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Urban Energy Systems

Convening Lead Author (CLA)
Arnulf Grubler (International Institute for Applied Systems Analysis, Austria and Yale University, USA)

Lead Authors (LA)
Xuemei Bai (Australian National University)
Thomas Buettner (United Nations Department of Economic and Social Affairs)
Shobhakar Dhakal (Global Carbon Project and National Institute for Environmental Studies, Japan)
David J. Fisk (Imperial College London, UK)
Toshiaki Ichinose (National Institute for Environmental Studies, Japan)
James E. Keirstead (Imperial College London, UK)
Gerd Sammer (University of Natural Resources and Applied Life Sciences, Austria)
David Satterthwaite (International Institute for Environment and Development, UK)
Niels B. Schulz (International Institute for Applied Systems Analysis, Austria and Imperial College London, UK)
Nilay Shah (Imperial College London, UK)
Julia Steinberger (The Institute of Social Ecology, Austria and University of Leeds, UK)
Helga Weisz (Potsdam Institute for Climate Impact Research, Germany)

Contributing Authors (CA) *including contributors to GEA City Energy Data Base
Gilbert Ahamer* (University of Graz, Austria)
Timothy Baynes* (Commonwealth Scientific and Industrial Research Organisation, Australia)
Daniel Curtis* (Oxford University Centre for the Environment, UK)
Michael Doherty (Commonwealth Scientific and Industrial Research Organisation, Australia)
Nick Eyre* (Oxford University Centre for the Environment, UK)
Junichi Fujino* (National Institute for Environmental Studies, Japan)
Keisuke Hanaki (University of Tokyo, Japan)
Mikiko Kainuma* (National Institute for Environmental Studies, Japan)
Shinji Kaneko (Hiroshima University, Japan)
Manfred Lenzen (University of Sydney, Australia)
Jacqui Meyers (Commonwealth Scientific and Industrial Research Organisation, Australia)
Hitomi Nakanishi (University of Canberra, Australia)
Victoria Novikova* (Oxford University Centre for the Environment, UK)
Krishnan S. Rajan (International Institute of Information Technology, India)
Seongwon Seo* (Commonwealth Scientific and Industrial Research Organisation, Australia)
Ram M. Shrestha* (Asian Institute of Technology, Thailand)
Priyadarshi R. Shukla* (Indian Institute of Management)
Alice Sverdlik (International Institute for Environment and Development, UK)

Review Editor
Jayant Sathaye (Lawrence Berkeley National Laboratory, USA)

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Executive Summary

More than 50% of the global population already lives in urban settlements and urban areas are projected to absorb almost all the global population growth to 2050, amounting to some additional three billion people. Over the next decades the increase in rural population in many developing countries will be overshadowed by population flows to cities. Rural populations globally are expected to peak at a level of 3.5 billion people by around 2020 and decline thereafter, albeit with heterogeneous regional trends. This adds urgency in addressing rural energy access, but our common future will be predominantly urban. Most of urban growth will continue to occur in small- to medium-sized urban centers. Growth in these smaller cities poses serious policy challenges, especially in the developing world. In small cities, data and information to guide policy are largely absent, local resources to tackle development challenges are limited, and governance and institutional capacities are weak, requiring serious efforts in capacity building, novel applications of remote sensing, information, and decision support techniques, and new institutional partnerships. While 'megacities' with more than 10 million inhabitants have distinctive challenges, their contribution to global urban growth will remain comparatively small.

Energy-wise, the world is already predominantly urban. This assessment estimates that between 60–80% of final energy use globally is urban, with a central estimate of 75%. Applying national energy (or GHG inventory) reporting formats to the urban scale and to urban administrative boundaries is often referred to as a ‘production’ accounting approach and underlies the above GEA estimate. This contrasts to a ‘consumption’ accounting approach that pro-rates associated energy uses per unit of urban consumer expenditures, thus allocating energy uses to urban consumers irrespective of the form energy is used (direct or embodied energy) or its location (within or outside a city’s administrative boundary). Available consumption-based energy accounts for cities are too limited (estimates exist for only a handful of megacities) to allow generalization but it is highly likely that urban energy use under a consumption accounting approach approximates the urban share in the world GDP, estimated by this assessment to be some 80%. There is great heterogeneity in urban energy-use patterns as revealed by this assessment drawing together a novel urban energy use data set. In many developing countries, urban dwellers use substantially *more* final energy per capita than their rural compatriots. This primarily reflects their much higher average urban incomes. Conversely, in many industrialized countries per capita final energy use of city dwellers is often *lower* than the national average, which reflects the effects of compact urban form, settlement types (multi- versus single-family dwellings) and availability and/or practicability of public transport infrastructure systems compared with those in the suburban or rural sprawl. The few available data, however, suggest that urban energy use in high-income countries is not substantially different from the national average when using a consumption-based accounting approach, whereas in low-income countries the urban-rural energy difference is likely to be even larger under this alternative energy accounting method. This Assessment concludes that both accounting methodologies provide complementary, valuable information to inform urban policy decisions. However, because of complexities in systems boundaries and accounting, urban studies need to adhere to high standards in terms of clarity and documentation of the terminology, methodology, and documentation of underlying energy data used.

Addressing Urban Challenges

Rapid migration rates and natural population growth in cities can overwhelm the provision of basic urban services, particularly for the poorest urban dwellers. Several hundred million urbanites in low- and middle-income nations lack access to electricity and are unable to afford cleaner, safer fuels which results in significant adverse consequences for human health and local air quality. Most are in low-income nations in Southeast Asia and sub-Saharan Africa. Innovations have reduced access costs – for instance, rising tariffs with low prices for ‘lifeline’ consumption, pay-as-you-use meters, and standard ‘boards’ that remove the need for individualized household wiring—but urban energy access also faces political and institutional obstacles. A large part of the urban population that lack clean energy and electricity (and other basic services like water, sanitation, and transport) live in informal settlements. It is mostly in situations where the often antagonistic relationship between local government and the inhabitants of informal settlements has changed, through widespread public support to upgrade 'slums' and squatters, that clean energy and electricity and other public services have reached the urban poor.

Housing, water supply and sanitation infrastructure, energy, and transport services are the key sustainability challenges to accommodate some three billion additional urban dwellers in the decades to come, especially in low-income countries. Informal settlements will often be one of the transitional forms of settlement for many of these new urban dwellers and will require a much more proactive, anticipatory policy approach, especially with respect to the location of informal settlements and subsequent infrastructure connections and upgrading programs. Energy-wise, low-cost and fast implementation options will take precedence over 'grand' new urban designs that require unrealistically large sustained capital provision over long periods. In low-income countries access to clean cooking fuels and electricity, as well as pro-poor transport policies, which include safer use of roads by non-motorized modes (walking and bicycling) and making public transport choices available need to be ranked high on the urban policy agenda.

From all the major determinants of urban energy use – climate, position in the global economy, consumption patterns, quality of built environment, urban form and density (including transport systems), and urban energy systems and their integration – only the final three are amenable to policymaking by city administrations, at least partially. Therefore, both in terms of leverage and potentials, energy policy at the urban scale needs to focus above all on *demand management* with a focus on energy efficient buildings, structuring urban form and density conductive to energy efficient housing forms, high-quality public transport services, and to urban energy systems integration. This demand-side focus at the urban scale represents a paradigm shift compared to the traditional, more supply-side energy policy focus at the national scale.

Systemic characteristics of urban energy use are generally more important determinants of the efficiency of urban energy use than those of individual consumers or of technological artifacts. For instance, the share of high occupancy public and/or non-motorized transport modes in urban mobility is a more important determinant of urban transport energy use than the efficiency of the urban vehicle fleet (be it buses or hybrid automobiles). Denser, multifamily dwellings in compact settlement forms with a corresponding higher share of non-automobile mobility (even without thermal retrofit) can use less *total energy* than low-density, single-family 'Passivhaus'-standard (or even 'active,' net energy generating) homes in dispersed suburbs deploying two hybrid automobiles for work commutes and daily family chores. Evidently, urban policies need to address both systemic and individual characteristics in urban energy use, but their different long-term leverage effects should structure policy attention and perseverance. In terms of urban energy-demand management, the quality of the built environment (buildings efficiency) and urban form and density that, to a large degree, structure urban transport energy use are roughly of equal importance. Also, energy-systems integration (cogeneration, waste heat cascading) can give substantial efficiency gains, but ranks second after buildings efficiency and urban form and density, and associated transport efficiency measures, as shown both by empirical cross-city comparisons and modeling studies commissioned by this assessment. The potential for energy-efficiency improvements in urban areas remains enormous, as indicated by corresponding urban exergy analyses reviewed in this Assessment and that suggest urban energy-use efficiency is generally less than 20% of the thermodynamic efficiency frontier; representing an improvement potential of more than a factor five. Conversely, the potential of supply-side measures within the immediate spatial and functional confines of urban systems is very limited, especially for renewable energies. *Locally harvested* renewables can, at best, provide 1% of the energy needs of a megacity and a few percentage points in smaller, low-density cities because of the mismatch between (high) urban energy demand density and (low) renewable energy supply densities at the local level.

Urban Policy Choices and Priorities

The historical evolutionary processes that govern urban growth have largely been *path dependent* with variation that played out differently over time and space. Cities that evolved along alternative pathways have alternative density levels from high-density 'Asian' (e.g., Tokyo, Shanghai, Mumbai) and 'old European' (e.g., London, Madrid, Warsaw) to low density 'new frontier' (e.g., Los Angeles, Brasilia, Melbourne) pathways, each of which have different structural options available to improve energy efficiency and optimize urban energy and transport systems in terms of sustainability criteria. Despite this diversity, two important generalizations can be drawn.

First, the implications of urban density on the requirements of urban energy systems are that they need to be basically *pollution free*, as otherwise even relatively clean energy forms can quickly overwhelm the assimilative capacity of urban environments. This especially applies to the million, decentralized energy end-use combustion devices (stoves, heating systems, vehicles) for which end-of-pipe pollution control is often not an option. Thus, in the long-term all end-use energy fuels burnt in urban areas need to be of zero-emission quality. This requires energy vectors from remote 'clean' plants, as exemplified by electricity or (possibly) hydrogen. Natural gas plays the role of the transitional fuel of choice in many urban areas. This 'zero-emission' requirement for urban energy transcends the customary sustainability divide between fossil and renewable energies, as even 'carbon-neutral' biofuels when used by millions of automobiles in an urban environment will produce unacceptable levels of NO_x or O_3 pollution. The observed significant improvements in urban air quality caused by the elimination of traditional air pollutants, such as soot, particles, and SO_2, in cities of high-income countries are a powerful illustration that cities act as innovation centers and hubs for environmental improvements that can lead to a sustainability transition path. First signs of progress in traditional air pollutants are evident in low-income countries as well, as illustrated by the recent decline in the emissions of some traditional pollutants in Asian megacities discussed in this assessment. Nonetheless, an exceedingly high fraction of urban dwellers worldwide are still exposed to high levels of urban air pollution, especially total suspended particles (TSPs), with fine particle emissions (PM-10s) continuing their upward trend. A wide portfolio of policy options is available, ranging from regulatory instruments such as mandated fuel choice ('smokeless zone' regulations), air-pollution standards, regulation of large point-source emissions and vehicle exhaust standards, to market-based instruments (or hybrid) approaches that incentivize technological change. An important feature of these regulatory approaches is *dynamic target setting* to reflect changing technology options and to counter the consequences of urban growth and potential consumer 'take-back' effects. Air pollution is also the area of urban environmental policymaking where the most significant co-benefits of policies can be realized: improving access to clean cooking fuels, for example, improves human health and lowers traditional pollutant emissions, and also has (through reduced black carbon emissions) significant net global warming co-benefits.

Second, the literature repeatedly identifies important size and density thresholds as useful guides for urban planning. The importance of these urban thresholds extends to specialized urban infrastructures, such as underground (metro) transport networks that are, as a rule, economically (in terms of potential customers and users) not feasible below a threshold population size of less than one million. It also extends to energy (e.g., cogeneration-based district heating and cooling) and public transport networks, whose feasibility are framed by a gross[1] population density threshold between 50 and 150 inhabitants/hectare (ha) (5000–15,000 people/km^2). Such density levels of 50–150 inhabitants/ha certainly do *not* imply the need for high-rise buildings, as they can be achieved by compact building structures and designs, both traditional and new, including town or terraced houses, while still allowing for open public (parks) or private (courtyard) spaces – but they do not allow for unlimited (aboveground parking) spaces for private vehicles. Zoning and parking regulation, combined with public transport policies and policies that promote non-motorized transport modes and walkability thus constitute the essential 'building blocks' of urban energy efficiency and sustainability 'policy packages.'

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[1] i.e., a minimum density level over the entire settlement area that comprises residential zones of higher density with low density green spaces.

The wide variation in urban transport choices observed in the modal split in different cities illustrates that urban mobility patterns are not *ex ante* given, but rather result from specific choices of individuals and decision makers. Urban transport choices can be modified, if both a strong determination for a sustainable urban transport policy *and* a corresponding wide public acceptance of the overall goals of such a policy exist. Restrictive measures that limit individual mobility by automobiles need to be complemented by proactive policies that enhance the attractiveness of non-motorized and public transport choices, and 'soft' policy measures (e.g., fees, tariffs) also need to be complemented by 'hard' (i.e., infrastructural investment) measures. Investments in public transport systems need to find an appropriate balance between improvements that are less capital intensive and faster to implement, and radical solutions. Bus-based Rapid Transit systems (BRT) with own dedicated lanes are, therefore, a much more attractive option for many cities in low-income countries than are capital-intensive subway or light-rail systems, even though, in the long term, the latter offer the possibility of higher passenger fluxes and greater energy efficiency. Often there is no contradiction between incremental versus radical public transport policy options: for instance, BRT can also be considered as a transitional infrastructure strategy to secure public transport 'rights of way,' which offer subsequent possibilities for infrastructure upgrades, for example in putting light rail systems in BRT lanes. Many of the new urban settlements being formed meet the required density targets for attractive and efficient public transport systems. The policy issue is to exploit the available advantages before a 'lock-in' into a private automobile-dependent 'vicious' development cycle becomes entrenched.

A common characteristic of sustainable urban energy system options and policies is that they are usually systemic: for example, the integration of land-use and urban transport planning that extends beyond traditional administrative boundaries; the increasing integration of urban resource streams, including water, wastes, and energy, that can further both resource (e.g., heat) recovery and improve environmental performance. This view of a more integrated (and often also more decentralized) urban infrastructures also offers possibilities to improve the resilience and security of urban energy systems. And yet, this systemic perspective reveals a new kind of 'governance paradox.' Whereas the largest policy leverages are from systemic approaches and policy integration, these policies are also the most difficult to implement and require that policy fragmentation and uncoordinated, dispersed decision making be overcome. The urban governance paradox is compounded by weak institutional capacities, especially in small- to medium-sized cities that are the focus of projected urban growth, as well as from the legacies of market deregulation and privatization that have made integrated urban planning and coordinated energy, transport, and other infrastructural policy approaches more difficult to design and yet more difficult to implement. However, there are good reasons for (cautionary) optimism. Urban areas will continue to act as innovation centers for experimentation and as diffusion nodes for the introduction of new systems and individual technological options by providing critical niche market sizes in the needed transition toward more sustainable urban energy systems.

18.1 Introduction

18.1.1 Preamble

Towns and cities and their increasing coalescence into urban agglomerations are now the dominant form of spatial organization in which people live, economies operate, technologies are generated and used, corresponding demands for *energy services* arise and environmental sustainability is critically defined. The decade 2000–2010 marked an important watershed in human history: for the first time more than 50% of the global population are urban dwellers and estimates indicate that already some three-quarters of global (direct) final energy use is urban, with corresponding primary energy and carbon dioxide (CO_2) emissions probably being comparable.

Given the robust trends toward a convergence of much of the developing world to levels of urbanization already found in the developed world, the energy and sustainability challenges of equitable access to clean-energy services, of energy security, and of environmental compatibility at local through global scales cannot be addressed without explicit consideration of urban energy systems and their specific sustainability challenges and opportunities. The future development of the demand side for energy cannot be described without understanding changes at the level of the urban settlements. Research shows how the properties of urban areas across the world are scalable, revealing distinct patterns. Just as it is possible 'to fail to see the forest for the trees,' it is possible 'to fail to see the city for the buildings.' Hence the GEA includes a specific chapter on urbanization and urban energy use.

Paradoxes in conventional analysis abound. A single urban agglomeration, such as greater Tokyo, generates more gross domestic product (GDP) than the venerable pioneer country of the Industrial Revolution – the current United Kingdom. And yet, our statistical reporting systems almost exclusively focus on nation states, as represented by Systems of National Accounts, Energy Balances, or similar reporting standards. In fact, as detailed throughout this chapter, the difficulty of finding data at the urban level starts with the very definition of urban areas and urban populations. The study of urban energy must take this diversity and uncertainty into account. Accordingly, this chapter draws attention to the limits of comparability and policy guidance of existing studies that suffer from inconsistent or unclear system boundaries and accounting methodologies, and concludes with the need to develop clear methods and guidelines for a range of complementary urban energy accounting tools to guide policy. The energy-accounting system boundary issue thus adds to the conundrum of different territorial and administrative boundaries that range from core cities through metropolitan agglomerations to transnational urban corridors.

In this chapter the terminology used is of an 'urban system' when describing the urban phenomenon from a *functional* perspective in addition to the traditional territorial or administrative perspective. Thus, an *urban energy system* comprises all components related to the use and provision of energy services associated with a functional urban system, irrespective where the associated energy use and conversion are located in space, such as power plants and transport fuel requirements both locally and internationally (airports, ports). The full urban energy system entails both energy flows proper (fuels, 'direct' energy flows) and 'embodied' energy (energy used in the production of goods and provision of services *imported* into but also *exported* from an urban system). The functional perspective of urban energy systems highlights that urban locations and their growth (urbanization) are not only the locations of people and economic activities in space, but also include the types of activities they pursue and the infrastructural and functional framing conditions (service functions) urban agglomerations provide. Functional characteristics increasingly define urban areas and need to be reflected in urban energy systems analysis, and thus need to combine both 'production' and 'consumption' perspectives. From a spatial perspective, this chapter also extends – within the limits of available data – the traditional discussion of cities as defined by political and/or administrative boundaries toward urban agglomerations, including 'peri-iurban' and larger metropolitan areas, through urban 'clusters' or 'corridors' to Doxiadis' (Doxiadis and Papaioannou, 1974) 'ecumenopolis.'

The future development of urban energy systems is characterized by specific challenges and opportunities. The high density of population, economic activities, and resulting energy use severely limit an obvious sustainable energy choice: In many larger cities locally harnessed renewables can provide for only some *one per cent* of urban energy use which implies large-scale *imports* of renewable energies generated elsewhere, much like in the currently dominating fossil energy systems. The diversity of activities and energy uses characteristic of urban systems opens numerous opportunities for intelligent energy management and 'recycling' (e.g., electricity-heat cogeneration and 'heat cascading', in which different energy end uses can 'feed' on waste energy flows from energy conversion and industrial applications). Both *diversity and density* (at least above a critical threshold value of some 50–150 inhabitants/ha) can be considered as key *strategic assets* of urban areas that help to use energy more efficiently by energy-systems integration, compact energy-efficient housing, and co-location of activities that can help to minimize transport distances and automobile dependence. The provision of transport services via environmentally friendly, high-quality urban public transport systems is a unique option for cities, generally not available in low-density sub-urban or rural contexts.

The vital urban infrastructures all depend on energy: water supply, treatment and waste water disposal, transport and communication systems, complex webs of food and material supplies, the resulting disposal of wastes, and, of course, energy supply itself. Many urban infrastructures have shown great adaptability, but catastrophes like hurricane Katrina, or the 9/11 attacks on New York, show that urban systems and, by extension, their populations are vulnerable. Urban infrastructures are almost always considered in isolation, but this ignores their interdependence, and common vulnerabilities, as well as their potential synergies and efficiency gains. This highlights the importance of improved planning, but this will require new institutional frameworks and the inclusion of different stakeholders to address the complex coordination issues across sectors and across spatial scales.

Urban agglomerations are dominant in terms of production, consumption, and associated energy use (irrespective of where these take place physically). But they are also unique centers of human capital, ingenuity and innovation, financial resources, and local decision-making processes, which are all 'human' resources that can be harnessed for a sustainability transition. While global and national policy frameworks are clearly needed, ultimately all implementation is *place-based* and requires local formal and informal supportive frameworks. To promote more sustainable development, cities may thus be the right scale for an 'intermediate' (even mediating) actor level between the individual and national and transnational initiatives. The urban scale is also the appropriate one to identify and realize many options in promoting energy efficiency that may not always be apparent at higher levels of policymaking.

Cities thus could become *the* innovation centers in developing and implementing solutions in the sustainability transition, a perspective that well merits their explicit consideration in an assessment like GEA.

18.1.1 Objectives and Approach

Given the above, the broad objective is to address urban energy issues in an increasingly urbanizing world from a *systemic* perspective that focuses on the specific energy challenges and opportunities represented by urban settlements.

The specific objectives of this chapter are to perform first a global assessment to establish the order of magnitude of urban energy systems and their drivers, then develop some generalized hypotheses to understand urban energy use, its differences and dynamics, and finally test these hypotheses through case studies at the local and regional levels, drawing on specific examples of individual cities.

This chapter addresses the systemic and structural interlinkages of urban systems and how these interact within and outside traditional territorial urban system boundaries. It adds to the information and knowledge of the sectorial GEA chapters (buildings, industry, transport) by addressing the *integrated* issues specific and unique to urban systems. Sectoral perspectives are therefore addressed here only to the extent that they contain an explicit urban specificity, e.g., (public) urban transport systems, or urban energy cogeneration systems.

Urbanization is a multidimensional phenomenon that can be described from demographic, land use, or economics perspectives. Empirical data are well developed for demographics (through regular population censuses) and for land-use perspectives (through remote sensing data). Conversely, there is a paucity of widely available and comparable economic data at the urban scale. Systems of National Accounts that underlie much of the available economic data were developed and continue to be used predominantly at the national scale, with comparatively few applications at the urban scale, which explains the significant gap between urban economic data[2] and the largely theoretical discussion of urbanization in the economics literature. The literature on urban land use and urban land-cover changes, while most valuable for describing a physical dimension of urbanization, is of limited use in an energy assessment despite the richness of quantitative data available. After all, it is not the square kilometers of urban extent that can explain urban energy use, but only the linkage of urban land use with demographic and economic data and characteristics as reflected through urban form and population density, infrastructure endowments, level and structure of economic activities, lifestyles of city dwellers, among other factors. Therefore, *demographics* (population) is adopted quite naturally as a fundamental driver and core metric to discuss urbanization and urban energy use, drawing on the urban land-use change and economics literature only to the degree necessary to understand urban energy use and its variation through derived metrics centered on population, like population density, or per capita incomes and expenditures, in addition to more narrow disciplinary land-use and economic metrics, such as urban extents/form or economic structure.

As comprehensive energy information and accounts at the urban scale are extremely limited, developing a robust assessment storyline from the bottom-up alone is challenging. Therefore in this analyses a mixed approach of both top-down and bottom-up perspectives is utilized, combining estimates derived from 'downscaling' or remote sensing approaches with bottom-up statistical information where available.

18.1.2 Roadmap

After the introductory section (18.1), Section 18.2 gives an overview of the urbanization phenomenon and the contexts for understanding urban energy use. Its focus is on the demographic dimension of urbanization, both from historical and futures (scenarios) perspectives, and on the drivers and patterns of urbanization dynamics. It also addresses the specifics of urban energy systems and elaborates on the importance of system boundaries.

Section 18.3 analyzes current global, regional, and city-specific urban energy use, and comprises new 'top down' estimates of urban energy from a global perspective, complemented by 'bottom up' urban-scale energy-use data collected through the GEA Chapter 18 City Energy Data Base.

Urban energy use and systems as a whole are accompanied and shaped by multiple challenges, discussed in detail in Section 18.4. These include

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[2] With a paucity of 'official' urban scale economic data reporting, this assessment also relies heavily on estimates rather than statistics, with data derived either from 'grey literature' expert estimates (e.g., Hawksworth et al., 2007) or spatially explicit 'downscaling' exercises (e.g., Grubler et al., 2007).

issues of energy access, energy demand densities, and associated key environmental externalities, as well as energy supply constraints, which include reliability and security.

Section 18.5 outlines opportunities and response options to the urban energy challenges. Key drivers of urban energy use, policy players and main policy leverages, and some of the key infrastructure issues linked to specifics of urban systems, such as urban transport, urban energy infrastructure planning, design and implementation, and urban air-quality management are discussed. Section 18.5 also includes novel model simulations to illustrate the respective impacts of policy interventions along three main opportunity areas: urban form and density (and their influence on transport energy demand), buildings efficiency, and urban energy systems integration and optimization.

Section 18.6 summarizes the key messages and conclusions. The research, data, and information needs identified are summarized at the end of the each section rather than in a separate section at the end of the chapter.

18.2 An Overview of Urbanization

18.2.1 Overview of Urbanization, Past and Scenario Trends

18.2.1.1 The Multiple Dimensions of Urbanization

The process of urbanization involves multiple dimensions, characterized by different theories, methodologies, and literatures that follow four distinct disciplinary perspectives: demography, geography, economics, and sociology.

The resulting effects of the scale and concentration of human activity in urbanized areas are the focus of research in various disciplines. Economists often emphasize the benefits of scale of larger labor markets in cities and agglomeration effects of clustering of various industrial and service activities (Krugman, 1991; Fujita et al., 1999; UNIDO, 2009; World Bank, 2009). Climatologists discuss the consequence of urbanization on albedo changes, radiation balances, and weather patterns (Kalnay and Cai, 2003; IAUC and WMO, 2006; Souch and Grimmond, 2006). Transport planners are concerned with avoiding negative externalities of urban density, such as traffic congestion. Environmental researchers study typical patterns of the generation and distribution of pollutants in urban centers and the exposure of target populations to such hazards (McGranahan et al., 2001; McGranahan and Marcotullio, 2007). Social scientists are investigating particular urban social structures and challenges, and urban cultural modes of creativity and innovation that result from the immediate proximity of many million people that can exchange, cooperate and profit from high degrees of specialization. Understanding the consequences of urbanization on energy use in general, however, is an area of research that has attained surprisingly little attention in empirical studies, given the relevance of urban areas for overall energy demand (IEA, 2008), their particular vulnerability to energy supply disruption, and their potential for energy savings and climate-change mitigation.

The economic, geographic, and sociological perspectives of urbanization are discussed in greater detail as driving forces of urban energy demand (see Section 18.5.2). Following these different disciplinary perspectives, four complementary concepts describe the process of urbanization:

- The demographer's approach emphasizes population. To a demographer, urbanization is the process by which a rural population becomes urban. That is, the *population* is becoming urbanized by an increase in the proportion of the population classified as urban.

- In the geographer's approach, a defined geographic area gradually loses the characteristics associated with rural areas (e.g., dominance of agricultural land uses) and gains characteristics associated with urban areas (e.g., built-up land, and high density of buildings and technological infrastructures) – the *region* is becoming urbanized).

- The economist's approach is the process of economic structural change away from primary economic activities (agriculture, forestry, mining, etc.) toward manufacturing and services (secondary and tertiary economic activities). This usually involves spatial concentration and co-location of economic actors[3] that profit from agglomeration externalities: the *economy* is becoming urbanized.

- In the sociologist's approach, individuals move from rural to urban areas and take on urban characteristics: individuals and their aggregate (i.e., *society*) are becoming urbanized.

The demographic study of urbanization is among the oldest research traditions and also the most quantitative, including scenario projections into the future. Along with economics it is also the dimension with the closest direct causal link to urban energy use. This being the reason why in the subsequent discussion the demographic perspective of urbanization is highlighted. The economic, geographical, and sociological perspectives of urbanization in turn are discussed in greater detail as driving forces of urban energy demand (see Section 18.5.2 below).

Table 18.1 illustrates these multiple dimensions of urbanization at the global level for the year 2000, the latest common year for which the various indicator data sets available. With the exception of remotely sensed urban land areas (that turn out to display the largest uncertainty range of a factor of ten) and population for which data are available directly at

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[3] In economics this is referred to as agglomeration externalities that arise from economies of scale and economies of scope effects. See Chapter 24 for a more detailed discussion and exposition of these concepts.

Table 18.1 | Various indicators of urbanization for the year 2000 at the global level in absolute amounts and as percentage urban with associated uncertainty ranges derived from the literature or estimated in this study.

Indicator		Value	Uncertainty Range	References for Uncertainty Range
Area[1]	(1000 km^2)	2929	313–3524	Schneider et al., 2009
	% of total	***2.2***	*0.2–2.7*	range of globcover-grump data
Population[2]	(million)	2855	2650–3150	Uchida and Nelson, 2008
	% of total	***47***	*44–52*	Size threshold: 50,000–100,000
GDP (MER US2005$)[1]	(billion)	32008		not available
	% of total	***81***		
Final energy use[1]	(EJ)	239	176–246	this assessment
	% of total	***76***	*56–78*	(see Section 18.3.1)
Light luminosity[1,3]	(million NLIS)	33		Chapter 18 estimate
	% of total	***57***	*50–82*	
Internet routers[1,4]	(number in 1000)	8592		Chapter 18 estimate
	% of total	***96***	*73–97*	

Notes – MER: Market Exchange Rates; NLIS: Light Luminosity Intensity Sum (Index)

Sources: (1) Grubler et al., 2007; (2) UN DESA, 2010; (3) NOAA, 2008; (4) Crovella, 2007 and Lakhina et al., 2003.

the urban scale, all other indicators represent derived estimates, combining spatially explicit data sets of urban extents consistent with UN urban population statistics with other spatially explicit data of human activity.

18.2.1.2 Urbanization in a Historical and Demographic Context

People have lived in cities for millennia. Cities and their associated urban agglomerations have and continue to play key roles as centers of government, production, and trade, as well as knowledge, innovation, and productivity growth (UN, 2008). Yet during most of the past, the number of city dwellers remained exceedingly small – the majority of the population continued to live in rural areas and worked in agriculture.

Before 1800, large cities (by contemporary standards) being exceedingly rare, with Chang'an and Baghdad being likely the first examples of cities that approached one million inhabitants (Chandler and Fox, 1974; Chandler, 1987). This started to change dramatically with the (rapid) improvement of agricultural productivity, which freed people for new industrial jobs and migration into cities (the Industrial Revolution). Many cities grew to much larger sizes; rural settlements were transformed into cities, and new cities were founded. The rate of urban population growth (the twin result of natural growth in urban populations plus net in-migration into cities) exceeded significantly that of the overall population and resulted in a secular trend toward *urbanization* (i.e., an increase in the rate or percentage of a population living in urban areas). Estimates suggest that by 1900–1920, between 12 and 14% of the global population could be classified as urban. Because of their lead in industrialization and agricultural productivity growth, the more developed countries had an urbanization rate of some 30% by the 1920s, and developing countries of only some 6% (UN DESA, 1973). Urbanization trends have accelerated ever since.

The UN reconstruction of global population trends from 1950 onwards (UN, 2008) documents a historically unprecedented global population growth in the second half of the 20th century, peaking at about 2% annually between 1965 and 1970. Global population growth rates have declined since, and current projections indicate a leveling off of global population growth toward the third quarter of the 21st century.

In 55 years, the world's population grew by about 4 billion people to approximately 6.5 billion in 2005. A defining feature of this growth is its diversity across regions, especially between more- and less-developed ones. Having entered the demographic transition earlier, OECD90 countries and countries undergoing economic reform (Eastern Europe and the former USSR) increased their population between 1950 and 2005 by a comparatively modest 62% and 51%, respectively. All other GEA regions, by contrast, more than doubled their populations. The fastest population growth occurred in the Middle Eastern and African regions, where the population more than quadrupled between 1950 and 2005. The population in Latin America and the Caribbean more than tripled, and in Asia, already the most populous region of the world, in 2005 the population was 2.7 times larger than that in 1950.

18.2.1.3 Past Urbanization Trends

The inevitable uncertainty in urban population and urbanization levels does not affect an assessment of the dynamics of the urbanization process, provided the system of national definitional criteria does not change too often over time (occasional definitional changes of individual countries do not markedly affect global or regional trends).

While populations in all regions grew over the past half century, urban populations grew even faster (Table 18.2). Between 1950 and 2005, the UN DESA (2010) estimate suggests that the Middle Eastern and African urban population multiplied more than ten-fold, increasing from 44 million to 478 million. Asia registered in 2005 an urban population almost six-times higher than it had in 1950 (175 million versus 1.3 billion), and the urban population of Latin America and the Caribbean increased more than five times, from 68 million to about 429 million people (UN DESA, 2010). By 2005 about half of the global population (3.2 out of 6.5 billion) was urban. By the time of the publication of the GEA report (2012), more than half of global population will be urban.

Table 18.2 | Urban population (millions) and as a percentage of world total urban population, and total population (in millions) for the five GEA regions and the world since 1950. Countries undergoing economic reform = Eastern Europe and former USSR.

	Urban Population				Total Population	
GEA Region	**1950**	**2005**	**1950**	**2005**	**1950**	**2005**
	in Millions		**in percent of world**		**in Millions**	
OECD90	340	730	46.6	23.1	593	963
Countries undergoing Econ. Reform	102	254	14.0	8.0	269	404
Asia	175	1276	24.0	40.3	1237	3478
Middle East and Africa	44	478	6.0	15.1	266	1115
Latin American and the Caribbean	68	429	9.4	13.5	165	552
World	**729**	**3167**	**100**	**100**	**2529**	**6512**

Source: UN DESA, 2010.

18.2.1.4 Urbanization Levels

As the urban population grew, its relative weight also increased. In 1950, just about 30% of the world's population of 2.5 billion people lived in urban areas, while the vast majority still lived in rural areas. Even for the more advanced OECD90 region, in 1950, 57% of its population lived in urban areas, while a substantial proportion of its population (43%) lived in rural areas. All other major regions were predominantly rural. Latin America and the Caribbean, and the countries of Eastern Europe and the former USSR currently undergoing economic (transition) reform already had high urbanization levels (41% and 38%, respectively) in 1950. Populations in the Asian and the Middle Eastern and African regions were still predominately rural, with just about 14% and 16% of their populations living in urban areas, respectively.

By 2005, the world had become almost 50% urban, but with significant differences across the regions. In the OECD90 and Latin America and the Caribbean countries, three out of four people lived in urban settlements; and in the Asian and the Middle Eastern and African regions about two out of five people were urban dwellers.

18.2.1.5 An Urban Future

Trends in population aging and urbanization are inevitably important to the immediate and medium-term demographic future. Population growth is still a persistent element of demographic trends in developing countries. For some developed countries, however, population growth has not only tapered off, but may be reversed with population decline as a defining feature.

Significant negative population growth is currently expected to persist for countries undergoing economic reform (i.e., the countries of the former Soviet Union/USSR and of Eastern Europe), with their population projected to shrink by about 39 million people: from 404 million in 2005 to 365 million in 2050. All other GEA regions are projected to increase their populations between 2005 and 2050 (UN DESA, 2010). There is, however, great diversity not only between GEA regions, but also, and more significantly, within the regions and between countries. There are also different causes for the continued population growth within most GEA regions. Populations in the OECD region, which have experienced low or even very low fertility during recent decades, are expected to increase slightly, mainly because of net gains from international migration. For example, Western Europe is projected to lose about 1.4 million people between 2005 and 2050, when net migration gains are included. In the absence of that gain, in 2050 Western Europe would have about 15 million less inhabitants than in 2005 (UN DESA, 2010).

Population growth in the other GEA regions is caused by very different factors: momentum that stems from young populations and above-replacement fertility. The latter is increasingly less important because of a continued fertility decline. Combined, these factors generate the addition of 1.1 billion people to Asia, 1.2 billion to the Middle Eastern and African region, and 173 million to Latin America and the Caribbean to 2050.

Against this background, the growth of the global urban population is estimated to range from some additional 2.7 to 3.2 billion people, depending on the projected urbanization rate of growth (see Box 18.1). The generally larger growth of the projected urban population not only means that urban settlements will absorb all of the population growth between 2005 and 2050, but also that there will be a sizable redistribution of rural populations to urban areas. In addition, urban growth will be predominantly a phenomenon of the less-developed regions.

Figure 18.1 summarizes the GEA scenario results on the global level, and Figure 18.2 summarizes the five GEA world regions in terms of urban and rural populations. The continued growth of the world's urban population is set against a different growth path of the rural population.

Globally, rural population growth is projected to come to a halt around 2020, when it will reach a peak at about 3.5 billion people. This figure

Box 18.1 | Urbanization Projections Methodology

I. The UN World Urbanization Prospects

The UN World Urbanization Prospects (WUP) provides biannual estimates and projections of core demographic indicators of urbanization for all 229 countries or areas of the world and for the most populous urban settlements. The data include time series of total populations by urban and rural residence for the period 1950 to 2050, and of populations in 590 large urban settlements with 750,000 and more inhabitants for the period 1950 to 2025. In total, the entire WUP database contains estimates and projections for 4501 urban locations, covering two-thirds of the global urban population.

The WUP use a projection method that is described and discussed extensively (UN DESA, 1971; 1974; Ledent, 1980; UN DESA, 1980; Ledent, 1982; Rogers, 1982; Ledent, 1986; O'Neill et al., 2001; National Research Council, 2003; Bocquier, 2005; O'Neill and Scherbov, 2006). Such long-term projections include many uncertainties, reflected in the three urbanization scenarios discussed here. The method uses the growth difference between urban and rural populations or between city populations and total urban populations to model the dynamics of the urbanization process, an approach that is equivalent to a logistic curve fit (UN DESA, 1974). Starting with the most recent observed growth rates, future trends are calculated by taking into account the empirical observations that the pace of urbanization slows down as the proportion of the urban population increases (a characteristic feature of logistic growth processes beyond the 50% level of its asymptote). Consequently, the observed growth differentials are adjusted such that they approach a hypothetical norm obtained from past empirical observations (UN DESA, 1980). A distinguishing characteristic of the WUP is that only one central projection is performed in which the ultimate upper level of the urbanization process is not constrained; that is, all countries could ultimately converge to an urbanization rate of up to 100%.

