9

Drivers of urban energy use and main policy leverages

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9.1 Introduction

This section synthesizes existing knowledge of the main drivers of urban energy use and related policy considerations. Traditionally, comparisons and analyses of energy use and the drivers of differences are carried out at the national level. In comparison, research on the factors that determine urban energy use is still in its early stages, severely hampered by the limited availability of comparable city-level data.

Keeping the above caveats in mind, the factors that determine urban energy use can be classified into a few major groups: *natural environment* (geographic location, climate, and resource endowments), *socioeconomic characteristics* of a city (household characteristics, economic structure and dynamics, demography), *national/international urban function and integration* (i.e., the specific roles different cities play in the national and global division of labor, from production and a consumption perspectives), *urban energy systems characteristics including governance and access* (i.e., the structure and governance of the urban energy supply system and its characteristics), and last, but certainly not least, *urban form* (including the built urban environment, transportation infrastructure, and density and functional integration or separation of urban activities).

These factors do not work in isolation, but rather are linked and exhibit feedback behavior, which prohibits simple linear relations with aggregated energy use. The interaction between the driving factors may change from city to city – moreover, many of the factors are dynamic and path dependent, i.e., are contingent on historical development. There is, however, one factor that underpins all these determinants in a complex and nondeterministic way: the *history* of a city. The location of a city and the initial layout of its urban form are determined historically: witness the difference between sprawling North American cities that developed in the age of the automobile and older, compact European cities that developed their cores in the Middle Ages. Likewise, the economic activities of a city often stem from historical functions, whether as a major harbor, like Cape Town and Rotterdam, an industrial center, like Beijing now and Manchester historically, or a market and exchange center, like London, New York, and Singapore. These historical legacies may have long-term implications on urban energy use. However, there are also cases in which relatively rapid changes in the historical layout and/or the economic role of a city occur. This can be the result of war, natural disasters, or rapid socioeconomic transitions, such as industrialization or deindustrialization. Examples are Tokyo after World War II, Beijing in the past decade as transformed by China's accelerated transition from an agrarian to an industrial society, or many Eastern European cities after the fall of the Iron Curtain in 1989 and the subsequent economic restructuring from a centrally planned toward a market economy.

9.2 Geography, climate, and resource endowments

Climate is an important factor in determining final energy use, especially for heating and cooling demands. Its influence on energy use can be measured through the metrics of heating and cooling degree days, which, in combination with the thermal quality of buildings and settings for indoor temperature, determine energy use. Urban energy demand is, in principle, not markedly different in its climate dependence than that in nonurban settings or national averages, but it is structured by the influence of other variables, such as urban form (e.g., higher settlement densities lead to smaller per capita residential floor areas), access to specific heating fuels, or income (e.g., more affluent urban households use more air conditioning), that can amplify or dampen the effect of climate variations on urban energy demand.

National studies illustrate the quantitative impact of climate variables on energy demand. For example, Schipper (2004) reports differences in space-heating energy use (measured as useful energy) normalized to heating degree days and square meters living space for seven industrial countries. This analysis reveals substantial ranges from 50 kJ/m^2/degree-day for Australia to 250 kJ/m^2/degree-day for the United States in the early 1970s, and from 60 (Australia) to 160 kJ/m^2/degree-day for Germany in the mid-1990s. Assuming a residential floor space of 100 m^2, a difference of 1500 heating degree-days, which is characteristic between northern (Denmark) and southern (Greece) Europe, translates into a variation in residential energy demand between 9 and 24 GJ, which is significant compared to a typical European household residential energy use of some 60 GJ, but nonetheless only constitutes between 9 percent and 24 percent of the typical 100 GJ/capita Western European total urban final energy use. Conversely, little is known on the differences in the demand for thermal comfort as reflected in ambient indoor temperatures. A case study carried out for Metro Manila indicated that people in the highest income brackets have much lower indoor room temperature setting preferences, which leads to an increased air-conditioning demand (Sahakian and Steinberger 2010).

The relationship between climate and urban energy use is a two-way street: climate not only influences urban energy demand, but urban areas also influence their local climate through the 'urban heat island' effect (see Chapter 7). This effect can reduce the heat demand during winter, but also enhance the need for cooling in the summer, especially in warm and humid climates. Studies show increases in the summer time cooling load in tropical and midlatitude cities (Dhakal et al, 2003). A series of studies on California show that a 0.5°C increase in temperature causes a 1.5–3 percent increase in peak electricity demand (Akbari et al. 1997).

To a certain extent cities inherit the resource dependencies of their respective countries, which explains, for instance, the continued use of coal in urban areas in countries endowed with large coal resources. The connection to national energy systems and their dependence on the resource base is especially pronounced for power generation, since cities often draw electricity from the national grid. In some cases, urban power plants are designed to use local resources, such as hydropower, geothermal, or wastes, but these potential resources are usually extremely limited in urban areas and provide only a small contribution to the high energy demand associated with high urban population and income densities. On the distribution and end-use side, district heating and cooling infrastructures, which allow reaping of scale and scope economies, cogeneration, and energy-efficient 'cascading' schemes, are specific urban-efficiency assets, but only economically possible when the density of demand is above a threshold that warrants the investment.

9.3 Socioeconomic characteristics

The positive correlation between income and (final) energy use is long established in the traditional energy literature, especially for analyses at the national level. For the household level, correlations between income and energy use have been shown for the Netherlands (Vringer and Blok 1995), India (Pachauri and Spreng 2002), Brazilian cities (Cohen et al. 2005), Denmark (Wier et al. 2001), and Japan (Lenzen et al. 2006), with similar results for GHG emissions in Australia (Dey et al. 2007) and CO_2 emissions in the United States (Weber and Matthews 2008). For Sydney, Lenzen et al. (2004) showed that urban household energy increases with household expenditure, and that most of this increase results from the energy embodied by goods and services, since direct final energy use, in contrast, increases only slowly with expenditure (albeit from high baseline levels).

