Reconstructing the Energy History of a City

Melbourne's Population, Urban Development, Energy Supply and Use from 1973 to 2005

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Summary

For informed decision making about the current state and near future of any city, it is important to consider the long-term resource use trajectory and legacy of its past. Such information is not always readily available. Urban metabolism analysis for any given time period can be challenging due to the lack of metropolitan- or city-level data, and reconstructing a time series of urban energy or material flows is seldom attempted. For the case of Melbourne, Australia, we demonstrate how time series operational energy demand and supply data can be reconstructed from original sources. Primary energy consumption is calculated based on direct and upstream energy use in common with "scope 2" standards for emissions reporting. This extends the usual treatment of energy in urban metabolism studies by (1) providing time series data and (2) attributing upstream primary energy consumption to sectors based on their direct secondary energy usage. Results indicate that the transport, commercial, manufacturing, and residential sectors have contributed most to the doubling of Melbourne's energy consumption over four decades. We discuss recent urban development history and its relation to energy consumption and briefly examine potential scenarios of and responses to future change.

Introduction

Reporting on urban energy consumption provides a useful gauge of both the material wealth and potential environmental impact of a city and its population. More often this reporting is in the form of a static account similar to that used in national assessments (IEA 2010). Of equal utility is the historical perspective that informs us of long-term trends and transitions.

There are several reasons for taking a long-term perspective at the city level. First, it provides a foundation for statistical/econometric analysis to understand causal effects and mechanisms behind the urban energy trajectory, requiring long-term time series data (Bai 2003; Bai and Imura 2000; Global Energy Assessment 2012). Second, an intergenerational perspective of at least 30 years can enable us to link energy use to the development and evolution of a city. A long-term understanding of energy use in the history of a developed city like Melbourne can also provide a useful precursor for understanding developing cities where most future population growth and the most significant increases in energy consumption are expected.

Short-term urban management decisions can have a much longer period of environmental impact (Bai 2007). It is worthwhile to have a long time series of transport energy data to be able to review the long-term effect, if any, of past land use planning decisions that were intended to resolve nonenergy

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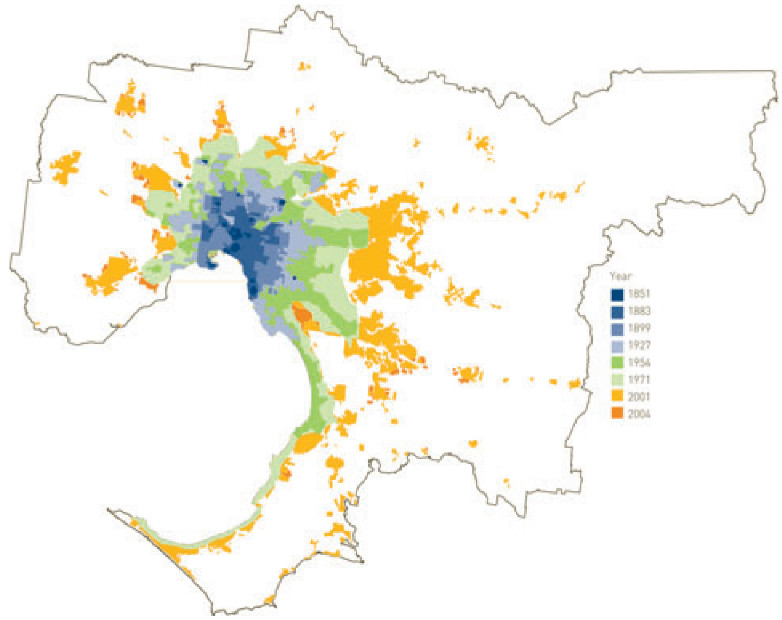

Figure 1 Historical land development around Melbourne (1851–2004) as defined by the boundary of the Melbourne Statistical Division (used with permission from the Atlas of Melbourne 2006 [DPCD 2007, 1.2]).

issues (e.g., housing) over shorter timescales. Observing, or reconstructing, shorter historical time series does not necessarily engender poorer decisions or policies, but less information is available to assess and respond to long-term trends and it is easier to develop policies that are insensitive to long-term impacts.

Detailed urban or metropolitan energy data as used in recent studies (Baynes et al. 2011a; Hillman and Ramaswami 2010; Kennedy et al. 2009; Lenzen et al. 2008; Parshall et al. 2010) are not always available at the appropriate scale over historical time. Urban metabolism studies, that would also capture urban energy flows, are rarely repeated for the same city and not at regular time intervals (Decker et al. 2000; Kennedy et al. 2011).

There are some exceptions to this claim. Singapore is an island state dominated by its sole urban center and the national materials flow accounts (MFAs[1]) have effectively been used to represent urban metabolism since 1962[2] (Schulz 2007). Chinese statistical yearbooks contain time series data, but only for a few large cities (Dhakal 2009), and the City of New York, New York, USA, has maintained an inventory of greenhouse gas (GHG) emissions every 5 years since 1995, within which is an account of direct energy use (New York City 2007).

Despite the counterexamples above, the general experience is that there is a need to use some sort of scaling to estimate urban- or metropolitan-level data from regional or national reporting. In the present work we have spent considerable effort on reconstructing historical data to form a complete and consistent time series of energy demand and supply for the example case study of Melbourne, Australia, using the general approach suggested in an article by Baynes and colleagues (2011b). We employ scaling methods similar to those used by Niza and colleagues (2009), which have been previously applied in a static urban energy account for Melbourne (Baynes et al. 2011a).

This article has six sections including this one. In the following section is a short commentary on the growth and development of Melbourne, including the planning history, population trends, and transitions in employment since 1961. Subsequently we discuss the methodology, present results on constructed trends of energy supply and demand in residential, industry, and transportation sectors, and relate this to the urban development trajectory of Melbourne. The penultimate section examines some current policy responses and possible elements of future scenarios. We conclude that the method presented can be useful in constructing time series energy metabolism at the city level, which in turn can provide valuable information for understanding urban development trajectories, past and future. We define the metropolitan area of Melbourne to be the same as that of the Melbourne Statistical Division shown by the outer boundary in figure 1.