II. Other Urbanization Projections

There are no real independent urbanization projections to the UN Urbanization Prospects as alternative scenarios invariably use the UN historical and current data as model inputs and also deploy a comparable methodological framework. The literature, however, reports scenario variants on the UN projection by either extending the time horizon beyond 2050 (the end-year reported by the UN projections) and/or alternatively relaxing the convergence assumption toward a 100% urbanization rate. For an OECD study on the climate vulnerability of port cities, Nicholls et al. (2008) extend the UN projections to 2100 and then apply a constant growth fraction to port cities at the national level to determine future port-city populations exposed to climate-change risk. In an integrated scenario exercise that explores future uncertainty in GHG emissions, Grubler et al. (2007) also extend the UN urbanization projection to 2100 and develop two additional scenario variants in which the asymptotic urbanization level is varied to explore the implications of lower urbanization. These three urbanization-rate scenarios were then combined with three alternative total population-growth scenarios (low, medium, and high) to determine the uncertainty range of future urban populations. This alternative scenario method estimated the uncertainty in the level of world urban population to range from 4.7 to 10.5 billion people by 2100, and from 5.6 to 7 billion compared to the 6.3 billion projected by the latest UN Urbanization Prospects projection for 2050 (UN DESA, 2010).

III. GEA Urbanization Scenarios

Methods and qualitative and quantitative assumptions that underlie the GEA transition pathways are described in detail in Chapter 17. In collaboration, this chapter and Chapter 17 also explore the issue of urbanization scenarios. In this context, two main features of the GEA scenario approach stand out: (1) their focus on energy issues and (2) their normative nature; that is, their objective to describe alternative, but successful, pathways toward an energy sustainability transition. As a result, the scenarios are based on a single central demographic-economic development scenario (e.g., based on the most recent UN medium population projection). The scenarios also describe pathways in which current widespread economic and energy disadvantages of poor rural populations are addressed successfully, for example with universal energy access achieved by ca. 2030. As a result, the qualitative scenario storylines describe developments in which, arguably, the pressure for rural to urban migration is significantly relieved, which suggests their reflection in the GEA urbanization scenarios. Therefore, three urbanization scenario variants based on a single medium population projection were developed. One scenario (GEA-supply) uses the UN Urbanization Prospects projection directly as input, whereas the other (lower) scenarios (GEA-mix and GEA-efficiency) adopt the methodology outlined in Grubler et al. (2007) using a model recalibrated to the most recent (2010) UN urbanization data. The resulting scenario differences in projected rural and urban populations bracket the potential impact of successful rural development policies that relieve urban migration pressures (GEA-efficiency) compared to largely unaltered patterns in rural and/or urban locational advantages (GEA-supply) and illustrate to policymakers the potential effects of altered policies that change the locational advantage of rural versus urban places.

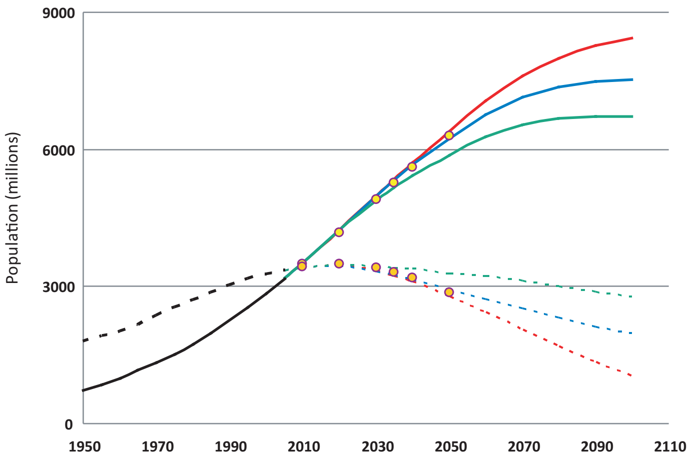

Figure 18.1 | Global urban (solid lines) and rural (dashed lines) population (in million). Historical trends 1950–2005 and scenarios to 2100 combining a medium population growth scenario (see also Chapter 17) with three alternative scenarios of urbanization rate growth (red, green, and blue, based on Grubler et al., 2007) and comparison to the most recent UN Urbanization Prospects projection (yellow and orange circles). Source: adapted from UN DESA, 2010.

is unaffected by the uncertainty of the urbanization scenarios and is a major, robust conclusion emerging from this assessment. The finding also adds urgency to corresponding efforts to improve energy access for the rural poor because if energy does not reach them soon, they will have an additional incentive to seek access in urban areas. After entering a path of negative growth, the rural population is projected to range from 2.8 to 3.3 billion by 2050 and to decline even further thereafter. However, the global picture masks stark regional differences: the Middle Eastern and African region will likely experience rural population growth until 2050 (or at the latest to 2080 in the GEA-efficiency scenario), while for all other regions the beginning of the decline the scenatio in rural populations is imminent or is already occurring (in the OECD90 region and in countries undergoing economic reform).

In 2050, the world is projected to be 70% urban with a comparatively narrow scenario uncertainty range of 64–70%. Latin America and the Caribbean, as well as the OECD90 countries, are expected to approach 90% urban, about the level of urbanization of the United Kingdom or Australia today.[4] By 2100, world urbanization levels could range from 71% to 89% with a corresponding urban population from 6.7 to 8.4 billion people. Thus, even in the lowest scenario, the world urban population in 2050 will be larger than the entire global population today.

18.2.1.6 Heterogeneity in Urban Growth

Patterns of urbanization are heterogeneous, including settlements of rapid growth, slower growth, and even cases of declining cities (Box 18.2). Urbanization is often equated with the growth of megacities. These vast, often crowded and complex, metropolitan areas with populations of 10 million or more are highly visible, and epitomize the challenges and problems of a rapidly urbanizing world, with pervasive poverty, slums, stressed infrastructures, etc. However, the reality of urbanization, both in terms of current settlement sizes (Table 18.3) and as historical and projected growth trends, is dominated by cities of smaller size (Figure 18.3). By 2005, just 19 cities worldwide met the megacity criteria (>10 million inhabitants) and their 284 million residents accounted for only about 9% of the global urban population. Conversely, some two billion people lived in cities with less than one million inhabitants, which corresponded to 63% of the world's urban population. Some one billion people or 37% of the urban population lived in smaller cities, less than 100,000 inhabitants,[5] in the year 2005.

The virtual absence of smaller cities and towns in statistical reporting, data collation, and modelling poses a serious problem and adds substantial uncertainty to any statement on urbanization trends. However, this should not lead to the erroneous conclusion not to focus analytical and policy attention on those cities that dominate the global urbanization phenomenon, most with <100,000 inhabitants. These numerous smaller cities pose a triple challenge for policymaking: data are largely absent, local resources to tackle problems with urban growth are limited, and governance and institutional capacities to implement policies for more sustainable urban growth are thin.

18.2.2 Urbanization Dynamics

18.2.2.1 Introduction

Modern towns and cities are generally recognized in the urban studies' literature as complex, largely self-organizing systems (Allen, 1997; Amaral and Ottino, 2004; Batty, 2005) that exhibit important agglomeration effects (National Research Council, 2003; World Bank, 2009). Cities are complex in the formal sense that recording their detailed behavior has vast information requirements. They are self-organizing in that interactions between partially informed citizens and between citizens and the city's 'hardware' form self-reinforcing patterns of land use and allocation of time. What was 'town planning' in the early 20th century is now seen more realistically as the facilitation of spatial patterns trying to emerge naturally (Hall, 2002).

Urban settlements show extraordinary resilience. Long-standing settlements reinvent their *raison d'être* many, many times. Large cities usually

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[4] Projected urban populations by 2050 at the country level (UN DESA, 2010) suggest that the two countries with by far the largest urban populations by 2050 will be China and India with some 1 and 0.9 billion, respectively. Ten countries are projected to have urban populations above 100 million by 2050 and, with the exception of the US (370 million), all of these are currently developing countries (projections by 2050 in millions: China, 1040 million; India, 875; Nigeria, 220; Brazil, 200; Pakistan, 200; Indonesia, 190; Bangladesh, 125; Mexico, 110; Philippines, 100).

[5] Calculated mainly as a residual to the estimates of total urban population.

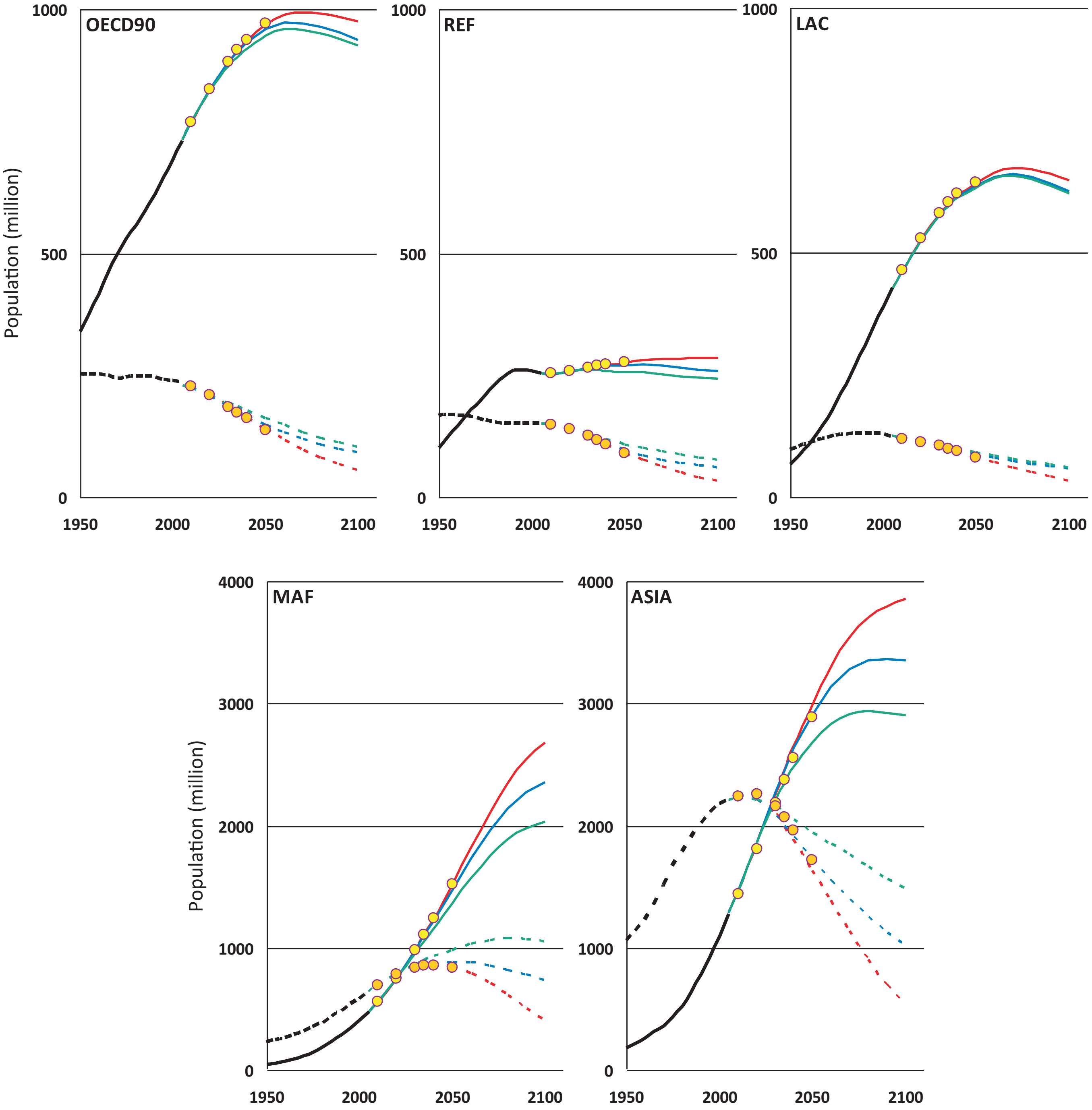

Figure 18.2 | Regional scenarios of urban and rural population (millions) for a medium population growth scenario (see also Chapter 17). Historical trends 1950–2005 and scenarios to 2100 for the five GEA regions (in millions). Regions: OECD90, OECD countries as per 1990 membership; REF: Countries undergoing economic reform, i.e., the reforming economies of Eastern Europe and the ex-USSR; LAC: Latin America and the Caribbean; MAF: Middle East and Africa; ASIA: developing economies of Asia. Urban population, solid lines; rural population, dashed lines. UN Projections (yellow and orange circles) and three alternative scenarios (red: GEA-supply, blue: GEA-mix, and green: GEA-efficiency).

confront constraints to existing paradigms first and have to develop innovative solutions (like freshwater-supply networks, and the use of clean secondary fuels) that are then taken up by innovation diffusion to smaller settlements. Energy *demand* considerations often serve as a shaping factor in settlements. Urban settlements, at least in times of peace, are more easily served by transport when in a valley, on a river, or on the seacoast. Differentiation of rental value takes place downwind of the pollution of energy-intensive industries. Prevalent solar and wind conditions often account for orientation patterns of streets and squares. In contrast, energy *supply* considerations have taken a secondary role in determining urban *form*. Indeed, the reverse has been true – urban form selects the energy mix. Large 19th century settlements needed coal because of the

Box 18.2 | Shrinking Cities

Urban growth is not a law of nature, as cities have stagnated in size over long periods of time, or even shrunk, and may well do so in the future. In addition, as national and international production and trade patterns change, some cities may lose their economic or strategic advantage and so shrink or even be abandoned entirely, for which history also provides ample examples. In the United States and Europe, many of the great 19th and early 20th century steel, textile, and mining centers and ports have lost economic importance and population (Cunningham-Sabot and Fol, 2009; Wiechmann, 2009); so too have some of the major manufacturing cities – for instance Detroit as a center of motor vehicle production. Also, in various high-income nations, from the 1970s there appeared to be a reversal of long-established urbanization trends nationally or within some regions with a net migration from large to small urban centers or from urban to rural areas. This was labeled counterurbanization, although much of it is more accurately described as demetropolitanization because it was population shifts from large metropolitan centers or central cities to smaller urban centers or suburbs or commuter communities.

Few systematic analyses have been performed on contemporary shrinking cities (UN HABITAT, 2008). Based on the latest assessment by the UN (UN DESA, 2010), of the 3552 cities with 100,000 and more inhabitants in 2005, 392 experienced a combined population loss of 10.4 million people between 1990 and 2005. While this seems a rather modest figure given the 3.2 billion urban dwellers in 2005, but for some cities population decline was substantial: a few hundred thousand inhabitants. The decline in urban population can, in some cases, be far from gradual but very fast, as in the eastern German city of Hoyerswerda (Pearce, 2010).

In the 80s, it had a population of 75,000 and the highest birth rate in East Germany. Today, the town's population has halved. It has gone from being Germany's fastest-growing town to its fastest-shrinking one. The biggest age groups are in their 60s and 70s, and the town's former birth clinic is an old people's home. Its population pyramid is upturned – more like a mushroom cloud.

Fearing decay, vandalism, and costs, high-rise apartment buildings are now being torn down. Cities also shrink as a reaction to an often painful economic restructuring process, as observed in countries of Eastern Europe and the former USSR undergoing economic reform. Most OECD90 countries have had persistently low fertility, well below replacement levels, for extended periods of time. If low fertility rates continue, overall population decline will become a reality. Shrinking cities amidst a growing or stable national population could then be replaced by a regime of national and city populations shrinking simultaneously. How this will affect urbanization remains one of the biggest challenges for understanding long-term urbanization trends.

The energy implications also remain an important area to be explored. Shrinking urban populations yield reductions in urban energy use. Such trends are, however, likely to be counterbalanced by the effects of potentially larger residential floor space available for the remaining population as well as increases in transport energy use associated with lower population density. The economic viability of urban transport and energy infrastructures in shrinking cities may also be challenged, but on this aspect no data or studies are available currently.

transportation problems associated with taking wood into the dense center. Later, they needed the coal processed into town gas to provide better quality services, like lighting. Urban settlements developed in inhospitable environments once they could depend on the provision of high-grade energy to run mechanical and electrical building services (Banham, 1969). Over the long perspective of future energy-infrastructure planning and population growth, the self-organizing properties of urban space need to be taken seriously. An historical novelty would be a reconfiguration of the urban form to reflect constraints on energy supply.

18.2.2.2 Inter-Urban Complexity

Some of the most compelling evidence that complexity theory is at work is that settlements within the range of a mobile population as ranked by population size approximately conform to Zipf's rule – size is inversely proportional to rank (Zipf, 1949; see Figure 18.4). This is true at least to within the indeterminacy of the definition of an urban population. Each urban center is then in a dynamic equilibrium with the larger urban system and, although urban settlements may present themselves as 'self-contained,' they are far from it. The implication is that at the margin, urban settlements show no total economies or diseconomies of scale. If they did, they would simply disperse to a uniform size or accumulate in a single megatropolis. This conclusion may not apply to any specific economic activity (e.g., the location of energy-intensive industries or finance centers). Large cities and small towns do different things, but large and small appear to show no special advantages in the economy as a whole. The implications of the urban rank-size rule for this assessment suggest that any undue overemphasis on the top end of the distribution curve (i.e., an exclusive focus on 'megacities') is certainly not

Table 18.3 | Population in urban locations by city size class in 2005.

Size class	Total City population	Proportion of total urban population
	2005	
	Millions	*%*
Total urban population	3,167	100
<100,000	1069	34
100,000–1,000,000	932	29
1,000,000–5,000,000	673	21
5,000,000–10,000,000	209	7
>10,000,000	284	9

Source: UN DESA, 2010.

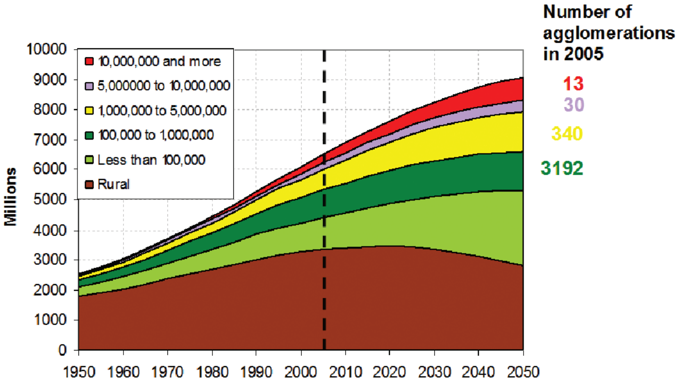

Figure 18.3 | Population by residence and settlement type (millions). Historical (1950–2005) and projection data (to 2050) (for 2005 statistics, see Table 18.3). The number of agglomerations within each size class are also shown for reference. The total number of urban settlements/agglomerations in the size class below 100,000 inhabitants remains unknown. Source: adapted from UN DESA, 2010.

warranted, as smaller cities constitute the majority of the continuum of the rank-size distribution curve.

At present, few data or studies are available that explore the implications of the rank-size rule for urban energy use. Bettencourt et al. (2007) identified economies of scale effects for urban energy infrastructures for gasoline distribution and electricity distribution grids (cables); i.e., large cities (in terms of population size) have proportionately smaller energy infrastructures than smaller cities, at least in Germany and the United States. In terms of energy use, the sparse available evidence is mixed: transport energy use (gasoline sales) seems to be somewhat lower in larger cities in the United States, which appears plausible in view of the impacts of higher population density on lower automobile dependency. Conversely, electricity use appears to grow somewhat overproportionally with city size (United States, Germany, and China). However, it is unclear whether this is a genuine urban scale effect or simply reflects fuel substitution effects where larger and denser cities exhibit higher preferences for clean, grid-dependent energy carriers (more electricity and/or gas and less oil and/or coal) compared to smaller cities. This remains an important area for future urban energy research.

It now seems likely that the power-law size distribution results from many co-existing stochastic processes (Sornette and Cont, 1997) with a similar statistical effect to that of a long tail power law. The only constraint on candidate processes is that the stochastic growth retains a long tail power-law distribution on average as the national population grows. In fact, very simple growth processes can generate power laws. For example, Ijiri and Simon (1975) obtained a power-law tail by assuming that annual population growth is randomly distributed across settlements in proportion to their size. The key to maintaining a power-law distribution over time is not the modeling of the largest settlement, but the model mechanisms for creating and retiring the smallest.

The robustness of the Zipf law means mechanisms that populate the large number of smaller settlements play a more important role in urbanization dynamics in most countries than the growth of the few largest cities, as amply confirmed by urbanization statistics (see Section 18.2.1.6), which adds to the conclusion herein on the urgent need to study smaller sized cities in terms of their energy and environmental implications.

18.2.2.3 Intra-Urban Complexity

While the smallest settlement is, to some extent, a matter of statistical definition, at its most basic level there is an economic and physical limit to the size of settlement that can manage its own water, sewage, power, and administration collectively, at a few thousand people. This reasoning about the dynamics of growth replicates within the urban settlement itself (Batty, 2008). Quanta of growth similar in size to the minimum urban settlement appear in the history of large cities, marked out by physically distinct districts. There is a subtle interplay between the technical quanta defined by the constraints of urban engineering and the economic and social aspirations of citizens. It is possible to think of a district as a cellular automaton that can be flipped in status according to rules that relate the status of adjoining districts. This dynamic suggests that up to some rate-of-event threshold the city remains heterogeneous, with districts changing their designation from time to time. Above some co-existence threshold, groups of districts start to cluster together in one class and the designations segregate (Schelling, 1969), which can act as a precursor to the formation of slums and ghettos as development capital is diverted elsewhere. This phase change can be seeded by an infrastructure change (an investment in public space or a waste incinerator). Cellular automata models can reproduce many of the key social spatial statistics of urban settlements (Batty, 2005).

The attachment of new zones and transformation of others reflect urban-area attempts to gain the advantages of agglomeration while

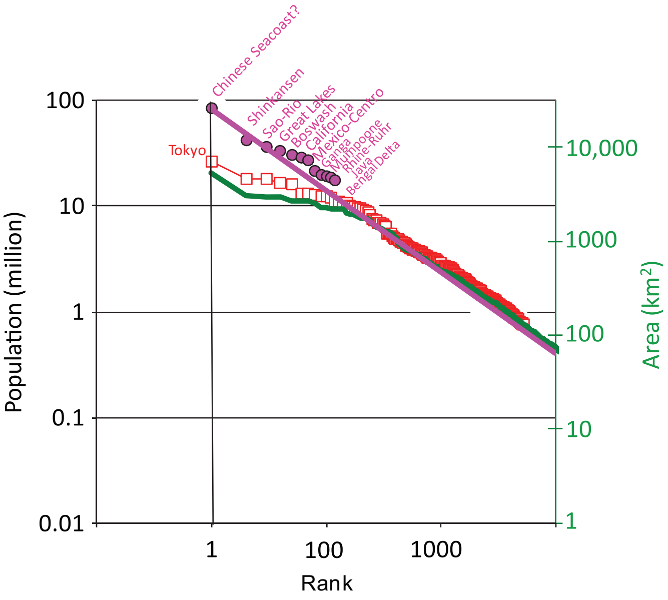

Figure 18.4 | Rank-size distribution of global cities by population. Note the irregularity in the distribution at the largest cities when defined by their administrative boundaries. Conversely, by aggregating individual cities to 'urban clusters' or 'corridors' the regularity of the global city rank-size distribution is maintained. The designation of an emerging urban cluster along the Chinese seacoast is entirely speculative. The currently largest urban cluster is found in Japan along the Shinkansen corridor, with some 70 million inhabitants. The rank-size distribution of global cities not only extends to their populations (red for cities and magenta for urban agglomerations), but also to their area (land cover; green). Source: Grubler et al., 2007, based on Marchetti, 1994; city area distribution from Yamagata, 2010, based on Kinoshita et al., 2008.

internally separating discordant functions (Fujita et al., 1999). Zoning, whether imposed or emergent, is then a natural property of an urban settlement. The dynamics of these processes have long been recognized as complex (Forrester, 1969). Indeed, modern urban planning frequently uses techniques from statistical mechanics to find the most likely aggregate properties from the nearly random effect of the thousands of citizen choices (Wilson, 2000). Administrative boundaries do not always follow the expansion of an urban area and care needs to be taken, for example, as to whether an urban settlement's quoted energy statistics refer to the current political or to the practical spatial reality.

Urban expansion can be seen as a process with land as an input, in effect making the town or city a 'space machine' reorganizing land use and connections (Hillier, 1999). Indeed, only a limited number of stable connectivity patterns seem to emerge for expanding urban spaces. This may, in part, reflect that the existing connection patterns have a very strong influence on the optimal connections within a new zone or district. Such an assumption underlies much of the modeling with cellular automata applied to understanding urban growth. Preferred joining rules are a common property in large complex systems that grow while remaining unconditionally stable (Fisk and Kerhervéa, 2006).

One constraint on the network is that expansion needs to occur such that the urban settlement remains socially and economically viable at all stages of growth. It may, in part, explain why urban areas adopt one of only a few configurations. The 'idealized' European city physically expands by absorbing smaller satellite centers and creating annular transport networks, to form a scale-free connectivity that enables access on foot to public transport. Low-income, low-rent areas cluster around those areas where transport to work is cheap.[6] In contrast, the 'idealized' North American grid city expands along its major axes and maintains a uniformity that avoids overstressing its original center, again using beltways to relieve congestion at intersections from clipping journeys. Although grid cities are superficially uniform, partitioning of rental value is often triggered by environmental factors (downwind, downriver, across the tracks) and agglomeration by local economies of scale. Both these urban configurations are characterized historically by capital investment in the city that matched the influx of population. Conversely, in many developing countries the migration rates from rural areas currently run ahead of capital formation, creating serious issues of energy access and infrastructure development (see Section 18.4.1).

18.2.2.4 Time and the City

While urban geography is naturally expressed as space, an urban settlement might equally be thought of as a complex time machine. Since the urban rationale is to bring specified people together at the same place at the same time to get things done, motion within the area needs to meet socially determined constraints in absolute time. Zahavi's rule (Zahavi, 1974) notes the rough constancy, in many countries over many decades, of the time spent traveling during a working day. This presumably reflects the constancy of many shared social norms, such as when work starts and ends and when entertainment begins. Since different modes of travel involve different amounts of physical work by the traveler, the social norm also sets upper limits on how tired the traveler can be on arrival (Kölbl and Helbing, 2003). The dynamics of land-use changes then 'solve' the consequent set of time constraints. Thinking of a city as a vast set of service connections self-consistently feasible within given absolute time windows is a complementary dynamics paradigm with some useful explicative power.

Transport improvements (or the prospect of them) tend to induce land-use changes and investment, and not save traveling time (as reviewed in Metz, 2008). In urban areas the local density of travelers on the move directly affects the average speed of travel and also indirectly decides safe speed limits. A city with high values of speed averaged over complete journeys can support journeys of longer length, within social

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[6] In cities of developing countries, economic pressures to relocate slums that enjoy a transport locational advantage are therefore high. Conversely, locating the poor far outside the city with poor (and expensive) transport access (as was the case in apartheid South Africa) further disadvantages them socially and economically.

norms, and so individual service points sweep larger areas of clients. Increased average speed supports larger agglomerations (e.g., large retail shopping malls) and so gains economies of scale. Higher speeds can give greater separation between incompatible land uses without breaking scheduling norms.

As a consequence of land-use adjustments, high-speed cities have longer average journey lengths, but this means their growth dynamics can relax to lower densities with greater local accumulation. An hour or so traveling time represents the effective limit to the radius of commercial activity of an urban settlement. The resulting dependency of transport-energy use on urban density is roughly linear when plotted against the mean interpersonal distance interpreted from two-dimensional urban density (Kenworthy and Newman, 1990), as might be expected from a largely traveler-interaction effect. Since the total start-to-finish journey time is the key determinant of location there are densities below which only individual motorized transport can provide a plausible service. By the same token, as urban density increases the interaction between travelers becomes increasingly significant and energy use ceases to fall as energy is wasted in congestion and traffic queues. Very high density centers offer little advantage to transportation because congestion is so severe (especially true in cities in which both the mass transit and private transit systems become embroiled in the same gridlock). Urban areas in this state tend to spill outwards and create a self-organizing critical density consistent with the underlying social norms.

18.2.2.5 Economic Complexity

The new insights of complex system 'econophysics' complement rather than displace traditional urban economics. The timescales and spatial statistics employed tend to be different. Ecophysics focuses on changes over long timescales and wide spatial averages, while traditional models the short-term dynamics that manage the scarcity and surplus of individual space. The overlap is the understanding of the dynamics of rents, both in the form of local taxation and 'ground' rents. These influence income distribution and the dynamics of investments and also change the economics of urban- versus rural-based activities (Irwin et al., 2009). Differences between urban settlement dynamics in different societies may also reflect institutional differences (e.g., as reviewed by Diamond, 2004).

18.2.2.6 Future Dynamics

The energy demand and energy mix of urban settlements normally follows rather than leads urban expansion (Seto and Shepherd, 2009). However, the historical generalities of urban growth hide the continual adoption and invention within the settlements themselves. Even new transport technologies that made such a fundamental contribution to urban form usually arose from solving a problem caused by an existing technology. So projecting the urban future on the basis of past trends is dangerous if attention is not paid to changes in detailed mechanisms. Indeed, some signs indicate that this new urbanized century might be different in character from the urban-rural mix that preceded it.

For example, the simplicity of Zipf's law is now retained for the world's largest cities only if the associated metropolitan region is treated with the city as one (see Figure 18.4 above). If airline connectivity is a new paradigm of interurban transport, the connectivity of the largest cities appears not to have caught up with expectations from a natural extension of the power law to describe airline connectivity of smaller towns (Guimerà et al., 2005). Indeed, scaling arguments (Kühnert et al., 2006) suggest that the frequency with which settlements need to find paradigm-shifting innovations must increase as they grow. Since breakthroughs are, by definition, unforeseeable there is a future scenario in which the growth of the world's largest metropolitan areas falters.

Urbanization forms part of the demographic transition and is expected to deliver a stabilization and then decline in world population around the middle of this century. As a consequence urban settlements may face retractions in some unspecified form. How built form relaxes to new configurations poses a fascinating question to a new understanding of urban structure.

18.2.3 Specifics of Urban Energy Systems

In principle, urban systems are not fundamentally different from other energy systems in that they need both to satisfy a suite of energy-service demands and to mobilize a portfolio of technological options and resources. However, urban systems also have distinguishing characteristic that sets them apart:

- A high density of population, activities, and the resulting energy use and pollution (see Section 18.4.2 for a more detailed discussion).

- A high degree of openness in terms of exchanges of flows of information, people, and resources, including energy.

- A high concentration of economic and human capital resources that can be mobilized to institute innovation and transitional change.

Urban areas are characterized by high spatial densities of energy use, which correspond to their high population concentrations, and by low levels of energy harnessed and extracted: cities are loci of resource management, processing, trade, and use, rather than of resource extraction or energy generation. All settlements depend on a hinterland of agriculture, forestry, mining, and drilling; in the present fossil-fuel economy, this hinterland has a global reach. Indeed, the same may be true of many rural areas, which, in developed countries, often focus on a few crops. These specialized rural areas also require imports of energy, goods, and services, which often may be on the same scale, per capita, as those of urban areas. Indeed, spatial division of labor is a characteristic of modern societies, with consequences for local energy use and policies. In industrialized countries both urban and rural areas depend heavily on energy-intensive industry, which may be located in or outside cities. If heavy industry is located outside urban areas, urban energy use may apparently be lower than rural energy needs, even though urban dwellers also consume the products from industrial activities.

High levels of energy demand open possibilities to reap significant *economies-of-scale* effects in energy systems, in supply as well as in transport and distribution. (It is not a coincidence that, historically, many major, large hydropower resources were developed to supply electricity to large urban agglomerations, from Niagara Falls in the Unites States to Iguacu (Itaipu) in Brazil.) Simultaneous to cities being loci of a wide diversity of activities, significant *economies of scope* are possible. The wide range of different energy applications from high-temperature industrial processes down to low-temperature residential home heating, and even to the energy provision of greenhouses, allows the maximization of energy efficiency through better source-sink matching of energy flows in the system, be it through conventional cogeneration schemes or through more complex waste-heat 'cascading.' These can, however, only be realized if diverse energy uses in a city are sufficiently mixed and co-located to allow these concepts of 'industrial ecology' to be the implemented. On the negative side of density, typical urban agglomeration externalities are important: low transport efficiencies through congestion and high pollution densities add urgency to environmental improvement measures. Retrofitting a high-density built environment can also incur many transaction costs that would not apply in low-density developments. However, it is no coincidence that cities have always been the first innovation centers for environmental improvements (Tarr, 2001; 2005).

The latter perspective is perhaps the most fundamental for the transformation of energy systems. Urban agglomerations are *the* major centers and hubs for technological and social innovation (Kühnert et al., 2006), as they both dispose of and mobilize formidable resources in terms of human, innovation, and financial capital. Bringing these transformations to fruition may ultimately be of greater long-term environmental significance than any short-term environmental policies. So, energy and environmental policies in an urban context may have substantial leverage in inducing further much-needed innovation in the core, where such activities take place.

18.2.4 City Walls and Urban Hinterlands: The Importance of System Boundaries

18.2.4.1 Introduction

Measuring the energy use of cities is no easy task, compounded by the absence of widely agreed measurement concepts and data-reporting formats. And yet for reasons of scientific enquiry, policy guidance, and political negotiation the important issue of 'attribution' needs to be addressed. The seemingly easy question of "How large is the energy use (or associated GHG emissions) of a city and what can be done to reduce it?" can vary enormously as a function of alternative geographic and system boundaries chosen. Therefore, this section reviews the different issues that must be addressed in urban energy assessments and aims to clarify the various concepts and definitions and help make their differences more transparent. In a modification of an old adage that only what get's measured gets controlled, this chapter postulates that only what is measured correctly and transparently at an urban scale is useful for policy guidance.

As a simple example of the importance of boundaries in urban energy assessments consider the issue of the administrative/territorial boundary chosen for defining a given city. Barles (2009) studied the fossil-fuel use of Paris, its suburbs, and the larger Parisian metropolitan region. The per capita fossil-fuel use was lowest in the city of Paris, and increased as the region considered expanded. This phenomenon is caused by a combination of inherent and apparent factors: the inherent factor is the lower transportation energy required by areas of higher population density (in central Paris with its formidable Metro system, compared to its suburbs); the apparent effect is the changing of the system boundary to encompass more energy-intensive industrial activities located beyond the city center.

Generally, urban-energy assessments must be oriented either to physical, and hence local, energy flows (a 'territorial' or 'production' perspective) or, if trade effects are included, follow economic exchanges linked to energy use (a 'consumption' perspective). The joint consideration of the production and consumption perspectives is most likely to yield a full assessment of urban energy,[7] albeit to date the literature and data base for such a comprehensive perspectives is extremely limited.

In assessing a variety of local and upstream contributions to the urban metabolism, it is sometimes tempting to aggregate the disparate elements into one indicator. For instance, the ecological footprint (see Rees and Wackernagel, 1996) is increasingly used to describe the impact of urban resource use (e.g., in London, Barcelona, and Vancouver). The ecological footprint of an urban area is invariably larger than the surface area of the city itself, which leads to the facile (but erroneous) conclusion that the city is 'unsustainable.' Cities are part of an exchange process, whereby they produce manufactured goods and services while depending on a hinterland for their supplies – and the existence of this hinterland cannot of itself be unsustainable. Better indicators are the relative magnitude of resource use and emissions (per capita, household, or income), compared to rural or other urban populations, or environmental limits, like carbon accumulation in the atmosphere. Since the ecological footprint is, in any case, driven

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[7] The terms 'direct' and 'indirect' energy are avoided here, since they have a different meanings in each of the approaches considered. Instead, the terms 'final,' 'primary,' 'upstream,' and 'embodied' energy are used here.

Table 18.4 | Overview of urban energy-accounting frameworks.

Approaches	Data basis	Definition of energy users	Position along energy chain	Upstream or embodied energy	Territorial/Production or Consumption approach
Final energy	Physical	Final user (energetic)	Final	Not included, can be added using typical conversion efficiencies between primary to final energy for different energy carriers	Territorial Example: Regional energy statistics, Baynes and Bai, 2009
Regional energy metabolism	Physical	Region	Combination of final, secondary and primary	Not included, but can be added using typical conversion efficiencies	Territorial example: Schulz, 2007
Regional economic activity	Economic (physical extensions)	Final demand (economic)	Total Primary Energy Supply	Includes upstream & embodied energy of goods and services, no sectoral differentiation	Territorial Example: Dhakal, 2009
Energy Input-Output	Economic (physical extensions)	Final demand (economic)	Total Primary Energy Supply	Includes upstream & embodied energy of goods and services, no sectoral differentiation	Consumption Examples: Weisz et al., 2012; Wiedenhofer et al., 2011

by fossil-fuel carbon emissions, studying urban energy use directly appears to be a more constructive approach.

18.2.4.2 Energy Accounting Methods

Table 18.4 classifies the various methods used to estimate urban energy use. This classification utilizes two main criteria: the basis of the data and the definition of energy users. The first two methods are based on physical flows, and as such produce 'territorial' or 'production' oriented energy balances; the other two focus on economic flows, and are 'consumption' oriented. The economic-based models (regional economic activity and economic I-O (input-output) approaches) are further distinguished by the level of sectorial detail.

