with an important industrial and manufacturing base (with associated significant exports) a consumption-based accounting approach will likely lead to lower energy use estimates compared to a regional accounting approach based on final energy or direct data. This is also the case for cities with high concentrations of commercial activities (hotels or finance, for example) and relatively low resident populations, for example Routt in the US (Ramaswami et al 2011) and the City of London (Kennedy, personal communication) . Conversely, for residence- and service-oriented urban areas that typically import all energy and energy-intensive materials and goods, consumption-based accounting approach will more likely yield substantially higher energy use numbers compared to regional energy accounting. According to Hersey et al.(2009) p 14 "Using the perspective of consumption, London [in this case, the Greater London Area] is currently responsible for 90 Mt CO2 per year – twice the amount that is attributed to London under a production approach".

Weisz and Steinberger (2010) identify several features or drivers of urban energy consumption including income, industrialization, historical and planned urban form. For policies aimed at monitoring or influencing the drivers of energy consumption, especially in its indirect forms, an IO approach may yield more relevant information but if a policy is concerned with structural economic change (e.g. a transition from an industrial to a service orientated city) then a regional energy assessment may capture more of the energy-related impacts. Consumption-oriented policies may be more difficult to address at the local level, and thus require national-level leadership and coordination.

Rather than endorsing one approach over the other, we agree with Ramaswnu et alk 2011 that different accounting approaches should instead be seen as complementary.

Learning from both analyses simultaneously should be of particular value in assessing technical and economic transitions. For example, a decision about promoting higher efficiency industrial activity would only be visible in the regional assessment, whereas emphasis on changing household consumption patterns and lifestyles to reduce indirect impacts would mainly be observed through IO.

An example of structural economic transition might be land-use change allowing the conversion of factories or industrial areas into residential estates. This can have two important effects. One is to re-locate industrial activity further away from the city or curtail it altogether within the metropolitan area. This would certainly reduce territorial energy use, although since presumably the goods have to be produced somewhere, it may very well not reduce it globally (as could be seen from IO). Secondly, new development on this former industrial land presents the opportunity to construct a low-energy, mixed-use residential area, well connected to services and public transit. This new development could lead to lower per capita regional energy use, but the indirect energy use measured through IO would depend on the broader consumption pattern of the new residents. The question of what is the net impact cannot be answered easily through a single approach: a combined approach allows a more nuanced understanding as it depends on the lifestyle and employment of the new residents and the energy consumption of the prior industrial tenants.

A summary of the comparison of both analyses is shown in Table 3 with detail on the data starting points, the scope, the nature of the results and how each approach may suitably inform policy

Table 3. Summary of the comparison between the top-down regional approach and the bottom-up IO analysis methods in relation to urban energy assessment.

	Starting point	Items covered	Items not covered	What does the result reveal?	Suitable for
Top-down regional approach	Regional energy use	- Residential operational energy - Ground transportation energy (sometimes also air and maritime) - Direct energy consumption by industries within boundary	- Embodied energy in service and goods - Upstream energy consumed for the extraction, conversion and transportation of energy to region.	Per capita direct energy requirements for sustaining households, public administration and industry	- Quantifying ongoing direct energy demand of the city - Policy and management of economic structure and energy efficiency of the city
Bottom-up Input-Output approach	Household consumption	-Household residential operational energy -Household ground transportation, including public transit - Energy embodied in household consumption goods	- Industrial and administrative energy use within the city, other than that covered by the goods and services consumed by households.	Per capita total direct and embodied energy requirements for sustaining the lifestyle of urban households	- Understanding total energy demand, including those embodied in goods, of household consumption - Quantifying the total energy footprint and impact of households - Policy and measures for behavioral and macro-economic change for sustainability

5.2 General discussion

The pressures of climate change and resilience to changes in energy supply, including price increases and energy security issues, both require large reductions in energy demand in industrialized countries, which also have high levels of urbanization. As our study has shown, there are different ways of measuring and analysing urban energy demand. These different methods point towards very different types of measures for energy reductions. From a regional perspective, the local infrastructure must be transformed to low energy alternatives (ultra-efficient housing and transportation, efficient commercial and industrial activities). Different cities may identify different priorities and measures to enact these changes. From a consumption-based or IO perspective, it is apparent that these local measures alone will be insufficient, and that the consumption patterns and scale of households must also be addressed. (Lenzen et al 2008 in Droege book). The consumption-oriented measures are obviously much more challenging, since they require an in-depth transition of industrialized consumer societies to more sustainable (but prosperous) alternatives, a challenge which few governments are seemingly willing to face.