Melbourne's Development

The following is a short history of the land use planning, population, and economic structure of Melbourne, the major urban center of the State of Victoria, Australia.

From its beginnings in 1835, Melbourne has been well planned. Early urban designers established definite regulations on details such as the width of main thoroughfares and plot sizes. Planning strategies up to the 1980s allowed for geographical expansion, and initially, with a small population, this permitted people from a wide range of socioeconomic backgrounds to afford high-quality, low-density housing.

Over the last four decades Melbourne has expanded rapidly. Between 1961 and 2005 the population has increased from 1.9 million to 3.6 million (83%) coinciding with increases in automobile ownership (ABS 1998) and average house size (ABS 2001, 2008a). In combination with the egalitarian tradition of housing, this has produced a broad skirt of developed area punctuated by several local centers, but anchored by transport routes to a central core (see figure 1).

Melbourne retained its trams when other Australian cities were retiring them in the 1950s and 1960s, but beyond the inner city, the urban design has entrenched automobiles as the dominant mode of personal transport and intraurban freight transport. According to Melbourne Atlas 2006, "most of Victoria's freight activity is within the metropolitan area, with 99% of the [metropolitan] freight carried by the road network" (DPCD 2007, 4.1).

Conservative governance in the early to mid-1990s saw a strong emphasis on business developments in the center of the city and further growth in the residential outer fringe, particularly to the west and southeast (ABS 2006). During this time the areas closest to the central business district (CBD) experienced depopulation, although there has been a recent trend toward rejuvenation (ABS 2008b).

From the 1940s to the 1960s, Melbourne developed a significant manufacturing sector, notably in its contribution to Australia's automobile industry (see Forster 1996, 13). By 1971 more than one-third of all jobs in Melbourne were in manufacturing.

Over the next 30 years there was a structural economic transition, with a marked reduction in employment in manufacturing and secondary industries and a substantial increase in the proportion of people employed in service industries (ABS 2006). This was indicative of a change in the economic function of the city, with the proportion of people employed in manufacturing halving from 31% to 16% while those in financial, property, and business services increased from 8% to 18% and the proportion of people employed in hospitality and entertainment increased from 5% to 10%.

It is tempting to assume such a transition to a more service-based economy might also engender lower energy costs, but service industries still have significant direct and indirect material and energy needs (Foran et al. 2005; Minx et al. 2009; Oliver-Solà et al. 2007). Additionally, services that are not energy intensive themselves may still be integral to energy intensive secondary industries (e.g., maintenance services). Thus some services actively support or are intermediate in an energy intensive economy.

From 1961 to 2005 there was an 83% increase in population, which is responsible for some of the increase in total energy demand, but there has also been a 120% increase in per capita energy consumption. How this has arisen, whether from more energy intensive industries, more travel, or more energy intensive lifestyles, is the subject of this article.

Methods and Data

Energy consumption statistics have been (and continue to be) mostly reported at the state level, and direct energy-related data for Melbourne are rare. Data about bulk energy demand or supply has been available since 1961, but details on the end use have only been available since 1973. We have resisted the temptation to extrapolate backwards, although further research may reveal deeper historical trends. The scaling of sectoral energy use data relied on historical records of Melbourne's population, employment, and land use data, which has features in common with the urban scaling used by Niza and colleagues (2009).

Residential energy use was derived by applying the fraction of the state's population living within the Melbourne Statistical Division to the historically reported residential energy use for the whole state in the same year.

Data for energy end use by industry has only been collected consistently since 1973, and only at the state level. To scale these to the metropolitan level, we used a combination of employment data, land use information, and local knowledge of the sites of energy intensive industries to generate data for Melbourne.

For urban energy use by industrial and commercial sectors, other than mining and agriculture, we generally used employment statistics by sector from the historical Australian censuses. Energy use in agriculture and mining was derived by using data on land use from the Victoria State Department of Sustainability and the Environment (DSE 2004).

We modified the above scaling with local knowledge on the location of particular energy intensive industries. For example, we were aware that aluminum smelting is a significant consumer of electricity in Victoria. Since 1990 the aluminum industry has accounted for more than 30 petajoules/year (PJ/year) (45%) of direct electricity consumption by all industry sectors in the state (DNRE 2002). Some administrative employment in this sector occurs in Melbourne, but none of the energy intensive smelting activity. Therefore it would have been distorting to apply scaling based on employment statistics in attributing energy use by this industry to Melbourne. Hence energy use for aluminum smelting was subtracted from the state total before any scaling of industrial energy data.

When referring to "energy consumption" we begin with the definition used by our main data source, the Australian Bureau of Agriculture and Resource Economics and Sciences (ABARES): total energy consumption is the total quantity (in energy units) of primary and secondary energy consumed minus the quantity of secondary energy produced. For example, thermal electricity is a secondary energy vector. Thus, while the electricity sector is directly a major consumer of primary energy, its reported energy consumption subtracts the amount of thermal electricity it produces for consumption in other sectors. We believe even this measure conceals information about energy consumption of urban sectors. We expand the definition of "energy consumption" to direct primary energy consumption and upstream primary energy use consistent with the scope 2 definition widely used in reporting GHG emissions (WRI 2004) or the fourth category of local energy accounting referred to in Parshall and colleagues (2010). In the following sections "energy consumption" or "energy demand" refers to this metric unless specified otherwise. "Total energy consumption" refers

Table 1 Comparison of some general approaches to urban energy accounting with respect to scope, use of time series, and scaling methods employed if any.