The 'final energy' method uses physical data, such as energy statistics from utilities or fuel sales, as the data basis. Users are defined as energetic end users within the city boundaries. Energetic end users are the "consumers" of final energy (such as electricity, heat, gasoline, or heating fuels). It is important that both producers and consumers (i.e., firms and households) use final energy. By disaggregating the final energy use by sector, one can differentiate between residential, commercial, and industrial uses. These sectorial accounts of urban final energy use also allow comparisons with national level data or data of other cities and can serve as a useful guide, e.g., for energy-efficiency 'benchmarking' that can guide policy.

The direct final energy account can further be extended by estimating the *upstream energy* requirements needed to provide the final energy, using e.g., lifecycle analysis. The upstream energy is the primary or secondary energy use *linked to the final energy* utilized by the end users within a city. Depending on the estimation method, the upstream energy may or may not include the energy required to extract and transport the primary energy itself. For clarity, it is crucial to specify which type of upstream energy is considered: secondary, primary, or primary, including energy for extraction activities themselves. To avoid confusion with other terms used for upstream energy, this section reserves the term 'upstream' for energy-linked direct energy flows (mobilized outside the geographic city boundary, but linked to a city's final energy use), and the term 'embodied' for goods and services linked to indirect energy flows (i.e., energy embodied in resources, materials, and goods traded).

Final and upstream energy uses are not the total primary energy required by urban activities, since they do not include the energy needed to produce goods and services *imported* into the city. Conversely, the final and upstream energy uses of a city also include energy uses to manufacture goods and provision of services *exported* from the city (and consumed in other cities or in rural areas). Care therefore needs to be taken to avoid double counting of energy flows, for example by adding imported 'embodied' energy flows to the final and upstream energy uses of a city, but ignoring the (final and upstream) energy embodied in goods and services produced in a city, but exported for consumption elsewhere. This double counting is averted in I-O methods but can be a problem in approaches that rely on lifecycle analysis (Ramaswami et al., 2008; Hillman and Ramaswami, 2010).

The difference between the final and upstream energy use can be considerable. Take the example of electricity: typically, for 1 GJ of electricity consumed in a city, up to 3 GJ of primary energy in the form of coal must be burned in a conventional steam power plant. (This ratio is substantially lower for combined-cycle power plants fired by natural gas, which illustrates the need to consider the *actual* urban energy system characteristics rather than aggregate 'upstream' adjustment factors.) Heating fuels, such as gas and fuel oil, also have upstream energy use through their extraction and transport. According to Kennedy et al. (2009), who applied this method to the GHG emissions of 10 global cities, the lifecycle GHG emissions associated with urban fuel use are between 9% and 25% higher than their local emissions. This approach is also that followed by the Harmonized Emissions Analysis Tool of the International Council for Local Environmental Initiatives (ICLEI, 2009), although since the software is proprietary (and not transparent),

Table 18.5 | Energy and material flows of selected cities showing the importance of energy flows in the total metabolism of cities.*

City	Cape Town	Geneva	Hong Kong	Paris Petite Couronne	Singapore
Reference	**Gasson (2007)**	**Faist (2003)**	**Newcombe et al. (1978)**	**Barles (2009)**	**Schulz (2005)**
Population (millions)	3	0.4	3.9	6.3	4.1
Year	2000	2000	1971	2003	2000–2003
Energy (GJ/cap/year)					
Primary	40		72		258
Regional (city)	22	92	43		103
Domestic material consumption (tonnes/cap/year)					
Total		7.7		4.6	29.7
Fossils		1.8		2.1	5.2
Biomass		1.0			0.3
Construction minerals		4.8			22.5
Industrial minerals and ores		0.1			1.7[1]
Water	110	151	100		112

* Domestic material consumption = domestic extraction + imports – exports, which in the urban case is dominated by imports.

1 includes other products

geographically limited, and often applied only to municipal energy use, it is not clear how reliable or significant the results are.

The 'Regional Energy Metabolism' method also uses physical data, but defines the user as a geographic region (in this case, boundary of the urban area): thus, all energy flows that cross the regional boundary are measured. This method is based on a socio-metabolic understanding of the city, including energy, materials, water, important waste flows, infrastructure stocks, and other relevant physical attributes of a city. Indeed, a complete urban metabolism would include other energy flows, such as the calorific value of physical goods entering and leaving the city and biomass for human (and animal) nutrition, which are not included in other approaches. This method includes all the energy that is imported into the city, regardless of its conversion stage. In contrast to the final energy method, the primary energy used by the energy sector *within the city* is included in the regional energy metabolism. Thus, the location of a power plant inside or outside a city's boundaries has a large influence on the measurement of its energy use in this method. As a result, the regional energy metabolism of a city is always larger than its final energy. The mixture of primary and final energy, however, makes it difficult to compare this method's results with national level data and those of other cities.

So far, the urban metabolism approach has been applied to material flows rather than energy flows for Cape Town (Gasson, 2007), Geneva (Faist et al., 2003), Hong Kong (Newcombe et al., 1978), Paris (Barles, 2009), and Singapore (Schulz, 2006; 2010b; see also Chapter 1). Table 18.5 summarizes some findings from urban metabolism studies. Energy is extremely important in the urban metabolism: energy carriers represent a significant share (a quarter to a half) of domestic material consumption. Moreover, other materials consumed (biomass, construction and industrial minerals, and ores) also represent important flows of embodied energy.

The 'Regional Economic Activity' approach uses the urban final demand aggregate (defined in *economic* (monetary) terms, that is as gross regional product (GRP)) and a national or regional energy-to-GDP relationship to estimate the city-specific energy use. This method was used by Dhakal (2009) for major Chinese urban areas (see Section 18.5.2), and is the only possible approach when no city-specific energy data are available. However, the limitation of this method is that it ignores all city-specific drivers of urban energy use except income. The national or regional energy-to-GDP ratio usually uses total primary energy supply as the energy variable. This method is thus fully comparable with statistics on the national level.

'Energy I-O' accounting approaches are based on national economic I-O tables, which measure (usually in monetary terms) all sales and purchases of goods and services among the producing sectors and to final demand. These tables can be extended to account for physical energy flows or emissions. Based on I-O tables, the 'embodied' energy (i.e., the energy used throughout the whole production chain to produce the final goods and services) can be calculated. This approach allows allocation of energy use to specific sectors of economic activity. Using consumer-expenditure surveys for urban areas, I-O studies have assessed the energy use of Indian urban and rural populations (Pachauri et al., 2004; Pachauri, 2007), Brazilian urban households (Cohen et al., 2005), Sydney's energy use (Lenzen et al., 2004), as well as for postal district resolution maps of Australia (Dey et al., 2007). Illustrative results on direct versus embodied energy use in Asian megacities based on I-O analyses are given in Figure 18.5.

First, it is important to recognize how embodied energy flows compare with direct energy flows, particularly for high-income cities such as Tokyo. Second, the dynamics of energy flows are characterized by the

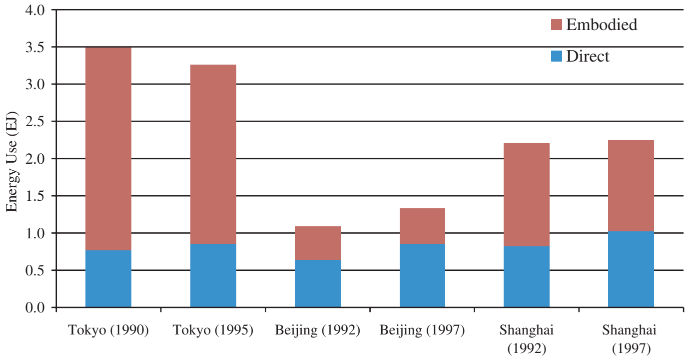

Figure 18.5 | Estimates of direct (on-site) versus embodied (via imports of embodied energy in goods and services) energy use of Asian megacities. Source: Dhakal, 2004, based on Keneko et al., 2003.

growth of direct energy flows (income growth leading to buildings and transport energy demand growth), whereas embodied energy growth remains comparatively flat. In these examples the income effect on direct energy use is larger than changes in trade flows into the city over the limited time period considered in the studies.

I-O avoids the thorny issue of double counting, as only the final demand (i.e., household consumption – and that of government, even though this is rarely reported) serves as the allocation unit of all direct (including upstream) and indirect energy flows, whereas industrial and service-sector energy uses are treated as intermediary uses, allocated to final consumption (in a city and elsewhere) based on expenditure levels and structure. Hence, this approach is often referred to as a 'consumption' approach, as opposed to the 'production' approach that focuses on apparent energy use. The I-O based 'consumption' approach can thus differentiate between cities with different incomes and final consumption patterns, but cannot capture differences in industrial and service energy use, not to mention differences in energy systems (e.g., degree of cogeneration) between different cities. The issue of the representativeness of national I-O tables for cities with different consumption structures, even within identical expenditure categories, and with different (usually higher) price levels has not been addressed by systematic studies. National I-O analyses do not provide information on embodied energy flows in commodities and goods traded internationally, which requires the use of multiregional I-O models, whose data quality is often weak. Studies performed for Norway (Peters et al., 2004), the United Kingdom (Wiedmann et al., 2007), and the United States (Weber and Matthews, 2008) show that a significant fraction of energy use can be attributed to imports, especially in industrial economies (Peters and Hertwich, 2008). The application of the I-O method to developing countries is, however, not straightforward, since the large informal sector is absent from the official I-O tables, which themselves exist in up-to-date versions only for a few developing countries. It has also been shown that uncertainties are very large for the GTAP (Global Trade Analysis Project) database used in multiregional I-O models (Weber and Matthews, 2008).

From the I-O studies, the largest categories in urban household energy use are housing, electricity, transportation, and food. Of these, food and electricity have the largest upstream and embodied energy "content." Thermal electricity generation involves heat losses up to two-thirds during transformation, plus transmission and distribution losses. Food has both nutritional and embodied energy components: a diet of 3000 kcal/day corresponds to 4.5 GJ/year in nutritional energy per person. The commercial primary energy required to produce food ranges from 2.5 to 4.0 GJ/capita for Indian urban households and from 6 to 30 GJ/household for Brazilian urban households (where the ranges correspond to low and high income brackets) to around 40 GJ/capita for European households (Vringer and Blok, 1995; Pachauri, 2004; Cohen et al., 2005). The majority of the energy embodied in food production is consumed outside city boundaries.

Comparison of energy-accounting frameworks

To compare and contrast the results from different accounting approaches Chapter 18 initiated a collaboration among various research teams to provide a quantitative illustration, applying two different methodologies ('final energy' and 'energy I-O') for two different cities: London and Melbourne. Recent (partial) results for Beijing are also included for comparison. These two approaches are often contrasted at the national level for energy or GHG, where they are generally known as 'production'[8] or 'territorial' (for the 'final energy' method), and 'consumption' (for the 'energy I-O' method) (see, for instance, Peters, 2008).

For the Melbourne study, Manfred Lenzen and his group at the University of Sydney used environmentally extended I-O methods coupled with household expenditure surveys to map direct and embodied GHG emissions of household consumption (Dey et al., 2007). This method was adapted to provide results in terms of primary energy use for the city of Melbourne (Australia). Baynes and Bai (2009) scaled state data down to the urban level, focusing on the (direct) final energy use of Melbourne city. The London study compares final energy use from official statistics (UKDECC, 2010) and results from a multiregional, environmentally extended I-O analysis with explicit representation of the household consumption vectors for the Greater London Authority. The yet unpublished study is based on a method of Minx et al., (2009) and was carried out by the Technical University of Berlin, the Potsdam Institute for Climate Impact Research, and the Stockholm Environment Institute.[9] The Beijing study (Arvesen et al., 2010) only considered household energy use (and hence misses the large industrial and service sector energy use) and combined both the final energy method (with additional approximate fuel-specific estimates of upstream conversion energy needs) with an I-O approach.

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[8] The term 'production' accounting as applied to household energy use is somewhat misleading, but to not introduce further terminological complexity, the term (well established in the national scale literature) is retained here.

[9] Weisz et al., 2012.

Table 18.6 | Primary energy use for two different energy-accounting approaches for three cities for which (partial) data are available: Melbourne, London, and Beijing. All values are expressed in GJ/capita (permanent) resident population. Dashes (-) indicate categories of energy use that cannot be compared directly between the two different accounting methods.

Primary energy GJ/capita for:	Melbourne 2001		Greater London 2004		Beijing 2007 Household energy only	
	Pop.: 3.2 million		Pop.: 7.6 million		Pop.: 12.1 million	
	Prod. acc.	Cons. acc.	Prod. acc.	Cons. acc.	Prod. acc.	Cons. acc.
Residential heating	22	12	28	–	9	–
Residential electricity	28	30	17	–	9	–
Residential housing (heating + electricity)	50	42	45	35	18	11
Private cars	33–41	27	10	–	7	7
Nonresidential use	197	–	56	–	n.a.	–
Household consumption of goods and services	–	116	–	108	–	34
Total	279–288	184	111	143	25	52

Pop = population; Prod. acc. = production accounting; Cons. acc. = consumption accounting; n.a. = not available.

The results are summarized in Table 18.6. To enable comparison, the position along the energy chain has to be the same, so the primary energy equivalent of final energy is estimated where detailed statistics are unavailable (using standard conversion efficiency factors from Kennedy et al., 2010). To correct for different sizes of the cities, all values are expressed in GJ/capita.

The two methods cover different types of energy flows, some of which can be compared, and others cannot (denoted by dashes in Table 18.6). Energy I-O ('consumption accounting') focuses on the energy use of households within the city boundary, directly and embodied in the purchase of goods and services. A direct comparison with the territorial final energy ('production accounting') method is only possible, therefore, for the energy directly purchased by households: for residential housing (heating and electricity) and (in the case of Melbourne and Beijing) private transportation. The final energy method also measures urban nonresidential energy (for industry and commercial activities, as well a non-private transportation), which the energy I-O method does not cover. Conversely, the energy embodied in the household purchase of goods and services is not covered by final energy method.

The most interesting result lies in the (first ever) quantification of the differences between the two different accounting methods. As expected, the consumption-based accounting method yields much higher energy use for London (+30%)[10] and Beijing (+100%). Conversely, Melbourne's territorial energy use is significantly higher than the energy used directly and indirectly by its households. This is not because the Melbourne households consume less energy: in fact, in total, they consume almost one-third more than the London households, mainly through private transportation (cars). Instead, it is because Melbourne's nonresidential energy use is almost quadruple that of London's, on a per capita basis. Melbourne is still a major industrial production center, and this industrial activity results in more energy per capita than that of household consumption. London, in contrast, has very little industrial activity, with services dominating its economic activities, and so household consumption is larger than the territorial production-account energy use. The importance of industrial energy use is also illustrated in the case of Beijing. Total secondary energy use (all sectors) in Beijing in 2007 was some 145 GJ/capita (Beijing Government, 2010), i.e., three times larger than the total direct plus embodied estimated household energy use reported in Table 18.6. Taking upstream energy conversion losses into account, the primary energy use (the energy level directly comparable to the other cities in Table 18.6) of Beijing is approximately 200 GJ/capita, i.e., in the same ballpark as Melbourne or London (production accounting). The major difference is that average per capita income in Beijing is with 10,000 *purchasing power parity* dollars (PPP$) per capita, approximately a factor four lower than that of Melbourne and a factor of six lower than London's, suggesting the twin importance of economic structure and efficiency of energy end-use as determinants of urban energy-use levels, with the latter offering a substantial potential for improvement.

The above results confirm that production accounting of energy reflects the economic structure of urban areas, and their role in the international division of labor, whereas consumption accounting energy reflects a mixture of local conditions (climate and transit infrastructure) and expenditure levels (income and lifestyle effects). This exercise also demonstrates the power of applying and comparing different methods at the urban level. By showcasing the differences in production and consumption accounting of energy, the potential role of local policy measures (e.g., transport) versus broader consumption measures (consumption

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[10] CO_2 accounts for London (Hersey et al., 2009) suggest that the differences between the two accounting methods could be 100% (some 45 versus 90 million tonnes CO_2 for the production versus the consumption accounting, respectively), a difference that appears very large in view of the results form the energy comparison reported here. I-O techniques are used here (Table 18.3.6) whereas the London CO_2 study used a lifecycle assessment approach to estimate consumption based CO_2 emissions (but the method and data have not been published), so there might be an additional methodological explanation for the large differences in estimates of the energy and CO_2 consumption-accounting 'footprint' of London.

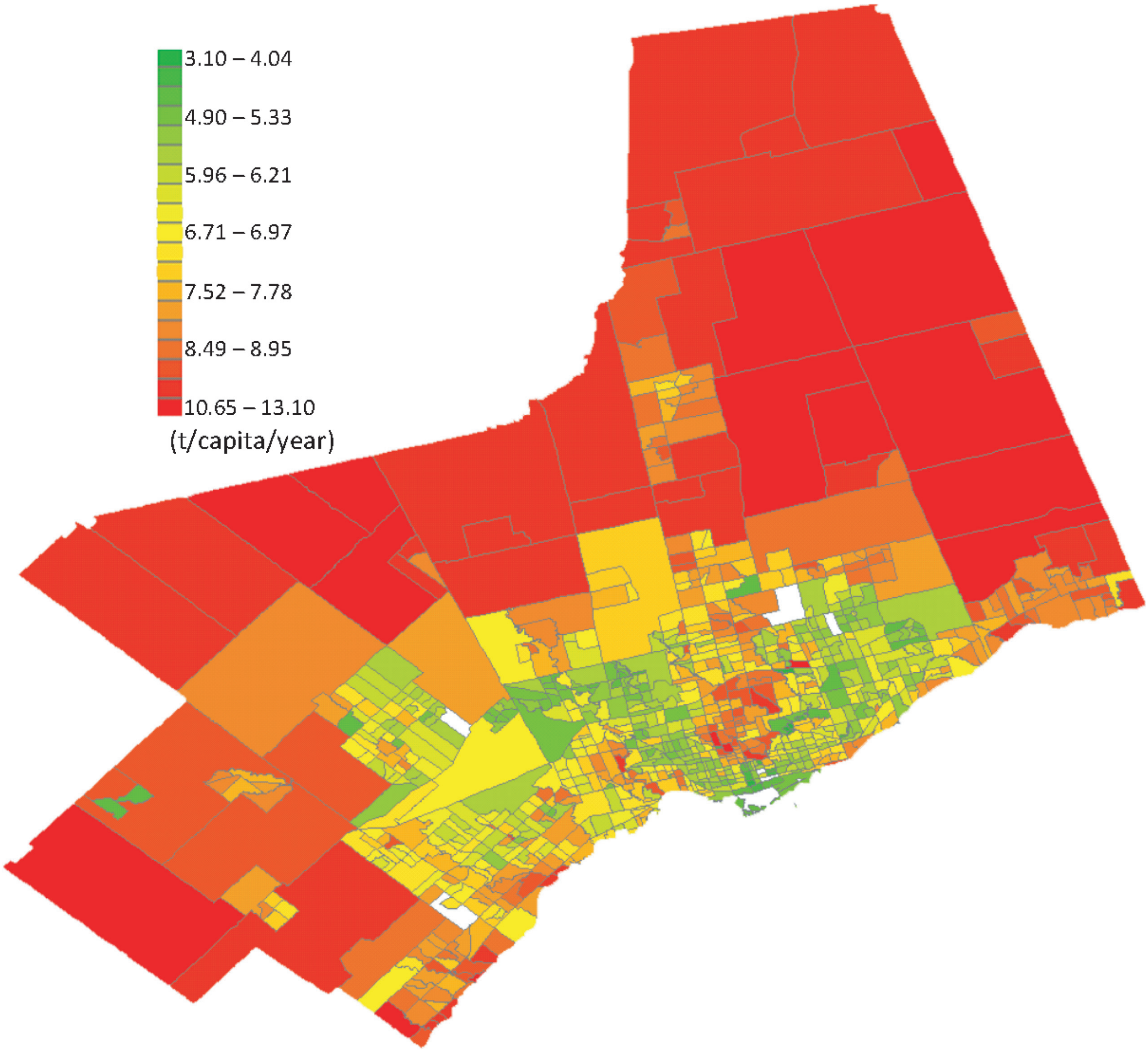

Figure 18.6 | Total GHG emissions from Toronto (tonnes CO_2-equivalent/capita/year). High-resolution images as well as maps for various energy-demand subcategories (residential, transport, etc.) are available from VandeWeghe and Kennedy, 2007.

reduction, or low energy/emissions supply chain management) can be made explicit.

The comparison of the two methods indicates two policy avenues. Local policy priorities should focus on housing, transit, and industrial energy savings. But these must imperatively be complemented by shifts and reductions in the energy embodied in household purchases of goods and services to avoid that savings at the regional level are offset by increased energy demand from the consumption of goods and services, which occurs somewhere else in the world. Such a policy agenda clearly goes beyond the local level and needs to be addressed on multiple scales.

18.2.4.3 Spatially Explicit Urban Energy Accounts

Spatially explicit energy-use studies may be the key to understanding the influence of urban form and periurban and urban specificities. For Sydney, Lenzen et al. (2004) disaggregated total primary energy use in 14 areas, and followed this up with a GHG emissions atlas of Australia at the postal district level (Dey et al., 2007). For Toronto, VandeWeghe and Kennedy (2007) derived spatially explicit direct-energy use based on transportation and energy-expenditure surveys (see Figure 18.6). Andrews (2008) analyzed direct energy use of several districts in New Jersey, ranging from rural to urban. A comprehensive spatial GHG account, including discussions of uncertainties, was recently completed for the city of Lviv, Ukraine. An innovative study used the Vulcan emissions atlas to compare transportation and building emissions in urban, periurban, and rural counties of the United States (Parshall et al., 2010).

The Sydney and Toronto studies found higher energy and emissions in the outer, low-density suburbs. The US study also found a 'threshold' effect in per capita urban transportation energy compared to more rural counties. In Sydney and Toronto, building fuel use was higher in the center city. The causes for higher building energy in the center city could be the age and quality of the housing stock, the presence of an energy-intensive central business district, and higher incomes in those areas. In the Sydney study, where economic information is available, building energy use is highly correlated with income, but less correlated with population density. In Sydney, central districts tended to have higher incomes than the outer suburbs, a trend absent in the New Jersey study. Since these studies are of industrialized countries and automobile-based urban areas of North America and Australia, their results may not apply to urban areas more generally.

18.2.4.4 Recommendations for Urban Energy Assessments

The indeterminacy in defining 'urban energy' should not be misinterpreted as a flaw in the urban systems perspective. It reflects that the data are approaching the actual final-decision level at which the purpose of the decision, to some degree, can resolve many of the statistical and data ambiguities. For example, administrative boundaries and a production perspective are appropriate system boundaries if the decisions are to be undertaken by local administrations. Final energy-use data remain an essential and useful tool for analysis of energy efficiency and for crafting policies for improved efficiency. Conversely, a 'consumption' perspective on urban energy and GHG use helps to raise awareness that, ultimately, urban energy and GHG management cannot be relegated to an energy optimization task, but equally involve changing lifestyles and consumption patterns.

As urban energy statistics have a vital role in allowing agents to benchmark, it is essential to be sure that the methods are comparable and that 'gaming' is not taking place. Each of the methods described above can produce results that allow benchmarking and comparisons, as long as the method and data sources are described clearly, and consistent data, sectorial definitions, and system boundaries are applied and spelled out clearly. The method should also be as transparent and as open as possible, to guarantee reproducibility and fact checking. Moreover, examples of energy assessments that only account for some sectors are not measurements of urban energy. The sectorial distribution of energy use (residential, commercial, industrial, administrative) as well as purpose (transportation, heating) are essential complementary elements for informed analysis and decision making and should be an integral part of urban energy reporting.

Urban energy and GHG statistics should provide a basis for policy formulation, investment decisions, and further action toward climate protection. Therefore, it is essential that their origin and data quality is made transparent and methodologies are comparable. Suggestions to improve terminology are provided in this chapter. It is far too common to read 'the energy use of this city is *X* Joules,' without any qualification what type of energy (final or primary, including upstream or embodied energy) is referred to. There is also a rich field in enhancing the usefulness of urban energy accounts by expanded information on energy quality (e.g., separating heat demand by low, medium, and high temperature regimes), which can form the basis of extended energy efficiency studies, for example in the form of exergy analysis (see Box 18.6).

City energy assessments should also include clear definitions of the system boundary used. Currently, many urban energy assessments, in effect, arbitrarily choose the system boundary to reduce the reported energy use or GHG emissions, for instance by claiming their electricity comes from different sources than the average regional mix, or by excluding certain energy uses that are, nonetheless, central to the very functioning of cities, such as airports or a large tourist population. Arbitrary, or ill-defined, system boundaries defy the very purpose of urban energy assessments: to guide public and private sector policies and decisions and to allow comparability and credibility of the entire process.

18.3 Urban Energy Use

18.3.1 Current Urban Energy Use (Global and Regional)

How large is the urban fraction of global energy use? This seemingly simple question is hard to answer as, contrary to the data for countries, no comprehensive statistical compilation of urban energy use data exists. With 50% of the world population being urban, a range of (largely ballpark) estimates put the urban energy share between two-thirds to three-quarters of global energy use, but such global estimates have, until recently, not been supported by more detailed assessments. This Section reviews the two detailed assessments of urban energy use available to date: the estimate of the IEA published in its 2008 *World Energy Outlook* (IEA, 2008) as well as an estimate developed by a team of researchers at the International Institute for Applied Systems Analysis (IIASA) for this study.

In the absence of detailed, comprehensive urban energy-use statistics, two analytical approaches were pursued to derive global (and regional) urban energy use estimates. One technique, which might be labeled 'upscaling,' uses a limited number of national or regional estimates of urban energy use and then extrapolates these results to the global level. This is the approach followed by the IEA (2008) study that estimated (direct) urban energy use at the primary energy level. The second approach adopts 'downscaling' techniques in which national level statistics are 'downscaled' to the grid-cell level, and then combined with geographic information system (GIS)-based data sets on

Box 18.3 | Urban Energy Data: Measurement and Quality Issues

For urban energy data and assessments two major issues need to be spelled out in a clear and transparent way: (1) system boundaries, and (2) data availability and quality issues.

(1) Within the discussion of system boundaries two issues need to be considered:

   (a) What is the spatial or functional definition of the urban system under consideration? Does the city definition refer to the core city alone, or does the assessment include the larger metropolitan area? Does the system definition include recognition of bunker fuels[11] (transport fuels used outside of the spatial system boundary, e.g., in national and international territory) or not? Does it consider also the embodied energy associated with the use of material resources and goods other than energy carriers, or not?

   (b) What is the energy system considered? Is primary or final energy reported, and to what extent is a lifecycle perspective for the fuel provision followed (e.g., upstream energy conversion losses and associated emissions, or the costs of exploration, drilling, transporting, and refining fuels before import into the urban system are included or omitted in the analysis)?

(2) Quality and availability of energy data: are actual statistics used or extrapolated/downscaled data? Does the assessment include noncommercial energy?[12] Which spatial and temporal resolution was considered to calculate the fuel mix for electricity provision? Are differences in technology, efficiency, etc., of power plants and other energy conversion processes recognized?

In an ideal world, urban energy reporting should adopt as wide systems boundaries and complementary accounting frameworks as is reasonably possible and available data allow.

When narrower system boundaries are adopted, a simplified sensitivity analysis of the effects of inclusion of omitted system components can help to put reported numbers into a proper perspective (i.e., complementing final energy accounts with estimates of corresponding primary energy needs, or production-based accounts by estimates of consumption-based accounts based on national I-O tables).

Incomplete reporting (e.g., of only municipal energy use) should be avoided as only a comprehensive sectorial perspective of all urban energy uses can reveal the full potential for policy intervention and assure comparability across different urban energy accounts.

Finally, data disclosure and documentation of assumptions and methods are a 'must.' Particularly, the area of urban GHG inventories is replete with examples of glossy policy briefs that do not allow the reproducibility of the numbers presented (not to mention unreported uncertainty ranges). Transparency and data disclosure are not only key from the perspective of scientific integrity, quality, and reproducibility, but they are also the key for well-informed policy choices. A comparable effort to the standardization of energy and GHG accounts at the national scale along the OECD/IPCC model is long overdue for the urban scale as well.

urban extents is used to derive spatially explicit estimates of urban energy use. These are then aggregated to the national, regional, and global levels. This approach underlies the IIASA study that estimated urban energy use at the level of (direct) final energy, also reported in this section.

In the 2008 *World Energy Outlook* (IEA, 2008), a separate chapter is devoted to urban energy use and contains estimates of 2006 base-year urban primary energy use data and a reference scenario projection to 2030. Detailed urban energy use assessments were first commissioned for a limited number of countries and regions (China,

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[11] Bunker fuels, i.e. energy used for (international) air transport and shipping, can be a substantial fraction of urban energy use. In 'world cities,' like London and New York, air and maritime bunker fuels can account for about one-third of the direct final energy use, suggesting the importance of their inclusion in urban energy accounts.

[12] For many cities in developing countries, noncommercial energy forms can account for a substantial fraction of urban energy use (one-third to half). Its reporting is therefore not only key for a comprehensive urban energy accounting, but also yields important information on the potential of fuel substitution with rising urban incomes and hence future energy infrastructure needs.

the United States, the European Union, and Australasia (i.e., Australia and New Zealand)). In these regions urban energy use is estimated to range from 69% (European Union) to 80% (United States) of the primary energy use of these regions, which reflects their high degree of urbanization. For China the estimate is 75%, despite a comparatively lower urbanization rate (41% compared to 81% in the United States), but is explained by the substantially higher urban energy use in Chinese cities compared to the national average because of higher urban incomes and industrial activities. The results of the 'upscaling' of these four regional sets of data to the global level are not reported separately by region by IEA, so only global totals are discussed here.

The IEA (2008) estimates urban primary energy use at the global level to amount to some 330 EJ in the year 2006, or 67% of world primary energy use. Using an average global primary-to-final energy conversion efficiency of about 69%, the estimate translates to 230 EJ urban final energy use worldwide, which is in good agreement with the IIASA study results reported below. Estimates are also provided by major primary energy source and for electricity, assuming that the primary energy mix of cities is the same as at the national or regional average. This assumption is problematic, especially for countries of low-income, low-urbanization, particularly in Asia and Africa, where available data suggest that urban energy use structures are, in fact, very different from rural and national averages. Urban energy use is invariably characterized by much higher shares of grid-dependent energy carriers (electricity and gas) and by much lower reliance on traditional biomass fuels. This simplifying assumption in the IEA (2008) study also diminishes the plausibility of the study's scenario projections by primary energy carrier to 2030, where total urban primary energy use is projected to grow by some 56% from 2006 to 2030. In the IEA reference scenario almost 90% of global energy growth to 2030 is projected to result from urban energy use.

The IIASA study follows a different approach. Drawing on methods and data sets (see Grubler et al., 2007) developed for spatially explicit GHG emission scenarios, the IIASA study used spatially explicit GIS data sets of urban extents, constrained to be consistent with the latest UN WUP statistics (see Section18.2.2 above) for the year 2005 as initial input. In a subsequent step, national level final energy use data by fuel (traditional biomass and electricity) as well as by end-use activity (primary, light and heavy manufacturing industries, households, and transportation) were downscaled to the grid-cell level in proportion to available spatially explicit activity variables (population, GDP, light luminosity, etc.) under a range of plausible algorithms (hence the study provides central as well as minima/maxima estimates to illustrate uncertainty). The scenarios of individual final energy use categories were then aggregated per individual grid-cell and overlaid with the urban extent map to derive the total estimated (direct) final energy use (including noncommercial traditional biomass fuels) in urban areas. Table 18.7 summarizes the results for the 11 GEA regions and five GEA world regions, as well as for the global total.

Globally, urban final energy use in the IIASA study is estimated to range from 180 to 250 EJ with a central estimate of 240 EJ, or between 56% and 78% (central estimate, 76%) of total final energy. So, in terms of final energy use (as opposed to primary energy use reported in the IEA study), cities use 240 EJ, or some three-quarters, of final energy worldwide. The absolute amounts are in good agreement with the IEA (2008) study discussed above, at least globally.[13] Readers should not be confused by the somewhat higher urban percentage (76%) of urban *final energy* use of the IIASA study when compared to the 67% estimate of the IEA for *primary energy* use. As discussed above, the assumed identity in urban fuel and energy mix with national and/or regional averages in the IEA study underestimates the level of high-quality, processed-energy forms in urban areas that entail correspondingly higher upstream energy-conversion losses. If this simplifying assumption in the IEA calculations could be relaxed, the corresponding urban primary energy estimate would become higher and much closer to the three-quarter benchmark of the IIASA study.

These observations are corroborated by commercial final energy use in urban areas, i.e., excluding traditional biomass use. For industrialized countries, estimates of urban commercial fuel use are identical to the totals reported in Table 18.7. Major differences exist, however, for some developing regions. For sub-Saharan Africa, estimates suggest that 4 EJ, or some 80% of all commercial energy use, can be classified as urban (compared to 8 EJ and 54% for total final energy, see Table 18.7). Differences for South Asia are also noticeable: 8 EJ, or 71% of final commercial energy, are classified as urban, compared to 10 EJ and 51% for total final energy. Differences for the other developing GEA regions are comparatively minor, as little noncommercial energy continues to be used in cities. The higher urban share in commercial energy results both from higher urban incomes and better urban energy access and infrastructure endowments, particularly the much higher degrees of electrification in urban areas.

Nonetheless, despite some uncertainties[14] (see Table 18.7), both the IEA and the IIASA estimates confirm a highly policy-relevant finding: While some 50% of the world's population is urban, *urban energy already dominates global energy use*, which means that the energy sustainability challenges need to be solved predominantly for urban systems.

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[13] The lack of available IEA regional estimates limits the possibilities for a more detailed comparison, but in the reported four IEA regions, urban energy use is within the respective minima/maxima regional values of the IIASA study.

[14] The main source of uncertainty for the ranges reported in Table 18.7 is the fuzziness in delineating urban areas and population and hence the attribution of national energy use to the urban category. Conversely, the uncertainty in energy statistics is comparatively small, with the main uncertainty source being the lack of reliable data on urban noncommercial (traditional biomass) energy use, particularly in Africa.

Table 18.7 | Estimates of urban (direct) final energy use (including traditional biomass) for the GEA regions and the world in 2005 (in EJ and % of total final energy). See text for a discussion of urban commercial energy use and its corresponding (somewhat higher) urban share.

GEA Regions		Central estimate	%	min	%	max	%
NAM	North America	63	86%	51	69%	64	87%
PAO	Pacific OECD	14	78%	11	59%	16	92%
WEU	Western Europe	40	81%	31	64%	41	83%
EEU	Eastern Europe	6	72%	4	51%	6	72%
FSU	Former USSR	20	78%	14	54%	20	78%
AFR	Sub-Saharan Africa	8	54%	5	35%	10	71%
LAM	Latin America	17	85%	16	77%	18	89%
MEA	North Africa & Middle East	15	84%	10	58%	15	86%
CPA	China & Central Pacific Asia	32	65%	19	40%	31	65%
PAS	Pacific Asia	15	75%	10	51%	16	77%
SAS	South Asia	10	51%	5	29%	10	51%
OECD90	NAM+PAO+WEU	117	83%	92	66%	121	86%
REF	EEU+FSU	26	76%	18	54%	25	76%
MAF	AFR+MEA	23	71%	15	47%	25	79%
LAC	LAM	17	85%	16	77%	18	89%
ASIA	CPA+PAS+SAS	57	64%	35	40%	57	64%
WORLD		**240**	**76%**	**176**	**56%**	**246**	**78%**

18.3.2 GEA City Energy Data and Analysis

18.3.2.1 The GEA City Energy Data Base

An effort to compile a database with literature values of energy use on the urban scale was conducted as part of this assessment to improve understanding of the variation in energy demand of urban areas (for an example of such analyses, see Steemers, 2003).[15] The study, therefore, chose a cross-sectorial approach to compare as large a number of urban areas from as wide range of regional settings, geographies, sizes, and functions as possible, with minimal definitional constraints with respect to urban system boundaries so as to maximize data availability. In terms of energy-use, data are reported at the level of *total (direct) final energy use*, as this level of analysis creates the least ambiguity in terms of energy accounting and is also the indicator most widely available and comparable among case studies. (Accounting for primary energy equivalents or GHG emissions requires assumptions on boundary definitions, conversion factors, and efficiencies, etc., which introduce additional uncertainties in the comparisons.) Given the extreme paucity of consumption-based estimates of urban energy use (e.g., via I-O techniques), the decision to focus the database on a production approach was also straightforward.

18.3.2.2 Data Coverage

Three categories of urban statistical data were brought together in the GEA City Energy Data Base from a variety of sources: population statistics (UN, 2008), energy statistics (e.g., Dhakal, 2009; Kennedy et al., 2009; Kennedy et al., 2010), and economic statistics on gross regional economic output (or GRP, which is the urban-scale equivalent of national GDP) converted into a common 2005 denominator in purchasing power parity (PPP expressed in International$ – $\text{Int}_{2005}\$$) terms, including Eurostat (2008) and PriceWaterhouseCoopers (2007). While population statistics are routinely collected at various levels of spatial resolution, this is rarely the case for both economic and energy data. Coherent data sets were, nonetheless, found for 200 urban units, of which 132 were from UNFCC Annex 1 (i.e., industrialized) countries and 68 were urban areas located in non-Annex-1 (i.e., developing) countries. Details on data-source limitations, as well as further statistical analyses, are reported in a GEA Chapter 18 Working Paper (Schulz, 2010a).

18.3.2.3 Analysis

Comparisons of urban scale and national scale data

This section compares data on energy use per capita, (urban) per capita income (GRP/GDP), and energy intensity of GRP/GDP at the urban scale with their national scale metrics.

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[15] A more complete GEA Chapter 18 working paper on the GEA city energy data base and its data analysis is posted on the GEA website, www.globalenergyassessment.org.