6 Conclusions

The comparison of the regional (top-down) approach and Input-Output (bottom-up) approach applied in Melbourne metropolitan area reveals several important facts.

In terms of methodology, the advantages of the regional energy assessment approach are proximity to raw data and the clear lineage from that data to results. However, there is no explicit link between local consumption and production and embodied energy is either not represented at all or, at best, implicitly in the energy consumed by local commerce and industry. The methods of the IO consumption approach have an explicit mathematically link to data but the main comparative advantage is a much broader scope for direct and embodied energy use through the proxy of local household expenditure as the locus of final demand. For cities, such as Melbourne, that export direct or embodied energy, some final demand lies outside the metropolitan boundary and a regional approach will capture the local economic activity that supplies to it.

In terms of results, the differences between the IO and regional methods in comparable measures of residential primary energy consumption (heating, electricity, private transport) are most likely due to combinations of measurement errors – stochastic, systematic or categorical. The disparity between total primary energy for all sectors in the metropolitan area reveals more about the economic structure of the city. In the case of Melbourne, the IO result is significantly lower than the regional account, demonstrating the contribution of local energy intensive industries which export direct and embodied energy.

We conclude that the differences in method, scope and detail actually makes these two approaches extremely complementary and useful for overlapping policy applications: IO results have more relevance to managing consumption behaviour and consumer responsibility and the regional energy assessment relates to economic structure, the management of the metropolitan economy and potential transitions in urban production.

7 Acknowledgements

Timothy Baynes was supported by the Global Energy Assessment and CSIRO's Urban Futures Project. The regional approach analysis was prepared as a technical paper for Global Energy Assessment. The algorithm used by Manfred Lenzen for regionalising the energy catchment was developed in the scope of Linkage Project LP0347812 funded by the Australian Research Council. Julia Steinberger acknowledges funding from the SUME project, European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement 212034. We thank

Arnulf Grübler for the inspiration to conduct a methodological comparison, and Helga Weisz, Heinz Schandl and Steve Hatfield-Dodds for their critical input.

8 Glossary of terms and acronyms

ABS	Australian Bureau of Statistics
ABARE	Australian Bureau of Agricultural and Regional Economics
BITRE	Bureau of Infrastructure, Transport and Regional Economics (Australian)
Consumption approach	Measures final energy consumption and estimates all associated direct and embodied energy by the various expenditure categories based on proxy energy per $ value indicators derived from LCAs or national IO tables.
Direct energy use (regional assessment)	Primary, secondary or final energy consumed directly by a sector in the study area.
Direct energy use (IO consumption)	Primary energy purchased and used directly by households
Embodied energy	Defined here as in an IO consumption analysis: refers to energy used in the production and transport of goods and services consumed by households.
Energy catchment	The (location of) direct and embodied energy consumed by all industries that supply Melbourne households with goods and services.
Final energy use	Energy ultimately consumed (e.g. petrol used in cars)
GDP	Gross Domestic Product
GRP	Gross Regional Product
Indirect energy use	Is defined here as in regional production analysis. It refers to any primary, secondary or final energy imported from

	outside the boundary of a region.
IO	Input Output Analysis
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
MRIO	Multi-region Input Output analysis
PKT	Passenger-kilometres travelled
Primary energy	The energy source as extracted from nature (e.g. crude oil)
Regional Energy Assessment	An account of direct energy production and consumption across all sectors for a defined territory. This may also be referred to as a ‘production’ approach elsewhere in the literature.
Secondary energy	That used in any process between the primary and final forms of energy
TPES	Total primary energy supply
Upstream energy use	Primary or secondary energy required to produce the final energy consumed.
VKT	Vehicle-kilometres travelled
UITP	The International Association of Public Transport

9 References

ABARE, 2006. Table F3 Victorian energy consumption, by industry and fuel type. Australian Bureau of Agriculture and Resource Economics.