	Urban metabolism[a]	*This approach*	*Consumption based*	*Hybrid transboundary*
Scope	1	2	3	1–3
Time series	Rare	Yes	Possible[b]	Possible[c]
Scaling				
Residential	Population fraction in urban area	Population fraction in urban area	HES sampling for urban area and number of households in urban area	No scaling. In-boundary household direct energy use and upstream primary energy consumption
Industrial sectors	Employment fraction in urban area	Employment fraction in urban area	Industry location or land use data, multiregion IO needed for complete picture of local production[d]	No scaling. In-boundary direct energy use in commercial and industrial buildings and transboundary industrial activity supplying key materials
Transport	VKT, fuel sales, or in mass balance of fossil fuels	VKT by vehicle type (energy units)	Sampling of HES for expenditure on private transport, number of urban households	VKT for road travel; fraction of all road trips to airport that start from the city for air travel

[a]For example, Niza and colleagues (2009) only treated urban energy use in mass terms.
[b]See, for example, the work by Lenzen and colleagues (2010).
[c]See repeated application of this approach (Hillman and Ramaswami 2010; Ramaswami et al. 2008, 2011) to several cities, though not yet repeated at different dates.
[d]In Baynes and colleagues (2011a) an "energy catchment" map shows the location of direct and indirect primary energy consumed for the full chain of supply to household demand in Melbourne. Of this energy catchment, 30% is within the Melbourne metropolitan area, but Melbourne can be part of the energy catchment of other states and cities, and this requires multiregional input-output (IO) analysis.
HES = household expenditure surveys; VKT = vehicle kilometers travelled.

to the sum of the scope 2 primary energy consumption across sectors.

In ABARES Table F3 (2008c) there is detail on the direct consumption of primary energy sources and the use of electricity by different Victoria industry sectors, including the electricity generation sector. These data were used to attribute the upstream primary energy consumed in electricity generation, transmission, and losses[3] to the different electricity consuming sectors as follows:

$$PEEC[s] = PEElec^{*}SFEC[s]/TEG, \quad (1)$$

where s is the set of sectors including the residential sector and the electricity generation sector, and

- PEC[s] = primary energy consumption (direct);
- PEElec = primary energy for electricity generation, transmission, and losses;
- SFEC[s] = sectoral final electricity consumption;
- TEG = total electricity generated – exports;[4] and
- PEEC[s] = primary energy associated with electricity consumption.

This was then added to any direct primary energy consumption by a sector:

$$\text{Scope 1 and 2 primary energy use by each sector} = PEC[s] + PEEC[s]. \quad (2)$$

Raw data were sourced from the Energy Supply Association of Australia (ESAA 2002, 2005) and ABARES's energy data Tables B, C, F, G. and L (2008a, 2008b, 2008c, 2008d, 2008e).

In table 1 is a comparison of scaling methods used in urban energy accounting elsewhere: urban metabolism-based approaches (Niza et al. 2009), consumption based approaches that use state-level input output (IO) tables and household consumption surveys (Baynes et al. 2011a), and hybrid transboundary approaches that also use life cycle information and include transboundary exchange of selected key materials (food, water, concrete, fuel) (Hillman and Ramaswami 2010; Ramaswami et al. 2008). Further detail on scaling factors used in this research are available in the supporting information available on the Journal's Web site or in Baynes and colleagues (2011a).

Limitations of Downscaling

Time series derived from a product of higher-level data and scaling information potentially only reflects changes in the scaling data. There is the implicit assumption that the relationship between the two factors is static. Further research is needed to acquire an understanding of any changes in fuel type, efficiencies, or energy practices that may have also influenced energy use over time. Triangulating the derived time series with tertiary evidence like fuel surveys can help overcome this limitation.

Using census employment statistics for downscaling energy demand leads to the possibility that there may be commuting into or out of the Melbourne area for work. Our choice of scale for this study is such that there are a relatively small

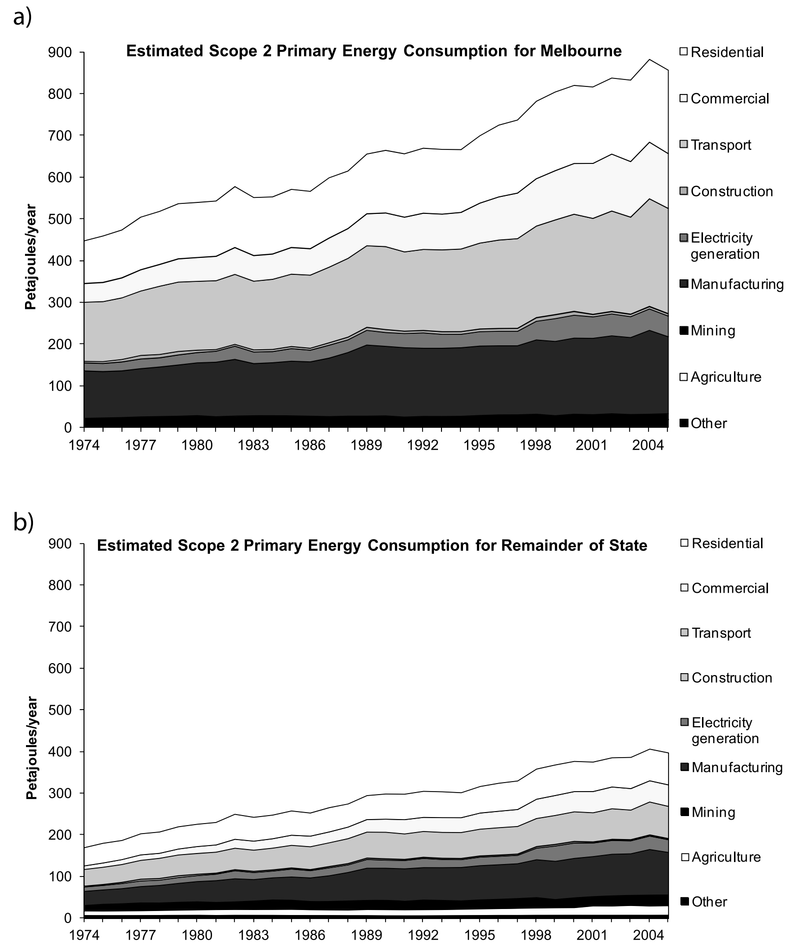

Figure 2 Estimated scope 2 primary energy consumption for (a) Melbourne and (b) the remainder of the state, by sector (data derived from ABARES [2008c] Table F3). The consumption of primary energy associated with electricity generation has been attributed to sectors in proportion to their final use of electricity and "Transport" includes all forms and uses of transport.

number of people traversing Melbourne's boundary for work. The Melbourne Statistical Division is nearly 100 kilometers (km) in diameter[5] and certainly contains the vast majority of the city's commutershed.