Based on a production approach, urban per capita energy use is very often lower than nonurban energy use or the national average, particularly for postindustrial, service-sector oriented cities in the OECD countries (see Chapter 5; Brown et al. 2008; Parshall et al. 2010).

Figures 9.1 and 9.2 show the urban income–energy relationship from a production perspective. The GRP/resident is plotted in a cross-sectional analysis against energy use for a sample of Chinese cities (Figure 9.1). Figure 9.2 complements the Chinese cross-sectional analysis by a longitudinal analysis for six megacities. For both cases, income and energy increase together, albeit along distinctly different trajectories, which illustrates *path dependency*. Income is therefore far from the sole determinant of the level of energy use: for instance, Beijing and Shanghai have a higher average energy use than Tokyo, despite a lower per capita income.

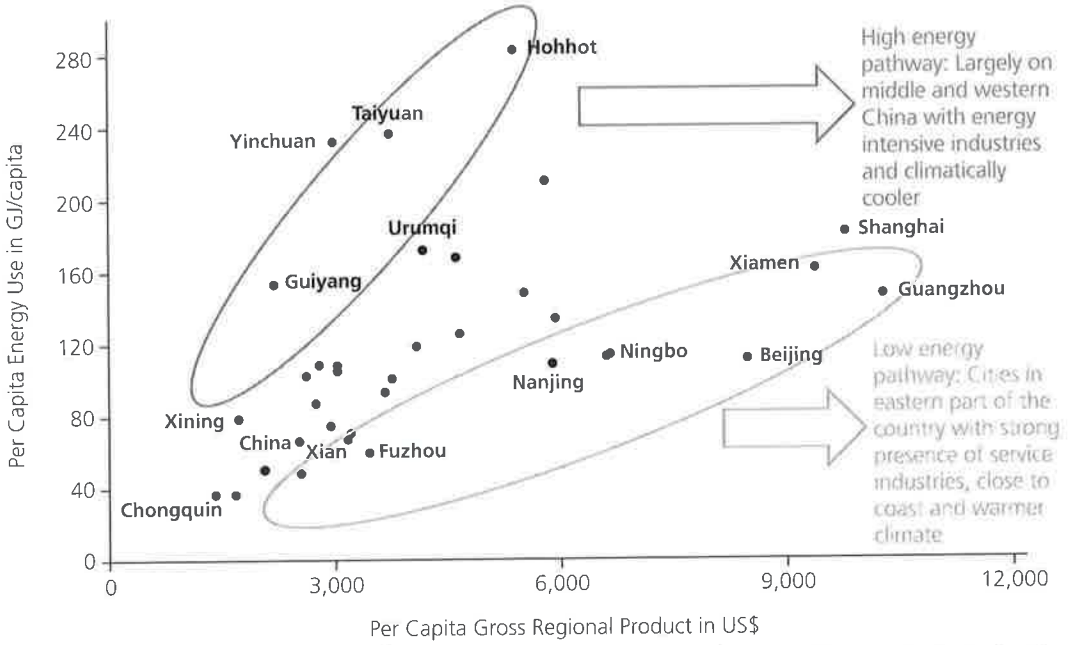


Figure 9.1 Per capita energy use (GJ/capita) versus income for a sample of Chinese cities for 2006, illustrating path dependency

Source: Dhakal (2009) (per capita GRP is expressed in US$2006 calculated using market exchange rates (MER))

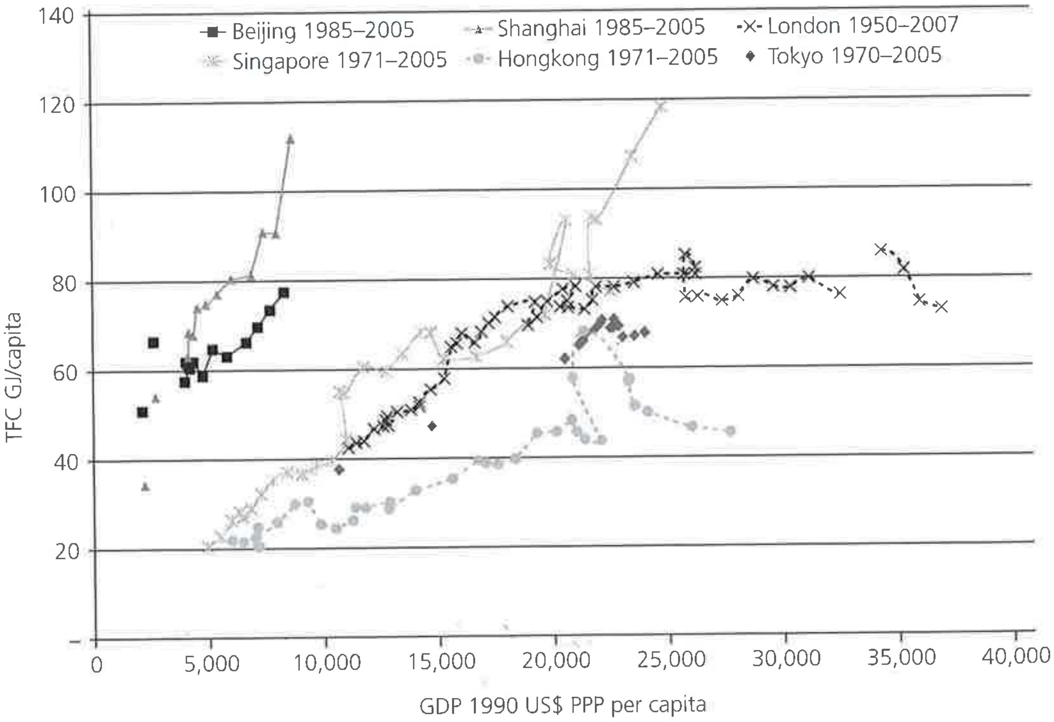


Figure 9.2 Longitudinal trends in final energy (GJ) versus income (at PPP, in Int.$ 1990)[1] per capita for six megacities. Note the path-dependent behavior

Source: Schulz (2010b)

In addition to income, demographic factors play a role in determining urban energy use (Liu et al. 2003; O'Neill et al. 2010). For instance, studies suggest that household size, that is, the number of people living in one household, plays a role in energy use: above two people per household, economies of scale can reduce the energy use per capita. This phenomenon is observed in India (Pachauri 2004), Sydney (Lenzen et al. 2004), the United States (Weber and Matthews 2008), and Denmark and Brazil (Lenzen et al. 2006). In Japan, in contrast, larger household sizes correlate with slightly larger energy use (Lenzen et al. 2006). Urban populations often have significantly smaller household sizes than rural populations because of smaller families and a larger generation gap, as well as smaller dwellings, and so shelter for extended families or many generations under the same roof is less likely.