ABARE, 2007. Table F3: Australian energy consumption, by industry and fuel type - energy units. Australian Bureau of Agriculture and Resource Economics.

ABARE, 2008a. Table B Australian consumption of energy by industry - energy units (PJ) 1960-2007. Australian Bureau of Agriculture and Resource Economics.

ABARE, 2008b. Table C Australian consumption of energy by state by fuel energy units (PJ) 1960-2007. Australian Bureau of Agriculture and Resource Economics.

ABARE, 2008c. Table G3 Victoria energy consumption by fuel type. Australian Bureau of Agriculture and Resource Economics.

ABARE, 2008d. Table L Australian petroleum supply and disposal 1960-2007. Australian Bureau of Agriculture and Resource Economics.

Bai, X., 2007. Industrial Ecology and the Global Impacts of Cities. Journal of Industrial Ecology 11, 1-6.

Baynes, T.M., Bai, X., 2009. Trajectories of Change: Melbourne's population, urban development, energy supply and use from 1960-2006. A working paper for the Global Energy Assessment Project. Global Energy Assessment Project, Vienna.

BITRE, 2008. Australian Transport Statistics Yearbook 2007. Bureau of Infrastructure, Transport and Regional Economics, Canberra.

Bose, R.K. (Ed.), 2010. Energy Efficient Cities: Assessment Tools and Benchmarking Practices. The World Bank, Washington DC.

Bullard, C.W., Herendeen, R.A., 1975a. The energy cost of goods and services. Energy Policy 3, 268-278.

Bullard, C.W., Herendeen, R.A., 1975b. Energy impact of consumption decisions. Proceedings of the IEEE 63, 484-493.

Bullard, C.W., Penner, P.S., Pilati, D.A., 1978. Net energy analysis - handbook for combining process and input-output analysis. Resources and Energy 1, 267-313.

CES Victoria, 2008. Public transport's role in reducing greenhouse emissions. Commissioner for Environmental Sustainability, Melbourne, Australia.

Chartered Institute of Waste Management, 2002. A resource flow and ecological footprint analysis of Greater London. Best Foot Forward Ltd, London.

Cohen, C.A.M.J., Lenzen, M., Schaeffer, R., 2005. Energy requirements of households in Brazil. Energy Policy 55, 555-562.

Collins, G., Powell, A., 2002. A Guide to the Petroleum Industry in Victoria. Energy and Minerals Division, Department of Natural Resources and Environment, Melbourne.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. Energy and Material Flow Through the Urban Ecosystem. Annual Review of Energy and the Environment 25, 685-740.

Dey, C., Berger, C., Foran, B., Foran, M., Joske, R., Lenzen, M., Wood, R., 2007. An Australian environmental atlas: household environmental pressure from consumption, in: Birch, G. (Ed.), Water, Wind, Art and Debate: how environmental concerns impact on disciplinary research. Sydney University Press, Sydney, pp. pp. 280-315.

Dhakal, S., 2009. Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 37, 4208-4219.

DPCD, 2005. Car travel conditions. Department of Planning and Community Development Melbourne, Australia.

ESAA, 2002. Electricity Australia 2002. Energy Supply Association of Australia Ltd., Melbourne.

ESAA, 2005. Electricity Gas Australia 2005. Energy Supply Association of Australia Ltd., Melbourne.

Gasson, B., 2002. The ecological footprint of Cape Town: Unsustainable resource use and planning implications, SAPI International conference: Planning Africa, Durban, South Africa.

Greater London Authority Environment Group, 2006. The London Energy and CO2 Emissions Inventory (LECI) 2003 Methodology Manual. Greater London Authority, London.