Table 18.8 | Comparison of per capita urban final energy (GJ/capita), GDP (1000 $\mathrm{Int}_{2005}\$$/capita) and energy intensity (MJ/Int$) statistics (number of observations and indicator values) at the urban and national levels. Data cover 200 urban areas, of which 132 were located in Annex-1 countries. Reported data refer approximately to the year 2000, albeit different city studies report different base years. Average and standard deviations (SD) are presented for three sample groups: 'lower,' all those cities in which urban indicators are below the respective national averages; 'higher,' indicators are higher than the national average; and 'Total,' indicators for all cities in the sample taken together.

		count (# of cities) higher/lower than national average			statistical values in GEA city energy data base					
					average	SD	average	SD	average	SD
		Energy/cap.	GDP/cap.	Energy/GDP	GJ/cap.		GDP/cap.		MJ/$	
World	lower	134	94	124	85.5	30.9	29863	12629	3.1	1.1
	higher	66	106	76	126.4	100	17075	11685	9.6	1.3
	total	200	200	200	99	65.4	25643	13695	5.3	5.2
UNFCC Annex-1 countries	lower	107	67	93	93.5	23.2	33093	10274	3	0.9
	higher	25	65	39	171.9	132.3	29018	9677	6.4	4.6
	total	132	132	132	107.6	66.3	32360	10256	3.6	2.5
Non Annex-1 countries	lower	27	27	31	40.3	31	11453	8329	3.9	1.9
	higher	41	41	37	98.7	60.5	9792	4711	11.5	8
	total	68	68	68	79.5	59.2	10337	6114	9	7.5
Asia w/o Japan	lower	13	15	18	55.2	41.1	14538	14112	4	1.9
	higher	37	35	32	87.9	37.8	9938	4905	10.1	5.6
	total	50	50	50	83.3	41.3	10580	6851	9.3	5.6
Latin America, Middle East, Africa	lower	14	12	13	42.8	36.1	10121	4146	4.7	3.8
	higher	4	6	5	198.5	130.1	8446	2127	24.5	15.2
	total	18	18	18	70.5	89.7	9757	3933	8.4	11

Table 18.8 presents the overall results and a regional breakdown by status regarding Annex-1 versus non-Annex-1 assignation and geographic regions. Demographic data at the national scale are derived from UNDESA (2008; 2010), national energy statistics from IEA energy balances (IEA, 2010a; 2010b), and economic data from the International Monetary Fund (IMF, 2010).

Per capita energy use

An initial observation is that almost two out of three urban areas have a *lower than national average (direct) final energy use on a per capita basis*. This trend is more pronounced (107 out of 132) among Annex-I countries, which are overrepresented in this sample (132 out of 200). The main reason for this is the effect of urban economic structures (a higher share of less energy-intensive service activities compared to national averages) and, to a lesser degree, the effect of urban density on lower transport energy use (more public transport and soft mobility modes compared to national averages that reflect rural automobile dependence).

In non-Annex-I urban areas the reverse pattern is observed, with more than two out of three urban areas having *higher per capita final energy use* compared to their respective national averages. Among non-Annex-I countries there is pronounced *regional heterogeneity*: Africa and Latin America share the prevalence of *lower than national average urban per capita final energy use*, in contrast to Asia where urban per capita final energy use is predominantly (37 out of 50 cases) *higher than the national average*. These patterns reflect primarily the different influences of income with the urban-rural income differential, being particularly pronounced in Asia as reflected in a corresponding higher per capita final energy use gradient.

To explain these differences requires further analysis, but preliminary findings suggest that differences in levels of incomes and in economic structure (degree of service versus industry orientation of urban economies) are likely to be the main explanatory variables. In general, the number of observations in rapidly growing economies of non-OECD Asia is much larger in the sample than those of Latin America and Africa (50 vs. 18), illustrating the need for improved energy information in urban settlements in these regions particularly.

Figures 18.7 and 18.8 summarize this statistical analysis, showing all the city observations as a cumulative plot (over population) sorted by decreasing per capita final energy use. The color code indicates whether a city is above (red) or below (blue) its respective national average. The inverse per capita energy use pattern of cities in Annex-I versus non-Annex-I countries is clear from this comparison. On average, the *lower energy-use cities in Annex-I countries have a final energy use that is one-third lower than the Annex I national average*. For non-Annex-I countries the relationship is inverse: *most non-Annex-I cities have higher (about twice) per capita final energy use* than their respective national averages, being in the same ballpark as the lower energy use city sample in the Annex-I countries (at some 100 GJ/capita).

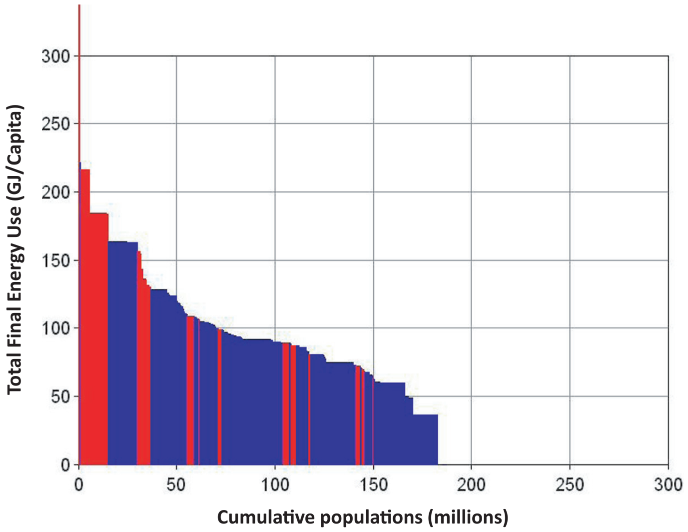

Figure 18.7 | Per capita (direct) final energy use (GJ) versus cumulative population (millions) in urban areas (*n* =132) of Annex-1 (industrialized) countries. Red indicates urban areas with per capita TFC *above* the national average. Blue indicates per capita final energy *below* the national average.

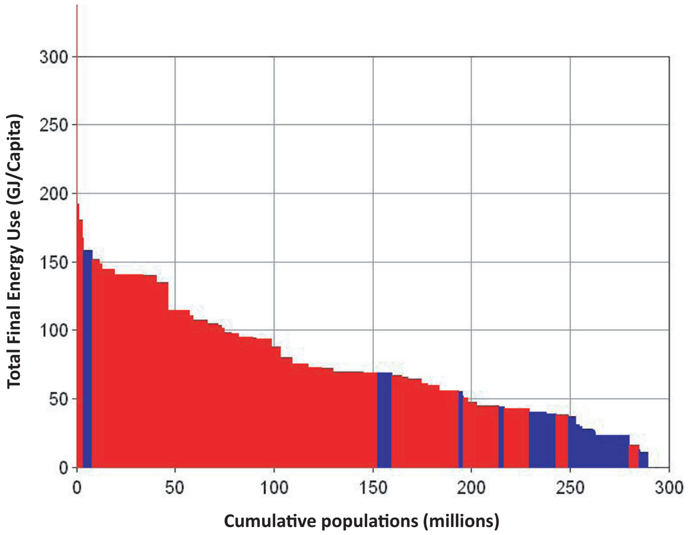

Figure 18.8 | Per capita (direct) final energy use (GJ) versus cumulative population (millions) in urban areas (*n* = 68) of non-Annex-1 (developing) countries. Red indicates urban areas with per capita TFC *above* the national average. Blue indicates per capita final energy *below* the national average.

These conclusions only refer to the (direct) final energy use metric adopted for the comparative analysis of our sample of 200 urban areas.

Evidence suggests that for Annex-I country cities the lower final energy use is likely to hold only for the production-accounting approach adopted for this comparison. Adding 'embodied' energy use (corrected for net trade of imports and exports of manufactured goods and services from and to urban economies) is likely to weaken the conclusion of a lower urban energy footprint in cities of Annex-I countries compared to the national average (see Section 18.2.4 above) as lower (direct) final urban energy use is likely to be (largely) compensated by higher 'embodied energy' use associated with higher urban incomes. And yet, the lower (direct) final energy use of many urban compared to rural areas in Annex-I countries illustrates well the *urban comparative advantage for a sustainability transition*: urban areas with their corresponding more energy-efficient compact settlement structures and lesser (energy-intensive) automobile dependence and greater potential for efficiency improvements through energy 'recycling' (i.e., cogeneration and heat cascading) have larger efficiency-leverage potentials compared to those of rural areas. The challenge to reduce the energy and environmental footprint from (over)consumption (i.e., embodied energy) is not unique to urban dwellers as it applies equally to rural ones in Annex-I countries.

The situation of cities in non-Annex-I countries, particularly in Asia, is markedly different. Compared to rural areas, cities not only have higher (direct) final energy use, they also have generally much higher incomes. Thus, the urban-rural gradient in terms of per capita (direct) final energy use is amplified yet more by higher urban incomes, which further increases the rural-urban energy gradient when considering the 'embodied' energy use associated with consumption. Given the dynamics of urbanization trends (see Section 18.2.1) it is thus fair to conclude that the sustainability 'hot spot' in the decades to come will reside particularly in the rapidly growing cities of non-Annex-I countries, especially in Asia.

Per capita income

Regarding per capita income the data sample reveals much more heterogeneity than the popular conceptions of invariably rich urbanites.[16] Almost half of the urban areas in our sample had per capita GRP/GDP values below the national average. Again, the patterns diverge between Annex-I countries (where this trend is driven by the large number of relatively deprived smaller UK urban centers in the data sample, but also by such prominent examples like the capital of Germany, Berlin) and non-Annex-I countries.

In non-Annex-I urban areas the majority showed above national average per capita GRP/GDP values. In Asia, two out of three urban areas had GRP/GDP above the national per capita average. In Africa and Latin America, just over one-third of the urban areas had GRP/GDP values that exceeded the national per capita average, but two-thirds ranked below it.

Energy Intensity

Regarding energy intensity of urban GRP/GDP, the majority of urban settlements studied showed lower than national average energy intensities,

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[16] GRP data is provided only by a limited number of statistical offices or other sources. They differ in methodology and are not always strictly comparable. A more detailed discussion of economic measurement issues at the urban scale is beyond the scope of this energy assessment.

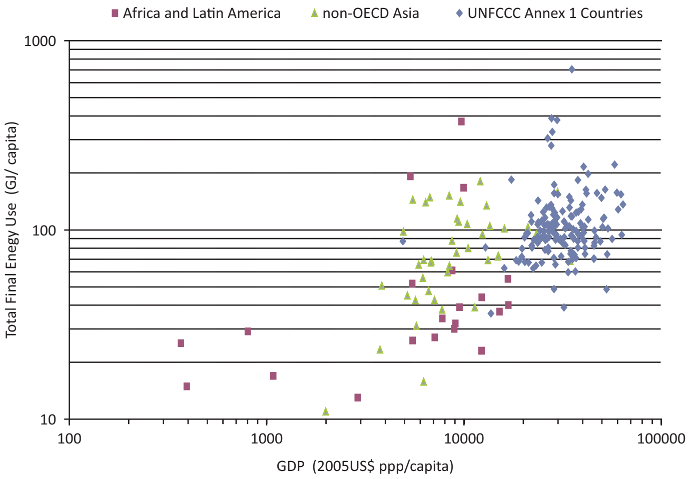

Figure 18.9 | Comparison of urban total final use (TFC) and urban income (GRP/GDP at PPP in Int_{2005}\$) per capita for cities in Annex-I and non-Annex-I countries.

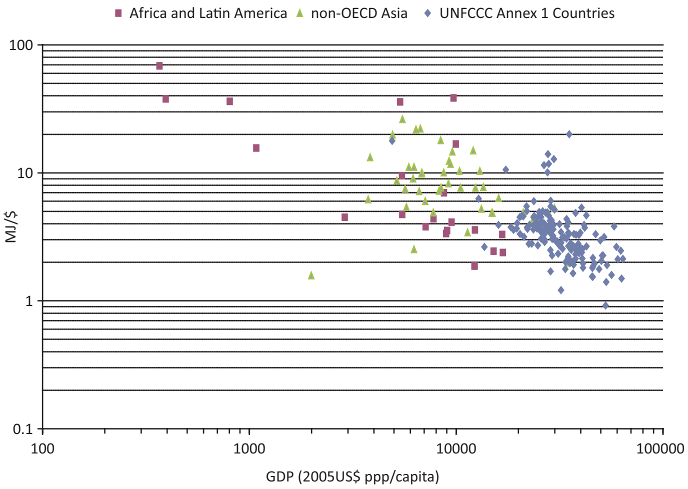

Figure 18.10 | Comparison of urban energy intensity and urban per capita income (at purchasing power parities) for cities in Annex-I and non-Annex-I countries.

which indicates the dominance of less energy-intensive tertiary sector activities in urban areas. In Annex-I countries more than two out of three settlements show lower than national level energy intensities of GDP. In the non-Annex-I countries the general trend is almost balanced, with just a few more cases of urban energy intensity that exceed the national average values. Again, the Asian urban areas show a very different pattern to those from the Latin America, Middle East, and Africa regions. Three out of four urban areas in non-OECD Asia have energy intensities that exceed the national average, while four out of five of the African, Middle East, and Latin American urban cases have the same pattern as OECD countries, with urban area energy intensities below their respective national average.

General observations

For the non-Annex-I urban areas at least three general patterns of energy use can be discerned.

One is the lower end, with final energy use under 30 GJ/capita. Per capita income is mostly less than 5000 PPP$/capita and energy intensity is, in many cases, also quite low, below 5 MJ/$. This low energy intensity in low-income, non-Annex-I cities does not necessarily suggest highly efficient energy systems, but rather different consumption structures (particularly lower private transport energy use). In all likelihood, the low energy intensities may also reflect an underreporting of noncommercial, traditional biofuels used by low-income urban households.

The medium range of per capita final energy use in non-Annex-I cities is from 30–100 GJ/capita and coincides with a wide range of incomes and energy intensities.

Heavy industrial urban areas show yet higher per capita final energy use of up to 350 GJ/year and over a highly variable range of income levels. In practically all urban settlements of the third group of non-Annex-I countries energy intensity is above 10 MJ/$ (up to 39 MJ/$ in the sample).

Patterns for Annex-I cities are markedly different. The Annex-I city panel in general appears more coherent in final energy use patterns. First, the correlation between higher urban incomes and higher final energy use tends to weaken significantly, with richer cities not necessarily using more (direct) final energy on a per capita basis (but highly likely to use much more embodied energy compared to poorer cities). Second, there is a strong and inverse correlation between urban incomes and energy intensity, with the latter falling with rising urban incomes. Only three out of the 118 Annex-I urban areas show energy-intensity values above 10 MJ/$ and the vast majority are below 5 MJ/$.

Variable correlations

Figure 18.9 presents the overall positive correlation between per capita incomes and (direct) final energy use. The general positive correlation, familiar from national level analyses, is also found at the urban scale. However, the variation appears to be larger at the urban level than at the national scale, which suggests a much broader spread for path-dependent urban development trajectories. Also, within the panel of Annex-I countries there is a large variation in energy use per capita (with some urban areas using more than 600 GJ/capita final energy). A proposed 'turning' (or saturation) point cannot be identified at a statistical significant level in this data set, which covers GRP/GDP ranges up to about 80,000 Int_{2005}\$/capita (in PPP terms), despite a visible weakening of the income-energy use link for high-income cities.

Figure 18.10 presents the relation of GRP per capita and energy intensity of GRP. Trends in non-OECD Asian cities come closest to the often proposed 'hill' (Goldemberg, 1991), with a peak in energy intensity at about 10,000 PPP$/capita and a pronounced decline in energy intensity at higher per capita incomes. At lower income ranges, however, the data in our sample are sparse, and often also exclude the dominant noncommercial traditional biofuels, so the above findings are consistent with the observation of a 'hill' in the development of *commercial* energy intensity (Goldemberg, 1991) against a background of continuously falling *total* (including noncommercial) energy intensities with rising incomes (see Nakicenovic et al., 1998) as evident in the cities of Africa and Latin America in Figure 18.10.

18.4 The Urban Energy Challenges

The urban energy challenges are embedded within overall social, economic, and environmental development challenges and their numerous interdependencies and linkages. This energy assessment focuses on the interdependencies that bear directly on urban energy. The linkages between development and energy are most straightforward in the area of the literature on 'energy poverty,' energy access, and adequate housing and transport access for the urban poor. Hence the discussion begins with a discussion of energy access and poverty within an urban context (Section 18.4.1). The discussion then moves on to the nexus of urban energy use and urban environmental quality and the challenges imposed by the high densities of energy demand and the corresponding need for efficient and low-emission energy systems (Section 18.4.2). Lastly, Section 18.4.3 discusses the challenges for urban energy infrastructures, including reliability and security.

Other urban development challenges with more indirect implications on energy, such as urban transport, land-use, and density planning, are discussed Section 18.5.

18.4.1 Energy Access and Housing for the Urban Poor

18.4.1.1 Introduction

In the development literature, energy is not generally recognized as one of the basic needs (Pachauri et al., 2004), although it is in discussions of poverty in high-income nations (where it is referred to as 'energy poverty,' see Boardman, 1993; Buzar, 2006). One reason for this absence is that one of the main indicators of 'energy poverty' in high-income nations is the substantial proportion of household income spent on fuels and electricity (typically more than 10%). However, this is not an appropriate measure for much of the urban population in low-income and some middle-income nations because their incomes are so low in relation to the costs of food and necessities other than food that their energy use is very low. This is both in the energy used within their homes (lighting, cooking, and, where relevant, space heating and appliances), in the energy implications of the transport modes they use, and, for those who are self-employed, in the energy used in their livelihoods. Thus, the main indicator for their 'energy poverty' is in the inadequacies of the energy they can afford and in the poor quality of the energy sources they use (Boardman, 1993; Buzar, 2006) which in this assessment is referred to as "energy access." Such individuals or households also have so few consumer goods that their individual embodied energy is also low.

Thus, for nations with a proportion of fuel use from noncommercial fuels and where low-income urban households keep energy expenditures down by using dirty fuels (including wastes) or cutting fuel use, the proportion of income spent on energy is not a good indicator of poverty. In addition, an analysis of poverty in relation to energy should also consider the time and effort used to obtain needed fuels, the health implications (including those that arise from indoor air pollution and the risks of fire and burns), and the quality and convenience of the fuels used to meet daily needs (i.e., in space heating or cooling, and for hot water). Pachauri et al. (2004) suggest that, ideally, the analysis of the adequacy of energy should include primary energy use, end-use energy (especially electricity), useful energy (e.g., whether the primary or end-use energy delivers the energy needed), and the quality and adequacy of energy services for households (including transport). However, data are often only available for the first two of these. Moving out of poverty involves shifts away from the dirtier and less convenient fuels[17] and obtaining access to electricity, as well as keeping down total monetary expenditures on energy.[18]

Thus, the two most common implications of poverty in regard to energy use among urban populations in low- and most middle-income nations are, first, use of the cheapest fuels and energy-using equipment (including stoves, which bring disadvantages, especially in regard to indoor air pollution, inefficient fuel combustion, and convenience) and, second, no access to electricity. Low-income households may also limit the number of meals (in extreme circumstances to one a day) to save money both on food and cooking fuel. Poverty is also evident in the lack of space heating within cold climates or seasons – although this is difficult to measure as expenditure surveys cannot identify what consumers forgo. Owners of home-based enterprises often make significant energy purchases. Urban poor households often face much higher risks of burns and scalds for household members (especially children) and of accidental fires, underpinned by a combination of extreme overcrowding (often three or more people to each room), unsafe fires or stoves, the absence of electricity for lighting (candles and kerosene lights are used), housing built of flammable materials, high-density settlements, a lack of firebreaks, and no emergency services, including fire services (Hardoy et al., 2001; Pelling and Wisner, 2009). All the above are also often associated with homes and livelihoods in informal settlements – which helps explain the lack of electricity (with electricity utilities unwilling or not allowed to operate there), the poor-quality housing, and the lack of provision for fire-prevention and emergency services.

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[17] This includes a shift to 'clean' fuels – clean in the sense of minimizing raw pollution and health impacts for the users – for instance, with electricity and gas or energy derived from renewable energy sources being 'clean' and coal and raw biomass being 'dirty' (how dirty these are depends on the technology used in the home). Kerosene and charcoal fall between these two extremes. The term 'clean fuels' is ambiguous in that it is used to mean different things – for instance, for fuels or energy sources that have low or no CO_2 emissions rather than lower health impacts for users. In addition, electricity at the point of use may be 'clean,' but it often comes from coal-fired power stations that have high CO_2 emissions and often high levels of pollution.

[18] For a more detailed discussion see also Chapter 4.

Table 18.9 | The housing submarkets used by low-income urban dwellers and their energy-use implications.

Housing type	Energy implications in the home	Energy implications for transport
Rooms rented in tenements	Typically one room per household; often electricity available, but usually too expensive to use for cooking and space heating	Usually close to sources of livelihood or demand for casual work (hence this type of accommodation is in demand)
Cheap boarding houses/dormitories (including hot beds)	Very low energy use; no provision for cooking?	As above
Informal settlement 1: squatter settlements (in many cities these house 30–60% of the entire population)	In low-income nations, usually reliance on dirtier fuels and lack of electricity; in many middle-income nations less so; for many households, part of fuel/electricity expenditure is for livelihoods in the home; illegal electricity connections may be common; often high risks from accidental fires	Many in peripheral locations, which implies high transport costs in time and money; better located squatter settlements often become expensive through informal rental or sale
Informal settlement 2: housing in illegal subdivision	More expensive than illegal land occupation, but less at risk from eviction and often with more provision of infrastructure (including electricity) or at least more possibilities of provision as the land occupation is not illegal	Many in peripheral locations which implies high transport costs; in large cities, the cheapest illegal subdivisions can imply several hours traveling a day to and from sources of income
Accommodation at the workplace	Common for single men in some cities; extent not known and includes apprentices	
Pavement dwellers and those who sleep in open or public spaces	Very low incomes so very low fuel use	Walk to work

Source: Hardoy and Satterthwaite, 1989; Yapi-Diahou, 1995; Harms, 1997; Mitlin, 1997; Mwangi, 1997; Bhan, 2009.

However, it is important to also consider the cost burdens of energy to low-income households who have access to electricity and who use cleaner, more convenient fuels. For instance, in cities such as Mumbai (India), low-income households who move from informal to formal housing benefit from access to electricity, but often find it difficult to pay the bills. Here, there are more parallels with what the literature refers to as 'energy poverty' in high-income nations. Buzar (2006) notes that increasing numbers of households in former communist states in Eastern and Central Europe[19] face difficulties in affording energy, in part because of significant energy-price increases as subsidies are removed, and in part because of the failure of the state to develop safety nets to protect low-income groups. This leaves many families with no option but to cut back on energy purchases, a problem further aggravated by cold climates and the poor energy efficiency of the building stock.

18.4.1.2 Housing Quality and Location

Around 800 million urban dwellers in low- and middle-income nations live in poor-quality, overcrowded housing with inadequate provision for basic services (UN HABITAT, 2003; 2008). A taxonomy of their housing submarkets with associated energy implications is given in Table 18.9.

Low-income groups in urban areas face limited choices in renting, buying, or building accommodation that they can afford and so have to make trade-offs between a good location, housing size and quality, infrastructure and service provision, and secure tenure (see references Table 18.9). Good locations in relation to income-earning opportunities mean that transport expenditures can be kept down and more central locations usually have more possibilities of infrastructure and service provision. But they are also more expensive and generally have less possibility of space and of keeping down housing costs through illegally occupying land and self-built homes. At their most extreme, to obtain central locations, low-income groups live in shacks built on pavements or waste dumps or in small rooms with more than three people to a room or share beds (so a single person pays to sleep in a bed in a shared dormitory with each bed serving two or three people over a 24-hour period, known as hot beds).

One of the most extreme examples of this are the tens of thousands of pavement dwellers in Mumbai, where the choice to live on the pavement (and usually with low lean-to shacks too small to sleep in) is from a combination of their very low incomes, the central location of where they earn their incomes (they walk to work), and the impossibility of affording transport costs from less central locations (SPARC, 1990). Another example are households in Indore (India) who choose to live on land sites adjacent to small rivers that flood regularly. These have economic advantages because they are close to jobs or to markets for the goods the households produce or collect (many earn a living collecting waste). The land is cheap and, because it is public land, the residents are less likely to be evicted. These sites have social advantages because they are close to health services, schools, electricity, and water, and there are strong family, kinship, and community ties with other inhabitants (Stephens et al., 1996).

Rented accommodation or land on which houses can be built is cheaper in more peripheral locations and often more distant from income-earning opportunities – the cheaper the cost and the greater the possibility of

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[19] This section does not cover high-income nations and low- and middle-income nations that were formerly part of COMECON (termed countries undergoing economic reform in GEA).

Table 18.10 | The proportion and number of the urban population that lacks electricity and access to 'modern fuels' in developing countries, least-developed countries, and sub-Saharan Africa.

Percentage and number of the urban population	Developing countries	Least-developed countries	Sub-Saharan Africa
Lacking access to electricity	10% (226 million)	56% (116 million)	46% (124 million)
Lacking access to modern fuels	30% (679 million)	63% (130 million)	58% (156 million)

Source: UNDP and WHO (2009).[20] Statistics on the urban population are drawn from UN Population Division (UN DESA, 2008) and are for 2005. The dates for the statistics on access to electricity and modern fuels vary by country, with most being between 2003 and 2007.

building a home illegally (and so avoid paying a full rent, which is often among the main reasons why distant informal settlements develop). But this means high time- and monetary-transport costs, and it is difficult to establish the high transport costs for those living in peripheral locations because most of the data on the proportion of income spent on transport are averages for cities. In addition, it is likely that many household surveys under-represent those who live in informal settlements – for instance, a lack of formal addresses and maps makes it difficult to include their inhabitants in surveys or those responsible for collecting data fear to work in informal settlements (for an example of this, see Sabry, 2009). Peripheral locations also constrain the inhabitants' access to economic opportunities, as many locations are too distant or too expensive to commute to.

18.4.1.3 Urban Populations and Energy use in Low- and Middle-Income Nations

There are some general statistics on the forms of energy use for urban populations – for instance, in what fuels (and mix of fuels) are used and whether or not they have access to electricity (Table 18.10). However, there are no general statistics on how fuel use and access to electricity vary within nations' urban populations or within cities by income group. In part, this is because many 'energy' statistics for individuals or households are only available for national populations. Where these are disaggregated, it is often only as averages for 'urban populations' when there are very large differences between different urban centers and between different income groups within each urban center. In part, this is because the documentation of 'energy' provision deficiencies has not been given the same level of attention as, say, deficiencies in provision for water and sanitation. The only exception is the very considerable documentation on the health impacts of pollution from the use of 'dirty' fuels (and other factors, including poor ventilation and inefficient stoves), although much of this literature is for rural households and perhaps underestimates the extent of this problem among urban poor households.

Table 18.10 highlights the very considerable proportion of the urban population in low- and middle-income nations that lacks access to modern fuels – 30% (which implies close to 700 million urban dwellers). A higher proportion has access to electricity, but about half the urban population within the least-developed nations and within sub-Saharan Africa lack access to electricity. In sub-Saharan Africa alone, this implies that around 120 million urban dwellers lack access to electricity. For all developing countries taken together some 230 million urban residents lack such access.

Particular studies suggest that it is common for urban poor households in Africa and Asia to use a mix of fuels – for instance, different fuels for different kinds of food and fuel-switching at certain times of year when fuel prices or household incomes change (see Pachauri and Jiang, 2008 for China and Meikle and North, 2005 for Arusha). Regional and seasonal differences may be significant, and households are also influenced by subsidies and incentives, fuel availability, and cultural preferences. Policymakers rarely understand these complexities.

The available data on energy use by low-income urban dwellers range from very large numbers who use little or no fossil fuels and electricity (i.e., wood, dung, straw, and charcoal) through those who use kerosene and coal or coal-based fuels to those who use gas (bottled or piped) and electricity. For electricity, in some nations almost all urban households (including low-income households) have electricity and in others only a very small proportion of urban households have electricity.

Available studies also give examples of the scale of the differentials in energy used between high-income and low-income households within particular urban centers; some show that these can vary by a factor of 10 or more, but of course the scale of the differentials depends, in part, on how 'the urban population' is divided for this comparison (e.g., differentials will be greater if the richest and poorest deciles are compared instead of the richest and poorest quartiles).

The two nations with the world's largest urban populations are China and India (by 2010 these accounted for more than a quarter of the world's urban population). In India, fossil-fuel based energy sources increasingly dominate the energy mix of urban households, although biomass (including firewood and dung) continues to be used, especially by the lowest income groups. In addition, during the mid-1990s there was an evident rise in the use of liquefied petroleum gas (LPG) and

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[20] This source is inconsistent in how it reports some of the figures for access to electricity; the figures above for the least-developed countries and sub-Saharan Africa are from Figure 3, but the accompanying text (page 12) says that 46% of the urban population of least-developed countries and 56% of urban dwellers in sub-Saharan Africa lack electricity access. The report does not specify where its population figures come from, although it lists the UN Population Division's *World Population Prospects: the 2006 revision* in its sources.

electricity among urban households (Pachauri and Jiang, 2008). In China, among urban households there has been a shift away from the direct use of coal to gas and electricity (although coal is still important for a significant proportion of urban households). Energy use among urban households declined from 1985 to 2002 (from 9 GJ/capita to around 5 GJ/capita), because of a shift to more-efficient fuels (Pachauri and Jiang, 2008). Also, dependence on coal may not be reduced if coal-fired power stations are an important part of meeting the consequent rising demand for electricity.

Table 18.10 shows how most (90%) of the urban population in 'developing countries' had access to electricity and 70% had access to modern fuels (mostly gas) in 2007 – but also how the picture on energy access for urban populations was very different for the least-developed countries and for sub-Saharan Africa. When considering fuel use among urban poor households in all low- and middle-income nations, this varies from, at one extreme, continued reliance on fuelwood, charcoal, and waste materials (and no electricity) through to greater use of solid or liquid fossil fuels (coal and/or kerosene, often called transition fuels) and a proportion of households with electricity, and on to the use of cleaner fuels (LPG or connection to gas) and electricity.

This diversity in the forms of energy used is also likely to be present between urban poor households within most (but see above). The only obvious characteristics that all urban poor households share is limited purchasing power for energy (for all uses) and a desire to keep costs down, so their fuel use and fuel-energy mix is much influenced by the price and availability of different fuels and electricity. Having access to electricity at prices that low-income households can afford obviously represents a major advantage – for lighting and for key appliances (including fridges and, where needed, fans) and for the reduced risk of accidental fires. However, they will keep electricity use down (for instance, where it is expensive in comparison to other fuels, they may not use it for cooking or space heating) unless there is no better alternative (or they have made illegal connections to power grids that keep costs down).[21] Having gas for cooking and hot water (and, where needed, space heating) has great advantages of convenience and of low generation of indoor air pollution, but in many urban contexts it is only available as LPG canisters (and so less convenient and more expensive than gas piped to the home). This often makes it too expensive for large sections of the urban population.

Among the low-income households in urban centers in the lowest-income nations, fuel use is dominated by charcoal, firewood, or organic wastes (e.g., dung). The more access to fuels is commercialized, the less fuel is used. In many small urban centers in low-income nations, it may be that certain fuels (wood, dung, agricultural wastes, etc.) are cheap and that a proportion of the urban population can gather fuel rather than pay for it – but probably the larger the city, the greater the commercialization of all fuels. Also, the very limited space within the homes of most low-income urban households – especially those that live in central areas with, in many cases, less than 1 m^2/person – limits the capacity to store bulky solid fuels.

Table 18.11 | The main fuels used for cooking in urban areas in developing countries, least-developed countries, and sub-Saharan Africa (in percent of urban population using particular fuels).

Percentage of the urban population	Developing countries	Least-developed countries	Sub-Saharan Africa
Using wood, charcoal, and dung for cooking fuels	18	68	54
Using coal for cooking	8	3	2
Using kerosene for cooking	7	4	20
Using gas for cooking	57	20	11
Using electricity for cooking	6	4	11

Source: UNDP and WHO, 2009.

Fuel use for cooking

Table 18.11 shows the contrast between the proportion of the urban population using wood, charcoal, and dung in developing countries (less than one-fifth of households), in the least developed nations (two-thirds of urban households), and in sub-Saharan Africa (more than a half). In developing countries close to two-thirds of the urban population use gas or electricity for cooking; for the least-developed nations and sub-Saharan Africa, this is less than one-quarter. There are large differences in this within the least-developed nations and in sub-Saharan Africa. For instance, for many of these nations only a small percentage of the urban population has access to electricity.

For most nations with per capita GDPs under $1100, 85% or more of their urban population use wood and charcoal for cooking – and all these nations are in sub-Saharan Africa, except Haiti. For nations with per capita GDPs above $14,000 virtually all urban households do not use wood or charcoal. For nations with per capita GDPs of $1100–4000, the variations in the percentage of the urban population that use wood or charcoal are very large (UNDP and WHO, 2009).

Households select fuels for food preparation for reasons that include cost, availability, convenience, type of food, and cooking equipment, as illustrated by a study in Ibadan (Nigeria). Kerosene was the major cooking fuel for low- and middle-income households until subsidies on petroleum products were withdrawn in 1986. As a result of the increased kerosene and cooking-gas prices, surveyed households in 1993 had begun to use fuelwood, sawdust, and other cheaper energy sources. A follow-up in 1999 discovered that households had switched back to kerosene, while also reducing the frequency of cooking, eating cold leftovers, and substituting less nutritious but faster-cooking foods (Adelekan

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[21] Care is needed here: illegal connections are often not providing electricity free as the connection is through another household that charges for this or the occupants are tenants and have to pay the landlord extra for electricity.

and Jerome, 2006). A study of energy use in an informal settlement in the Cape Peninsular in South Africa showed how households that had legal electricity connections and meters could access 50 kWh/month free basic electricity, which encouraged them to cook with electricity rather than paraffin (Cowan, 2008).

Low-income urban households often cook with solid fuels that pose serious health threats to household members from indoor air pollution, especially for those with the longest exposure (see Chapter 4 for details). Among urban populations in many sub-Saharan African nations, wood and charcoal are still the most widely used cooking fuels (see, for instance, Ouedraogo, 2006 on Ouagadougou; Boadi and Kuitunen, 2005 on Accra; Kyokutamba, 2004 on Uganda; and van der Plas and Abdel-Hamid, 2005 on N'Djaména).

This reliance on charcoal by large sections of the population of major (and often rapidly growing) cities generated concerns regarding its contribution to deforestation, although a detailed study in several African nations in the late 1980s found very little evidence of this (Leach and Mearns, 1989) and a more recent review suggests that fuelwood is seldom a primary source of forest removal, although "in some of the areas where charcoal production is concentrated, this may be the case" (Arnold et al., 2006).

Urban dwellers in India are shifting to cleaner cooking fuels, although the shift between 1983 and 1999 was most evident among higher income groups. In 2000, less than 40% of the bottom two urban deciles cooked with clean fuels. And among the poorest urban groups, adoption of clean cooking fuels hardly increased from 1983 to 2000 (Viswanathan and Kavi Kumar, 2005). LPG and kerosene are highly subsidized in India, but nonpoor groups are the main beneficiaries and many low-income urban residents continue to cook with dirtier energy sources (Gangopadhyay et al., 2005; Pohekar et al., 2005).

Cooking with LPG is common in the Philippines, but poor urban households also buy kerosene or biomass fuels to keep costs down. In a survey of two low-income districts in metro-Manila, LPG was the main cooking fuel in 75% of households (APPROTECH, 2005). However, as LPG prices increased in 2004, low-income groups also began to cook with kerosene, fuelwood, or charcoal. Although residents intended to reduce expenditures, they still paid higher unit prices because they could only afford to purchase small quantities (APPROTECH, 2005).

High expenditures on energy

A considerable range of national and city studies and studies of particular settlements show how expenditures on fuels for household use are consistently burdensome for low-income households (but may not show up as high expenditures or high proportions of income spent on fuel, as discussed above). Examples of high expenditures on energy are:

- In Guatemala, cooking and lighting took up about 10% of household expenditures for the three poorest urban deciles in 2000 (ESMAP and UNDP, 2003).

- In Thailand, slum dwellers spent about 16% of their monthly income on energy (cooking, electricity, transport) in Bangkok and about 26% in Khon Kaen. Households in these slums with incomes below the poverty line spent 29% of total household income on energy in Khon Kaen and 18.5% in Bangkok – mainly because of the high cost of electricity (Shrestha et al., 2008).

- In Ethiopia, fuel and power took 11% of expenditure among urban poor (Kebede et al., 2002).

- In Sana'a, the capital of Yemen, the bottom two deciles spent over 10% of their incomes on electricity alone (ESMAP and UNDP, 2005).

- In Kibera, Nairobi's largest informal settlement, for over 100 households surveyed energy expenditures reached 20–40% of monthly incomes (Karekezi et al., 2008).

- In Rio de Janeiro (Brazil), many households in surveys in informal settlements were spending 15–25% of their incomes on energy (WEC, 2006).

- In Cairo (Egypt), households with incomes at the lower poverty line spent 8–20% of their income on electricity (Sabry, 2009).

Low-income households who obtain electricity through shared electricity meters can be charged higher rates because of rising block tariffs (examples in Kumasi (Ghana), Mumbai, and an informal settlement in South Africa are given by Devas and Korboe, 2000 and Cowan, 2008).