Results: Energy Demand

General Trends

From the derived data shown in figure 2, most of the state's energy consumption appears to be associated with Melbourne. The dominance of Melbourne is related to it being the state's center of population and employment and also where there is the greatest concentration of public and private transport use. These factors influence the scaling, but the economic structure of Melbourne's economy means that it is the location of the majority of retail, services, commercial activity, and most new construction.

Compared with the rest of the state, Melbourne consumes more energy in transport (see figure 2a), while outside of Melbourne there is more energy consumed in agriculture, mining, and manufacturing (see figure 2b). The estimated 96% (99.8 PJ)[6] increase in Melbourne's total residential energy consumption since 1974 and the increase in per capita energy demand since 1961 indicate that there have been changing energy consumption patterns in the residential sector.

Despite the evident changes to the character of sectoral employment in Melbourne, the relative proportions of sectoral energy demands for Melbourne, and the rest of Victoria, have remained reasonably stable for the last 30 years (see figure 2). The three industrial sectors that have consumed the most energy in the urban setting are the transport, manufacturing, and commercial sectors.

The transport, residential, commercial, and manufacturing sectors have contributed the most, respectively, to the change in energy consumption since 1974 (refer to figure S1 in the supporting information on the Web). The following subsections examine the energy consumption results for key sectors in relation to pertinent nonenergy historical information.

Residential Requirements

The raw data on energy use do not specify how or why urban residential demand has increased, although there is evidence to suggest that this has been manifested in increased ownership of appliances and increases in the size of dwellings. The penetration of electrical appliances since 1983 has seen a notable increase (>20%) in the use of air conditioners and dishwashers (ABS 1995, 2005; refer also to figure S2 in the supporting information on the Web).

Proliferation of electric appliances changes the seasonal distribution of energy demand. According to a report for Victorian Energy Networks Corporation (EES 2005, 1): "From the mid 1990's, rapid increases in the penetration of air-conditioners, particularly in the residential sector, has resulted in Victorian peak electricity demands consistently occurring during summer. Prior to this, peak demands consistently occurred in the winter season."

In addition to the increased ownership of appliances, the size and location of houses in Melbourne has changed. Location has more of an influence on residential transport (discussed in a subsequent section), but regarding dwelling size, between 1984 and 2005 new houses in Victoria increased their floor space by 36% (ABS 2005).

Other studies have found correlations between energy consumption and the size and location of housing (Perkins 2003) and the type of housing (Newton et al. 2000) in Australian cities. Newton and colleagues calculated embodied, operational, and life cycle energy costs for detached houses and apartments in major Australian cities. They found that detached houses have more than double the initial embodied energy of apartments, but they are also more likely to have more occupants. The result is that the two types of dwelling are roughly equivalent in life cycle energy measured in gigajoules per occupant.

However, decreasing occupancy of medium-density and detached houses has been the trend for Melbourne over the last 30 years (ABS 2006). The cumulative effect of the above statistics can be summarized coarsely as follows: at the same time that the total population has been increasing, an increasing number of larger houses have been built that are occupied by fewer people who generally own more appliances than their predecessors. This statement is, of course, a very broad generalization and there are suburbs where much of that description does not apply, but it does convey the essence of the lifestyle change that has occurred over the *whole* city since the 1960s.

Data simulations of residential energy end use at the state level between 1990 and 2005 reveal that, in Victoria, space heating has consistently been more than half of the household energy budget. While total energy for space heating has increased by nearly one-third, energy for electrical appliances has increased by more than 50% (Department of the Environment, Water, Heritage, and the Arts 2008). The number of Victorian households increased only 20% over the same period.

Industrial Energy Use

Manufacturing still contributed 17.4% of the total change in energy consumption between 1974 and 2005 and this may be because Melbourne does retain some legacy from a more industrial age. Since 1924 there has been an oil refinery about 10 km southwest of the city center and a related petrochemical plant was established there in 1961, expanding its production of petroleum by-products until 1990. Nearby there is also an electric arc steel furnace (operating since 1983), a car manufacturer that has progressively increased its output, and other light industrial activity.

Table 2 Relative and absolute change in annual energy use of industrial sectors, 1974–2005.

Industry sector	*Relative increase (%)*	*Absolute increase (PJ/year)*
Agriculture	73	0.22
Mining	135	9.2
Manufacturing	85	96
Electricity generation	182	34
Construction	1	0.05
Transport	79	113
Commercial	195	87
Other	15	2.4

PJ/year = petajoules per year; 1 petajoule = 10^{15} joules.

Although these sites remain, new energy intensive heavy industries have been located away from Melbourne. For example, while a new paper processing plant was established in Melbourne in the 1980s, at the same time a more energy intensive aluminum smelter was commissioned outside of Melbourne in the state's west.

For Melbourne, the sectors with the largest relative change in energy consumption, that have also translated into a significant (>30 PJ) absolute increase, are the commercial, transport, electricity generation, and manufacturing sectors (see table 2).

Transport

This sector has contributed most to the *change* in energy consumption for Victoria over the last 30 years, and although there have been improvements in the efficiency of motor vehicles in that time, there has also been a concurrent increase in their use and a decreasing popularity of alternative transport modes.

Results here include freight transport, although it should be noted that in the years since 1971, private vehicles have accounted for at least 75% of road transport within Melbourne (BITRE 2011; BTE 1998) and our discussion focuses on ownership and use of private automobiles and changes in the area and density of the urban form.