Herendeen, R., Ford, C., Hannon, B., 1981. Energy cost of living, 1972-1973. Energy 6, 1433-1450.

Herendeen, R., Tanaka, J., 1976. Energy cost of living. Energy 1, 165-178.

Hersey, J., Lazarus, N., Chance, T., Riddlestone, S., Head, P., Gurney, A., Heath, S., 2009. Capital consumption: the transition to sustainable consumption and production in London. BioRegional and the London Sustainable Development Commission, London.

Hertwich, E.G., Peters, G.P., 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. Environmental Science & Technology 43, 6414-6420.

Hillman, T., Ramaswami, A., 2010. Greenhouse Gas Emission Footprints and Energy Use Benchmarks for Eight U.S. Cities. Environmental Science & Technology 44, 1902-1910.

International Association of Public Transport (UITP), 2006. Mobility in Cities Database. UITP.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The Changing Metabolism of Cities. Journal of Industrial Ecology 11, 43-59.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., HavraÌánek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2009. Greenhouse Gas Emissions from Global Cities. Environmental Science & Technology 43, 7297-7302.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2010. Methodology for inventorying greenhouse gas emissions from global cities. Energy Policy 38, 4828-4837.

Kenway, S.J., Turner, G.M., Cook, S., Baynes, T.M., 2008. Water-energy futures for Melbourne: the effect of water strategies, water use and urban form. CSIRO: Water for a Healthy Country National Research Flagship. ISBN 978 0 643 09566 3, Melbourne.

Lenzen, M., 1998a. The energy and greenhouse gas cost of living for Australia during 1993-94. Energy 23, 497-516.

Lenzen, M., 1998b. Primary energy and greenhouse gases embodied in Australian final consumption: an input-output analysis. Energy Policy 26, 495-506.

Lenzen, M., 1999. Total requirements of energy and greenhouse gases for Australian transport. Transport Research Part D 4, 265-290.

Lenzen, M., Crawford, R.H., 2009. The path exchange method for hybrid LCA. Environmental Science & Technology 43, 8251-8256.

Lenzen, M., Dey, C., Foran, B., 2004. Energy requirements of Sydney households. Ecological Economics 49, 375-399.

Lenzen, M., Kanemoto, K., Geschke, A., Moran, D., Muñoz, P.J., Ugon, J., Wood, R., Yu, T., 2010. A global multi-region input-output time series at high country and sector detail, in: Rueda-Cantuche, J.M., Hubacek, K. (Eds.), 18th International Input-Output Conference, Sydney, Australia.

Lenzen, M., Peters, G.M., 2010. How City Dwellers Affect Their Resource Hinterland - A Spatial Impact Study of Australian Households. Journal of Industrial Ecology 14, 73-90.

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., Schaeffer, R., 2006. A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. Energy 31, 181-207.

Lenzen, M., Wood, R., Foran, B., 2008a. Direct versus Embodied Energy - The Need for Urban Lifestyle Transitions, in: Droege, P. (Ed.), Urban Energy Transition: From Fossil Fuels to Renewable Power. Elsevier, Sydney, pp. 91-120.

Lenzen, M., Wood, R., Foran, B., 2008b. Direct versus Embodied Energy – The Need for Urban Lifestyle Transitions, in: Droege, P. (Ed.), Urban Energy Transition. Elsevier, Amsterdam, Netherlands.

Lin, J., B. Cao, SH Cui, W. Wang, Bai, X.M., 2010. Evaluating the effectiveness of urban energy conservation and GHG mitigation measures: the case of Xiamen City, China. Energy Policy 38, 5123-5132.

Munksgaard, J., Lenzen, M., Jensen, T.C., Pade, L.-L., 2005. Transport energy embodied in consumer goods: a hybrid life-cycle analysis. Energy and Environment 16, 283-301.

New York City, 2007. Inventory of New York City Greenhouse Gas Emissions. Mayor's Office of Operations, Office of Long-Term Planning, New York.