Space heating

Data on heating expenditures are limited, but it is clear that where space heating is needed, low-income urban dwellers can face high costs to keep warm. For instance, surveys in 1999 found that low-income city-dwellers in Armenia, Moldova, and the Kyrgyz Republic devoted 5–10% of their household incomes to heating (Wu et al., 2004). Poor households may also heat their homes with inefficient, polluting fuels to reduce expenditures. During the winter of 2002, Tbilisi's poor households who were not on the gas network resorted to using wood for heating and cooking (ESMAP, 2007). Wood prices were cheaper than those of other fuels, except natural gas. In Buenos Aires' peripheral settlements of Villa Fiorito and Budge, the average household relies on charcoal for space heating and cooking, with space heating taking up nearly 13% of household annual net energy use (Bravo et al., 2008). In the heart of South Africa's coal-mining country, residents of Vosman Township rely on coal for space heating, water heating, ironing, and cooking (Balmer, 2007). Even in the United Kingdom, four million households were deemed to live in fuel poverty in 2007 (defined by spending 10% or more of income on maintaining an adequate level of warmth) (UKDECC, 2010).

In China, coal is a key heating fuel for the poor, particularly in cold northern cities where heating may take up as much as 40% of households total energy needs (Pachauri and Jiang, 2008). Although data are not specifically available on coal use for heating, national surveys indicate that 65% of the poorest urban households utilize coal (Pachauri and Jiang, 2008). Coal-using urban residents are exposed to extremely high levels of indoor air pollution (Mestl et al., 2007).

Lighting and access to electricity

There is a clear association between the percentage of the urban population with electricity and a nation's per capita GDP (UNDP and WHO, 2009). Almost all nations with GDPs per capita of US$6000 or more have 95–100% of their urban population with electricity. For nations with per capita GDPs below US$3000, there is a quite consistent picture of rising proportions of urban households with electricity, with some variation. There is more variation between US$3000 and US$6000.

However, were the sample frames for the urban households interviewed in the surveys from which this data comes rigorous in including the needed proportion of households that are in informal or illegal settlements? For instance, half of Kenya's urban population is said to have access to electricity in 2003, yet a survey in 1998 of informal settlements in Nairobi (which house half of Nairobi's population) found that only 17.8% had electricity (APHRC, 2002).

In most middle-income nations and some low-income nations, most of the urban population has access to electricity. By 2002, there was near-universal access to power in Caracas, Buenos Aires, and Rio de Janeiro (WEC, 2006). India's household surveys in 2004–2005 found that 91% of urban households used electricity; for Chinese city dwellers, household surveys reported that 96% used electricity in 2001 (Pachauri and Jiang, 2008). Many nations, including Colombia, Dominican Republic, Egypt, Indonesia, Jordan, Pakistan, and Ukraine, report that more than 98% of their urban population has electricity (UNDP and WHO, 2009). These positive developments illustrate that the proximity to existing energy infrastructure in urban areas enables rapid progress when dedicated policies of connecting urban poor are in place. Barriers of low income and limited grid extensions therefore can be overcome.

Thus, many cities and national urban populations have a high proportion of urban poor households with access to electricity. For instance, a study of energy-use patterns in slums in Bangkok and Khon Kaen in Thailand found almost 100% with electricity connections (Shrestha et al., 2008), although in Bangkok 32% of households were connected through their neighbors (Shrestha et al., 2008). Almost all 'slum' dwellers in Cairo have electricity connections (Sabry, 2009). In Mexico in 2000, access to electricity was enjoyed by 91–97% of the lowest-quartile households in cities along the US border (Peña, 2005). National surveys in 2001 found that over 80% of Pakistan's poorest urban deciles had electricity (ESMAP, 2006).

Access to electricity is not only an issue of quantities. Quality of service in terms of regularity, reliability and the duration of provision are of equal importance.

Table 18.12 | The cost per household (in current US$) of providing electricity in different cities.

City	Cost per household (US$)
Ahmedabad	114
Manila	154
Rio de Janeiro	226
Salvador	350
Cape Town	417

Source: USAID, 2004.

The costs of electricity access for the urban poor are generally low (Table 18.12). Nonetheless, some caution is needed in using the figures in Table 18.12 because it is not clear whether these are just the cost of extending electricity to these households or also include other costs, such as the costs of extending overhead lines and upgrading the power-generation system (USAID, 2004).

A study of the costs of different 'slum' upgrading programs in Brazil showed that the provision of electricity and lighting was 1–3% of total costs, although these were comprehensive upgrading programs that included provision of water and sewer connections for each house, and building homes for those that had to be rehoused (Abiko et al., 2007). The costs would be higher as a proportion of total costs within a more minimalist upgrading program – for instance, one that only provided communal water provision and drainage and not piped water and sewer connections to each household.

Further discussion on energy access issues beyond electricity is contained in Chapter 4.

18.4.1.4 Transport

When choosing where to live, low-income individuals or households have to make trade-offs between good locations for access to income-earning opportunities, to housing quality, size, and tenure, and to infrastructure and services. In most cities in low- and middle-income nations, a significant proportion of low-income groups live in peripheral locations because it is cheaper (and often less crowded) or there are more possibilities of obtaining land on which to build housing (although usually illegally). But peripheral locations usually mean high monetary and time costs in traveling to and from work and services. Thus, transportation costs can eclipse household spending on cooking, heating, and lighting.

Various studies of transport use and expenditures in cities or of urban poor communities show that public transport costs represent a significant part of total household expenditure. For instance, for the inhabitants of eight informal settlements in Cairo transport costs were a major burden. Many such settlements on the outskirts are not adequately served by the public bus network or the metro. Many inhabitants have to use more expensive privately operated microbuses for part of the journey and a high proportion have to change to other buses or the metro for their journey. High travel costs were one reason why few children went to secondary school (Sabry, 2009). Other examples include:

- In Karachi, interviews with 108 transport users who lived in one central and four peripheral neighborhoods found that half were spending 10% or more of their income on transport (Urban Resource Centre, 2001).
- In Bandung City (Indonesia), interviews with a sample of 145 *kampong* residents found that nearly 7% of their monthly income was devoted to transport costs (Permana et al., 2008).
- In Buenos Aires, a 2002 survey found that the bottom quintile walked to work for 53% of their journeys, but they still spent over 30% of their family incomes on public transit (Carruthers et al., 2005).
- In Sao Paulo, a 2003 survey found that low-income groups spent 18–30% of their incomes on travel (Carruthers et al., 2005). Wealthy residents spent just 7% of their incomes on transport, but were able to travel far more frequently. The number of trips completed by Sao Paulo's poor was less than one-third of those completed by the highest-income residents.
- In Salvador (Brazil), low-income residents often live in the urban periphery and a survey of over 500 households in the poor neighborhoods of Plataforma and Calavera found that transport expenditures averaged 25% of monthly expenditures (Winrock International, 2005).

Thus, it is common in cities for low-income groups to face high transport expenses that curtail their travel possibilities and leave them with onerous journeys, often on foot. Transport costs also limit livelihood opportunities for low-income groups that live in peripheral locations, as the cost and time to reach parts of the city are too high. A 2003 survey in Wuhan, China, showed how prohibitively high transit costs resulted in the poor rejecting jobs far from their homes (Carruthers et al., 2005).

Some studies show how many low-income groups walk long distances to keep their transport expenditures down (see, for instance, Huq et al., 1996 for various cities in Bangladesh, and Barter, 1999 for central Bombay/Mumbai and Jakarta). So, while such individuals may pay little for transport costs, they 'pay' through long journey times and extra physical effort. In the survey of Wuhan, China (Carruthers et al., 2005), the bottom quintile reported walking for almost half of their journeys, while 27% of their travel was by public transit and 22% by cycling.

Marginalized neighborhoods may not be served by public transit, and low-income women can face particular challenges in accessing secure, efficient transportation (Watkiss et al., 2000). Informal buses have proliferated in many cities, and can help alleviate transport shortages (Zhou, 2000). However, in this unregulated sector vehicles are usually old and overcrowded, accidents are common, and customers are vulnerable to rising or erratic fares.

Table 18.13 | Grouping households in India by the amount of energy they use and the energy services available to them (average household of five persons) in Watt-years (1 Wyr = 31.55 MJ).

Energy services of households	Useful energy use per capita (Wyr)
Associated with extreme poverty: up to one warm meal a day, a kerosene lamp, possibly a little hot water	<15 W
Associated with poverty: 1–2 warm meals per day, a few kerosene lamps or one electric bulb, some hot water	15–30
Associated with above the poverty line: two warm meals a day, hot water and lighting, some small electrical appliances for groups with electricity, possibly a scooter	30–60
Associated with a comfortable level of well-being: two or more warm meals a day, hot water, lighting, some space heating, for groups with electricity possibly some space cooling and electric appliances, possibly a scooter or an automobile	60+

Source: Pachauri et al., 2004.

18.4.1.5 Differentials within Urban Populations

Various studies show how it is common for low-income urban households in low- and middle-income nations with electricity connections to use 20–50 kWh/month (see Kulkarni et al., 1994; Karekezi et al., 2008). This is a small fraction of average household use in the United States (640–1329 kWh/month depending on the region) or Europe (341 kWh/month). So it is likely that differentials of the order of 100 or more are present between the world's wealthiest and least wealthy households with electricity. Pachauri et al. (2004) considered how the amount of energy used and the quality of energy services available varied by income-group (Table 18.13).

18.4.1.6 Summary

Development literature focuses principally on provision of water and sufficient food, not on clean energy and electricity. Several hundred million urban dwellers in low- and middle-income nations lack access to electricity and are unable to afford cleaner, safer fuels such as gas or LPG (or even kerosene). Most are in low-income nations in Asia and sub-Saharan Africa. In many such nations, more than half the urban population still rely on nonfossil fuel cooking fuels with obvious consequences for health problems (and large health burdens) and for the time needed to obtain fuels. In many low-income nations, more than half the urban population also lacks access to electricity, even though urban population concentrations lower unit costs for providing electricity and gas (or LPG gas distribution). For a large part of the urban population that lacks clean fuels and electricity, the reasons are not that they cannot afford these but that they face political or institutional obstacles to accessing them. Most live in informal settlements with no legal addresses and legal tenure, where they are also denied paved roads and provision for water, sanitation, and drainage, and often healthcare, schools, and emergency services.

A high proportion of urban dwellers in low- and middle-income nations find it difficult to afford their 'energy bills' (for fuel and, where available, electricity and expenditure on transport); these often take 10–15% of household income and for many a higher proportion.

However, in many middle-income nations (and all high-income nations) nearly all low-income urban dwellers have legal electricity connections and can afford clean fuels. The shift to clean fuels and the availability of electricity bring many advantages in terms of health, convenience, and time saved in accessing and using energy. If the cost of a legal connection to electricity and to natural gas supplies can be afforded and supplies are affordable and reliable, no time is needed to purchase or gather fuels, and then carry home solid or liquid fuels or LPG cylinders. Also, no space in the home is needed to store these. Reliable electricity supplies also bring many other obvious advantages – reliable, cheap, and safe lighting at night, the possibility of fridges, televisions, and electric fans, support for home enterprises, and a very large reduction in fire risk.

The costs of connection to an electricity grid and the use of electricity can be burdensome for low-income groups, but innovations have reduced these costs – for instance, rising tariffs with low prices for 'lifeline' electricity use (or in South Africa no charge for up to 50 kWh/month), pay-as-you-use meters, and standard 'boards' that remove the need for household wiring.

Climate change implications may pose problems for low-income urban dwellers obtaining electricity and clean fuels. However, the shift from dirty fuels to clean fuels produces a lower than expected contribution to global warming because of the inefficiencies in how dirty fuels are consumed and in the reduced contribution of fuel use to black soot aerosols. Thus, a shift to clean fossil fuels leads to major improvements in the global impacts associated with non-CO_2 emissions. In addition, current differentials in electricity use per household or in CO_2 emissions per household are likely to vary by a factor of at least 100 between the wealthiest households and the least-wealthy households.

The constraints on supporting the shift to clean fuels and providing all urban households with electricity are less in energy policy and far more in government policy and daily practice in regard to those who live in informal settlements and work in the informal economy. A large part of the population that lacks clean energy and electricity also lacks reliable piped water supplies and good provision for sanitation and drainage. They often lack access to schools and healthcare. Governments often ignore them, even though their settlements house 30–60% of the city population, most of its low-wage labor force, and many of its enterprises. It is mostly in nations where relationships between local government and the inhabitants of these informal settlements are not antagonistic, with widespread public support for 'slum' and squatter upgrading, that clean energy and electricity reaches urban poor groups.

18.4.2 Energy Demand and Air Pollution Densities, including Heat Island Effects

18.4.2.1 Introduction

The concepts of energy demand and pollution densities refer to the *quantity of energy* used and/or produced or the pollution emitted *per unit of land*. Their common denominator and driver is urban population density. Despite being of fundamental importance in an urban context, the literature on energy or pollution densities is surprisingly limited, apart from that on urban heat island effects, reviewed in detail in Section 18.4.2.4 below.

18.4.2.2 Urban Energy Demand Densities

This Section illustrates the concept of energy supply and demand densities both generally and by drawing from contrasting examples of two high-density megacities (Tokyo and London), as well as a small, low-density city (Osnabrück, Germany). A brief discussion of associated policy issues follows.

The classic reference on energy demand and supply densities remains Smil (1991), from which Figure 18.11 is adopted in modified form.

The customary unit for energy densities is Watts per square meter (W/m²), referring to a continuous use of the power of one Watt over a year.

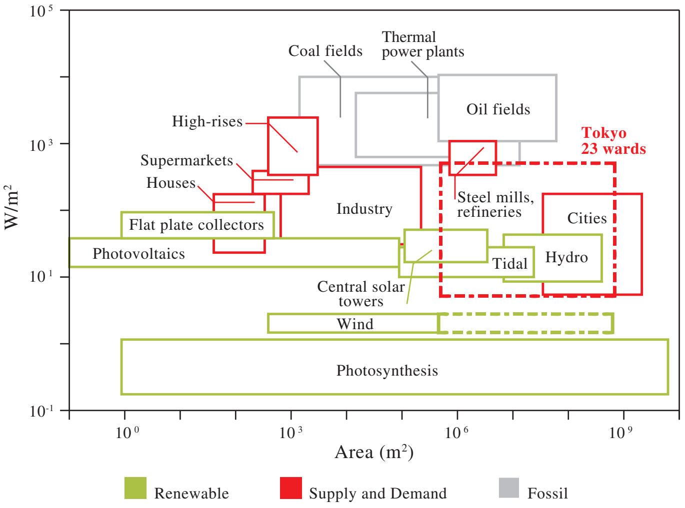

Figure 18.11 | Energy densities of energy supply from fossil (gray) and renewable sources (green) versus density of energy demand (red) for typical settings, in W/m² and m² area. Source: modified from Smil, 1991.

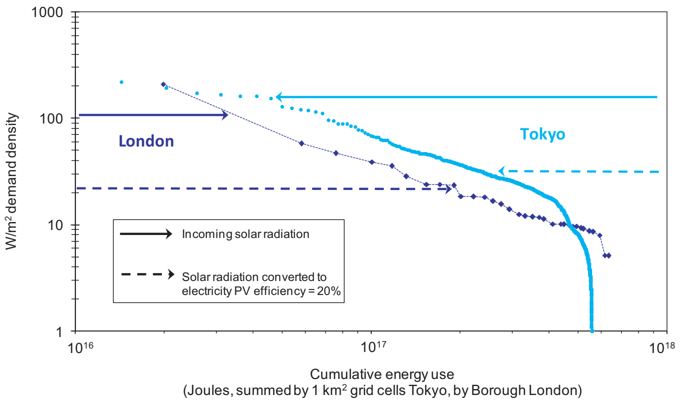

Figure 18.12 | Energy-demand densities (W/m^2) for London (33 boroughs) and Tokyo (1 km^2 grid cells, 23 wards) versus cumulative energy use of these spatial entities (in Joules). For comparison the energy flux of incoming solar radiation (W/m^2) and the electricity that could be generated (assuming photovoltaics (PVs) with a conversion efficiency of 20%) is also shown. Source: Dhakal et al., 2003; UKDECC, 2010.

Within an urban context particularly, energy demand densities are of significance. The twin influences of high population and high income mean that the spatial density of energy demand of cities typically ranges from 10–100 W/m^2, a range exemplified by cities such as Curitiba (Brazil) and Tokyo. Energy-demand densities in smaller portions of urban areas can approach values of 1000 W/m^2, as in sub-sections of the 23 wards of central Tokyo (Dhakal et al., 2003).

The significance of urban energy-demand density arises in three areas. First, the higher the energy density, the larger the impact of emissions, either as air pollutants or as waste-heat releases. Second, from an energy-demand perspective, high energy densities suggest opportunities for waste-heat recycling and economic provision of clean district heating and cooling services. Third, energy-demand densities are significant constraints for the provision of energy services through renewable energies, which (with the exception of geothermal) typically range from 0.1 to 1 W/m^2 and thus yield a significant mismatch between demand and supply at the urban scale.

From an energy-systems perspective it is important that the prevailing high energy-demand densities characteristic of urban areas are much in line with those of fossil fuel infrastructures and conversion devices (Grubler, 2004). The general mismatch between (high) urban energy demand and (low) renewable energy supply densities is shown with actual energy demand data for London and Tokyo in Figure 18.12.

The typical order of magnitude of energy use of a megacity is in the order of an exa-Joule (10^{18} J), a unit normally reserved reporting the energy use of entire countries. The (direct final) energy use of Tokyo's 23 wards is estimated to be about 0.6 EJ and that of the larger Tokyo Metropolitan area as 0.8 EJ (Tokyo Metropolitan Government, 2006), compared to 0.6 EJ for London (33 boroughs) and 0.8 EJ for New York City[22] (Kennedy et al., 2009). Energy-demand densities in Tokyo and London typically span a range from a few W/m^2 to >200 W/m^2, as in the City of London or in the top 25 grid cells (i.e., top 25 km^2) of the Tokyo wards that use close to 18% of Tokyo's total final energy. Such high energy-demand densities are comparable to the entirety of the solar influx, which equals 157 W/m^2 in Tokyo and 109 W/m^2 in London. Mean energy densities, 28.5 W/m^2 for the Tokyo 23 wards (621 km^2) and 27.4 W/m^2 for Inner London (319 km^2), are similar. (For Greater London with its larger size (1572 km^2), lower population densities, and greater extent of green areas, energy densities are naturally lower, at 13 W/m^2.)

Assuming that all the incoming solar radiation could be converted for human energy use (e.g., to electricity with 20% efficient PV panels), the maximum renewable energy supply density would range from 22 (London) to 31 (Tokyo) W/m^2 in line with average demand densities in the two cities, but only under the assumption that the entire city area could be covered by PV panels! Even assuming an upper bound of potential PV area availability (roofs, etc.), the results from a low-density urban area (Osnabrück, Germany, see below) of 2% of the city area, solar energy could provide a maximum of between 0.4 (London) and 0.6 W/m^2 (Tokyo), which would cover between 2% (Tokyo's 23 wards) and 1–3% (Inner to Greater London) of urban energy use in the two cities. *Local renewables* can therefore only supply urban energy in niche markets (e.g., low-density residential housing), but can provide *less than 1%* only of a megacity's energy needs.[23]

Given that local renewables in large cities are at best marginal niche options (because of the density mismatch between energy demand and supply), what is their potential in small, low-density cities? Using aerial survey techniques, Ludwig et al. (2008) performed a comprehensive assessment of suitable application of rooftop solar PVs for Osnabrück (Figure 18.13). Osnabrück, with an area of 120 km^2 and a population of 272,000 (a density of 23 people/ha) is characterized by an incoming solar radiation of 983 kWh/m^2 (112 W/m^2). In the study, all suitable roof areas of some 70,000 buildings in the city were assessed (considering optimal inclination as well as shadowing by adjacent buildings) and the results published for local residents in a database per individual dwelling.

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[22] Final energy use within the city limits and excluding bunker fuels (aviation, shipping). The latter are reported to be 0.28 EJ (0.2 EJ aviation fuel and 0.08 EJ marine bunkers) for New York City compared to 0.76 EJ final energy use in 2005 (Kennedy et al., 2010). For London, aviation fuel also accounted for some 0.2 EJ for the year 2000 (Mayor of London, 2004).

[23] This mind experiment considers a highly efficient conversion route of solar energy via high-efficiency PVs (with 20% net conversion efficiency). Assuming biomass as an alternative reduces the energy yield by a factor of up to 20, as the average conversion efficiency of solar energy via photosynthesis is only around 1%. Conversely, considering solar hot-water collectors (with a maximum efficiency approaching 100% of incoming solar energy) also does not change drastically the conclusion of the extremely limited local renewable potentials in high density cities, as solar hot water typically provides only a few percent of energy demand (hot water accounts for 2% of final energy demand in Europe (Eurostat, 1988)). Even if this were provided entirely by solar energy where feasible (in low- to medium-density housing, as high-rise buildings do not offer sufficiently large roof areas) the yield is less than 1% of energy demand in a densely populated large city.

Figure 18.13 | Example of assessing local renewable potentials: roof area (left panel) and suitable roof-area identification for solar PV applications (right panel) for the city of Osnabrück, Germany. Red: roof area well suited for PV; orange: suitable; yellow, only conditional suitability for PV applications; grey: shadowed roof area (unsuitable). Source: modified from Ludwig et al., 2008.

The study identified a total of two million m^2 of suitable PV roof area for Osnabrück (corresponding to 1.6% of the city area), which if used completely for PV applications could provide some 249 million KWh of electricity, or about the entire *residential* electricity demand of the city (235 million kWh) or up to 26% of the total electricity demand of Osnabrück (940 million kWh). It is of particular interest to interpret the Osnabrück results in terms of their corresponding renewable energy supply density, which adds up to some 0.2 W/m^2 and can be considered a realistic upper bound of the local renewable energy potential for low-density urban areas. In the example of Osnabrück, local renewables could provide some 3.3 GJ/capita or 2% of the average German per capita final energy use of 154 GJ/capita.

This example shows an important trade-off between population density, transport energy demand, and the potential for local renewables. Generally, the areas available for harvesting local renewable energy flows are higher for a *lower* population density in an urban area. Osnabrück, with a population density of 23 inhabitants/ha and a high proportion of low-density residential housing (single-family homes) evidently offers larger potentials to harness solar energy compared to a megacity with population densities of 130 people/ha and predominantly high-rise buildings (as for Tokyo's 23 wards). However, this higher potential for harnessing local renewables at lower population densities is at odds with the potential to lower the dependence on energy-intensive individual transport modes (automobile usage) in urban areas via public transport. Public transport systems require relatively high population densities to offer an attractive and economically viable alternative to private automobiles, with the minimum population density threshold required typically above 50–100 inhabitants/ha (see Section 18.5.3). In terms of energy, there is thus an inherent trade-off between urban form, transport choices, and the potential of harnessing local renewable energy flows. Put simply, the positive energy implications of an 'active' building (e.g., a 'Passivhaus' standard energy-efficient home with PV panels on the roof that produce electricity both for its own use and for the grid) can quickly turn negative if the building is situated in a low-density, suburban setting with a high automobile dependence.

Therefore, if renewable energies are increasingly to supply the urban energy needs on a large scale, the resulting needs for conversion and long-distance transport, as well as very large energy 'catchment' areas (the 'energy footprint' of cities), needs to be taken into account.

In an attempt to quantify the implications of the energy supply and demand-density mismatch, IIASA researchers used spatially explicit energy-demand estimates for Europe to calculate related energy-demand density zones (Figure 18.14). The study found that about 21% of final energy demand in Western Europe is below the supply density threshold of 1 W/m^2, a characteristic upper bound for locally harvested renewable energy flows. The corresponding value for Eastern Europe is somewhat higher, with 34% of energy demand below 1 W/m^2. Nonetheless, in all densely populated, highly urbanized regions, the majority of renewable energy supply has to come from areas of low population and energy-demand densities, where renewable energy flows can be harnessed and transported to the urban energy-use centers, which represents a formidable infrastructure challenge.

The findings of the IIASA study are also confirmed by a detailed, spatially explicit assessment of solar electricity (PV) potentials for all of Western Europe by Scholz (2010; 2011) (see also Chapter 11).

The Scholz study identified a total solar (rooftop)[24] PV generation potential of 638 TWh (equivalent to 2.3 EJ, or some 40% of the residential

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[24] Adding also building facades to the potential PV areas does not change the results significantly. In a study of solar PV potentials considering the entire building envelope Gutschner et al., (2001) estimated a total electricity potential of 600 TWh for a sample of 10 European countries, which is good agreement to the Scholz study (638 TWh). Facades were estimated to add another 25% to the rooftop PV potentials by Gutschner et al. (2001).

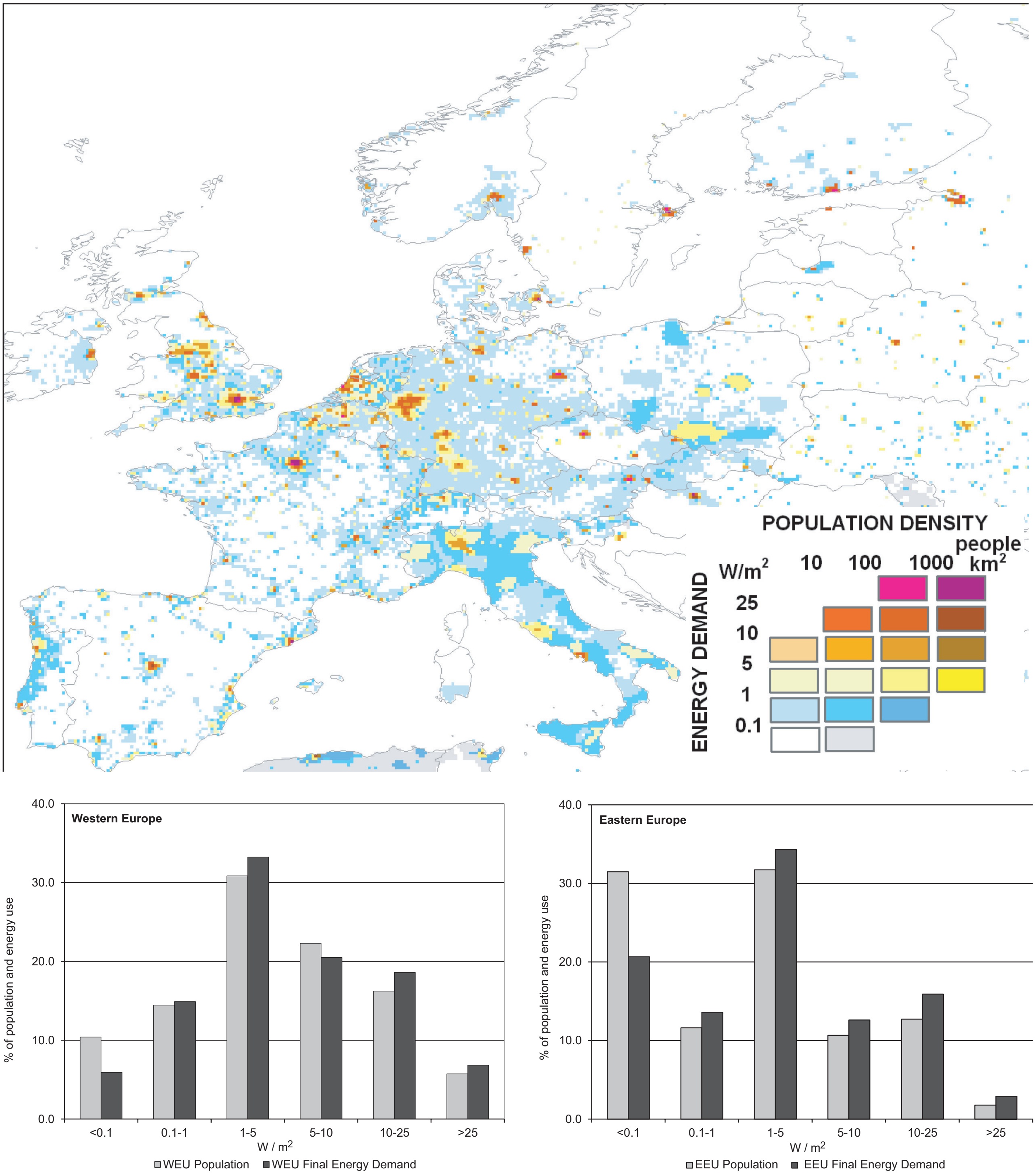

Figure 18.14 | Top: Spatially explicit energy demand densities in Europe (W/m^2): Blue and white areas indicate where local renewables can satisfy low-density energy demand (<0.5–1 W/m^2). Yellow, red and brown colors denote energy demand densities above 1, 5, 10, and 25 W/m^2 respectively.

Bottom: Distribution of population (grey) and final energy demand (black) (in percent) as a function of energy demand density classes in W/m^2 for Western Europe (left panel) and Eastern Europe (right panel). Only 21% (Western Europe) and 34% (Eastern Europe) of energy demand is below an energy demand density of 1 W/m^2 amenable to full provision by locally available renewable energy flows. The high energy densities of cities require vast energy 'hinterlands' that can be 100–200 times larger than the territorial footprint of cities proper requiring long-distance transport of renewable energies. Source: IIASA calculations commissioned by Chapter 18.

Table 18.14 | Global exposure equivalents to particulate emissions. Note, in particular, the continued dominance in developing countries of indoor air pollution from traditional biomass cook stoves compared to the urban outdoor air pollution exposure.

	Concentrations (μg/m³)		Exposures (GEE)[a]		
Group of Nations	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**	**Total**
Developed					
Urban	100	70	5	<1	**6**
Rural	60	40	1	<1	**1**
Developing					
Urban	255	278	19	7	**26**
Rural	551	93	62	5	**67**
Total			**87**	**13**	**100**

a GEE = Global Exposure Equivalent

Source: adapted from Smith, 1993.

electricity demand in Western Europe, and 23% of the total electricity demand in the region). 637 TWh (99.8%) of that solar PV potential is below a maximum energy supply density of 0.5 W/m^2, and 563 TWh (88.2%) below a energy supply density level of 0.2 W/m^2 (Scholz, 2011). Renewable energy supply densities in urban areas are therefore maximum in the range of 0.2 to 0.5 W/m^2 which are thus between 2 to 5 percent of characteristic urban energy demand densities of 10 W/m^2.

18.4.2.3 Pollution Densities

A corollary of energy densities is that of pollution density. High population density also leads to high *exposure*[25] density to pollution risks.

However, at least for traditional air pollutants such as particulates, urban pollution exposures also need to be seen in context, as only approximately one-third of the global pollution exposure is urban, whereas two-thirds are rural, because of the dominance in global particulate pollution exposure of indoor air pollution in rural households of developing countries (Table 18.14 and Chapter 4). Smith (1993) developed the concept of global exposure equivalent (GEE), which represents a renormalized index of the global summation of pollution exposure (pollution concentration times population exposed) calculated for a range of human environments. According to Smith (1993), global human exposure to traditional pollutants is dominated by indoor air pollution in rural and urban households in developing countries as a result of the continued use of traditional biomass for cooking.

For more modern forms of pollution (sulfur and nitrogen oxides (SO_x and NO_x) and ozone (O_3)), the corresponding GEEs have not been calculated, but it is highly likely that the respective role of indoor versus outdoor air pollution as the main source of a population's pollution exposure risk is reversed; that is outdoor air pollution and urban settings comprise the dominant form of pollution exposure. As an example, consider emissions of sulfur dioxide (SO_2). The 'hotspot' of sulfur emissions and pollution, which has for decades been the 'black triangle' (the coal-rich border area of Poland, the Czech Republic, and East Germany) in Europe, was remediated by successful European sulfur-emission reduction policies. The current sulfur-emission hotspot is now in China (Figure 18.15), where high elevated levels of sulfur emissions particularly affect the urban populations and triggered policy responses (see also Section 18.5.5 below).

From an environmental perspective high urban energy demand and the resulting pollution densities hold two important implications. First, energy use usually involves heat losses at well above ambient temperatures and high densities of urban energy use also imply high densities of urban waste-heat releases. These combined with the (high) thermal mass of buildings in densely built-up urban land give rise to the 'urban heat island effect' (see below) in which urban mean temperatures are several degrees higher than those of surrounding hinterlands.

Second, fuel choice becomes of paramount importance: pollution-intensive fuels (biomass or coal) used at the high demand densities of urban areas quickly result in unacceptably high levels of pollution concentration (such as the London 'killer smog' of 1952 or the current air-quality situation in many cities, especially in the developing world). Even low-pollution fuels, such as natural gas, can quickly overwhelm the pollution dissipative capacity of urban environments. So, high energy-demand density requires zero-emission fuels: electricity and perhaps, in the long run, hydrogen.

18.4.2.4 Urban Heat Island Effects

Formation of urban heat islands

Urban heat islands describe the frequently observed pattern of urban air temperatures that exceed those of neighboring, more rural areas. In temperature maps, which delineate neighborhoods of similar temperature with contour lines ('isotemperatures'), urban areas stand out as 'islands' that form 'heat domes.' For example, Figure 18.16 shows these for Tokyo, the city for which most literature on the heat island effect is available.

Urban temperatures typically peak some hours after midday, but the absolute temperature difference against rural areas can be even larger during the night under cloud-free conditions. Heat islands are facilitated in climatic situations of low air movement. Wind otherwise disperses temperature plumes. Heat islands are similar to air-pollution concentrations and they can be enhanced by local topography and climate patterns that prevent mixing of the boundary layer. In terms of average temperature difference, urban areas are often 1–3°C warmer than the

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[25] Exposure risk: product of population × pollution level × exposure time of population to pollution.

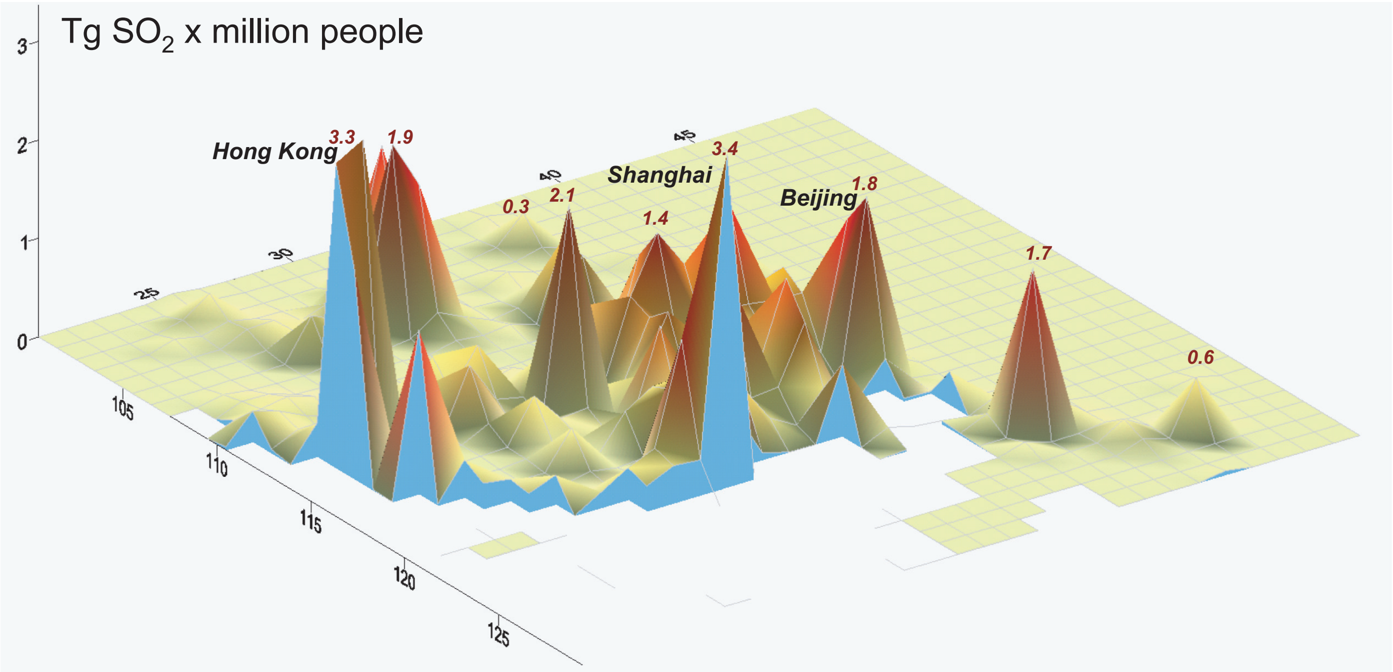

Figure 18.15 | Human exposure to sulfur emissions (population × emissions in million x Tg SO_2, z-axis) in China (2000), based on an analysis of gridded socioeconomic and emission data. (Units on x, and y-axis refer to geographical longitude and latitude). Note the high pollution exposure in major urban areas of China. Source: IPCC RCP scenario database (IIASA, 2010).