The evidence for age dependence is mixed. In Sydney, increasing age is correlated with a citizen's higher residential, but lower transportation energy use (Lenzen et al. 2004). Larivière and Lafrance (1999) found a positive correlation between residential electricity use with age for Canadian cities. At this point, not enough is known regarding the influence of age to make any general statement, much less predictions, applicable to cities with very diverse age pyramids that range from young and growing, to old and declining populations.

9.4 Role of the city in the national or global economy

A city's function in regional, national, and international economies has a strong bearing on its energy signature when measured from a production perspective. In the extreme case of Singapore (Box 9.1), a major center for oil-refining and petrochemical production and a major international transport hub, the energy use associated with international trade in oil products, shipping, and air transport (usually subsumed[2] under 'apparent consumption' of the city's primary energy use) is four times larger than the direct primary energy use of Singapore and more than eight times larger than the final energy use of the city.

That urban areas are usually in an intense process of energy exchange (imported and exported) with surrounding markets is again shown dramatically in Figure 9.4 for Tokyo in terms of CO_2 emissions. Emissions attributable to the direct and indirect energy and resource uses of Tokyo ('inflows') are balanced with the final consumption categories of these inputs as well as exports ('outflows'). Embodied energy and emission flows have gained increasing importance, comprising some 80 percent of Tokyo's 'inflows' and still slightly half of its 'outflows,' which illustrates Tokyo's embeddedness in the global economy. The Tokyo example also indicates the importance of energy and emissions embodied in maintaining and expanding the physical infrastructures and capital goods (reported under capital formation in Figure 9.4). Generally, private households only account for a small fraction of total capital formation (dominated by government, industry, and commerce). A consumption-based accounting that only uses

Box 9.1 Singapore: the importance of trade[3]

The case of Singapore illustrates the intricacies of energy (and emissions) accounting in trade-oriented cities that import primary energy, such as crude oil, re-export processed energy (fuels), energy-intensive products (petrochemicals), refuel ships and aircraft (bunker fuels), and import and export numerous other products and services that all 'embody' energy (see Figure 9.3). In terms of energy or CO_2-emission accounting, this extreme example amply illustrates the limitations of applying current inventory methodologies developed for national applications to the extremely open economies of cities. New, internationally agreed accounting standards are needed, as otherwise the risk of either misinforming policy or drawing arbitrary system boundaries is significant. There is a risk of 'defining away' energy use and emissions (e.g., international bunker fuels for aircraft and ships) associated with the inherent functioning of spatially defined entities (cities, city states, even small national open economies) whose interdependencies and energy/emissions integration into the international economy provide for their very *raison d'être* and therefore need to be included in energy and GHG emission inventories.

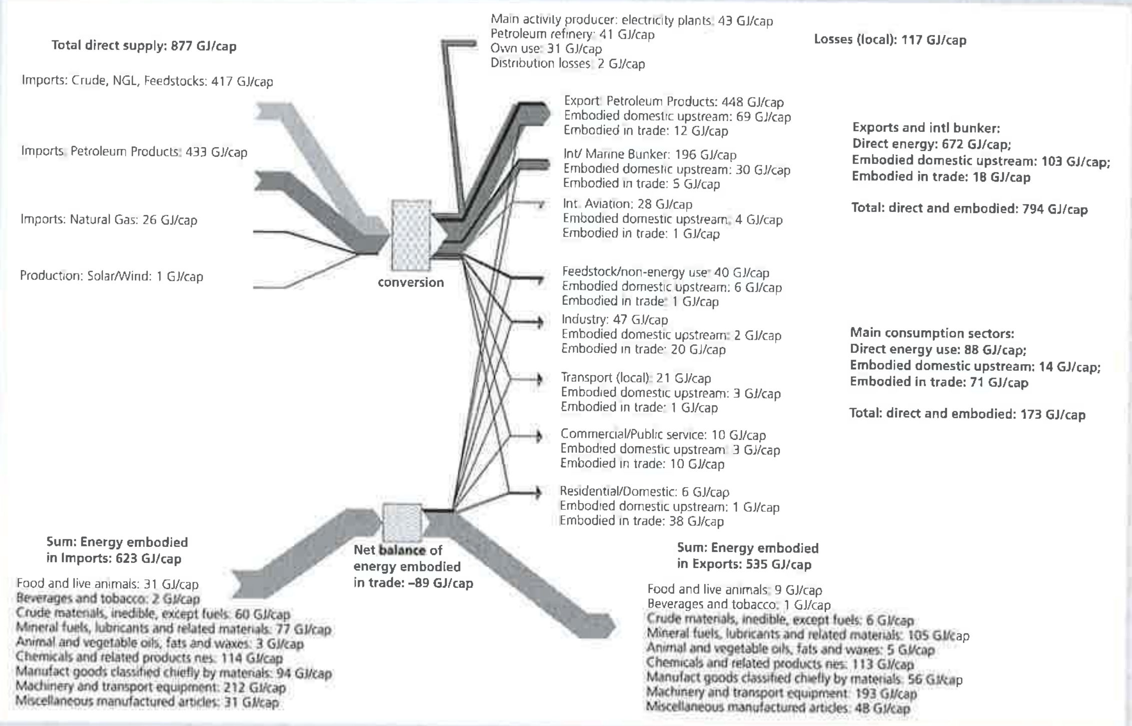


Figure 9.3 Full per capita energy accounting for both direct and embodied energy flows of a large urban trade city, Singapore (in GJ/capita). Domestic direct and embodied energy use is 173 GJ/capita, but is dwarfed by the total energy imports to the city of 1490 GJ/capita. Total energy re-exports (direct and embodied) are 1225 GJ/capita

Source: Schulz (2007, 2010a)

household expenditures (as frequently done) therefore misses these important embodied energy and emission flows.