Newman, P.W.G., Birrell, B., Holmes, D., Mathers, C., Newton, P., Oakley, G., O'Connor, A., Walker, B., Spessa, A., Tait, D., 1996. Chapter 3: Human Settlements, Australian State of the Environment Report 1996. Commonwealth of Australia.

OECD/IEA, 2010. Energy Balance of OECD Countries, 2010 ed. International Energy Agency, Paris.

OECD/IEA, Eurostat, 2004. Energy Statistics Manual. OECD/IEA and Eurostat, Paris.

Peters, G.P., Hertwich, E.G., 2008. CO2 Embodied in International Trade with Implications for Global Climate Policy. Environmental Science and Technology 42, 1401-1407.

Ramaswami, A., Hillman, T., Janson, B., Reiner, M., Thomas, G., 2008. A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories. Environmental Science & Technology 42, 6455-6461.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agricultural Systems 57, 599-630.

Rueda-Cantuche, J.M., Beutel, J., Neuwahl, F., Mongelli, I., Loeschel, A., 2009. A symmetric input-output table for EU27: Latest progress. Economic Systems Research 21, 59-79.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System boundary selection in Life-Cycle Inventories. Environmental Science & Technology 38, 657-664.

Suh, S., Nakamura, S., 2007. Five years in the area of input-output and Hybrid LCA. International Journal of Life Cycle Assessment 12, 351-352.

Troy, P., Holloway, D., Pullen, S., Bunker, R., 2003. Embodied and Operational Energy Consumption in the City. Urban Policy and Research 21, 9-44.

Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J.M., Giljum, S., Moll, S., Oosterhaven, J., Bouwmeester, M., 2009. Towards a global multi-regional environmentally extended input-output database. Ecological Economics 68, 1928-1937.

UITP, 2006. Mobility in Cities Database. International Association of Public Transport (UITP).

USEIA, 2010. Annual Energy Review 2009. United States Energy Information Administration.

Weisz, H., Steinberger, J.K., 2010. Reducing energy and material flows in cities. Current Opinion in Environmental Sustainability 2, 185-192.

Wiedmann, T., Wood, R., Lenzen, M., Minx, J., Guan, D., Barrett, J., 2010. The carbon footprint of the UK - Results from a Multi-Region Input-Output model. Economic Systems Research 22, 19-42.

10 Footnotes

1 See Appendix for details

2 These authors acknowledge some data quality issues for IO tables (GPAT) and estimates of energy embodied in international trade flows.

3 Only stationary energy was accounted for in the Residential category. Residential transport energy was accounted for within the Transport (road) category – see Table 5 in the Appendix.

4 This difference is explained in note 87 of ABS, 2006. Australian National Accounts: Input-Output Tables - Electronic Publication, 2001-02 Catalogue number 5209.0.55.001. Australian Bureau of Statistics, Canberra.

5 1.28 inferred from Tabs 4.3b and 5.7 in BITRE, 2008. Australian Transport Statistics Yearbook 2007. Bureau of Infrastructure, Transport and Regional Economics, Canberra.; 1.4 reported in CES Victoria, 2008. Public transport's role in reducing greenhouse emissions. Commissioner for Environmental Sustainability, Melbourne, Australia., and 1.6 reported by Lenzen, M., 1999. Total requirements of energy and greenhouse gases for Australian transport. Transport Research Part D 4, 265-290.

11 Appendix

Table 4. The assumptions and methods used to derive metropolitan level, direct energy consumption data for Melbourne.