Ownership of cars in Melbourne has multiplied more than six times in 50 years, from 112.5 cars per 1,000 people in 1950 to 679.8 cars per 1,000 people in 2004 (DPCD 2007). Melbourne shares with Perth the highest level of automobile ownership in Australian cities, with 35% of Melbourne households having at least two automobiles (Commissioner for Environmental Sustainability 2006).

In 1945 approximately 50% of the urban transport task was conducted using the automobile; by 1997 this was more

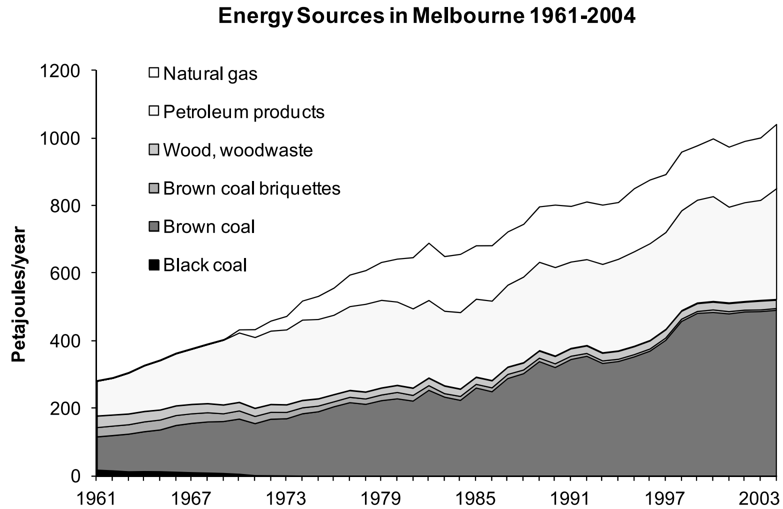

Figure 3 Sources of energy for Melbourne between 1961 and 2004 by fuel type. Derived data first subtracted energy use for conspicuous energy intensive industries outside of Melbourne from total consumption for Victoria. The result was then multiplied by the proportion of population living in Melbourne. There is a base assumption that nonindustry energy use is distributed on an equal per capita basis across the state. The contribution from renewable energy sources was too small to show. Original data from ABARES (2008d).

than 90% (BTE 1998). Within Melbourne the total number of passenger-kilometers also doubled between 1977 and 2004 (to 46.53 billion passenger-kilometers). Although some of this is explained by the 33% increase in population, clearly most of that change can be attributed to increased car use per person.

The kilometers travelled by bus in Melbourne has remained fairly constant since the 1970s, but the number of people using public transport has declined from a peak of more than 500 million trips per year in 1950 to less than 300 million trips in the 1980s, rising more modestly to about 350 million trips at the end of the century (BTE 1998). Meanwhile the annual passenger-kilometers travelled by the average Melbournian has increased from 8,300 km in 1977 to 14,000 km in 2007 (BITRE 2008).

We suggest that these latter figures are related to changes in the spread and density of Melbourne. In 1961 70% of Melbournians lived within 10 km of the city CBD and the average population density was 8.4 persons per hectare (p/ha).[7] By 2001 84% lived further than 10 km from the CBD. This could be partly explained by the increase in population simply needing more area, but this has been exacerbated by the average population density, decreasing it to 4.8 p/ha[8] (DPCD 2007).

The operational energy intensity of urban passenger transport in Melbourne has been calculated by Lenzen (1999), who included the fuel, operation, and maintenance of each transport mode in his calculation. The product of these intensities with the data on passenger-kilometers above indicates that the energy required by Melbourne passenger automobiles alone was approximately 200 PJ, nearly half of Victoria's petroleum energy budget in 2004.

Results: Energy Supply

The total supply of energy has more than tripled during 1961–2004, and the structure of the energy supply has also changed (see figure 3). Melbourne is dependent on imported electricity from elsewhere in its host state of Victoria. This electricity has been generated using brown coal (lignite) found locally in the Latrobe Valley, 130 km to the east of the city, but outside our definition of the Melbourne metropolitan area. Victoria has increased its coal-powered generation capacity over the last 40 years both in absolute (1,170 megawatts [MW] to 7,105 MW)[9] and relative terms. In the 1960s 75% of Victoria's electricity was generated using brown coal either in its raw form or manufactured into brown coal briquettes (ABS 1966). Today this is 96%, with the remainder of electricity generation powered by natural gas[10] (1.6%) and renewable energy sources (2.4%) (DPCD 2007).

In 1965 natural gas reserves were discovered off the southern coast of Victoria in Bass Strait and a pipeline into Melbourne was constructed in 1969. Natural gas has steadily increased in prominence as a fuel source for electricity generation, transport, heating, and residential uses. Between 2001 and 2002 gas-powered electricity generation capacity in Victoria more than doubled with the addition of another 552 MW of capacity. At least 160 MW of this is located within metropolitan Melbourne (ESAA 2005).

Melbourne's energy supply is currently dominated by three fuel sources: brown coal, petroleum products (including diesel), and natural gas (see figure 3). With statewide distribution networks and the possibility of interstate energy trading since the late 1980s, it is difficult to determine what source of energy has been consumed where. The derived data of figure 3 assume that the history of energy for Melbourne strongly parallels the history for Victoria, though there are some regional specifics, such as a local gas-powered electricity generator used predominantly for Melbourne's peak loads.