The thirty-five largest cities in China (China's key industrialization and economic drivers) are responsible for 40 percent of the nation's GDP and contribute overproportionally to national commercial energy use (Dhakal 2009). Cities often specialize in certain types of manufacturing, commercial, or administrative functions. Some urban areas are also large transport hubs, such as London for air transit, or

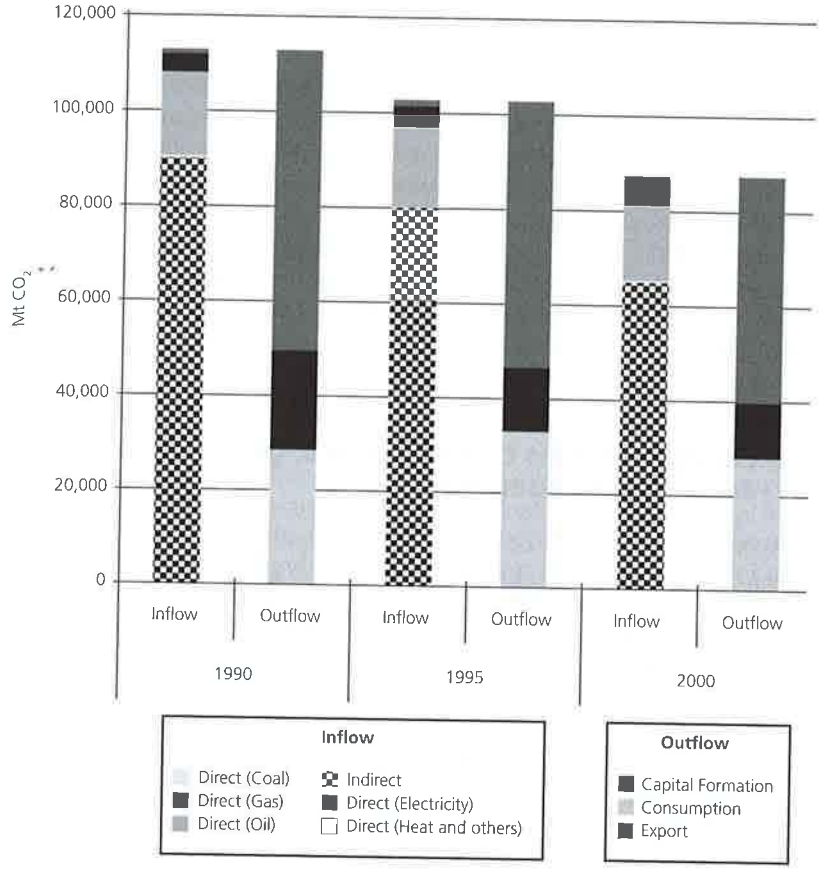


Figure 9.4 CO$_2$ balance of Tokyo 1990, 1995, and 2000 using I-O analyses, in million tons CO$_2$
Source: Draft estimates by Shinji Kaneko and Shobhakar Dhakal (2012)

Cape Town and Rotterdam for shipping, that adds significantly to urban energy use, and is too often omitted from urban energy and GHG accounts. For instance, London's twin functions as a major international airport hub and as a global city result in an energy use from air transport that corresponds to one-third of London's total (direct) final energy use (Mayor of London 2004).

A service-based economy can generate the same income with less energy than an economy based on the production of goods, which is one reason city per capita energy use in advanced, service-oriented economies is lower than national averages. This is also why Shanghai and Beijing have higher energy use per capita than Tokyo (see Figure 9.2 above), despite their lower GDP/capita.

If the economic activities located within a city determine its local energy use, its economic transactions with other areas entail energy use in those areas. Any product or service bought or sold entails energy use, and for service-oriented cities it may well be that the energy used, indirectly, through their economic transactions is larger than the energy used locally by their services industry. This phenomenon was shown at the level of urban household expenditures: rich households consume more energy indirectly than they do on housing, utilities, and local transit (Lenzen et al. 2004).

In addition to economic globalization, cultural globalization encourages urban upper and middle classes to adopt consumption patterns from global elites. Globalization-influenced urban development tends to favor private automobile-based individual transport modes and suburban sprawl for those who can afford it. Foreign direct investments (FDIs) and trade agreements affect the location and technology of manufacturing and commercial activities and labor reorganization (Romero Lankao et al. 2005). In China, individual cities compete with each other to attract FDIs and compromise their local environmental conditions and tax policies (Dhakal and Schipper 2005). This type of intra-national competition also occurs in other countries, such as Vietnam and India.

9.5 Energy systems characteristics: governance, access, and cogeneration

The organization of energy markets and their controls at the urban level also influence urban energy use. Alternative organizational forms, such as state or municipal monopolies, cartels, or free-markets, impact access, affordability, and the possibility of implementing energy-saving policies. Localized energy monopolies may work closely with urban governments to further local policies, whereas free-market structures often challenge the enactment of environmental or social policies, such as renewable mandates, or the possibility of performance contracting. New York City requires (because of energy security and reliability concerns) 80 percent of electricity-generating capacity to be located within its territory; this means that the ability to influence the energy system is different to that in other cases. Vienna city owns its respective electricity, gas, and district-heating utility companies, and thus may have greater influence compared to cities with completely privatized and deregulated utilities. In Chinese cities, where energy companies are state-owned enterprises, the city government policies can exert strong influence on the suppliers, albeit less on the energy demand side. Many industrialized cities have put in place City Climate Actions Plans, which are expected to reduce or dampen energy use or promote shifts to renewables in the coming decades, but their success will depend on the links between city government and local energy providers. In many cities across the world, the local government is hardly able to influence the energy-supply side (because of jurisdictional and capacity limits), but may be in a position to address demand-side energy issues.