Sector	Factor used to derive Melbourne data
Agriculture	Based on the fraction of Melbourne Statistical division zoned for agricultural use in 2004 (Source: Victorian Department of Sustainability and the Environment)
Mining	Based on the fraction of Melbourne Statistical division zoned for mining in 2004 (Source: Victorian Department of Sustainability and the Environment)
Manufacturing	Derived from the ratio of (the total energy for Manufacturing **not** used in aluminium smelting) : (total energy for Manufacturing) × (the Melbourne fraction of Victorian population employed in Manufacturing)
Electricity generation	The primary energy for electricity generation in Victoria was distributed to all sectors based on their electrical energy consumption from ABARE (2007). The weights used to determine the Melbourne only fraction of these sectors' use of primary energy are the respective other factors for Melbourne shown in this table.
Construction	Based on census data for employment in this sector in Melbourne from 1971-2006
Transport	
Road transport	Used split of vehicle kilometres travelled in Melbourne compared with Victoria from p58 of BITRE Year Book 2007 (BITRE, 2008).
Railway transport	Attributed to Melbourne by the split of rail freight task - from p1 of *Aspects of Greater Melbourne Freight Task* Victorian Department of Infrastructure Report for *Melbourne 2030* (2000)
International bunkers	100% attributed to Melbourne
Coastal bunkers	100% attributed to Melbourne
Water transport	Factor of 0.75 derived from information on Victoria's ports available on Victorian Department of Transport website*.
Domestic air transport	100% attributed to Melbourne
International air transport	not attributed to Melbourne or Victoria
Commercial and Services	Based on census data for employment in this sector in Melbourne from 2001
Residential	Based on census data for population and housing in Melbourne from 2001

Other	All other energy uses were attributed to Melbourne according to census data for population and housing in Melbourne between 2001

*www.transport.vic.gov.au/Doi/Internet/Freight.nsf/AllDocs/89050061DB069A00CA256FF000235DDC?OpenDocument

In Baynes and Bai (2009) generally the upstream energy was not calculated with the exception of the primary energy due to electricity consumption. In ABARE's statistical tables (ABARE, 2007, 2008a) there is detail on the consumption of electricity by different Victorian industry sectors and the primary energy consumption for electricity generation.. These data were used to attribute the primary energy consumed in generating electricity to the different electricity consuming sectors. This was added to the primary energy use, for each sector as follows:

Where *s* is the set of sectors and *f* the set of fuel types mentioned above:

- PEC[*s*] = Primary Energy Consumption
- PEEG[*s* = *Electricity generation*] = Primary Energy Consumption for Electricity Generation
- PEEC[*s*] = Primary Energy associated with Electricity Consumption
- SFEC[*s*, *f* = *electricity*] = Sectoral Final Electricity Consumption[1]
- TEG = Total Electricity Generated

$$\mathrm{PEEC}[s] = \mathrm{PEEG}[s = \textit{Electricity generation}] * \mathrm{SFEC}[s, f = \textit{electricity}] / \mathrm{TEG}$$

$$\text{Total primary energy use by each sector} = \mathrm{PEC}[s] + \mathrm{PEEC}[s]$$

[1] This includes the electricity required by the Electricity generation sector.

Table 5. Direct energy account for Melbourne 2001 – all measures in PJ.

	Brown Coal	Brown Coal Briquettes	Oil	Oil products	Gas	Hydro	Electricity[a]	Total
Primary Energy Production			218.00[b]					**218.00**
Import	0[c]	3.18[d]			127.65[e]		117.36[f]	**248.19**
Export			19.52					**19.52**
Stock Changes								**0.00**
Total primary energy available [g]	**0.0**	**3.18**	**198.5**	**0.0**	**127.7**	**0.0**	**117.4**	**466.7**
Electricity Generation [h]				0.21	10.76			**10.97**
Conversion to other fuels								
Own needs and losses			7.88[i]		5.41		18.27[j]	**31.55**
Secondary energy used	**0.00**	**0.00**	**7.88**	**0.21**	**16.17**	**0.00**	**18.27**	**42.52**
Agriculture and Forestry				0.38			0.06	**0.43**
Mining				0.36			3.69	**9.24[r]**
Industry total		0.85		3.38	24.70		**36.03**	**127.29[r]**
Petroleum Coal and Chemical [k]							3.55	**45.85[r]**
Machinery and Metal Processing [l]				2.84			23.03	**30.12[r]**
Textile and Clothing [m]		0.39			3.41		0.54	**4.34**
Wood, paper and printing [m]				0.08			3.33	**19.20[r]**
Food and Beverages [m]		0.46		0.15	11.15		4.10	**15.87**
Other manufacturing [m, n]				0.31	10.14		1.47	**11.92**
Construction				4.05	1.25		0.07	**5.38**
Commercial and Services		2.26		1.30	20.36		29.47	**53.40**
Transport (excl. Int. travel and bunkers)				177.88			1.30	**179.18**
Road				152.98				**152.98**
Railway [o]				0.57			1.30	**1.87**
Water				9.53				**9.53**
Domestic Air				14.80				**14.80**
Residential [p]		0.07		2.96	59.54		27.31	**89.88**
Water and Gas Utilities [p]				0.07	5.64		1.16	**6.86**
Final Energy consumption [q]	**0.00**	**3.18**	**0.00**	**190.38**	**111.48**		**99.09**	**471.68[r]**