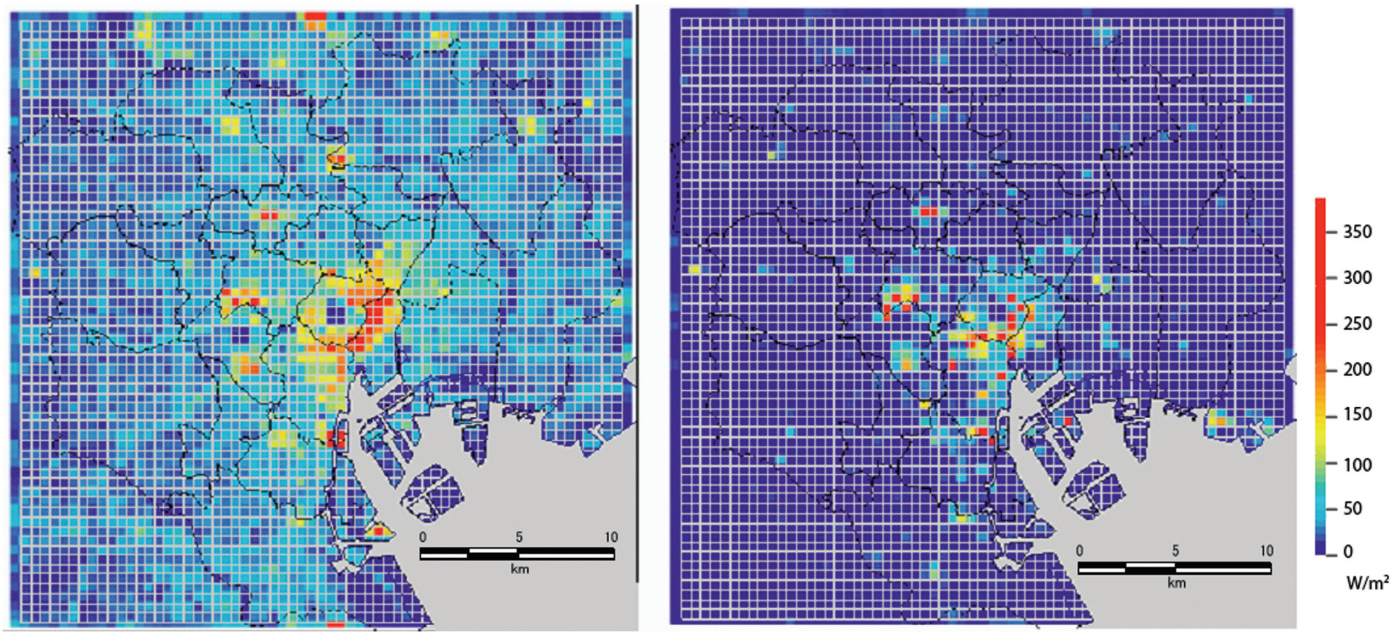

Figure 18.16 | Sensible (left) and latent (right) anthropogenic heat[26] emission in Tokyo (W/m²). Source: Ichinose, 2008.

surrounding air, and at individual locations in calm and clear nights temperature differences can exceed 12°C (Klysik and Fortuniak, 1999). With increasing energy use, the extent of urban heat island effects increases (Figure 18.17), which results in local warming.

Heat islands are, among other factors, caused by urban energy use through anthropogenic heat release. Without planning or intervention strategies there is a risk of maladaptation feedbacks, in which heat island countermeasures trigger increasing energy use, which amplify

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[26] Sensible heat flux: air is heated directly by the heated ground surface. Latent heat flux: evaporation from wet ground surface or from cooling towers settled on top of buildings and evapotranspiration from vegetation. This type of energy exchange does not change air temperature. Its energy is consumed in the phase change from water to moisture.

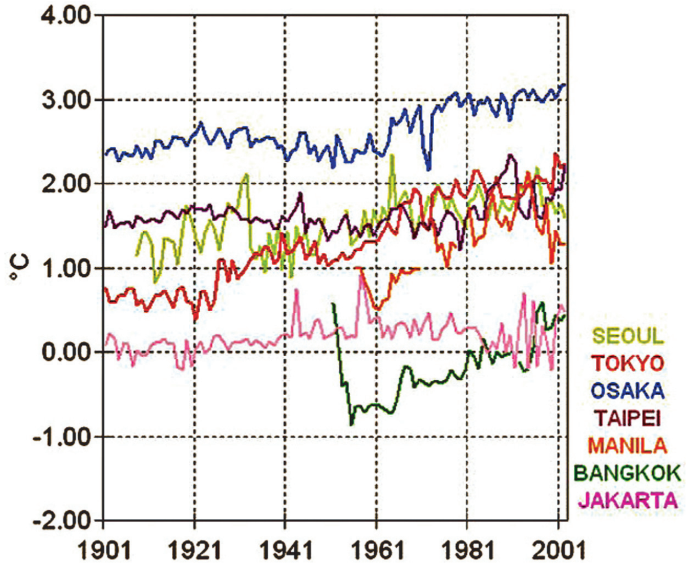

Figure 18.17 | Estimated urban heat island intensity in large Asian cities. Source: Kataoka et al., 2009.

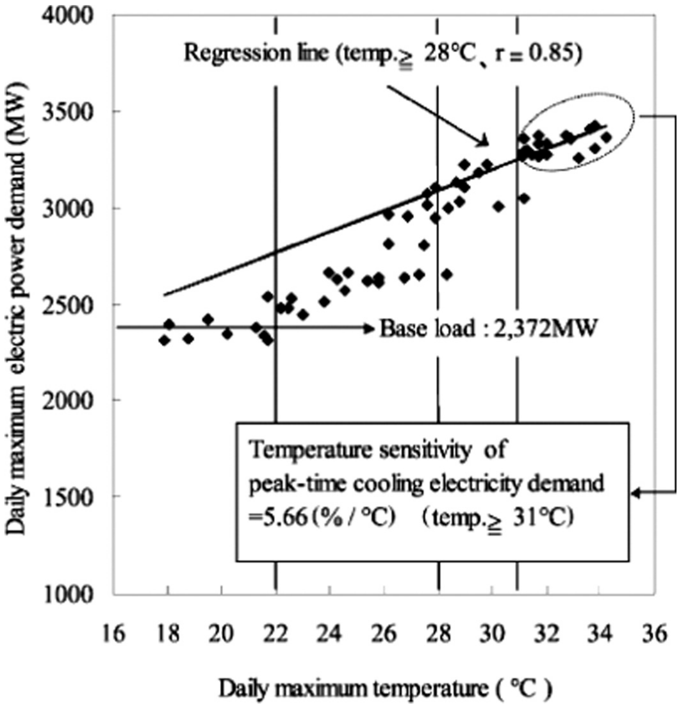

Figure 18.18 | Daily electric power demand and maximum temperature in Tokyo, June to August 1998. Source: Kikegawa et al., 2003.

the heat island (Figure 18.18). The increasing use of air-conditioning equipment in buildings and automobiles (which dump waste heat into the atmosphere) are one such example (Kikegawa et al., 2003; Crutzen, 2004).

Urban heat islands also affect the energy system directly. Elevated environmental temperatures reduce the efficiency of thermal power plants. Also, the availability of cooling water for thermal or industrial plants can be reduced as water bodies warm up.

A range of factors contribute to the formation of urban heat islands and their relative contribution varies among urban areas (Seto and Shepherd, 2009):

a) The geographic context defines the natural radiation balance across seasons, temperature, precipitation patterns, topography, and exposure to prevailing wind patterns. In humid climate regions, the natural vegetation is often forest dominated. Urban surface-temperature variation is then, at least partly, moderated by the latent-heat transfer through evapotranspiration of adjacent vegetation (Oke, 1987). Parks with water bodies and extensive vegetation cover reduce heat island formation. In more arid climate regions with low vegetation cover, daily temperature variation is more pronounced and heat island formation is more likely.

b) The replacement of natural vegetation with artificial surface materials for buildings, squares, and transport infrastructure results in more incoming radiation being stored during daytime, particularly if materials are dark, such as bitumen and asphalt. The albedo changes and differences in specific heat capacity of construction material result in more incoming energy being accumulated in surface material during daytime, which is later emitted as infrared radiation (Taha, 1997). Thermal insulation of buildings can reduce their specific heat capacity drastically.

c) Urbanization modifies the local hydrology. Natural groundwater recharge is typically prevented by the extensive use of impermeable surface materials. Rain gutters, drainage systems, sewers, and canals channel precipitation rapidly away to avert urban flooding. Additionally, the extraction of water from local wells and for construction projects often lowers water tables, which results in lower water availability for the remaining vegetation, and consequently lower evapotranspiration and associated cooling through latent heat transfer.

d) Also, structural characteristics of the urban form (Weng et al., 2004) affect the efficiency of heat loss through radiation and convection. Narrow street canyons with a limited sky view prevent heat loss through direct radiation upward. The urban layout and orientation of street corridors in relation to prevailing wind patterns affect the efficiency of heat transfer through convection and boundary layer mixing. These factors can be addressed through planning regulations. In Germany, for example, the concept of urban ventilation pathways ('Luftleitbahnen') aims to maintain radial corridors of cold winds to reach urban centers.

e) The metropolitan area size (extent) amplifies the magnitude of the urban heat island effect. For some rapidly growing urban areas, such as Los Angeles or Kobe, a continuous increase in urban heat island temperature of up to 0.5°C/decade occurred over the past 60 years. This trend is partly amplified by changes in energy-use patterns (Böhm, 1998) and needs to be compared against general trends of global surface temperature warming of about 0.7°C over the past century (Oke, 2006; IPCC, 2007; Kataoka et al., 2009) (see Figure 18.17).

f) As energy demand is concentrated particularly in urban centers, the consequential release of anthropogenic heat is similarly dense in these areas. Industrial and service-sector activity, residential housing, and transport functions are typically clustered in close proximity. Electricity use and combustion processes in buildings and vehicles, for heating and cooling, lighting, or motion, all result in vast quantities of waste heat being released (Rosenfeld et al., 1995). To a small extent, the metabolic activity of biological body functions of the human population also contributes to this.[27] Global average estimates attribute a resulting climate forcing of about 0.028 W/m^2 to anthropogenic heat release (technical and biogenic). In North America and Europe these figures are estimated to be higher, at +0.39 and +0.68 W/m^2, respectively (Flanner, 2009). For the Ruhr area in Germany, average anthropogenic heat-related forcing values of 20 W/m^2 were calculated by Block et al. (2004). At higher spatial and temporal resolution, the values are much larger, often between 20 and 100 W/m^2. Numerical simulations for heat discharge of individual neighborhoods in the Tokyo metropolitan region, for example, indicate radiative forcing values of up to 700 W/m^2 during the day and in summer time (Dhakal et al., 2003). However, urban heat islands do not always increase urban energy demand. In higher latitudes the resulting reduction in heating demand in winter can more than compensate the additional cooling energy demand in summer. Integrated climate-energy system models increasingly aim to capture such effects (Kanda, 2006; Oleson et al., 2010).

Mitigation

Strategies for heat-island mitigation include behavioral and technological solutions. They can provide various co-benefits, including energy savings, peak-load reduction, air-quality improvements, and beneficial health, psychological, and socioeconomic effects.

Building design and layout allow solar gains of houses in summer to be minimized and increased passive gains during winter (e.g., in Passivhaus designs). Reduction in cooling demand can also be achieved through the use of deciduous vegetation for shading (including vertical greening of facades) or the application of mechanical shades, shutters, or 'smart glass windows,' with modified transmission properties of heat and light on demand. Albedo changes and the use of reflective paint and surface material on roofs and transport infrastructure is another particularly cost-effective mechanism to reduce heat absorption in urban areas. Improving the insulation of the building stock to prevent the warming and storage of solar influx in material of high specific heat capacity, such as concrete, is another measure, just like the expansion of shading structures (vegetation or textile) in general. The shading of parking lots, for example, not only provides thermal comfort, but also reduces emission of volatile organic compounds (significant precursors of low-level O_3 formation) from parked vehicles.

Active cooling via enhanced evapotranspiration can be induced through ponds or fountains, green roofs, and tree planting, or through the generation of artificial mist (microdroplets of water) to create local cooling clouds. In preparation for urban heat waves, the city of London considered the need to prepare 'cooling shelters' for vulnerable or elderly population, as the typical UK housing stock is not equipped with air-conditioning (City of London, 2007).

Changing the timing of activity patterns to avoid the hottest hours of the day was a traditional response to hot climates. In peak-load management programs some of this rationale is revived. Operators of office space in New York City are given price incentives to start air-conditioning in the early hours of the day to reduce demand during peak hours of electricity demand (Bloomberg, 2007). While the primary motivation was to reduce peak power demand in a grid of constrained capacity, this measure also reduces the peak in waste-heat emission in the early afternoon hours. While probably not the most suitable for dense, high-rise developments like Manhattan, solar cooling devices that provide a maximum cooling output at periods of peaking outdoor temperatures appear to be suitable for low-density cities.

In 2005, the Japanese environmental ministry started a campaign titled 'Cool biz' to restrain the use of air-conditioning units to an indoor temperature of 28°C. The campaign aimed to loosen the strict dress code of full-suit, tie, and long-sleeved shirts for office workers during the hot season (June 1 to September 30) and promoted a more heat-tolerant dress code of short-sleeved shirts without ties (Pedersen, 2007).

18.4.3 Supply Constraints, including Reliability and Security

Cities depend on extended energy networks and failures can occur on a regional and national scale. On August 14, 2003, a cascading outage of transmission and generation facilities in the North American Eastern Interconnection resulted in a blackout of most of New York State as well as parts of Pennsylvania, Ohio, Michigan, and Ontario, Canada. On September 23, 2003, nearly four million customers lost power in eastern Denmark and southern Sweden following a cascading outage that struck Scandinavia. Days later, a cascading outage between

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[27] Assuming about 100 W of biological energy use per person and maximum population densities of 40,000/km^2 in some cities in developing countries, this factor can contribute up to 4 W/m^2 additional forcing. Typical urban population densities are lower.

Italy and the rest of central Europe left most of Italy in darkness on September 28. These major blackouts are among the worst power-system failures in the past few decades. They had a profound effect on power-system philosophy because these networks were some of the world's most sophisticated power-generation distribution systems. In particular, the US failure was promoted by an early underlying failure in software used to control networks, which meant the scale of the emerging problem was recognized too late to protect the cascading failure.

Energy efficiency and resilience are not coincidental outcomes. Thus, a low-energy settlement might be even more sensitive to disruptions in supply than a settlement with some slack in its energy system. A dense city with no power for its elevators may be in a worse state than a low-density urban settlement without power. Renewable power sources based on wind or solar alter the reliability profile. As they are of a much smaller unit size, they do not induce major dropouts, as happens when a large nuclear power station needs to come offline very rapidly. Conversely, the variability in available power they supply may require them to be shadowed by a rapid-response plant. They may also exacerbate failure cascades because of switching out for self-protection when the power system is stressed heavily.

The increasing dependency on power even for simple clerical work, let alone for critical functions like hospitals, means that stand-by power supplies could be an increasing feature in urban systems. One suggestion (Patterson, 2009) is that it is possible for the local distributed power generation to become dominant and the national distribution systems only handle back-up. This is already effectively the case for dwellings that use microgenerators for power and heat. Another suggestion is that more sophisticated metering and tariffs could incentivize the extension of demand-side load management from large facilities of 'interruptible supply' at the microscale. In line with the efficiency-resilience argument it is expected that vulnerability to societal interruption is higher in countries with generally very secure supplies in which the economy has sought an equilibrium that assumes secure power supplies than in countries with frequent brownouts and blackouts in which the economy has adjusted to coping with the risk.

The winter of 2008/2009 in Europe showed the vulnerability of gas-supply networks to urban areas. Gas can be stored both in the mains and in dedicated storage facilities, but gas is currently supplied directly to consumers and power generation, and so indirectly to mass-transit systems. Thus, a failure of supply pressure has wide implications. Coastal cities can increase their robustness with liquid natural gas (LNG) terminals, but LNG is a world-trade product and may come at a high price in a regional emergency.

Liberalization of gas and electricity market pressures gives the lowest prices to consumers, but the effect is to incentivize producers to 'sweat' their existing assets (e.g., Drukker, 2000). It may then become necessary to introduce further complexity into tariffs to incentivize investment and reflect the value to the consumer of lost load. Undercapitalization of energy networks, many of which were built in the 1960s, remains a real risk over the next 20 years in developed world systems.

Possibly the greatest vulnerability in an urban context is the supply of transport fuels. The weakness of the low-density settlement is its complete dependence on oil at a density below around 30–40 persons/ha (Levinson and Kumar, 1997). There are ways to save oil quickly (IEA, 2005), largely based on increasing load factors, but there is a mounting recognition of the advantages of diversifying the transport energy vector away from oil.

18.5 Urban Public and Private Sector Opportunities and Responses

18.5.1 Introduction

18.5.1.1 Concepts of Sustainable Cities and Designs

The term 'sustainable city' dates from the 1990s. The term 'sustainable development' is usually dated from the World Commission on Environment and Development Report (WCED, 1987), which devotes a chapter to 'the urban challenge.' The WCED concern was principally about issues of the urban poor in rapidly growing large cities of the South. The term sustainable development is now used more frequently in the narrower context of the need to protect the environment that underpins social and economic capital. For this reason the term 'sustainable cities' is more often associated with civic initiatives in cities of the North, addressing what is perceived as the unsustainable impact of their citizen's lifestyles, especially the generation of large volumes of waste and GHG emissions. It is largely coincident with the earlier idea of an 'ecocity.' Ecocities essentially try to contain their 'ecological footprint' (Andersson, 2006; Jabareen, 2006; Kenworthy, 2006; Pickett et al., 2008). This focus means that some projects are not always more broadly sustainable, especially as economic units.

Attempts to achieve an optimal 'sustainable urban system' in new settlements invariably resorts to some form of spatial organization. This may be provided by a city authority, but it could equally be the covenants imposed by a land developer. The intention is to gain from bringing the various strands of urban activity together into a more integrated whole. For example, reducing urban traffic noise through less need to travel by automobile and the use of quiet road surfaces or electric vehicles enables citizens to keep windows open in summer. This provides the opportunity to avoid mechanical ventilation by recovering the opportunity for natural ventilation. 'Sustainable' urban configurations are often expressed in terms of optimal residential densities linked to low-profile transport networks. This fairly crude metric is often employed in zoning regulations. The optimal configuration then seeks to avoid a very high density with highly congested services and a very low density automobile-dependent networks. This configuration is expected to induce a stronger sense of community by providing some local retail and commercial space with local interaction, itself reducing the need for automobile travel.

Energy implications of 'sustainable cities' arise naturally from their move away from automobile dependency. But overlaid is an attempt to exploit the area of the city as a source of renewable energy. At the current state of technology, most 'zero-carbon' developments are essentially *net* zero carbon, and rely on the existence of a market for surplus renewable electricity at some time of the day and the ability to import electricity at others. The installed PV capacity for the proposed new Masdar city in Abu Dhabi is nearly 200 MW within its city boundary of 6 km^2. Wind is less likely to be exploited in a sustainable city, except as an aid to natural ventilation, because of the ground-effect drag in urban environments. For the purist to import green electricity is wrong. While wind generators sometimes appear in iconic building structures, drag resistance of the urban surface makes them a less compelling investment than wind generators in more exposed localities. However, while the proposed ecocity at Dongtan outside Shanghai uses local agricultural wastes as an energy supply, it is not obvious how this differs from using waste collected from a wider area.

Waste is a particular issue for all cities. Cities of the ancient world produced little nonbiodegradable waste, in contrast to the large volume of solid waste that large urban settlements currently need to dispose of. 'Sustainable city' discourses thus focused on reducing waste sent to land fill by providing recycling and incineration facilities. In ironic contrast, the large cities of the developing world already have an informal economy in the periurban areas that pick clean the waste of the formal urban centers. Sustainable cities frequently try to capture waste heat from electricity generation by locating combined heat and power (CHP) sets within the city or encouraging microgeneration. For large urban areas this strategy can only maintain urban air quality if other measures designed to reduce air pollution are successful – which emphasizes the importance of treating issues and systems holistically (Box 18.4).

Box 18.4 | Zero-Carbon Cities

Planners are exploring new urban paradigms in which urban energy use is not entailed by urban form, but in part defines the urban master plan. Dongtan near Shanghai and Masdar in the Arab Emirates are two recent high-profile design studies that exemplify this.

Both Masdar and Dongtan represent a new development strategy whereby the creation of the city forms its own economic rationale. This reflects the delocalization of some classes of economic activity and hence the ability to bring these together in a desirable location. This is the theory behind the creation of Dubai as a global financial sector from scratch. Less ambitiously, Dongtan was to be a service center outside of Shanghai. Masdar was to be a knowledge center that specialized in renewable energy technologies. The master plans of both complexes are polycentric so that 'quarters' or districts are often defined by a locally dominant economic or social function. Whether the loss of monocentricity is significant is hard to tell. The cellular nature of both development plans enables stable modular growth in uncertain economic times. Both designs have a substantial external energy supply from local renewable resources and so 'to first order' are formally 'zero carbon.' The designs themselves sought to reduce energy demand substantially without affecting service delivery.

Dongtan was designed as a 'zero-carbon' development. The initial settlement study was for 80,000 inhabitants, but with expansion possibilities to over half a million. Its external supply of energy is regional biomass waste from rice production, along with solar power panels. In delivered energy terms, it is an all-electric city. Electric vehicles provide all motorized transport within the city. These can either be conventional battery-powered or fuel-cell powered vehicles that use hydrogen, but the short range is less important in Dongtan because the city is spatially organized to reduce distances for essential travel. Conventional transportation to the outside world has to be parked at the city boundary. The master design features not only low-energy concepts, but also self-sufficiency in water and waste recycling. A particular feature was the exposure of system synergies. For example, by switching to quiet clean electric vehicles, it became possible to revert to natural ventilation and day lighting for housing and offices. The estimated 'eco-foot print' for Dongtan was 1.9 ha/capita, only slightly above the WWF target (Cherry, 2007).

Masdar faces a notably different climate to Dongtan, dominated by cooling load. This demand is reduced by recourse to traditional Arabic architectural approaches that protect building facades and access routes from the sun, with narrow access spaces that still provide daylight penetration into occupied spaces. Like Dongtan, Masdar is a zero-carbon urban development. The scheme's energy supply is provided by a large solar-power energy park. Indeed, Masdar's economic rationale is as an international center in advanced renewable energy technology. Its first districts are already established and it hosts the International Renewable Energy Agency supported by over 130 nations. Industrial zoning places production facilities at the periphery of the neighborhood complex, where more conventional freight transport has access. Novel electric personal transport aims to shuttle residents between centers. As with the Dongtan design, there are no private vehicles within the city. The planned scope of the city is around 6 km^2.

Both Dongtan and Masdar were designed as showcases of a new vision of future master planning focused on low environmental impact, especially of energy. The focus on zero carbon and sustainability reflect the kind of private investment that the developments were intended to attract. The common theme is the value of integrated design in reducing the overall impact of urban processes. It is yet to be demonstrated whether less well-endowed and less well-organized new urban settlements can achieve similar impressive potentials. Given Masdar's initial investments of well above US$20 billion, the sheer magnitude of the investments need for housing some three billion additional urban dwellers in radical new zero-carbon city designs is staggering: well above US$1000 trillion, or some 20 years of current world GDP (Kluy, 2010)!

Whereas the Masdar project has completed at least its first phase, the Dongtan design has been set aside for the moment, although a number of new, perhaps less ambitious, settlements are under construction around Shanghai (Larson, 2009). In many ways the Dongtan design exercise has served as a valuable learning experience in 'holistic' master planning and is widely influential. As important as both projects are as showcases and experiments in new thinking and planning, the actual urban development reality is rather one of incremental, continuous change within an existing urban fabric that needs to incorporate the lessons learned from bold 'greenfield' ecocity design experiences.

The 'sustainable city' as currently conceived is not without its critics. The discourse is often so concerned with environmental factors that the local robustness of social and economic capital is unwisely taken for granted. However, examples that have been partially implemented show reductions in final energy use against normal benchmarks of 10–15% without any substantial changes in lifestyle norms. While sustainable urban form can often require significant capital 'up front' and is thus a serious obstacle under capital constraints, a possibly more fundamental issue is *institutional*. Is it possible that stakeholders within an urban context who are used to working independently can find an institutional structure where they can work together in an integrated manner. This may be easily done at the master planning stage, at which broad-brush issues are under the control of a single land-use planner, but to maintain the integrity of the master plan can be a challenge. If the problem can be solved, it would be a major disruptive technology to conventional urban planning and development and for which prototype design software is already in existence (Keirstead et al., 2009).

Summary

Urban planning measures have the potential to be very powerful methods of integrating urban services that minimize urban energy use and other ecological impacts. Nonetheless, many of the recent design exercises in 'sustainable cities' are for premium urban centers. The technology may be transferable with further development, but the systems are presently too expensive to treat them as realistic new paradigms for the urban built environment in the decades to come.

18.5.1.2 Overview of Main Policy Instruments of Relevance for Urban Energy Systems

The policy players

Policy instruments that apply to urban settlements are generally exercised through several layers of government, often as many as five or six. In theory, this plurality is to ensure that policy powers have an appropriate geographic reach for the issue at hand, and to ensure that destructive competitiveness between settlements does not undermine the quality of specific policy interventions (e.g., Baumol and Oates, 1975). Parallel arguments are deployed to explain the distribution of tax raising, tax collection, and spending powers at different levels of government. The system is extremely effective, but it can be prone to problems of coordination and regional politics. The universal tendency is to decentralize responsibility without decentralizing resources. Urban administrations are more often the delivery agent rather than the tax raiser and this frequently leads to accusations by lower tiers of government of 'underfunding' by higher levels. From time-to-time many of the cities, even in the richest nations, operate close to bankruptcy, which can limit their ability to obtain capital for projects. Generalizations are otherwise dangerous. Urban settlement patterns of governance are, in part, an accretion of local history.

The degree to which public policy is a meaningful term in an urban energy context varies greatly from the highly organized urban society of Singapore to the current chaos of Mogadishu. The issues important to energy use, such as regulation of construction standards for stationary infrastructure, are found at all levels. Control of transport provision also occurs at all levels, although land planning, infrastructure standards, and transport can be dealt with by distinct silos within several layers of public administration. Also, landowners, both private and public, often hold important powers through ownership rights that help define the urban form and its physical emergent properties. Houston is possibly the extreme with no state zoning, but relies largely on land covenants. Other relevant powers can reside with the public or private bodies that provide the utility services.

Energy use is currently an 'emergent' property of a complex urban system. Current governance structures were not designed specifically to manage energy outcomes. In any long-term perspective that embraces a very uncertain future in which energy and related environmental issues become important, it seems likely that greater clarity and effectiveness of governance-relevant structures is highly desirable. Increasingly, major cities in the world have developed 'energy plans' or 'energy strategies' (e.g., Mayor of London, 2004).

The policy instruments

Policy instruments are conveniently arranged in a hierarchy of leverage effects, with land-use planning at the base and control of infrastructure use at the apex. Sometimes the whole hierarchy is delivered at one stroke, as in a major rapid expansion of an economic zone, and energy optimization or 'zero carbon' has featured in a number of recent expansions (e.g., Masdar (Biello, 2008), Dongtan (Normile, 2008), and Incheon (Kim and Gallent, 1998)). These large enterprises are usually led by a development corporation or similar entity with powers to integrate the various s tiers of provision and exceptional access to capital. While impressive in concept, to devise a master plan durable against changes in external circumstances over decades is no mean feat (as the unrealization of the Dongtan project illustrates).

Normally, land-use planning is less ambitious and sets aggregate parameters for zones, such as permitted functions, density, or maximum building height, that guide rather than direct public and private investment. This is the pragmatic solution for the incremental redevelopment of an area. This means that upgrading and refurbishment frequently takes place in patchworks such as '22@' in Barcelona or 'Thames gateway' in London, usually within the framework of a local or regional government 'master plan.' This approach is potentially very powerful for realizing some of the advantages of economies of scale in low-energy or low-carbon technologies, but there is as yet relatively little experience as to how to exercise it effectively. There are some impressive examples in European towns, like Malmo and Freiburg, and US towns like Portland or Davis. These examples influenced recent thinking in urban design, but are apparently not impressive enough to induce widespread replication at current (low) energy or 'carbon' prices.

In many jurisdictions the planning authority has the power to apply conditions to new developments, such as mandatory connection to a district-heating scheme. These conditions can be overwritten by other energy-policy objectives. For example, in Europe a development might be required to install a renewable energy source, but energy competition policy would prohibit the imposition of an additional requirement for its exclusive use by tenants. Planning control can be effective in eliminating the most excessive energy use and giving some certainty to capital investment. However, because so much of the final energy use is delivered by instruments at lower levels in the hierarchy, planning control can seldom deliver very low-energy solutions on its own. Where a low-energy solution collides with other environmental factors, such as appearance or noise, it can militate against it.

The next level 'down' from planning control conventionally contains instruments that relate to the economic framework of the urban settlement. Since the 1980s the trend has been for local services to be provided by the private sector within a regulatory framework. Energy prices are usually regulated (or subsidized) at the national level, and not always in a manner conducive to good outcomes. Removing energy subsidies is theoretically a low-hanging fruit. In practice, the objections of those who benefit from them make such action politically contentious. However, lower tiers of government still have a number of economic instruments at their disposal, especially for transport. Thus, parking charges and more ambitious road-user charging can be used to favor or subsidize mass-transit systems. As these instruments are often redistributive, even when effective, their application can require considerable political skill. The London Congestion charge is a case in point (Taylor, 2004). More broadly, the price of land and stationary infrastructure is an important factor in all that goes on in urban settlements. Property taxes and taxes on sales can incentivize upgrading of the energy efficiency of the building stock. Where land ownership is heterogeneous, local government can facilitate the roll out of refurbishment programs, often working with large property developers. Programs of this kind can make up a substantial part of the work of 'energy-service companies' or ESCOMs (Dayton et al., 1998). The lowest tier of policy instruments relates to individual components and their direct use. Construction standards when coupled with standards for energy-control provision have a long history of application. The diffusion of new technologies is *inter alia* influenced by social networks (Fisk, 2008) and local networks, of which local government is a part and can accelerate take-up.

The provision of a mass-transport system is an important option when travel densities are sufficiently high to provide savings over private transport. However, success depends, in part, on delivering a service that is universal rather than just for the most disadvantaged. That, in turn, implies a system with sufficient coordination to ensure feasible journey times for a wide range of journeys.

Finally, urban administrations have an important role to play in administration during energy-security events (IEA, 2005).

18.5.2 Drivers of Urban Energy Use and Main Policy Leverages

18.5.2.1 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.

18.5.2.2 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% and 24% 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 Section 18.4.2.4). 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% increase in peak electricity demand (Akbari et al., 1990; 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 large economies of scale, 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.

18.5.2.3 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 Section 18.2.4; Brown et al., 2008; Parshall et al., 2010).

Figures 18.19 and 18.20 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 18.19). Figure 18.20 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.

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 used per capita (see above). 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 is mixed. In Sydney, increasing age is correlated with 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.

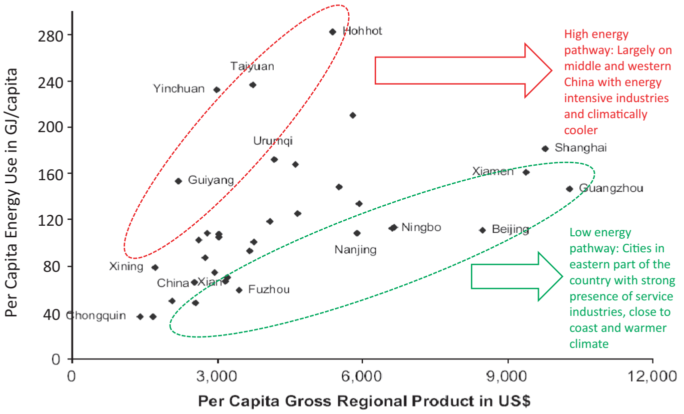

Figure 18.19 | Per capita energy use versus income for a sample of Chinese cities for the year 2006, illustrating path dependency. Per capita Gross Regional Product is expressed in US_{2006}\$ calculated using market exchange rates, MER. Source: Dhakal, 2009.

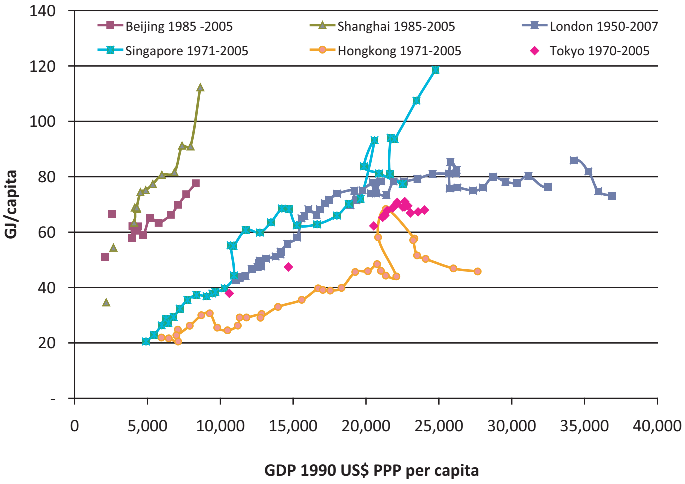

Figure 18.20 | Longitudinal trends in final energy (GJ) versus income (at PPP, in Int_{1990}\$)[28] per capita for six megacities. Note the path-dependent behavior. Source: Schulz, 2010a.

18.5.2.4 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 18.5), 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[29] 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.

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[28] For comparison: per capita GDP (in PPP terms) in 2005 and in $Int\$_{2005}$ are: Beijing: 9238, Hongkong: 34574, London: 53145, Shanghai: 9584, Singapore: 29810, and Tokyo: 33714. (Note that a change in base year for the PPP metric changes the relative position of urban incomes in a non-proportional way.)

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

Box 18.5 | Singapore: The Importance of Trade

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 18.21). 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.

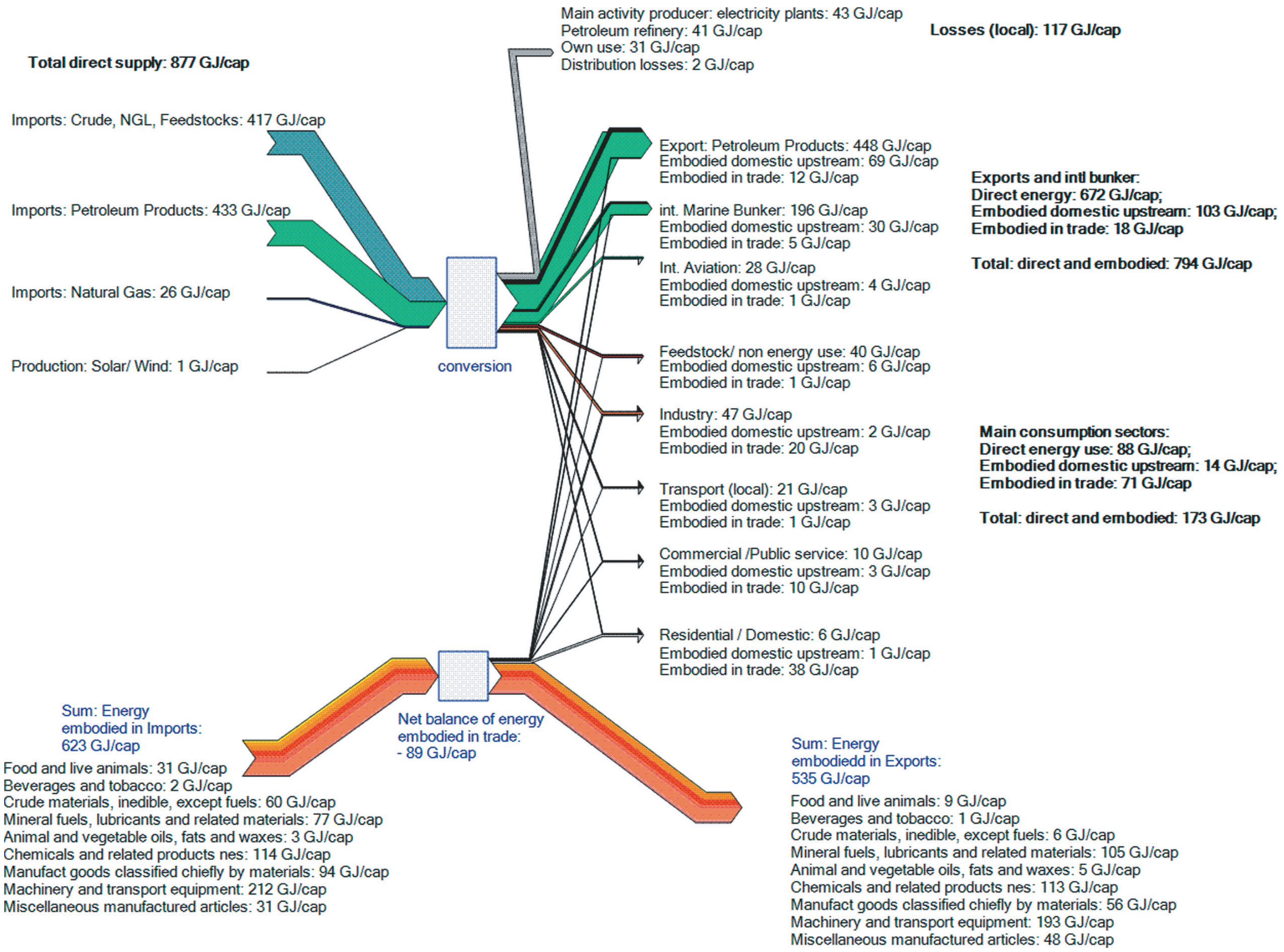

Figure 18.21 | Full per capita energy accounting for both direct and embodied energy flows of a large urban trade city, Singapore (in GJ/capita). Domestic direct and embodied energy use is 173 GJ/capita, but is dwarfed by the total energy imports to the city of 1490 GJ/capita. Total energy re-exports (direct and embodied) are 1225 GJ/capita. Source: Schulz, 2007; 2010b.