In developing countries, urban populations generally have higher levels of access to commercial energy forms than rural populations. This affects the efficiency and the intensity of the environmental impacts of energy use (Pachauri 2004; Pachauri and Jiang 2008): rural populations consume (often self-collected) fuels such as fuel wood, biomass, and coal; urban populations consume commercial and cleaner energy forms: electricity, oil, and gas. Owing to the low level of efficiency of biomass use, the quantity of primary energy use per capita may be similar in urban and rural settings (Pachauri and Jiang 2008), but the different fuel structure in urban, higher income settings provides for much higher levels of energy service provision. In this sense, urban populations benefit from the high efficiency of energy-service delivery of modern fuels and distribution systems, such as electricity, gas, or bottled LPG. Access to commercial energy is much less an issue in industrialized or industrializing countries, which already have electrification levels at 100 percent (IEA 2002) and where gas-distribution networks connect a majority of urban households.

Many European countries also have a long tradition of urban district heating (and more recently of district cooling) networks that either use district heating plants or CHP energy systems. CHPs, in particular, offer potential energy-efficiency gains as waste heat from electricity generation can be used for low- and medium-temperature heat demands in urban areas, with steam-driven chillers that also provide cooling energy. Traditionally, such centralized systems are capital intensive and only economic in higher density urban settings that provide for sufficiently high demand loads to warrant the investments. The recent advance in more decentralized energy solutions, including microgrids, allows such systems to be extended to lower density urban settings. Typically, cities with significant energy cogeneration have primary energy needs that can be 10–20 percent lower compared to systems in which all heat demands are provided by separate, individual boilers or furnaces.

A key issue for the improved efficiency of urban energy systems is therefore an optimal matching between the various energy-demand categories and forms to energy-conversion processes and flows, usually achieved by exergy analysis (see Box 9.2).

Box 9.2 Urban exergy analysis: efficiency – how far to go?[4]

An analysis of the efficiency of urban energy systems is far from a trivial task, but it is fundamental to identify options and priorities for improved efficiency in energy use. With respect to the system boundaries of the analysis, should the analysis extend to final energy (the usual level of market transactions in the energy field), to the level of useful energy, or to energy services? Should only simply energy outputs–inputs relationships be considered in defining efficiency (referred to as first law analysis in the literature, after the first law of thermodynamics) or the analysis be extended to consider quality differences in energy forms (which energy form is most adequate for delivering a particular task) and efficiency, not in absolute terms (as in first law analysis), but in relation to what thermodynamically represents an upper bound of energy conversion efficiency (as no conversion process that operates under real-world conditions can achieve 100 percent efficiency)? The latter concept is referred to in the literature as second law (after the second law of thermodynamics), or *exergy* analysis (e.g., Rosen 1992).

The literature (e.g., Nakicenovic et al. 1990; Gilli et al. 1995) identifies the value of both types of analyses (first and second law analysis), but also concludes that second law analysis enables us to extend the system boundaries to include also energy *service efficiency* (which cannot be captured in first law analysis as it lacks a common energy denominator) and important quality characteristics of different energy forms and their adequacy to deliver a particular energy service. Therefore, an illustration of the value of exergy analysis to assess the efficiency of urban energy systems is provided here using the example of Vienna, which is compared to a few fast-track European urban-exergy analyses obtained from various research groups.

The energy system of the city of Vienna is characterized by a number of unique features. First is that the city generates much of its electricity needs within the city itself allowing the use of resulting waste heat through a district-heating network (recently also extended to a district-cooling network). As a result, the corresponding first law efficiencies of Vienna's energy system are very high: 85 percent of secondary energy is delivered as final energy and about 50 percent can be used as useful energy to provide the energy service needs of the city (see Figure 9.5). The impact of cogeneration on the city's energy needs is also noticeable: without cogeneration Vienna's secondary energy use would be some 13 percent higher. The high first law efficiencies suggest limited improvement potentials. However, this is not the case as revealed by a second law analysis of Vienna's energy system, which shows the efficiency between secondary and useful exergy is only some 17 percent. This suggests significant improvement potentials, for example via heat-cascading schemes that better match the exergetic quality of energy carriers with the required temperature regime of energy end-uses.

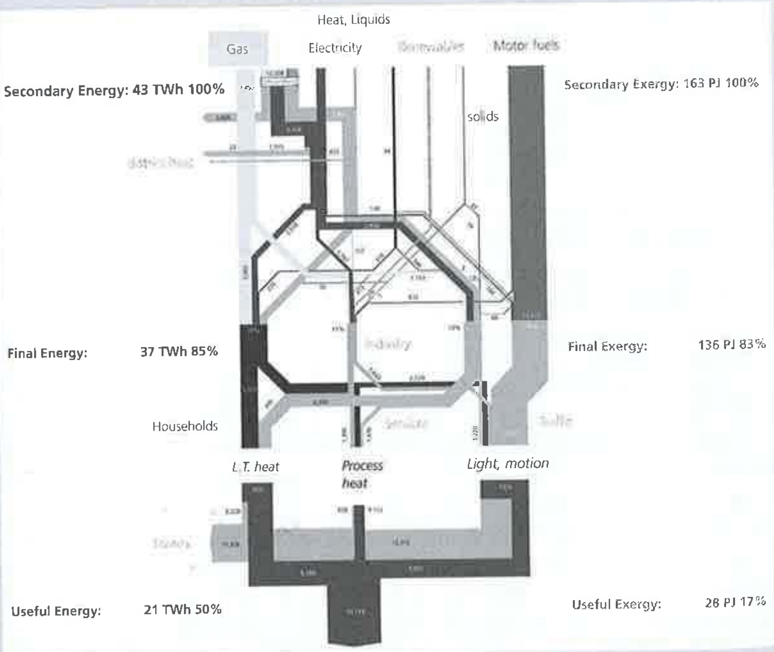
This assessment obtained the results of similar exergy analyses for Geneva, Switzerland (Giradin and Favrat 2010), the Swedish city of Malmo, and London (Fisk 2010). The results of the comparison in terms of the efficiency of useful exergy to that of secondary and primary exergy are summarized in Table 9.1.