Notes on Table 5:

Numbers in the Import and Export rows of the Primary energy Account may have been calculated as accounting items in order to balance Final energy consumption, Electricity Generation, Conversion to other fuels and Own needs and Losses. Some data concerning specific refinery input and output, production of petroleum products, and production and consumption of coal by-products were not available due to confidentiality, but are included in totals. Generally, data for the items of Final Energy Consumption have been derived from the corresponding data for Victoria using the procedures outlined in Table 4. Further manipulations are noted below.

a. Final consumption for an industry in this column includes consumption of any electricity generated by that industry.
b. Primary oil production actually occurs offshore but is attributed to Melbourne based on fraction of Victoria's refining capacity in Melbourne ~55%. This is also applied to Conversion to other fuels, Own needs and Losses in the Oil products column.
c. Assumes all direct consumption and transformation of brown coal energy occurs outside of Melbourne which is likely given the major electricity generators are in the Latrobe Valley outside of Melbourne Statistical Division.
d. Assumes all brown coal briquettes are imported into Melbourne.
e. Assumes all natural gas used is piped into Melbourne and does not account for storage in or near Melbourne.
f. Electricity is not a form of primary energy but is included here in to indicate primary equivalent energy imported into Melbourne.
g. Sum of primary production and imports minus exports +/- stock changes.

h. Derived from Victorian data using the share of final electricity energy consumption in Melbourne.

i. This includes uses and losses of oil during refinery processes and was calculated using loss fraction reported for the Australian petroleum industry = (petroleum refinery fuel use and losses) / (feedstock and petroleum products) from ABARE (2008d). This was 4.9% for 2004-05.

j. Includes losses in electricity generation.

k. Petroleum and Chemical energy use is allocated to Melbourne by production capacity within Melbourne relative to that in all of Victoria. Does not include the refinement of oil into oil products.

l. Derived from (corresponding Victorian data) × (the fraction of the total energy for Manufacturing **not** used in aluminium smelting) × (the Melbourne fraction of Victorian population employed in this category of Manufacturing).

m. Derived from (corresponding Victorian data) × (the Melbourne fraction of Victorian population employed in this category of Manufacturing).

n. Includes non-metallic mineral products.

o. Consumption of oil products by rail attributed to Melbourne by the split of rail freight task - from p1 of the Department of Infrastructure report for Melbourne 2030 planning: *Aspects of Greater Melbourne Freight Task* DOI for M2030 (2000). All Victoria's electric rail travel is assumed to be in Melbourne.

p. Attributed to Melbourne by proportion of Victorian population.

q. This equals the sum of Agriculture and Forestry, Mining, Industry total, Construction, Commercial and Services, Transport Total (excluding International travel and bunkers), Residential, Water and Gas Utilities.

r. These totals are affected by sectoral energy consumption data that were reported as totals for reasons of confidentiality and we do not know the fuel breakdown of the additional energy consumption. This means these totals do not concur with the accounting across rows in the table. For the purpose of deriving primary energy use in Table 1, the extra direct energy was assumed to be in the following form for these industry sectors:

- Mining, electricity
- Petroleum Coal and Chemical, oil products
- Machinery and Metal Processing, electricity
- Wood, paper and printing, electricity