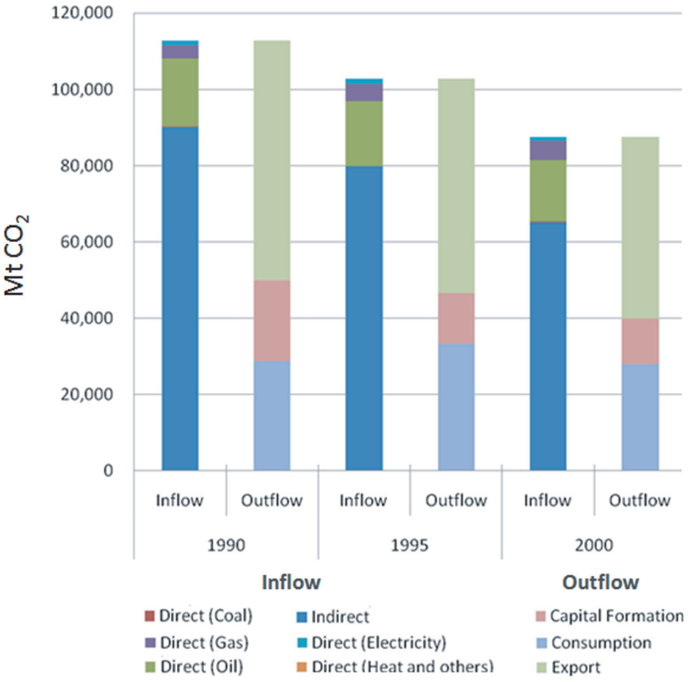

Figure 18.22 | CO_2 balance of Tokyo 1990, 1995, and 2000 using I-O analyses, in million tonnes CO_2. Source: Estimates by Shinji Kaneko and Shobhakar Dhakal.

That urban areas are usually in an intense process of energy exchange (imported and exported) with surrounding markets is again shown dramatically in Figure 18.22 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% 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 18.22). 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 household expenditures (as frequently done) therefore misses these important embodied energy and emission flows.

The 35 largest cities in China (China's key industrialization and economic drivers) are responsible for 40% 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 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 18.20 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 intranational competition also occurs in other countries, such as Vietnam and India.

18.5.2.5 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% 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 fuelwood, 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% (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% lower compared to systems in which all energy demands are provided by separate, individual conversion devices.

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 18.6).

Box 18.6 | Urban Exergy Analysis: Efficiency – How Far to Go?

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% 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 with 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% of secondary energy is delivered as final energy and about 50% can be used as useful energy to provide the energy service needs of the city (see Figure 18.23). The impact of cogeneration on the city’s energy needs is also noticeable: without cogeneration Vienna’s secondary energy use would be some 13% 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%. 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.

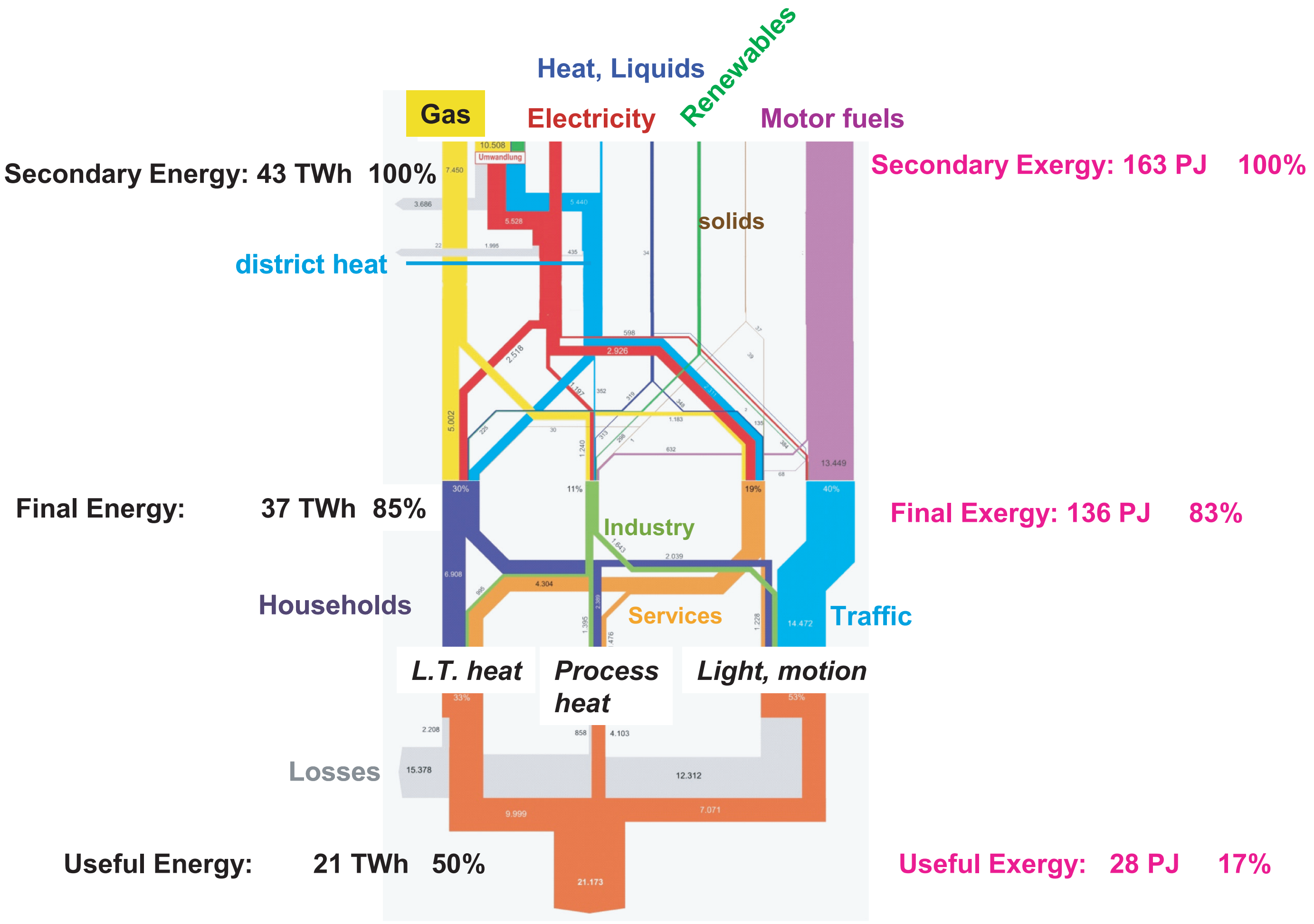

Figure 18.23 | Energy and exergy flows in the City of Vienna in 2007 between secondary and useful energy/exergy. Source: Energie Wien, 2009, (approximate) exergy efficiencies based on Gilli et al., 1996.

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 18.15.

Table 18.15 | 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 two. 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 2400 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%, compared to 11–23% for modern urban energy systems and uses.

18.5.2.6 The Urban Form: The Built Urban Environment and its Functions[30]

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 (for a detailed exposition of building energy use, see Chapter 10). 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.

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 midlatitude 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, whereas poor thermal insulation may cause energy use for space heating of 200–400 kWh/m^2 in mid-European latitudes.[31]

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% and 10% 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% 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% (Sartori and Hestnes, 2007) and 29% (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).

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 of apartments was significantly less (10–30%) 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 18th century, 19th 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 factor of up to 20 could be achieved

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[30] A working paper on urban form and morphology contains a more extended discussion and is accessible at www.globalenergyassessment.org.

[31] See http://energieberatung.ibs-hlk.de/

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).

Urban form and functions

Urbanization patterns affect the extent and location of urban activities and impact the accompanying choice of infrastructures. Newton (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 Section 18.5.3 below). 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). Intracity 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 suburban areas (sprawl) (Baynes and Bai, 2009).

In many of the less-compact cities, transportation[32] 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 Section 18.5.3). 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 efficincy 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

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

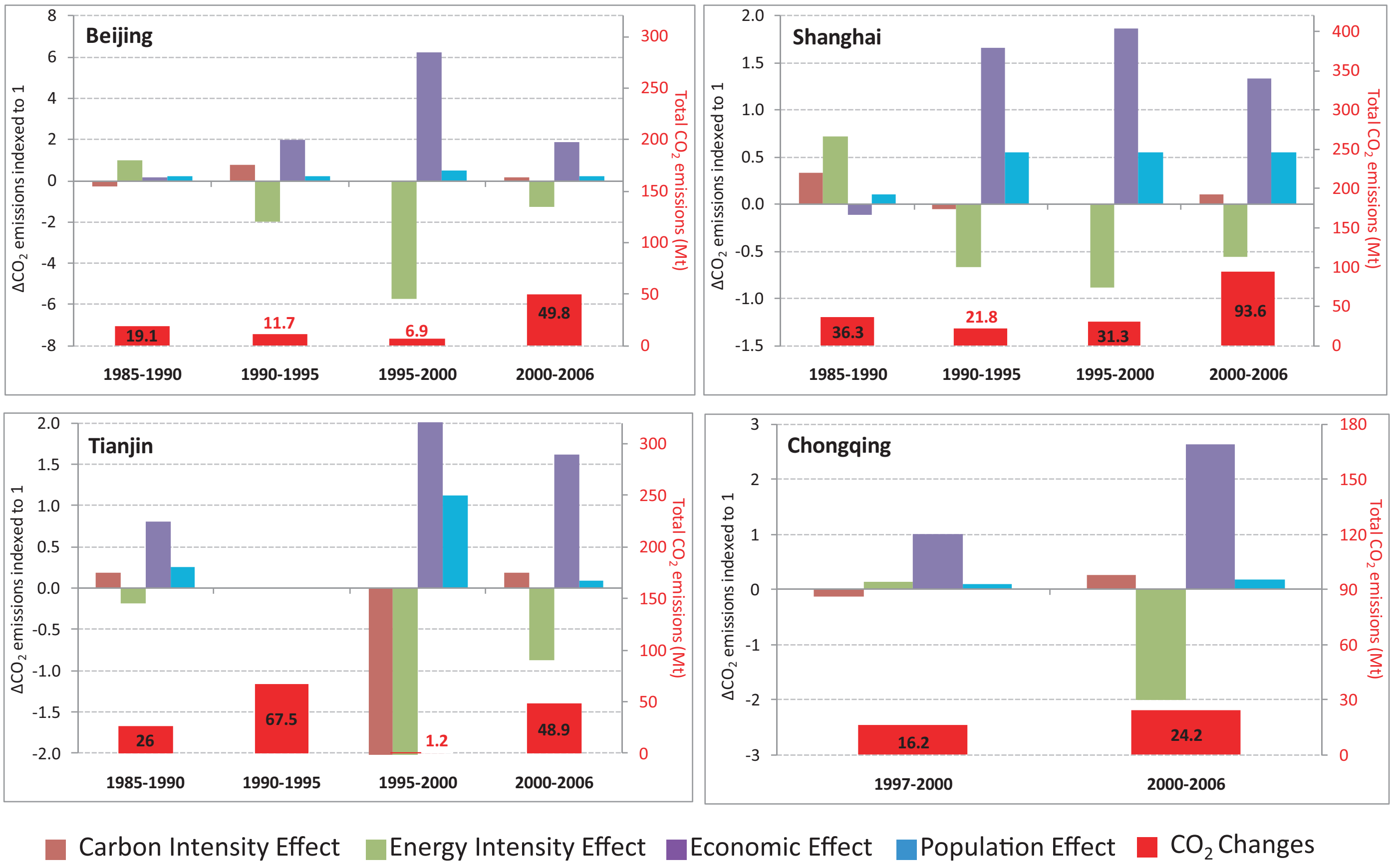

Figure 18.24 | Contribution of factors (indexed, left axis) to the changes in energy-related CO_2 emissions (million tonnes CO_2, right axis) for four Chinese cities. Source: Dhakal, 2009.

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.

18.5.2.7 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 macrodrivers as population, income, and technology, and thus follow the classic IPAT decomposition approach.[33] 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 18.24).

Earlier work by Dhakal and Hanaki (2002) and Dhakal et al. (2003) for Tokyo using 1970–1998 data and for Seoul using 1990–1997 data also

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[33] IPAT: Impacts = Population × Affluence × Technology. For a history and discussion of the concept see Chertow, 2000.

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 1970–1990 for Tokyo and 1990–1997 for Seoul. The analysis also showed that, despite an economic recession, energy-related CO_2 emissions continued to grow in Tokyo in 1990–1998, largely because of a drastic decline in the energy-intensity improvement rate (often observed in periods of economic growth stagnation or recession caused by the slower rate of capital turnover and hence the slowing introduction rate of more energy-efficient technologies and practices).

18.5.3 Transportation Systems[34]

18.5.3.1 Urban Travel Behavior

Introduction

To a large extent, traveling and mobility are a means to an end; they are necessary to enable people to fulfill essential functions (e.g., living, working, gaining education, acquiring necessary supplies, and relaxing) in the most suitable places. The situation is similar for the production of goods and services: fragmentation of the production process of goods and services implies different stages of the production chain, provided by different, more specialized enterprises at different sites, which improves the efficiency of the production at all. This causes travel demand, which is measured in different ways depending on the reasons for travel:

Frequency of trip making

This metric is a basic indicator for the degree of mobility and concurrent degrees of economic development and lifestyles. In urban settings the mean value of this figure ranges from 2.2 trips/day for people in low-income cities of developing countries (Padam and Singh, 2001) to up to 4.0 trips/day in industrialized countries (Hu and Reuscher, 2004; Sammer et al., 2009). It is expected that, in future, the frequency of trip making will rise slightly, particularly in developing countries. Generally, the frequency of trips is higher in cities than in rural areas because of higher degrees of specialization and division of labor and the higher number of attractive destinations with good accessibility, characteristic of urban areas.

Distance traveled per day

This metric reflects the transport modes used and the spatial structure and settlement density (NRC, 2009). The lower the settlement density and the more automobile-oriented an area, the longer the distances traveled per day. Globally, the mean values of these distances vary considerably, from 10 to 60 km/person/day in developing and industrialized countries, respectively (Salomon et al., 1993). In rural areas of developed countries the average distanced traveled per day is *higher* than that in cities. In developing countries the opposite is true: in rural areas distances traveled are generally very low (significantly below 10 km/person) and are significantly higher in urban areas because of both higher urban incomes and better availability of urban infrastructures and transport options. There is a close positive correlation between the distance traveled per day and transport energy use (Pischinger et al., 1997).

Travel time budget per day

This metric is an indication for the time spent traveling. For long periods this figure was comparatively stable with a small tendency to increase; it is currently on average around 70 minutes per person and day and 90 minutes per mobile person and day in countries with high motorization and automobile orientation (Hu and Reuscher, 2004; Joly, 2004). Assuming that, in the long run, working hours will decrease through continued productivity gains, this figure is expected to increase somewhat in future.

Traffic and mobility surveys help to determine the travel behavior, which is typical for various sections of the population and for different settings. Caution is, however, advised when comparing different mobility surveys because of differences in survey coverage and methods (e.g., does the survey include non-motorized modes?) and differences in sampled populations (commuters to work versus total population) and other methodological intricacies (e.g., weekday vs surveys that also include weekends). Therefore, there remain serious data gaps for comparable and up-to-date mobility surveys across a wide range of settlements and with comprehensive geographic coverage. The next sections summarize the current state of knowledge, with special emphasis on survey comparability rather than on how recent the survey date is. Despite important data limitations, some robust generic patterns can be discerned.

Modal split of cities

The modal split is an expression for the shares of different transport modes in the overall travel demand – usually measured as shares in total number of trips performed. It is a reasonable proxy for the evaluation of the environmental soundness of an urban transport system and its associated energy use. Higher shares of 'ecomobility' transport modes (including non-motorized modes like walking and cycling, as well as public transport) and corresponding smaller shares of private motorized transport imply a more environmentally friendly and energy-efficient transport system. The modal split can be conveniently depicted in a triangular diagram (Figures 18.25 and 18.26) that plots the respective shares of non-motorized modes (walking and cycling), public transport, and private motorized transport (automobiles, two-wheelers, etc.), respectively. In cities or towns with a modal-split point close to the center of the triangle, the three transport modes have fairly similar shares. In Figure 18.25, public transport dominates in the case of modal-split points close to the top of the triangle (e.g., New Delhi in 1994), private motorized transport is dominant in the lower right-hand corner (e.g., Chicago in 2001), and non-motorized transport in the lower left-hand corner of the triangle (e.g., Lackhnow in 1964). This

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[34] See also Chapter 9 for a review of transport energy.

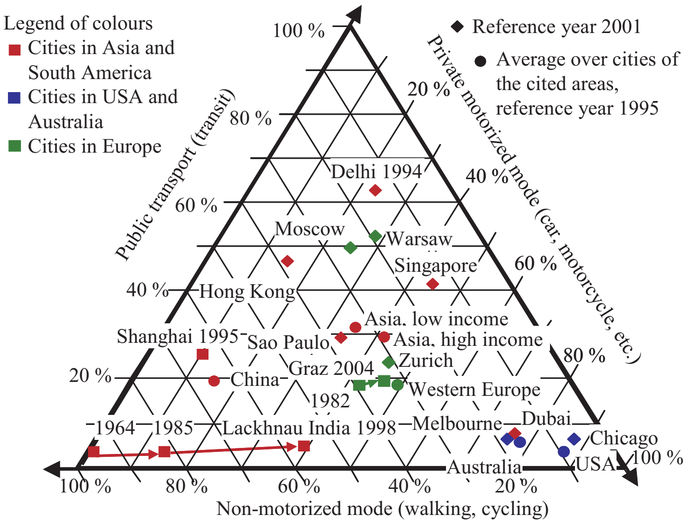


Figure 18.25 | Modal split for cities and towns on all continents (shares in trips). Source: Kenworthy and Laube, 2001; Padam and Singh, 2001; Zhou and Sperling, 2001.

representation enables the display of both cross-sectional and longitudinal observations.

Private motorized transport has a very high share between 88% and 79% in cities in the United States and Australia, where ecomobility has only a very low share of 12–21%. Thus, in these cities and towns transport systems depend strongly on private automobiles and so on fossil fuels. Cities and towns in Western Europe and well-developed Asian economies are roughly in the center of the diagram. There motorized private transport holds a share between 36% and 50%, that is transport systems are less automobile-oriented, and ecomobility holds a remarkably high share of 10–50%. In the cities and towns of China private motorized transport has thus far been fairly insignificant with a share of about 15%, but it is growing rapidly in importance.

Figure 18.25 indicates that with growing economic development and increasing incomes, the share of private motorized transport increases while the share of ecomobility decreases. This development is illustrated well by the longitudinal time trends of the modal split of the city of Lackhnau in India over the period 1964 to 1998. The United States and Australia seem to have reached a saturation level in this development; Western Europe and Asia have still some potential to develop further in this direction, unless they take countermeasures. This development does not follow any laws of nature: it is the result of transport policies and human behavior.

While Figure 18.25 shows the average modal split of cities and towns, Figure 18.26 shows the modal split for *commuter transport* in economically highly developed cities on different continents. These cities are divided in two groups: those with less and those with more than one million inhabitants.

For some selected cities the development of the modal split over time is also indicated, where comparable data are available. From the modal split for these cities and towns it is obvious that the range for individual elements is quite large, despite similar economic conditions and a high automobile-ownership rate. For example, non-motorized transport ranges from 4–50%. For walking as a separate mode, the range is from 4–21%, while cycling ranges from 0–39%. The range for public transport is also high, from 5–63%, while private motorized transport ranges from 24–80%. Thus, a high share of private motorized transport in towns and cities and an extensive use of automobiles are not an unavoidable outcome for cities in high-income countries, which illustrates the importance of urban form and transport policy choices.

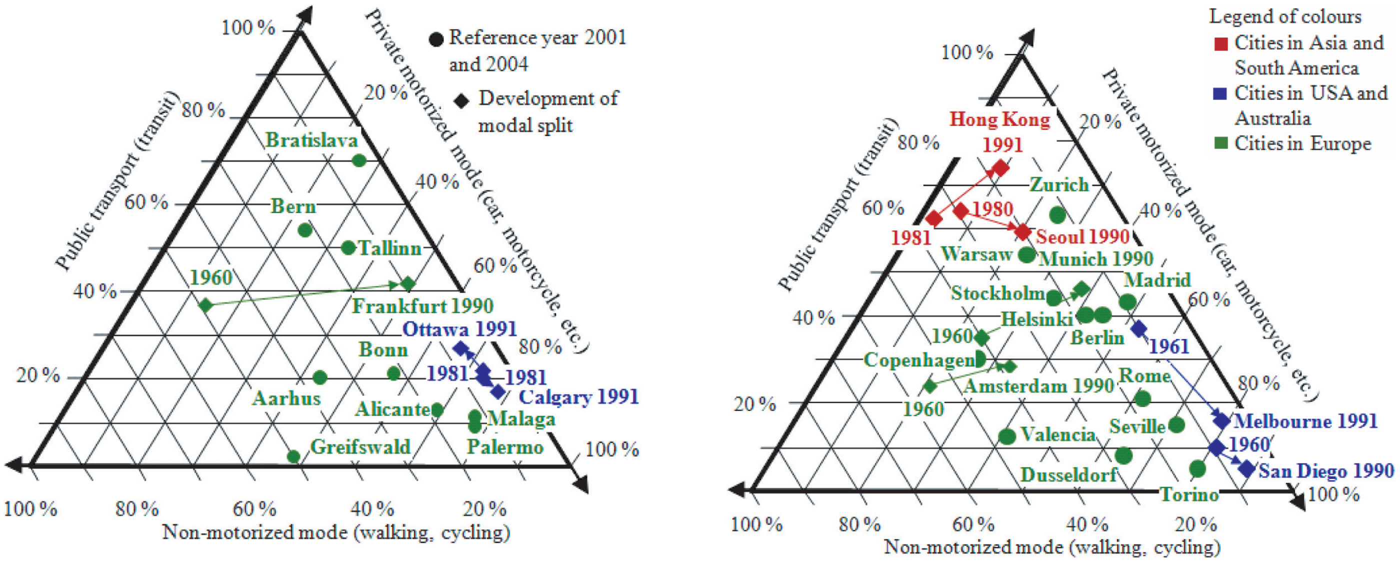
The modal split of commuter transport (Figure 18.26) also shows a significant difference compared with all-travel purposes (Figure 18.25). The share of non-motorized modes is significantly lower and that of public transport higher, which is caused mainly by the longer journeys for working trips. There is no significant difference between large (over one million inhabitants) cities and smaller towns. The development of the commuting modal split over the long term shows a clear trend: motorized modes gain shares at the expense of non-motorized modes.

A considerable range for the modal split and the associated energy use can thus be observed in towns, cities, and urban agglomerations of industrialized countries, a range influenced by several factors: lifestyles, awareness of environmentally friendly and energy-saving travel behavior, objectives of urban transport policy and the willingness to implement such policies, spatial structures and settlement density, fuel prices, parking management, provision and operation of transport infrastructures for walking, cycling, public, and automobile traffic, pricing of the various transport modes (fees for both moving and stationary traffic, public transport prices), and priorities accorded to the various transport modes. Counter examples are easily found to the myth that a modern and economically viable city with a high quality of life can only be achieved with automobile-oriented private transport modes (Newman and Kenworthy, 1999; Directorate-General for Energy, 2007; Susilo and Stead, 2008).

Modal split and energy use

There exists a specific characteristic amount of energy use for every mode of transport, usually measured in terms of liters of fuel or in megajoules per passenger-kilometer traveled. The specific energy use of each mode is determined by the respective vehicle technology (e.g., size and/or weight of vehicle, engine efficiency, etc.), the vehicle occupancy rate (passengers per vehicle), and traffic conditions (degree of congestion). Overall, the specific energy use is highest for private automobile transport (Table 18.16 and Figure 18.27).

A robust finding, illustrated in Table 18.16, is that the choice of transport modes (i.e., the modal split) is a more important determinant of overall transport energy use compared to the specific energy



Cities below 1 million people

Cities above 1 million people

Figure 18.26 | Modal split of journeys to work in medium-sized towns with a population below one million people (left panel) and in cities with a population above one million people (right panel) in high-income economies for reference years 2001 and 2004 and selected time trends since 1960. Sources: Vivier, 2006; Steingrube and Boerdlein, 2009; Urban Audit, 2009; Wapedia, 2009.

Table 18.16 | Primary energy use per passenger-kilometer traveled for different modes, characteristic ranges for reference year 2005. Calculation based on Pischinger et al., 1997.

	Energy use per passenger-kilometer traveled	
	Fuels (liter/passenger-kilometer)	Energy (MJ/passenger-kilometer)
Private automobile traffic	0.050–0.075 (100%)	1.65–2.45 (100%)
Private motorbike	0.028–0.038 (55%)	0.92–1.25 (55%)
Public bus	0.009–0.013 (20%)	0.32–0.40 (20%)
Electric railways and public transport	0.002–0.004 (5%)	0.53–0.65 (35%)

use of individual transport technologies. Put simply, using an (even energy-inefficient old) public bus is a more energy-efficient mode of transport than using a 'cutting-edge,' energy-efficient hybrid private automobile if the occupancy rate of the public bus is high (and that of the car is low). Policywise, this implies that if the objective is to minimize energy use, towns and cities should attempt to achieve a position for their modal split that favors 'ecomobility,' that is non-motorized and public transport, rather than incremental improvements in vehicle efficiency or biofuel supply for individual passenger automobiles, even if the latter may constitute important complementary options for sustainable transport planning in the interim before policy measures in urban form, traffic planning (especially for non-motorized mobility), and improved public transport systems take a long-term effect.

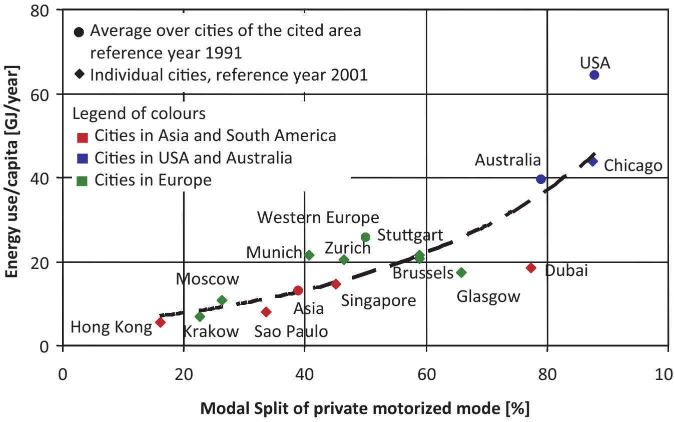


Figure 18.27 | Average energy use per capita in transport (average for countries and regions in 1991 and for selected global cities in 2001) versus share of private motorized transport in modal split. Source: data based on Kenworthy et al., 1999; Kenworthy and Laube, 2001; Vivier, 2006.

18.5.3.2 Specifics of Urban Transport Systems

Compared to rural and long-distance traffic, urban transport systems have some unique characteristics. Towns, cities, and urban agglomerations are places of high population and facility density. Their communication needs are high. This leads to a high density of travel demand within a limited space. Therefore transport modes are needed that require little space while offering high performance (Table 18.17). Pedestrians need the smallest amount of space, followed by public transport, cycling, shared taxis, and private motorized transport. The space required by the different transport modes and their capacity also depends critically on

Table 18.17 | Comparison of characteristic capacities of modes (assuming free-flowing traffic), space required with typical occupancy rates at peak traffic hours, infrastructure costs in urban settings, and maximum accepted distance for daily trips (ÖVG, 2009; Sammer et al., 2009).

	Non-motorized mode		Motorized mode			
	Walking	**Cycling**	**Motorbike, two wheeler**	**Automobile**	**Shared taxi**	**Public transport**
Capacity of a 3 m lane (person/h)	3600–4000	3600–4000	4300–5000 (max. 7200–8500)	2300–3000* (max. 9500–12,000)	5000–9000	Bus: 8000–16,000 Tram: 18,000–24,000 Underground: 30,000–60,000
Space required per person (m^2/person)	0.7–0.8	6.0–7.5	13.0–15.0	21.0–28.0	7.0–12.5	Bus: 1.25–2.5 Tram: 1.7–2.3 Underground: 0.75–1.50
Infrastructure investment costs for the space required per person (€/person)**	50–150	50–150	1500–3000	Urban road: 2500–5000 Urban motorway: 50,000–200,000	1250–2500	Bus: 200–500 Tram: 2500–7000 Underground: 15,000–60,000
Accepted distance for daily trips (km)	1–2	5–10	10–20	Practically unlimited	10–20	Practically unlimited
Type of mobility service	Door-to-door service, Temporarily unrestricted service					No door-to-door service, Scheduled service

* Average occupancy rate of 1.2 people/automobile at peak hours. **1 Euro = 1.245 US$ in 2005.

occupancy rates (load factors). The figures provided in Table 18.17 refer to peak-hour traffic, which means full occupation of public transport and about 1.2 people per automobile in private motorized transport, characteristic for average load factors during peak commuting times in high-income, high automobile-ownership cities.

With respect to energy use, emissions, required space, and noise, public transport is significantly superior to private motorized transport, if a sufficiently high occupancy rate of public transport modes can be assured. From the transport user's point of view, public transport has certain disadvantages compared to private motorized transport that can only partly be compensated for. Such disadvantages are the limited spatial and temporal availability because of a scheduled service with specific stops. To make public transport attractive, a dense public transport network and a high service frequency with short intervals is necessary. A headway of service of less than 10 minutes needs to be achieved so that passengers are able to use public transport spontaneously. To make access and egress attractive, the catchment area of a public transport stop should span not more than 300–500 meters. This can only be guaranteed if the densities of development of residential areas in cities (including traffic areas) are considerably higher than roughly 100 people/ha (10,000 people/km^2) and densities of development within the whole urban area are higher than 50 people/ha (5000 people/km^2). The large amount of space required for road areas and the low density housing types (e.g., single family dwellings) that preordain private automobile use mean that automobile-dependent urban settings typically have population densities far below these critical threshold levels (Figure 18.28) making attractive public transport not viable. An increasing share of private motorized transport modes causes a progressive increase of urban space and a progressive decrease of urban density. Since their density of development is unsuitable for offering attractive and economically viable public transport systems, automobile-dependent cities are Modd split of private molorized modes 'locked in' into high energy use and emissions.

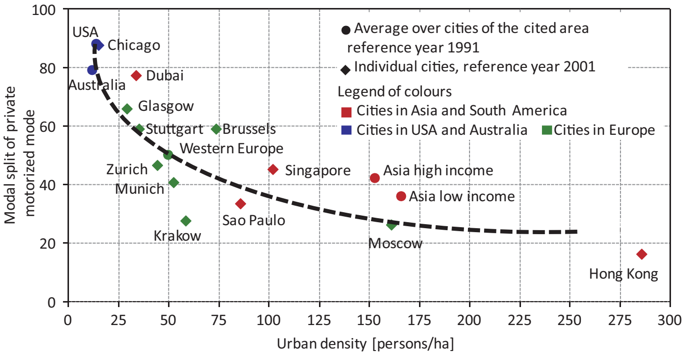


Figure 18.28 | Relation of urban density and share of private motorized transport modes (calculated from total mobility, including non-motorized modes) for individual cities and regional average cities. Source: Kenworthy et al., 1999; Kenworthy and Laube, 2001; Vivier, 2006.

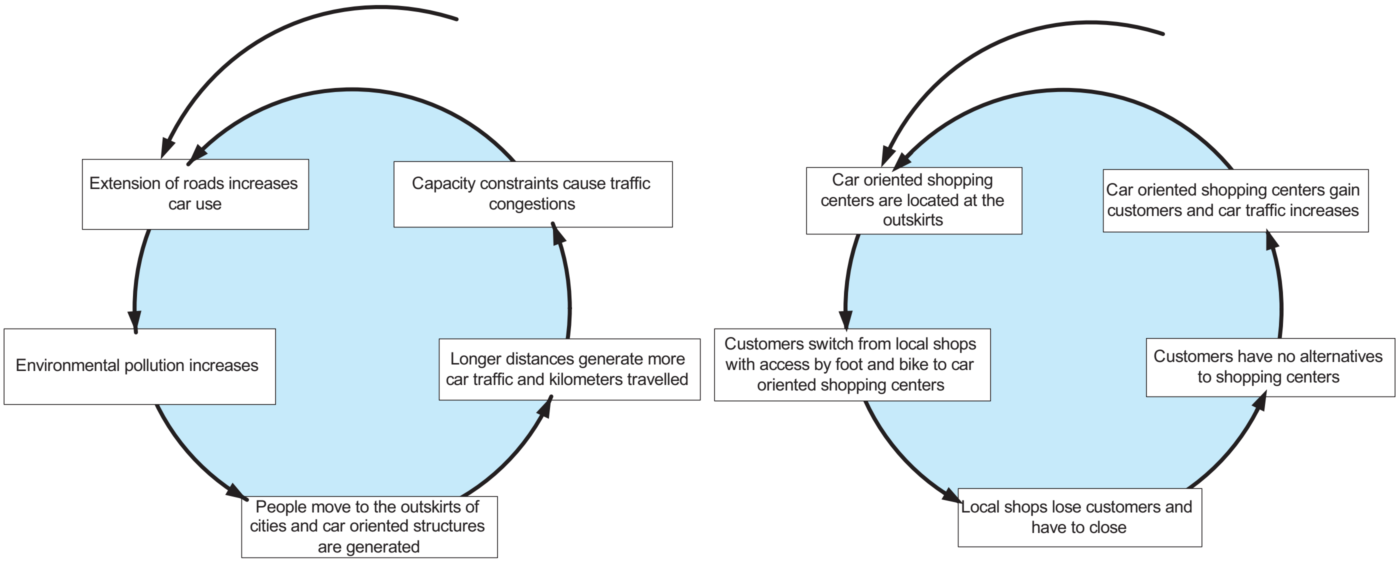


Figure 18.29 | Dynamic negative feedback effects between urban sprawl, automobile traffic, the quality of the environment, and viability of neighborhood stores in urban areas. Source: Sammer et al., 2009.

In terms of spatial planning, clear objectives with respect to sustainable urban-transport systems can be derived: stores for items of daily use need to be in locations that can be reached by non-motorized transport modes. The catchment area of such stores needs to be characterized by a sufficient density of use and compact settlement structures to make these stores economically viable. Thus, a concentration of stores for daily needs in shopping centers in automobile-oriented locations at the city perimeter should be avoided. The growth of decentralized shopping and other facilities leads to a negative feedback loop that further reinforces automobile dependence: fewer neighborhood stores, rising demand for shopping centers, increasing use of automobiles, and yet fewer customers for local stores (Figure 18.29). A similar negative feedback loop can be observed in the cause-effect chain from road-infrastructure development: the generation of more automobile traffic leads to environmental damages, lower urban quality of life, migration to suburbs, and then to yet further generation of more automobile traffic. Contrary to popular conception, any additional supply of urban road infrastructure (a frequent popular response to congestion by dense automobile traffic) inevitably also increases demand and entails more use of automobiles, ultimately simply shifting the point of congestion to higher levels of road and automobile traffic densities (Sammer et al., 2009).

Since trip lengths in local traffic are considerably shorter than those in long-distance traffic, high transport capacities at more moderate speed but with high traveling comfort are most important for short-distance, that is urban, traffic.

From an economic point of view, private motorized transport and public transport do not compete on an equal-level playing field, since the external costs of the two transport modes differ considerably. Table 18.18 offers an illustrative comparison of the external costs of road traffic and rail transport in Austria and Germany, where available data and estimation methods allow for one of the few 'apples-to-apples' comparisons possible in the extremely heterogeneous external-costs literature. Compared to rail transport, road traffic generally causes five to six times more external costs. The overall results for Austria and Germany are quite similar, but there are significant differences in some of the cost components, mostly caused by different assumptions with respect to external cost rates per externality category. (Thus, even in this case a fully consistent comparison of external costs is not possible. In the relevant literature (e.g., UNITE, 2003; Maibach et al., 2008), external cost estimates from transport vary considerably, which suggests the difficulty in arriving at widely agreed consensus values useful for policymakers.) The external costs caused by private automobile uses have to be paid for by other people. As far as the health costs of noise, emissions, and accidents are concerned, the people who finance the healthcare system have to pay for them, irrespective of whether they use an automobile frequently, infrequently, or not at all. The resulting costs of GHG emissions caused by fossil-fuel use in automobiles have to be paid by future generations that will face the consequences of climate change. From the perspective of sustainable transport systems and from an economic perspective of a fair competition among different transport modes, the externalization of costs needs to be overcome by *internalization.* Polluters should bear the resulting external costs by making them pay suitable fees or taxes. In reality this translates into an economic effect equivalent to a fuel price increase of at least a factor of 2–3, which does not look politically feasible at present. This suggests a more incremental policy strategy of a gradual phase in of external costs.

Table 18.18 | Estimates of external costs of road traffic and rail transport for passengers and freight in Austria and Germany, reference year 2005 (Pischinger et al., 1997; Sammer, 2009a) in €2005 cents per person- and tonne-km (1 Euro = 1.245US$ in 2005). For comparison, average total automobile operating costs (including taxes) per person-kilometer (paid by the driver) are about 24 €-cent per person-kilometer, including fuel cost of 6.5 €-cent (Austria, reference year 2005). External costs are thus at least up to twice the direct fuel costs (which, as mobility surveys show, dominate individual transport mode choices as few automobile drivers are aware of the total direct automobile mobility costs, including depreciation, maintenance, and operation).

External costs in €-cent per person-kilometer and ton-kilometer	Austria		Germany	
	Road traffic	Rail transport	Road traffic	Rail transport
Environment costs (caused by greenhouse and exhaust gas emissions, noise)	8.6	0.6	3.3	?
Accidents	3.1	1.5	5.1	?
External costs, Total	11.7	2.1	9.4	2.0

18.5.3.3 Strategies and Frameworks for Effective Policy Measures in Cities

This section summarizes the strategies, basic conditions, and measures to consider in policies for the effective reduction of urban transport energy use. Issues of vehicle technology and alternative fuels and the basic conditions for their use are not addressed here as they are covered in Chapter 9.

Strategies to encourage energy-efficient travel behavior need to be based on a systematic approach that takes into account the interaction of human behavior and travel demand with transport infrastructure supply, vehicle technologies, the environment, and financing.

The starting point is human decision-making which has a significant impact on urban transport systems and their energy use. Eight types of decisions by transport users have a crucial impact on urban transport systems and their effect upon the ecology, economy, and society. These decisions are usually taken in some sequence, with feedbacks taking place. Every decision taken has an impact upon subsequent decisions:

(1) **Selection of the place of residence and place of work.** The closer these two locations, the better equipped with local stores and other facilities, the more ecomobility transport choices are possible, mean less frequent motorized private transport and lower transport energy needs. To make this possible, compact settlement structures are needed; a minimum aggregate urban settlement density of well above 50 inhabitant/ha (5000 inhabitants/km^2) should be the policy objective.