Table 9.1 Comparison of the efficiency of useful exergy to that of secondary and primary exergy

	Useful exergy as % of:	
	secondary	primary
Geneva (CH)	23.2	15.5
Vienna (A)	17.2	
Malmö (S)	21.2	12.7
London (UK)	11.3	6.2
trad. Mexican village	5.7	

The results confirm earlier conclusions that, thermodynamically, urban energy systems could, in theory, be improved vastly, perhaps by as much as a factor of 20 (a similar order of magnitude as suggested by Nakicenovic et al. (1990) for OECD countries), and thus leave ample opportunity to realize feasible measures under real-world conditions and constraints that might deliver an improvement by at least a factor of 2. That modern urban energy systems are – despite their comparatively low exergy efficiencies – vastly more efficient (by a factor of 2–4) than traditional rural energy systems is also shown in the Masera and Dutt (1991) analysis of a traditional Mexican village with 2,400 inhabitants using mostly preindustrial energy forms and conversion technologies (draft animals and fuelwood) for the provision of their energy services yielding an exergetic efficiency of only some 6 percent, compared to 11–23 percent for modern urban energy systems and uses.

Figure 9.5 Energy and exergy flows in the City of Vienna in 2007 between secondary and useful energy/exergy. (See color plate 11)
Sources: Energie Wien (2009) (approximate) exergy efficiencies based on Gilli et al. (1996)



9.6 The urban form: the built urban environment and its functions[5]

9.6.1 The built environment

The built urban environment comprises the totality of the urban building stock: residential, commercial, administrative, and industrial buildings, their thermal quality and spatial distribution. It also includes built urban infrastructures for transport, energy, water, and sewage. This environment is one of the key components for understanding the special characteristics of urban energy use as compared to rural, economy-wide, or global patterns. The unique concentration and overall scale of the built urban environment allow both economies of scale and economies of scope to occur, and thus provide options for energy-efficiency gains.

9.6.1.1 Building design

The design and thermal integrity (e.g., insulation levels) of buildings are essential for the amount of energy intensity (energy/m^2) needed for heating and cooling. Reducing the energy associated with heating has been a strong focus in northern European countries, but mid-latitude countries have to attempt a design a balance between heating and cooling energy demands. In many cases, newer buildings have better thermal standards, but in some cases they are poorly adapted to their climate (e.g., European- and US-style villas and apartment buildings in tropical climates, which do not have adequate shade and ventilation). Old buildings may suffer from lack of renovations, or renovations that do not apply the best possible standards. The influence of building technology on the energy used for space heating is huge: a Passivhaus standard requires that energy use for space heating be no more than 15 kWh/m^2 floor area per year; for low-energy houses the corresponding number is around 50 kWh/m^2/yr, whereas poor thermal insulation may cause energy use for space heating of 200–400 kWh/m^2/yr in mid-European latitudes.[6]

The energy involved in the maintenance and replacement of components over a building's life should also be taken into account in assessing the energy performance of a building. For a 50+ year lifetime of office buildings, the embodied energy in construction materials plus the energy needed for decommissioning is estimated to range from 2.5 to 5 years of the building's lifetime operational energy use (Cole and Kernan 1996; Scheuer et al. 2003; Treberspurg 2005), with a typical value of embodied energy being between 5 percent and 10 percent of direct, operational energy needs of buildings. Including single and multifamily houses somewhat expands this range. The detailed literature review of Sartori and Hestnes (2007) reports a range from 4 to 15 percent embodied energy in total lifecycle energy use of buildings. Only in extremely low energy-use buildings (e.g., Passivhaus-standard or even below), with their extremely low operational energy use, does embodied energy play a somewhat greater role, reaching between 25 percent (Sartori and Hestnes 2007) and 29 percent (Treberspurg 2005): typical values of 20–30 kWh/m^2 building floor area/year of embodied energy compare to 50–60 kWh/m^2 building floor area/year for operational energy (heating plus electricity).

9.6.1.2 Type of buildings and uses

Next to the energy characteristics of an individual building, also the mix of building types and their density are important determinants of urban energy use.

The specificities of the urban built environment are usually a large existing stock, which requires renovation and maintenance, and new buildings in growing cities. The improvement in building stock to lower heating and cooling demands is counterbalanced by the increase in surfaces necessary to house new populations in growing cities, along with the demand of inhabitants for larger and larger apartments – even as the average household size decreases. Residential floor space per capita is known to be strongly correlated with income (e.g. Schipper 2004; Hu et al. 2010). National averages in industrial countries range from 30 m^2/person in Japan to 50 in Canada, 55 in Norway, and 80 in the United States (Schipper 2004; US DOE 2005). Typically, urban residential floor space per capita is lower than the national averages (to a degree counterbalanced by smaller household size), particularly for high-density cities with their corresponding high land and dwelling prices, but comprehensive statistics are lacking. For urban China, Hu et al. (2010) estimate 5 m^2/person in 1990 and approximately 25 m^2/person in 2007.