The Snowy Mountains Hydroelectric Scheme was constructed between 1949 and 1974, progressively increasing

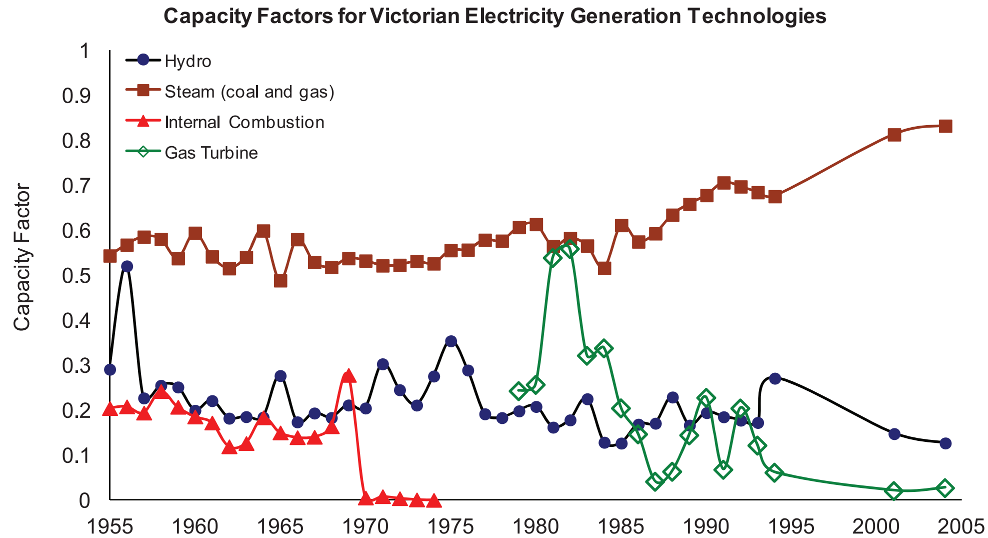

Figure 4 Capacity factors (load factors) for Victorian electricity generator types using data from the Energy Supply Association of Australia's historical time series data and reports.

installation of hydroelectric generation capacity up to 4 gigawatts (GW). The electricity from this scheme is shared between the Commonwealth of Australia, New South Wales, and Victoria, but Victoria has access to more than 500 MW of its own hydropower and there has been some recent investment in embedded renewable energy generation. The 654 MW of new generating capacity installed in the last 15 years has been powered either by natural gas or from renewable energy sources (ESAA 2002, 2005), compared with prior investment in coal-fired power stations: 1,000 MW in 1993 and 2,085 MW in 1984, both still operating.

Installed capacity does not directly translate into use and the "load factors" or "capacity factors" for different electricity generation technologies vary greatly. The term "capacity factor" is used here to describe the ratio of total energy sent out (megawatt-hours [MWh]) to total installed generation capacity (MW) × 8,760 hours; that is, the actual energy produced compared with the hypothetical energy produced if the installed capacity were operated continuously for a year (see figure 4).

The availability of coal in Australia combined with high industrial loading ensures that the capacity factors for coal-powered electricity generators are high—greater than 0.8 (ESAA 2002, 2005). The Snowy Mountains Hydroelectric Scheme has historically been run with a capacity factor of about 0.2, although this depends heavily on the availability of water, which has generally been extremely variable across southeastern Australia. The capacity factor of Victorian wind farms lies between 0.3 and 0.4 (Sustainability Victoria 2007), and at Melbourne's latitude, solar power capacity factors are between 0.15 and 0.2.

The oil refinery in the Melbourne suburb of Altona has a capacity of 6.16 megatonnes per year (Mt/year),[11] which is approximately 55% of the state's production capacity. According to Collins and Powell (2002), these plants operate at an annual average of 85% to 88% of their rated capacity, indicating a current output of about 300 PJ of oil products per year.[12] The other major Victorian oil refinery at Geelong (70 km from Melbourne) has a capacity of 5.34 Mt/year (approximate output[13] 265 PJ), and in combination these plant can comfortably provide for the current demand in oil products for Melbourne, and indeed the whole state[14] (462 PJ/year in 2005).

The Future: Limiting Factors and Possible Policy Measures

However comfortable the current energy supply situation is for Melbourne and Victoria, there are possibly some dramatic changes ahead in the long term. Here we discuss issues of concern in terms of supply and demand, and present and possible policy measures that might positively influence Melbourne's future energy trajectory.

Scenario analyses of resource use (Foran and Poldy 2002; Schandl et al. 2007) show how Australian, and particularly Victorian, gas and oil reserves are likely to become more scarce within the next 50 years. There is the time and potential for cities to adapt and potentially benefit from such changes, but if current drivers and patterns of oil consumption persist, there will undoubtedly be a sudden realization of the limits to resources.

The supply of brown coal has greater longevity, with one estimate suggesting that there are 550 years of economic reserves (CSIRO 2006). The limiting factors for coal-powered electricity are investment in generation capacity and the cost of GHG emissions. Projections in 2002 anticipated the need for approximately 11,500 MW in generation capacity by 2012–2013 (IPC 2002). In 2008 Victoria's electricity generation capacity was still around 9,000 MW, with another 550 MW of nonrenewable and 606 MW of renewable generation projects planned (Penney et al. 2008).

With capacity factors of 0.8 in the dominant coal-fired electricity generation plant, there is less time available for maintenance and current capacity may already be showing signs of strain. A heat wave in 2009 resulted in extreme demand for electricity in Melbourne, producing prolonged blackouts occurring over large areas of the city, affecting residents, and disabling transport and communications systems (O'Keefe 2009). Although this may be an isolated incident, it is worth noting that both the demand and the technical fault occurred because of a heat wave at a time of year that is increasingly becoming the peak season for electricity demand. Not only is there the question of limited capacity, but there is also the concern that infrastructure installed in the past may not be able to function at such high loads at the hottest time of year. These issues may well be exacerbated by the anticipated effects of climate change: increases in mean temperatures and frequencies of extremes.

The future demand for energy in Melbourne will be strongly coupled to its total population. At the last census this was 3.6 million, but that is forecast to increase to 5 million by 2030 (DPCD 2008b). It is an open question as to whether the per capita requirements for energy will continue to increase as they have done for the last 50 years or whether we will see them plateau or even decrease. With the increasing reliance on appliances, and particularly air conditioners, forecasts based on past trends anticipate energy use in the residential sector to grow by 35% by 2020 relative to 2005 levels (SEAV 2005).