Newton et al. (2000) evaluated and modeled the energy performance of two 'typical' dwelling types – detached houses and apartments – across a range of climatic zones in Australia. Two main conclusions were drawn: (1) annual heating and cooling energy and embodied energy per unit area were similar for apartments and detached houses; (2) per person, however, the lifecycle energy use of apartments was significantly less (10–30 percent) than that of detached houses in all circumstances, because the area occupied per person was much less. Norman et al. (2006) used a lifecycle analysis approach to assess residential energy use and GHG emissions, contrasting 'typical' inner-urban, high-density and outer-urban, low-density residential developments in Toronto. They found that that the energy embodied in the buildings themselves was 1.5 times higher in low-density areas than that in high-density areas on a per capita basis, but was 1.25 times higher in high-density areas than that in low-density areas on a per unit living area basis. Salat and Morterol (2006) compared eighteenth-century, nineteenth-century, and modernist urban areas in Paris, assessing five factors in relation to CO$_2$ emissions for heating: (1) the efficiency of urban form in relation to compactness; (2) a building's envelope performance; (3) heating equipment type, age, and efficiency; (4) inhabitant behavior; and (5) type of energy used. Salat and Morterol (2006) asserted that an efficiency improvement factor of up to 20 could be achieved from the worst-performing to the best-performing urban morphology by taking these five factors into account. Salat and Guesne (2008) investigated a greater range of morphologies in Paris and found that when considering heating energy, the less dense the area, the greater the energy required for heating (see also Ratti et al. 2005).

9.6.2 Urban form and functions

Urbanization patterns affect the extent and location of urban activities and impact the accompanying choice of infrastructures. Newton et al. (2000) summarized key alternative urban forms or 'archetypal urban geometries,' namely the dispersed city, the compact city, the edge city, the corridor city, and the fringe city. The merits of dispersed and compact cities ('suburban spread' versus 'urban densification') have been debated since the 19th century and a strong divide exists between the 'decentrist' (the dispersed city model) and 'centrist' (the compact city model) advocates (Brehny 1986).

Nonetheless, one the most important characteristic of cities is density. Overall, a certain density threshold is the most important necessary (although not sufficient) condition to allow efficient and economically viable public transit (see Chapter 10). In addition, in a dense environment distribution networks are shorter, infrastructure is more compact, and district-heating and -cooling systems become feasible. Unconventional energy sources, such as sewage and waste heat, are also more accessible. High density may thus help curb urban energy use (Rickaby 1991; Banister 1992; Ewing and Cervero 2001; Holden and Norland 2005).

Most importantly, a compact city brings the location of urban activities closer. In the context of transportation, from cross-city comparisons it is well established that higher urban densities are associated with less automobile dependency and thus less transport energy demand per capita (Newman and Kenworthy 1989; Kenworthy and Newman 1990; Newman and Kenworthy 1991; Brown et al. 2008; Kennedy et al. 2009). Intra-city studies for Sydney (Lenzen et al. 2004), Toronto (VandeWeghe and Kennedy 2007), and New Jersey (Andrews 2008) also show that denser neighborhoods have lower per capita transportation energy needs. As a result, in many low-density cities, per capita energy use has grown at approximately the same rate as that in sub-urban areas (sprawl) (Baynes and Bai 2009).

In many of the less-compact cities, transportation[7] by automobile is the biggest contributor to energy use (Newman and Kenworthy 1999). The data suggest that cities with a density of 30–40 people/ha or greater developed a less automobile-based urban transport system with typical density thresholds for viable public transport systems given as above 50–100 people/ha (see Chapter 10). On average, residents who live at a distance of 15 km from an urban center use more than twice the transport energy compared to residents living 5 km from the center (Stead and Williams 2000). Nijkamp and Rienstra (1996) note that the private automobile has brought low-density living within the reach of large groups of upper and lower middle-class families. Moreover, correlations between automobile ownership and income suggest that more affluent automobile owners have a higher propensity to travel longer distances by energy-consumptive modes (Banister et al. 1997).

Diversity of function may also play a role in managing urban transport demand (Cervero and Kockelman 1997). When strict zoning is enforced so that residential areas are separated from commercial, education, services, and work areas, private transportation is maximized. Mixed land uses and concepts of self-containment are important in reducing energy use in transport. Nevertheless, local jobs and local facilities must be suitable for local residents, otherwise long-distance, energy-intensive movements will continue (Banister et al. 1997). This coordination of land-use and transportation policies is termed transit-oriented development. The idea of location efficiency emphasizes the accessibility of opportunities, rather than how mobile one must be to find them (Doi et al. 2008); this is a central concept in recent approaches to transit-oriented development and other forms of sustainable urban development.

Also, urban density is an indicator of *potential* energy savings, especially in transportation. If infrastructure is inadequate to support the volume of traffic flow, the resulting congestion can lead to higher energy use, even in high-density, built-up areas. For energy efficiency potentials of urban densities to be realized, a chain of interdependent, appropriate infrastructure, technical, and consumption decisions must be made. The correct level of public transit infrastructure requires large up-front investment and maintenance, from light rail to subways, trams, or dedicated bus routes. Adopting public transit also requires appropriate consumer behavior. In many North American cities, public transit is associated with lower economic status, and thus avoided by most people who can afford to drive, which reinforces the initial perception. A contrary example is Tokyo where the per capita energy use is smaller than in many East Asian megacities; one of the key reasons for this is the efficient rail-based public transport in Tokyo (Dhakal 2004, 2009).

Another important energy implication of the urban form is the choice of urban energy-supply systems. District-heating and -cooling infrastructures, which allow large economies of scale and efficiency gains through cogeneration, are only possible when the density of demand is high enough to warrant the capital-intensive investment, unless such systems are mandated (and costs added to land prices). Compact urban form may also play a role in the energy used for buildings. Apartment buildings generate economies of scale compared to single-family homes, but apartment buildings may compromise decentralized low-energy design practices, such as natural lighting, ventilation, and decentralized use of PVs. Another important influence of density is at the personal consumption level. Apartment size per person tends to decrease with population density (with Hong Kong and Manhattan representing extreme examples). Effectively, the high competition for central urban space creates rents that contract floor space. However, in cities without sufficient low-rental housing, even the smallest apartments can be out of reach for the poorer populations, who are forced to live in distant suburbs with poor transit connections. In many cities, suburbanization is also caused by industrial relocation from urban cores and the unplanned settlement of migrants and urban poor in the urban periphery.

More compact cities, however, may require special management to avoid the ill-effects of congestion and higher concentrations of local pollution (e.g., see Jenks et al. 1996). Urban heat island effects, for instance, may be exacerbated in dense urban cores. There may be a trade-off between the transport energy savings achieved with higher urban density versus the higher energy use of high-rise buildings. There are also trade-offs between urban density, dwelling type, block size, and the ecosystem services provided by vegetation. Both theoretically and empirically, it is by no means clear that there is an ideal urban form and morphology that can maximize energy performance and satisfy all other sustainability criteria.

9.7 Relative importance of the drivers of urban energy

No study so far has investigated the relative importance of all the factors known to influence urban energy use as described above. Existent approaches rather contrast energy and/or CO_2 emissions with such macro-drivers as population, income, and technology, and thus follow the classic IPAT decomposition approach.[8] Such decomposition analysis has, for example, been carried out for several Chinese cities (Dhakal 2009), where the relative changes in urban CO_2 emissions are decomposed into the factors population change, income change (measured as GDP/capita), and two technology factors: the carbon intensity of the energy system (measured as CO_2 emissions per unit of primary energy demand) and energy intensity (measured as primary energy demand per unit of GDP) for several periods of time. Although the relative contribution of these factors varies across cities and time periods, overall income is shown to be the most important driving factor for increases in carbon emissions (by far outpacing population growth), and improvements in energy efficiency to be the most important counterbalancing factor. The net result is, in all cases, an increase in carbon emissions, which indicates that economic growth has, to date, outpaced technology and efficiency gains (Figure 9.6).

Earlier work by Dhakal and Hanaki (2002) and Dhakal et al. (2003) for Tokyo using 1970–98 data and for Seoul using 1990–7 data also shows that the income effect was primarily responsible for the majority of energy-related CO_2 emissions growth in Tokyo and Seoul in their respective high growth periods, that is, 1970–90 for Tokyo and 1990–7 for Seoul. The analysis also showed that, despite an economic recession, energy-related CO_2 emissions continued to grow in Tokyo in 1990–8, largely because of a drastic decline in the energy-intensity improvement rate (often observed in periods of economic growth stagnation or

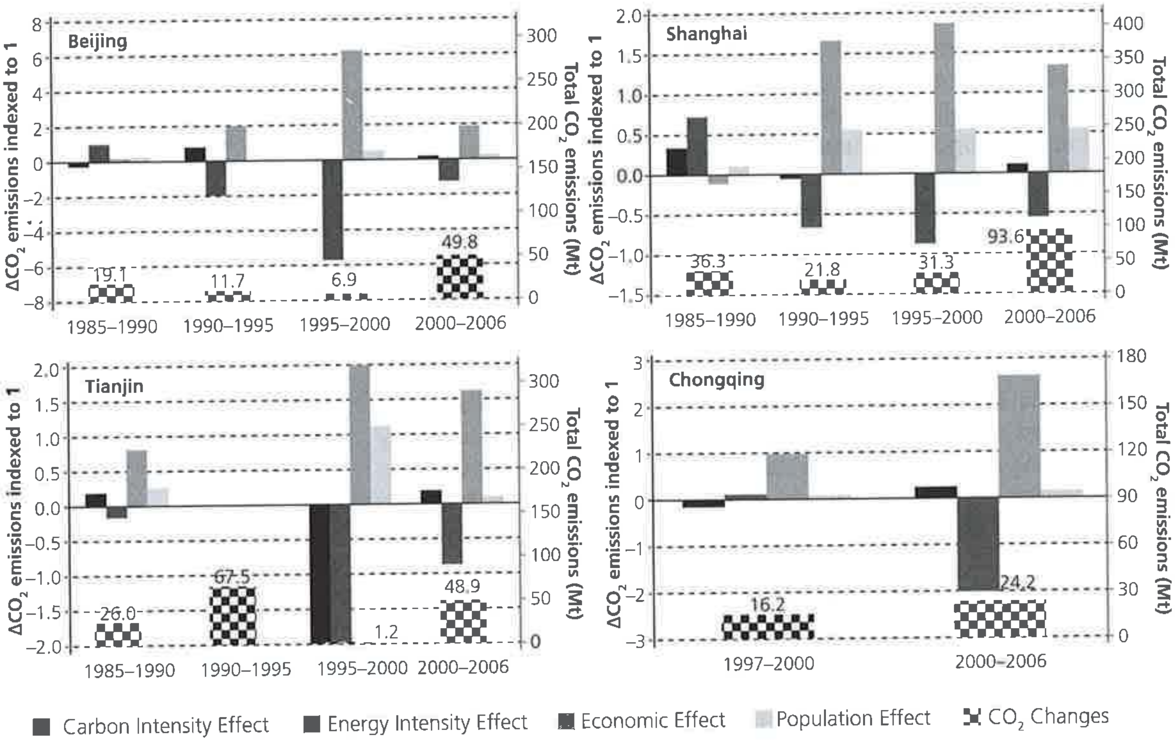


Figure 9.6 Contribution of factors (indexed, left axis) to the changes in energy-related CO_2 emissions (million tonnes CO_2, right axis) for four Chinese cities

Source: Dhakal (2009)

recession caused by the slower rate of capital turnover and hence the slowing introduction rate of more energy-efficient technologies and practices).

Notes

1 For comparison: per capita GDP (in PPP terms) in 2005 and in Int.$2005 are: Beijing: 9,238, Hong Kong: 3,4574, London: 5,3145, Shanghai: 9,584, Singapore: 2,9810, and Tokyo: 3,3714. (Note that a change in base year for the PPP metric changes the relative position of urban incomes in a non-proportional way.)

2 International bunker fuels are an important exception that, by simple definition, are excluded in national energy-use balances and the resulting emission inventories.

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4 Authors: Arnulf Grubler and David Fisk.

5 A working paper on urban form and morphology contains a more extended discussion and is available online at: www.globalenergyassessment.org.

6 See http://energieberatung.ibs-hlk.de/ebenev_begr.htm.

7 For a more in-depth discussion of transport energy use and its drivers, see also Chapter 9 of GEA.

8 IPAT: Impacts = Population × Affluence × Technology. For a history and discussion of the concept, see Chertow (2000).