Simultaneously the forecast is for energy consumption in the industrial sector to increase by 26% and in the commercial sector by 54% (SEAV 2005). The latter is sensitive to the number of people employed in Melbourne, which is expected to grow to nearly 3 million by 2036. Most new commercial sector jobs are expected to be located in central and inner Melbourne (DPCD 2008a).

The Australian Bureau of Transport and Regional Economics (BTRE 2007) has produced projections that Melbourne's road freight transport will also increase by 54% (relative to 2005 levels), to 17 billion tonne-kilometers, and that total vehicle kilometers travelled (VKT) in the city will increase 30% by 2020.

Policy Responses

Having identified several urban energy issues, it is surprising that Australian cities generally lack a dedicated metropolitan level of governance that would be a natural locus for collecting urban energy statistics and enacting urban energy policy. Many policy controls such as renewable energy targets and carbon pricing/taxes are imposed through legislation and regulation at a state or national level. Since each state has only one major urban area, the state-level urban policies are effectively the policies for the main city—in Victoria this is Melbourne.

Governments at all levels are attempting to defy some of the aforementioned projections and make a transition toward more energy efficient and low-carbon cities through a number of initiatives, including[15]

- energy sensitive urban planning,
- investing in low-carbon or renewable energy infrastructure,
- institutional and economic incentives, and
- promoting alternative transport modes.

We briefly discuss a few examples of these in relation to our observation of reconstructed historical trends.

Energy-Sensitive Urban Planning

Since 1974, Melbourne's population has grown 44%, its urban land use and total energy consumption have both increased 91%, and transport energy use has increased 79%. While further analysis is required to determine the causal effect of urban planning and energy use in Melbourne's case, existing research suggests a relationship between urban form and energy use (Newman and Kenworthy 1989). This is recognized and reflected in policy making in Melbourne, and in 2002 the Victoria government released a strategic planning document for Melbourne: *Melbourne 2030* (DOI 2002). Two key features of the strategy were an urban growth boundary (UGB) and the creation of a multicenter city through six new Central Activities Districts. Part of the intent was to contain the spread of Melbourne, provide alternative locations to the center of the city for work and other activity, and thus reduce much of the (energy) costs associated with transport. Employment corridors have been proposed that would link activity centers, education, research, and medical precincts, and areas with high employment.[16]

It is important to note that lower-density living, of itself, does not necessarily lead to a greater energy impost on society. If, as in the *Melbourne 2030* plans, the urban area is punctuated by local centers of business and activity, then there is every opportunity to realize a lower-energy configuration of the city. However, low-density urban forms that accommodate new residents, each of whom require more travel, will necessitate higher energy demands.

There are designs for the repopulation of the city center: several high-density residential buildings have been constructed on land that was previously inner-city docklands and the new City of Melbourne Council House and the Exhibition Centre are demonstrations of energy-conscious construction and operation of public buildings.

A key direction of current energy policy is in energy efficiency and demand management, particularly in buildings, appliances, industrial processes, and transport systems. One initiative is smart metering, whereby more information can be gathered about how much energy is used, for what purpose, and when, allowing for better targeted regulations and financial controls.

Investing in Low-Carbon or Renewable Energy Infrastructure

Decisions made decades ago about the installation of coal-fired generating capacity have locked in a dominant industry of mining and using brown coal in Victoria, which is largely defining the carbon profile of Melbourne's energy use. One response has been to prioritize research on carbon sequestration technologies, but even proponents of these recognize that it will be some decades before this can be made operational. There are, however, alternatives that have already been implemented. For example, through generating electricity from biogas at a treatment plant, Melbourne Water is able to generate 100 gigawatt-hours (GWh) for their own operations and sell another 29 GWh back to the grid.[17]

Much of the recent investment in generating plants is in the form of gas or renewable energy, and a number of electricity generators are embedded, that is, they are connected to the distribution network but supply power close to the community, business, or industrial area where they are located (ESAA 2005). Distributed power has significant advantages in energy efficiency, and there are at least 40 planned or existing distributed power projects.

The data we present on capacity factors (figure 4) show a rising trend above 0.8 for coal power, and a potential cause for concern. While there is no primary energy supply risk, the overuse of coal-fired power plants could begin to compromise maintenance schedules, and in combination with higher summer peak demands, there may be future risks to electricity supply.

Institutional and Economic Incentives

With no immediate brown coal resource constraints, institutional and economic incentives are essential for a transition to a cleaner energy source for GHG mitigation. At both the national and state levels there is financial support for solar power. Since July 2006 Victoria has had regulations requiring solar water heaters on all new houses.

Major energy companies have mandatory renewable energy targets (MRETs), which require them to provide a certain fraction of the energy they deliver from renewable sources. So far the level of MRETs have been relatively modest (approximately 5%), but the state government of Victoria currently sources 10% of its energy needs from green power, with plans to increase this to 25%, and most residents in major Australian cities have the choice of getting all their electricity from renewable sources. There is the possibility of a market-driven increase in renewable energy generation following the Australian federal government's recent implementation of carbon pricing (Garnaut 2008).

For most of the last 50 years electricity has been generated and supplied by a centralized authority. In the 1990s this was privatized and disassembled, and in the same period the National Electricity Market (NEM) was initiated. Consequently the retail market for electricity became much more fluid and heterogeneous.

This institutional disaggregation may result in genuine efficiencies from competitive energy markets, but it also means that there are fewer large players able to make the substantial investment in new coal-fired electricity generation. Even with a substantial supply of brown coal, it is possible that the structure of the electricity market will influence how much coal-fired generation will be replaced at the end of its working life compared with incremental investment in smaller, more distributed and potentially renewable electricity generation options.

Promoting Alternative Transport Modes

From the reconstructed data, it can be seen that transportation has an increasing share in Melbourne's total energy use and is the largest contributor to the energy trajectory of the city. This points to the importance of promoting alternative transport modes rather than continuing the current path of increasing use of private cars. Melbourne has retained an enviable tram system, and although this has been maintained, it has not increased commensurately with the expansion of the city. There has been an increasing commitment to cycling since 2002, and, like the long-standing mobility strategy of Copenhagen, Denmark, the city of Melbourne has developed long-term plans for making the inner city more available to pedestrians and cyclists (City of Melbourne 2007). A core feature of the transport strategies at both the inner city and metropolitan levels is one of improving networking: enabling people to use the various modes of the public transport system more easily and efficiently.

The urban form of Melbourne has transport and therefore energy consequences, and the current urban area, defined by the stock of dwellings, buildings, and roads will be around for many decades to come. Over the next 20 years the city may well see the impact of peak oil on personal mobility, but to retain the vitality and function of the city it may be the case that more public transport, intelligent networking, and active personal transport will be required.

Concluding Remarks

We have modeled and presented data concerning the long-term energy history of Melbourne. This is useful both to observe long-term changes in urban metabolism and as a companion to the socioeconomic history of the city.

The data scaling procedures we have used are in common with other published methods (Baynes et al. 2011a; Niza et al. 2009), but we advance these by applying them to time series data, reconstructing the past energy metabolism of a city from more common data at the regional or state level. The approach is limited by the raw time series data available and the veracity of assumptions used to scale the data. For example, residential data are scaled by population, but perhaps a more nuanced and accurate scaling would use additional data on the energy intensity characteristics of urban and nonurban dwellings. We have also calculated primary energy consumption based on direct and upstream energy use that also extends urban metabolism approaches to energy accounting.

From our estimations, Melbourne's annual primary energy consumption has increased from 260 PJ to 970 PJ in a little over four decades. We suggest this is driven directly by increases in the size of the total population (83%) and the mobility and energy intensive lifestyle of Melbourne's inhabitants. These are represented by increases in transport (79% since 1974) and residential (96% since 1974) energy requirements and corroborated by nonenergy data on appliance ownership, VKT, and increases in house size and urban area. The manufacturing sector remains a significant energy user, but the commercial sector has contributed a similar absolute amount to the total change in energy consumption while expanding its energy consumption relatively more than any other sector (195% since 1974). This concurs with a transition in employment from secondary to tertiary industries, although Melbourne retains some legacy of an industrial past. A formal approach, such as index composition analysis, would provide a more rigorous basis for quantifying these relations.

The energy future of Melbourne is dependent on a number of intersecting factors, including population, urban lifestyle, urban form, and current and alternative energy supplies. Efforts at reducing the energy and carbon intensity of Melbourne in the near to medium term will be mitigated by legacies of past energy supply infrastructure choices and of the increasingly affluent urban lifestyle to which citizens have become accustomed. At the metropolitan level, there is the opportunity to depress the trajectories of increasing energy consumption and realize a lower-carbon city through strategies that include energy-conscious urban planning, investment in renewable or low-carbon electricity generation, encouraging active and public transport, and, at a national level, imposing a cost to carbon.

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Notes

1. MFA may also refer to material flow analysis.
2. This derives from COMTRADE data that precedes Singapore's transition to an independent state in 1965.
3. According to page 23 of ICLEI's *International Local Government GHG Emissions Analysis Protocol* (IEAP) version 1.0 (October 2009), including transmission and losses is classified as scope 3.
4. The Victorian electricity grid connects to other Australian states and in our study period, Victoria has always been self-sufficient or an exporter of electricity.
5. One kilometer (km, SI) ≈ 0.621 miles (mi).
6. One petajoule (PJ) = 10^{15} joules (J, SI) ≈ 9.48×10^{11} British thermal units (BTU).
7. The figures for population density are quoted directly from page 1.3 of the Melbourne Atlas 2006 (DPCD 2007), which uses an area defined by statistical division boundaries. On page 1.5 of the same publication, the drop in density is reported as from 20.3 persons per hectare (p/ha) in 1961 to 13.7 p/h in 1996 using urban area as defined in Kenworthy and colleagues (1999). Analyses using other definitions of urban area might produce different numbers, but the fact of a significant decrease in population density remains. One hectare (ha) = 0.01 square kilometers (km^2, SI) ≈ 0.00386 square miles ≈ 2.47 acres.
8. The boundary definition of Melbourne has been enlarged since 1961, but the calculation of this density excludes the rural areas of Hume and the Yarra Valley currently contained within the Melbourne statistical division.
9. One megawatt (MW) = 10^6 watts (W, SI) = 1 megajoule/second (MJ/s) ≈ 56.91×10^3 British thermal units (BTU)/minute.
10. About 10 km southwest of Melbourne's central business district (CBD) a 500 MW gas-fired plant has operated since 1981, providing peak load electricity.
11. One megatonne (Mt) = 10^6 tonnes (t) = one teragram (Tg, SI) ≈ 1.102×10^6 short tons.
12. Calculated assuming 1 barrel of oil equivalent (BOE) equals approximately 6.1 GJ.
13. Values are mostly estimates, as the actual energy inputs and outputs regarding the petroleum industry are confidential and only reported at the national level.
14. Petroleum products are distributed nationally and Australia is a net importer of oil. It is entirely possible that there is some imported component to transport fuel sales in Melbourne, although that fraction will depend on global demand and supply and currency exchange rates.
15. This is not an exhaustive list. There are, for example, important and more complex connections between food production, food supply, and energy (Larsen et al. 2008), and between modes of water supply and energy (Kenway et al. 2008).
16. Following public scrutiny the policy has been revised; the UGB has been compromised to accommodate 284,000 new dwellings to maintain housing affordability. Some plans for activity areas have met with resistance from residents who do not want to see such development in their area.
17. www.melbournewater.com.au/content/sewerage/western_treatment_plant/western_treatment_plant.asp

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Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information provides additional information on historical energy use trends, particularly for electricity use, and expands on the factors employed to scale higher-level data to produce the time series for Melbourne. Energy accounts for Victoria and Melbourne in 2005 are also presented.