(2) **Selection of the availability of vehicles.** Ownership, availability, and types of vehicles (bicycle, motorbike, automobiles with different drive technologies and fuel use, season tickets for public transport, membership in an automobile-sharing organization, etc.) have a significant impact on travel behavior and energy use.

(3) **Trip generation choice.** This is to decide whether some physical distance needs to be covered (trip) or whether an activity can be done at the place of residence or handled with the help of telecommunication technologies: good facilities at the location, for example broadband information and communication technology infrastructures and/or a garden, can help to reduce the need to travel any distances.

(4) **Decision about the time of travel.** Flexibility regarding the time of travel helps to save time, money, and energy, and to use resources in an environment-friendly way, because traffic jams and overcrowding of public transport can be avoided. This implies that wherever possible 'oversynchronization' of social activities should be avoided, for example through 'stacked' timing of school and of workplace operating hours..

(5) **Choice of destination.** A good retail, work, and school infrastructure close to the place of residence and a compact settlement structure help to avoid long commuting and shopping trips and the need to use motorized transport.

(6) **Modal choice.** Compact developments with good public (e.g., schools) and private (e.g., retail) infrastructures at the place of origin and destination, as well as good connections between the two with an attractive ecomobility offer (walking, cycling, and public transport) or a suitable offer of intermodal transport (bike-and-ride, park-and-ride, park-and-drive, park-and-bike, etc.) help to avoid unnecessary automobile trips. The quality of door-to-door connections is crucial for modal choices.

(7) **Route choice from origin to destination.** The concept of environmental zones (i.e., protected zones for residential areas, etc.) in connection with a hierarchical road network for motorized private transport and transport of goods structured according to the principles of traffic calming improves the quality of the urban environment. It helps to avoid through traffic of motor vehicles in protected areas and supports a high quality of housing and traffic safety.

(8) **Travel behavior reflection.** Reflection about previous travel behavior analyses the appropriateness of the realized choices and suggests a possible revision of the previous travel behavior in regular intervals. Global positioning system technology in connection with new traffic-information technologies will soon make it possible to check automatically whether decisions about traffic behavior are appropriate for the specified objectives (time requirements, environmental friendliness, cost of transport, etc.) or whether alternatives are preferable. This kind of individual

mobility-information system can lead to more sensitivity and awareness of transport-related decisions.

Principles and frameworks to reduce the fossil energy use in transport

- Traditional 'supply-side' measures that focus only on private vehicle infrastructure ("more and better roads") are insufficient to solve urban transport problems and risk significant consumer 'take-back' effects (i.e., induce additional automobile mobility rather than reduce congestion).

- A new fact-based systemic decision-making culture is needed for urban transport policy. Policymakers must be prepared to suggest and implement unpopular but necessary measures (e.g., internalization of external costs). It is essential that mere reactive and adaptive planning by individual measures without consideration of systemic effects and feedbacks (e.g., demand responses), such as the often ill-considered simple extension of road networks in urban areas ('adaptive planning'), is replaced by systemic and goal-oriented planning.

- As long as the true cost of various transport modes, particularly motorized private transport and public transport, are not transparent to the users through the lack of internalization of external costs, an unfair competition between transport modes is perpetuated. The 'push-and-pull principle' of restricting automobile traffic while simultaneously enhancing ecomobility modes can help to compensate for the lack of internalization of external costs.

- Cost-effectiveness criteria should be used to select policy measures to reduce fossil-fuel use and to make effective the use of limited available financial resources.

- An effective program to reduce urban transport energy use can only work as an integrated concept that takes all modes of transport into account. For the concept to be successful, regularly supervised and adapted quantitative objectives for the reduction of energy use are essential.

- To safeguard political acceptance, the development and implementation of the program needs to be supported by some suitable measures to shape stakeholders' ideas and guarantee their participation and engagement (Kelly et al., 2004).

18.5.3.4 Effective measures to reduce fossil energy use in urban transport

- **Spatial planning.** The creation of compact settlement structures with a sufficient settlement density well above 50 people/ha is essential to offer attractive non-motorized and public transport options. To this end, regulatory measures alone are insufficient; some market-based policy instruments are needed also, such as charging infrastructure development cost to users in areas of lower density.

- **Integrated planning concepts to save energy.** Since no single measure will reduce urban transport energy use, successful programs, including whole-bundle measures, need to be planned at national, regional, and local levels and implemented in a continuous process. Coordination and harmonization of transport policy across all levels is necessary.

- **Internalization of external costs.** In principle, an internalization of external costs is essential for all transport modes to make the polluters pay for the cost they cause. This is an excellent market-based instrument to reduce fossil-fuel use, which can be achieved by fuel surcharges, but also by parking fees and road pricing. The latter policy option is most effective if linked to the distance traveled and the environmental damage caused.

- **Environment-oriented road pricing.** Reduced fees for automobile pools or a variable and dynamic kind of road pricing, depending on utilization rates and congestion status (Supernak, 2005), create additional incentives to save energy. If road tolls are used only in urban areas or certain areas within cities, there is a high risk that undesired side-effects might occur, such as shifting routes to side streets, moving stores and other facilities to the outskirts where no fees are levied, and, in the long run, even a relocation of companies to areas outside cities (Sammer, 2009b), which would lead to undesirable urban sprawl.

- **Parking management schemes.** Measures to limit parking in cities and towns that cover all densely populated areas are highly effective – such measures include parking fees on public streets. These are particularly effective if they are graded depending on environmental friendliness or energy use of automobiles (Graz, 2010). Since there is considerably more private than public parking space in many towns and cities, it is recommended to include large private automobile parks (e.g., of industrial enterprises) within the parking fee scheme and combine this with levies on parking spaces for their operators (Sammer et al., 2007). In areas with a well-developed public transport system, land-use and zoning planning should fix an upper limit for available parking slots instead of (the customary) minimum number of mandated parking spaces (Sammer et al., 2005).

- **Attractive public transport.** The transport user wants a qualitatively high door-to-door mobility service, and does not care which operator is responsible for different parts of the system. Therefore the good cooperation of all public transport operators, an integrated ticketing and timetable system, and some overall responsibility for the integrated public transport system are essential for an attractive system. There is an obvious need to improve public transport with respect to intermodality, more efficient and rationalized operations, intermodal connections, information, and marketing. To compensate for some disadvantages, public transport should be given priority over motorized private transport by the provision of high-occupancy-vehicle (HOV) lanes and priority treatment at crossings with the help of suitable traffic lights. To make public transport more attractive, good synergy effects can be achieved by linking the system to non-motorized traffic (bike-and-ride, etc.) and by combining the measures already mentioned with restrictions of motorized private transport under a 'push-and-pull' policy strategy.

- **Cost-effectiveness of public transport.** When choosing types of public transport a careful check of costs and effectiveness is needed, since investment and operating costs of various systems differ considerably. In general, buses tend to be considerably cheaper than trams or suburban railways, which require tracks, and underground track-bound systems are more expensive than above-ground systems. Experiences show that Bus Rapid Transit (BRT) systems are very efficient public transport systems that provide a very attractive service at a reasonable cost level for industrialized and developing cities (e.g., Curitiba, Bogota). Renovating existing transport systems is most cost effective, for example by eliminating existing obstructions by automobile traffic or by giving public transport priority over motorized private transport with the help of HOV lanes and traffic lights.

- **Non-motorized traffic (walking and cycling).** Measures to encourage and support non-motorized traffic are a highly efficient way to save energy, particularly if they are combined with support of public transport and restrictions for automobile traffic. Suitable measures are the extension of an area-wide network of walkways and cycling routes and making them more attractive to use, more places (public and private) to leave bicycles, more information, marketing, and measures to shape people's ideas, bicycle renting, permission to transport bicycles in the public transport systems, company bicycles, etc. (Meschik, 2008).

- **Access restrictions for motorized private transport.** Environment-oriented access restrictions for automobiles in city centers are highly effective measures to save fossil fuel, for example the temporally limited or unlimited prohibition of access for certain types of vehicles, as in environmental zones to keep the air clean (Umweltzone Berlin, 2009).

- **Access contingents for automobiles with combustion engines.** This means that egress is restricted by an area-wide traffic light system in such a way that only so many automobiles are allowed to pass so that no congestion will be caused at the next crossing regulated by traffic lights. Outside these areas with such traffic-light management, additional space needs to be provided for automobile traffic, and also HOV lanes and park-and-ride facilities.

- **Extension of road networks.** If the goal is to reduce fossil-fuel use, to extend the existing road infrastructure, as is frequently done in urban areas, cannot be recommended. Every extension of existing capacities induces an increase in motorized private transport, and further substitution away from other, more environmentally friendly transport modes.

- **Highway corridor management.** This concept aims to optimize traffic flow by suitable measures, such as HOV lanes, high occupancy-and-toll lanes by variable pricing, ramp-metering, information about suitable times, etc. Such management systems should help to avoid congestion and time loss because of congestion. It is doubtful that they would help to reduce energy use significantly in the long term. At present, some 'Integrated Corridor Management Projects' (RITA, 2009) are being conducted in the United States; they try to include public transport, for example by using emergency lanes as bus lanes.

- **Mobility management at the enterprise level.** This is a highly efficient tool. It includes many types of incentives to make individuals do without automobiles. Suitable measures are the support of automobile pools by providing incentives for their use (guaranteed home transport if the usual transport is missed, preferential parking slots, financial incentives), 'job tickets' for public transport (employers subsidize season tickets or provide them free of charge), repair and shower facilities for cyclists, etc. The effect can be increased by providing HOV lanes or by making large companies develop mobility-management plans (ICARO, 1999). In-company mobility management leads to a three-way win-win-win situation because employers, employees, and the general public all benefit. For mobility management at the company level to be successful, a permanent management process must be professionally run.

- **Voluntary programs to change travel behavior.** Such programs quite efficiently raise awareness of the impacts of energy-saving traffic behavior. They have the potential to reduce the use of fossil fuels of the target population in urban areas by 5–10%. Suitable ecomobility alternatives must be available for such programs to work. Currently, some attempts are being made to combine such programs with energy-saving measures in private households (Brög and Ker, 2009; DIALOG, 2010).

These generic policy options to reduce urban transport energy use are applicable to cities in industrialized and developing countries alike.

18.5.3.5 Summary and Conclusions for Urban Transport

- **Modal split.** The existing modal split of cities is one of the key determinants of urban transport energy use and also a good indicator for the progress toward improved sustainability of urban transport systems. A wide range of modal split and thus energy-use patterns can be observed across different urban settings. This variation in urban mobility is not *ex ante* given, but rather results from deliberate choices of individuals and of decision makers.

- **Public acceptance.** The factors that determine urban transport choices can be changed if a strong determination for sustainable traffic policy and a corresponding wide public acceptance of the overall goals of such a policy exists. This wider acceptance of the overarching goals is also the condition to implement some individual measures (e.g., traffic calming, parking fees, etc.) that often face public opposition.

- **Energy and environmental characteristics of transport supply.** An urban transport system has specific characteristics. For noise, emissions, energy use, and economic costs, non-motorized modes of transport are superior to motorized ones, and public transport is significantly superior to private motorized transport, provided a sufficiently high occupancy rate in public transport can be achieved which in turn is contingent on minimum density thresholds.

- **Precondition for attractive public transport:** To make public transport attractive, a dense public transport network and a high service frequency with short intervals is necessary. This can only be guaranteed if the densities of development of residential areas in cities are considerably higher than roughly 100 people/ha and densities of development within the whole urban area are more than 50 people/ha. The large amount of space required for road areas and the low-density housing types (e.g., single-family dwellings) that preordain private automobile uses mean automobile-dependent urban settings typically have population densities far below these critical threshold levels.

- **Strategies for more efficient energy use.** A remarkable number of suitable strategies and measures are known to reduce urban transport energy use. A very effective strategy is the promotion of high urban densities in combination with active promotion of a high-quality supply of non-motorized and public transport options combined with a restrictive automobile policy. Soft measures have generally a very high potential and high cost-effectiveness to reduce energy use, but politically they are the most difficult to sell. Transport fuel use can be reduced most effectively through well-coordinated bundles of policies and measures.

- **Internalization of external cost.** The key measure is the internalization of external costs of motorized private transport combined with the provision of a high-quality alternative offers of public and non-motorized transport. To be able to internalize external costs, political acceptance of this unpopular measure is essential.

18.5.4 Urban Energy Systems Planning, Design, and Implementation

18.5.4.1 Introduction

The energy-system elements and networks of a city reflect myriads of 'local optimizations.' The networks have thus evolved over time, but seldom exploit the opportunities for broader optimizations with other networks or urban form. They are consequently not usually resource efficient when viewed in aggregate. Systems and integration methods are now becoming available with the potential for reductions in direct primary-energy use by 30–50% without other significant physical impacts, except the advantages of reductions in externalities of energy use such as air pollution.

18.5.4.2 Modeling Urban Systems: The SynCity Model

Given the complexity of a city's energy and transport systems, it is not surprising that, to date, detailed holistic analyses of the interplay between urban form, a city's built environment, energy-demand characteristics, and its transport and energy systems have not been attempted. Bottom-up assessments of energy efficiency improvement potentials in different sectors have been developed for many cities to inform policy choices, but interactions, both in terms of potential synergies or trade-offs, cannot be explored by such compartmentalized approaches.

New computational modeling frameworks and access to new data sources promise to overcome these barriers. The relationship between key parameters, such as population density and energy, may be obscured in the real world by differences in other factors, such as wealth and income. To explore these interactions under comparable *ceteris paribus* conditions, this assessment commissioned illustrative model simulations with one such modeling framework (see Box 18.7), the results of which are reported here.[35]

In these examples, the synthetic city (SynCity) is an urban settlement for 20,000 people in a service-orientated local economy, in a moderate climate and with natural gas (and oil) as the primary fuels. Five SynCities were explored with the energy model optimizer. At one extreme, the optimization is constrained as a low-density city, fed from a power grid, with modest building-fabric energy performance. This city is taken as characteristic of one that has evolved in an economy in which resources are relatively inexpensive, such as the United States. The optimizer is left to choose the location of fixed infrastructures to minimize transport costs. The city at the other extreme is optimized with only a constraint on the lower bound to population density. It is comparable with an economy that is resource efficient, such as Japan. The location of housing and commerce, and the choice of whether to use embedded generation of power are left to the optimizer. Three intermediate cases are considered based on an intermediate density and imposed mononuclear layout (e.g., the United Kingdom).

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[35] Fuller detail is given in a GEA Chapter 18 working paper posted on the GEA website, www.globalenergyassessment.org.

Box 18.7 | SynCity Modeling Tool Kit

SynCity is a software platform for the integrated assessment and optimization of urban energy systems, developed at Imperial College London and supported by funding from BP. The goal of the tool kit is to bring together state-of-the-art optimization and simulation models so that urban energy use at different stages of a city's design can be examined within a single platform.

Three layered models within the system are used here:

- a *layout model*, which determines the optimal configuration of buildings, service provision, and transportation networks;
- an *agent-activity model*, which simulates the activities of heterogeneous agents that act within a specified urban layout to determine temporal and spatial patterns of resource demand; and
- a *resource technology network (RTN) model*, which determines the optimal configuration of energy-conversion technologies and supply networks.

The *layout model* is a mixed-integer linear programming model that seeks to satisfy urban demands for housing and activity provision, while minimizing energy demand from buildings and transport. Users specify average visit rates for each activity type and the model determines the optimal location for housing, commercial buildings and activities, and transport networks.

The *agent-activity model* is a simulation model designed to estimate the resource demands of a population that lives within a particular city layout. Briefly, the model operates as follows. First, it creates a synthetic population of individual agents with random characteristics, such as gender and education. Agents are grouped into household ensembles and assigned to jobs and dwellings. The model then loops over 16 indicative time periods that represent two seasons (summer and winter), two day types (weekday and weekend), and four time intervals during the day. For each interval, a probabilistic four-step transport model is used whereby citizens select an activity, an activity provider, a transport mode, and a travel route. The agents then move around the city and perform their planned activities, which results in spatially and temporally explicit demands for different end-use energy resources, such as electricity or heat.

The *RTN model* is also a mixed-integer linear programming model to determine the optimal configuration of energy-supply technologies to meet a given pattern of demand. The objective is to minimize the total cost of the energy-supply system that comprises the annualized cost of capital equipment (e.g., boilers, turbines, and distribution networks) and the annual cost of imported resources necessary to operate the system (e.g., supplies of gas and electricity). Users specify the full suite of possible technologies at the outset and the model returns the lowest cost system configuration.

Further details on the methodology are given in Keirstead et al., 2009.

The increased density in a compact urban layout means that individual dwellings are smaller and have less external wall area per dwelling, which results in reduced heating demands (and also in a saving of one-third, as for high-standard fabric implemented for all buildings, but at lower densities). So, efficient building design and urban density and form both yield comparable energy-demand reductions in the simulations. This highlights the importance of considering both policy options simultaneously, as to avoid the risk that the efficiency improvements of building structures with better insulation can easily be compensated by a shift toward less-compact settlement patterns.

Conversely, the construction of large houses in a low-density sparse layout increases these heat losses (one-third increase in primary energy) and also substantially increases transport energy use. This 'suburbanization' scenario, a worst-case scenario in the simulations, results in an almost three-fold increase in energy use compared to the optimized solution. That is, building a Passivhaus standard single-family home in a low density (sub)urban area would not lower energy use substantially compared to remaining in a much less-efficient home located in a more compact urban setting (e.g., a 19th century townhouse located close to education, leisure, and shopping facilities) with its corresponding lower individual transport needs. This is clearly shown by the alternative simulated urban layouts of the model runs (Figure 18.30).

The results for each simulated city type are summarized in Table 18.19 and Figure 18.31. Numerical values are indexed to the annual primary energy use of the sparse city design (144 GJ/capita in the simulation). 'Upstream' energy is energy used at power stations to supply grid electricity to the city. 'Delivered' energy is the energy delivered to stationary infrastructure, including CHP plants, and the final end-users (i.e., a combination of final and secondary energy). The total of delivered energy,

Table 18.19 | Primary energy use of five alternative urban designs for a town of 20,000 inhabitants. Results are indexed with sparse city =100.

Type	Building fabric	Density limit	Electrical power	Layout	Transport	Delivered	Upstream	Total
Sparse	Medium	USA	Grid	Optimized	26	57	17	100
Distributed generation	Medium	UK	CHP	Mononuclear	17	52	0	69
Efficient buildings	High	UK	Grid	Mononuclear	17	28	12	57
Compact layout	Medium	Japan	Grid	Optimized	12	28	10	50
Optimized	High	Japan	Optimized	Optimized	12	31	0	43

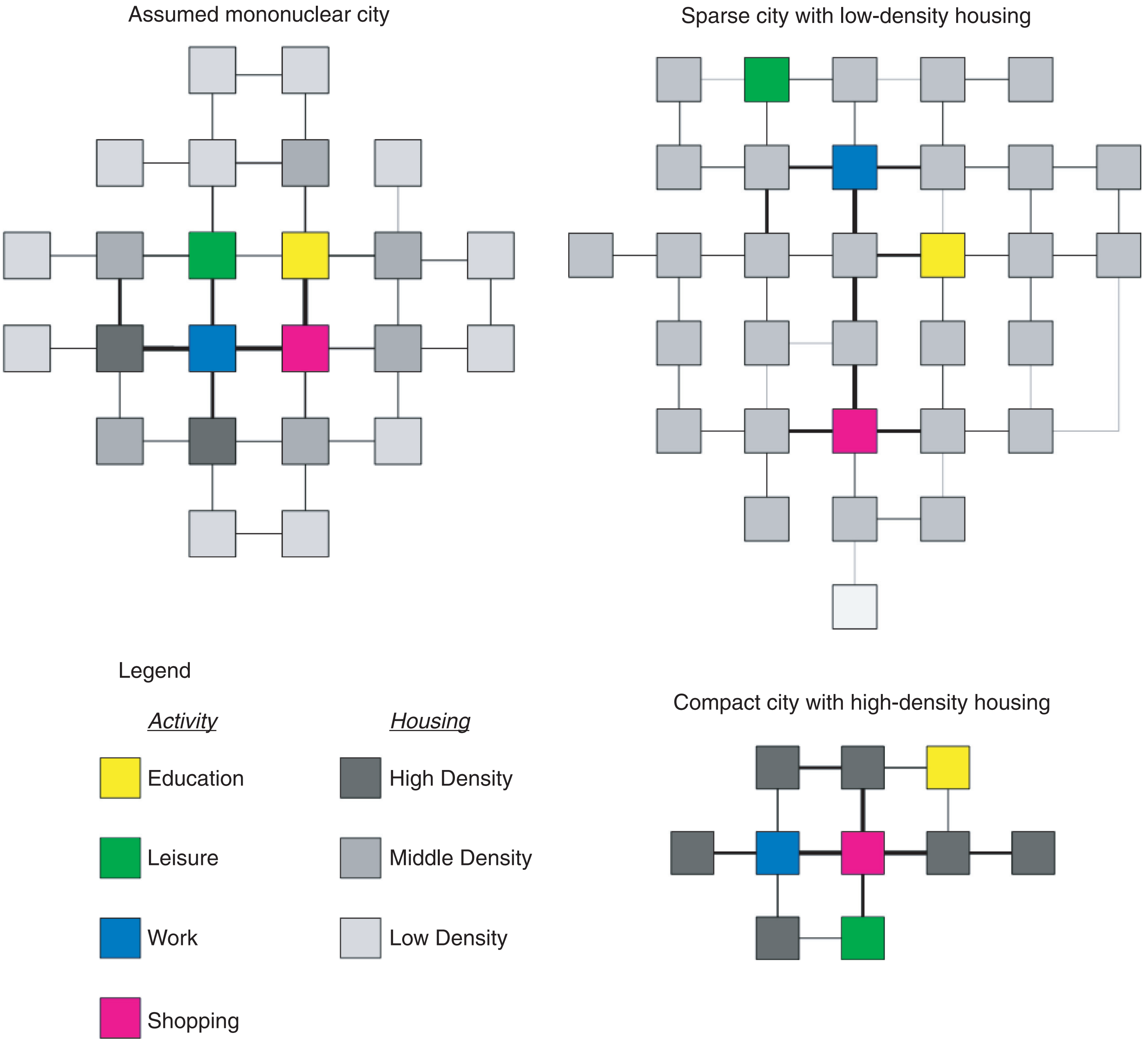

Figure 18.30 | Urban layouts, from left to right: the assumed mononuclear city, a compact city with high-density housing, and a sparse city with low-density housing. In each figure, the colored cells represent activity provision: green for leisure, blue for work, pink for shopping, and yellow for education. The gray cells represent housing at different densities, and the labels indicate the density in dwellings/ha. The black lines that connect the cells indicate road connections and indicative traffic flows.

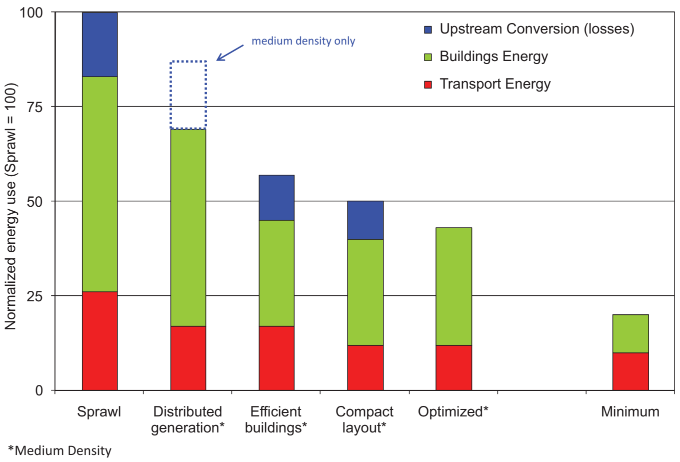

Figure 18.31 | Energy use for five alternative urban designs by major energy level and type. See Table 18.19 for definitions of the five simulations. The "Minimum" urban energy use estimates refers to implementation of the most efficient building designs (see Chapter 10) and transport options (see Chapter 9) available and which could not be considered in the scenario simulations.

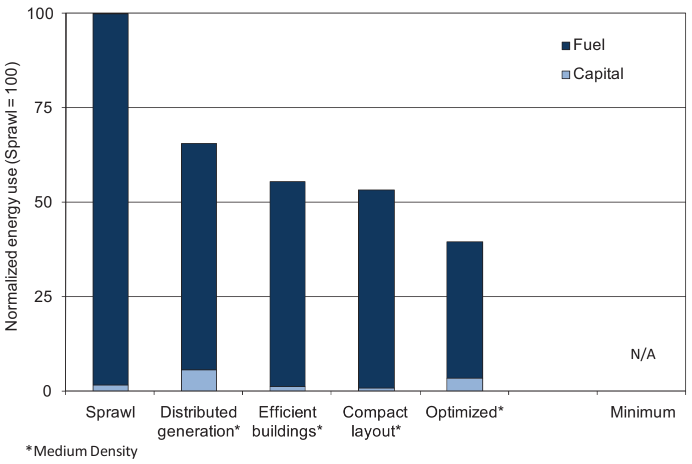

Figure 18.32 | Total lifecycle costs (capital plus fuel) of the five city designs indexed to sprawl city = 100 (see Table 18.19 for definitions of the five simulations).

transport, and 'upstream' energy corresponds to the customary reporting of primary energy use.

The model results generally support the interpretation of comparative city data analyses. First, 'upstream' energy loss in power generation represents 20% of primary energy where the grid is used. To ignore this contribution and focus only on delivered energy misses important upstream implications of energy choices for power. Second, a SynCity with low resource efficiency is likely to consume about twice as much primary energy as one designed for high resource efficiency. Both transport and primary energy for heating and power are reduced by about the same proportion. This, in part, reflects that low-density cities not only require higher speeds of travel over longer distances, but that buildings tend to occupy larger areas with consequently more exposed surface for the same standard of construction. The effects of urban planning and differences in fabric standards are comparable and should be considered together with upstream consequences.

To address these three policy fields simultaneously is also of prime importance for the economic viability of cogeneration and district-heating systems. Energy-efficient, single-family homes located in low-density suburban settings are unlikely to yield the head-load densities required to install capital-intensive cogeneration systems combined with local district-heating grids (not to mention large centralized cogeneration and distribution systems, although these may allow room for other technologies, such as PV or ground-source heat pumps). To test the consequences, these city models were rerun to minimize whole lifecycle costs. The layout model (see Box 18.7) optimizes transport costs, but it is instructive to see what the resource technology model makes of the stationary energy-service costs. The results in terms of total lifecycle costs are summarized in Figure 18.32 using UK electricity and natural gas costs as example. The discount rate used in the simulations was 6% in real terms.

The results encouragingly follow a similar pattern to that of primary-energy minimization, in part because capital costs remain a small part of the annuitized energy costs. However, minimizing only capital cost biases the outcomes away from the minimum energy solution. This emphasizes the importance of proper finance and pricing systems in bringing about optimal solutions for utilities and customers combined.

Summary

This brief analysis analyzed three ways in which cities can improve the efficiency of their energy systems: improving the quality of the built environment, increasing the density of the urban layout, and using integrated, distributed energy systems, such as CHP. A few general conclusions can be drawn from this case study:

- Cutting urban energy use by half is possible through integrated approaches that address the quality of the built environment (buildings efficiency), urban form and density, and urban energy-systems optimization (cogeneration).
- Final energy use is not a sufficient indicator of energy system performance. In cogeneration systems in particular, this metric may show an increase in delivered fuel use that masks upstream conversion and distribution losses. This effect also occurs in bioenergy-based supply systems. Primary energy use should, therefore, be the basis of scenario comparisons.
- Annual energy-system costs (i.e., the costs of energy conversion and distribution), but not demand-side measures, such as increased

> building efficiency or urban layout, are dominated by fuel costs. However, these costs are distributed differently between stakeholders in each of the scenarios. In current practice, most of the capital and fuel costs are paid by end consumers, whereas in a distributed energy system much more of the cost is borne by energy utilities. This suggests that to achieve overall system efficiency, policymakers should design markets that help utilities implement distributed energy installations despite their unique capital and fuel-cost structures.

Increased urban density and improved building efficiency deliver primary energy use and carbon-emission savings of about one-third each; distributed energy systems provide approximately 10% primary energy and carbon emissions saving. This indicates the importance of urban planning measures. These decisions – for example, on the building energy-performance standards or on the location of infrastructure – are difficult to change in retrofit and can lead to significant increases in energy use; in the cases studied here, urban sprawl led to a one-third increase in primary energy use. Efficient distributed-energy systems, to a certain extent, can be retrofitted into existing urban forms, but they too can benefit from long-sighted urban planning by encouraging sufficient demand density and by reducing the costs of the network infrastructure.

The above simulations suggest that the effects on energy demand of urban form and density, and that of the energy efficiency characteristics of technologies, processes, and practices (e.g., buildings) are of comparable magnitude, i.e., are comparable size 'mitigation wedges' to paraphrase a concept developed by Pacala and Socolow (2004). Conversely, the impact of narrow energy systems optimization (e.g., through cogeneration of renewables) is much smaller.

18.1.2.1 Urban Energy Systems Planning Design – Review

A holistic view of urban energy systems is multifaceted and relates to the analysis of city lifecycle, technologies, systems modeling, and optimization.

Existing versus planned layouts

The problem of planning improved urban energy systems is very different for existing and for new urban areas. The advantage of new developments (e.g., ecocities and zero-carbon cities planned in places such as China and the Middle East) is that holistic planning tools can be employed to integrate the design of the urban form, the built environment, the transportation infrastructure, and the energy system. Opportunities for resource efficiency – such as optimized transport, material, and energy cascading, demand heterogeneity, and robust network design – can be explored ahead of implementation.

Existing cities, however, are captives to their history and struggle to escape path dependency without massive capital investment. Nevertheless, relatively short turnover times for many technologies provide opportunities to improve in efficiency and integrated design. Large-scale upgrades of the built environment have been demonstrated, for example in Germany, where new technologies at the building and building-cluster level are being employed and new ideas are emerging for new uses of existing infrastructure (e.g., using a natural gas network to transmit bioderived gas in cities, see also Chapter 10).

Energy-related technologies and systems

Demand-side management and reduction

The primary focus of efficiency in most cities is on the built environment (dwellings and commercial properties) and transport. In the built environment, there is considerable inertia and irrational behavior given the relatively low or even negative cost of GHG abatement through refurbishment. This suggests that there is a strong argument for prescription and regulation regarding building standards.

Supply side

The supply side has seen much innovation in resource-efficient network design, where integrated thinking pervades the design of new ecocities – each of which is sympathetic to its hinterland and optimized for its local climate. The integration of water and energy systems is coming to the fore in supply-side planning. In these planning applications there is an important role for systems modeling and Life Cycle Assements (LCA) in support of holistic rather than piecemeal perspectives to avoid burden shifting. Given that all city systems are subject to uncertainty and change, there is also a need for option-based design techniques that allow city growth and technological evolution and that avoid strongly path-dependent solutions.

Role of real-time systems

There is a long history of promising designs related to urban energy systems that have not delivered the expected performance. For new, resource-efficient city designs, enough of the budget and expertise must focus on the postdesign, operational phase. There are fascinating opportunities for ubiquitous sensing and computing to embed sensing and distributed 'intelligent' and autonomous control (inspired by, for example, cybernetic modeling, which indicates how local control rules can result in system solutions close to those optimized centrally). This enables effective management of real-time performance, and perhaps eventually will ensure that resource use is minimized in operation. The interactions between systems and citizens can be augmented through real-time pricing of energy and virtual energy markets, real-time displays of household, large building, neighborhood, city resource-use profiles, and personalized decision-support services.

18.5.5 Urban Air Quality Management

18.5.5.1 Air Pollution Trends

Energy and air pollution are closely linked because urban outdoor[36] air pollution is primarily a result of fuel burning in power generation,

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[36] Residential energy use, e.g., for cooking, can result in high levels of indoor air pollution and result in health impacts (see Chapters 4 and 19).

industries for domestic production and exports,[37] transport, and commercial and residential sectors. Low-quality fuels, such as coal, biomass, and high-sulfur diesel, emit more air pollutants than cleaner energy sources. From the urban energy-usage perspective, the literature shows that high urban density tends to be associated with lower per capita energy uses (see Section 18.5.2), which reduces air-pollution problems somewhat. However, the trade-off at this density reflects on the issue of air-pollution control. High density makes air-pollution control more urgent and requires better management systems, especially in the rapidly growing dense and large Asian megacities.

Historically, the concentrations of pollutants such as SO_2 and TSPs, which mainly result from industrial production systems were concentrated in cities, have declined in industrialized cities. In the United States, the average national SO_2 level at 147 sites in 2007 was 0.0038 parts per million (ppm), which is 68% lower than 0.0118 ppm in 1980, while the National Ambient Air Quality Standard remains at 0.03 ppm (USEPA, 2009). In Japan, SO_2 average levels have declined from 0.06 ppm in 1967 to 0.017 ppm in 1980, and further by 50% in 1980–2005 alone (MOE, 2005). A key component of industrial air-pollution control mechanism was the development and deployment of end-of-pipe technologies (such as flue-gas desulfurization and particulate removal), and the introduction of cleaner fuels under stringent air-quality legislations. The 'pollute first and clean up later' paradigm had actually worked for many industrial cities, but one generation suffered acute air-pollution problems. Currently, the SO_x and TSP pollutants in industrialized countries are no longer an issue for energy use in cities, because urban energy systems are dominated by electricity or other cleaner fuels, and emissions from large point sources are tightly controlled.

In developing countries, SO_x and TSPs have shown a decreasing trend in recent years (Figure 18.33) for key Asian cities. SO_2 is reasonably within WHO limits in these cities (except Beijing), while TSPs remain far higher than the WHO limits. Today, cities in developing countries can learn from the experiences of the industrialized countries and have access to the technologies developed previously to tackle SO_x and TSP. In contrast to the developed countries, industrial relocation and FDIs constitute a key aspect of air-pollution control in the developing countries, with both positive and negative effects. At the same time, relocation of existing dirty industries of cities from populated areas to less populated area or outside the cities has contributed to reductions in industrial air pollutants. Given that pollution-control technologies are readily available, the industrial air pollution in developing countries today largely results from either an inability to pay for the technology or inherent institutional, policy, and market problems.

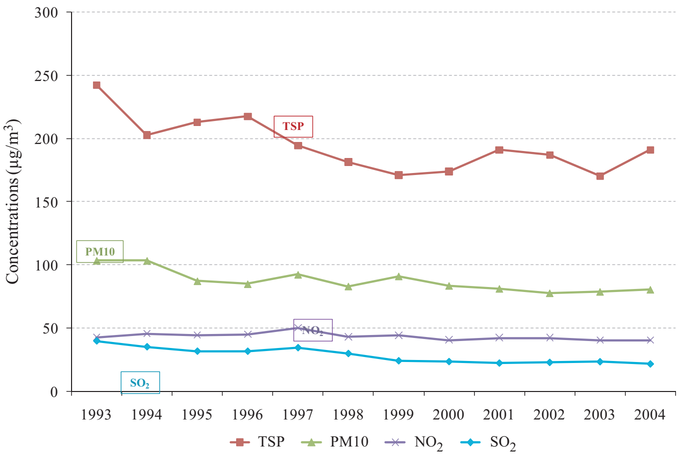

Figure 18.33 | Trends of major criteria air pollutants (1993–2004) for selected Asian cities. Source: Benchmarking Study on Air Quality Management Capability of selected Asian cities. Clean Air Initiatives in cooperation with UNEP and WHP (cf. Schwela et al., 2006). Cities included in the study: Bangkok, Beijing, Busan, Colombo, Dhaka, Delhi, Hanoi, Ho Chi Minh, Hong Kong, Jakarta, Kathmandu, Kolkata, Mumbai, Manila, Seoul, Shanghai, Singapore, Surabaya, Taipei, and Tokyo.

While industrial air pollutants are falling, the challenges to control pollutants from mobile sources, as a result of automobile dependency of cities, in particular for particulate matter (PM), NO_x, and O_3, are increasing. Even in the cities of industrialized nations, to reduce the levels of NO_x, O_3, and fine particles is proving a challenge. In the United States, monitored data show that the average levels of O_3 in 269 sites (0.078 ppm in 2007 – a reduction of 21% from 0.10 in 1980 – eight-hour average) slightly exceed National Air Quality Standards (USEPA, 2009). A recent report by the American Lung Association (ALA, 2009) shows that 125 million people (42%) in the United States live in counties that have unhealthy levels of either O_3 or particle pollution (PM-2.5). In Japan, the compliance rate of monitoring sites for O_3 is extremely low – merely 0.2% in 2004 (MOE, 2005).

PM-10 is one of the key public health issues in the cities of many developing countries, where their levels are many times higher than the WHO or USEPA. Only 160 million people in cities worldwide are breathing clean air, more than one billion need improved urban air quality, and for 740 million urban air quality is above the minimum WHO limits. While Figure 18.33 show that TSP and PM-10 generally have decreased in Asian cities, ambient concentration levels remain, nonetheless, above WHO, USEPA, and EU limits in numerous cities worldwide (Figure 18.34 and Table 18.20; See also Chapter 4).

A city-by-city analysis (Figure 18.35) further shows that PM-10 is lowest in Singapore at 30 μg/m³, which meets 50 μg/m³ standards set by USEPA (Singapore adopts USEPA standards), but fails if compared with the WHO 2005 updated guideline of 20 μg/m³. PM-10 values in all of the 20 Asian cities reviewed fail to meet WHO standards. Of 17 cities that monitor NO_x data, only eight meet the WHO guidelines, which indicates

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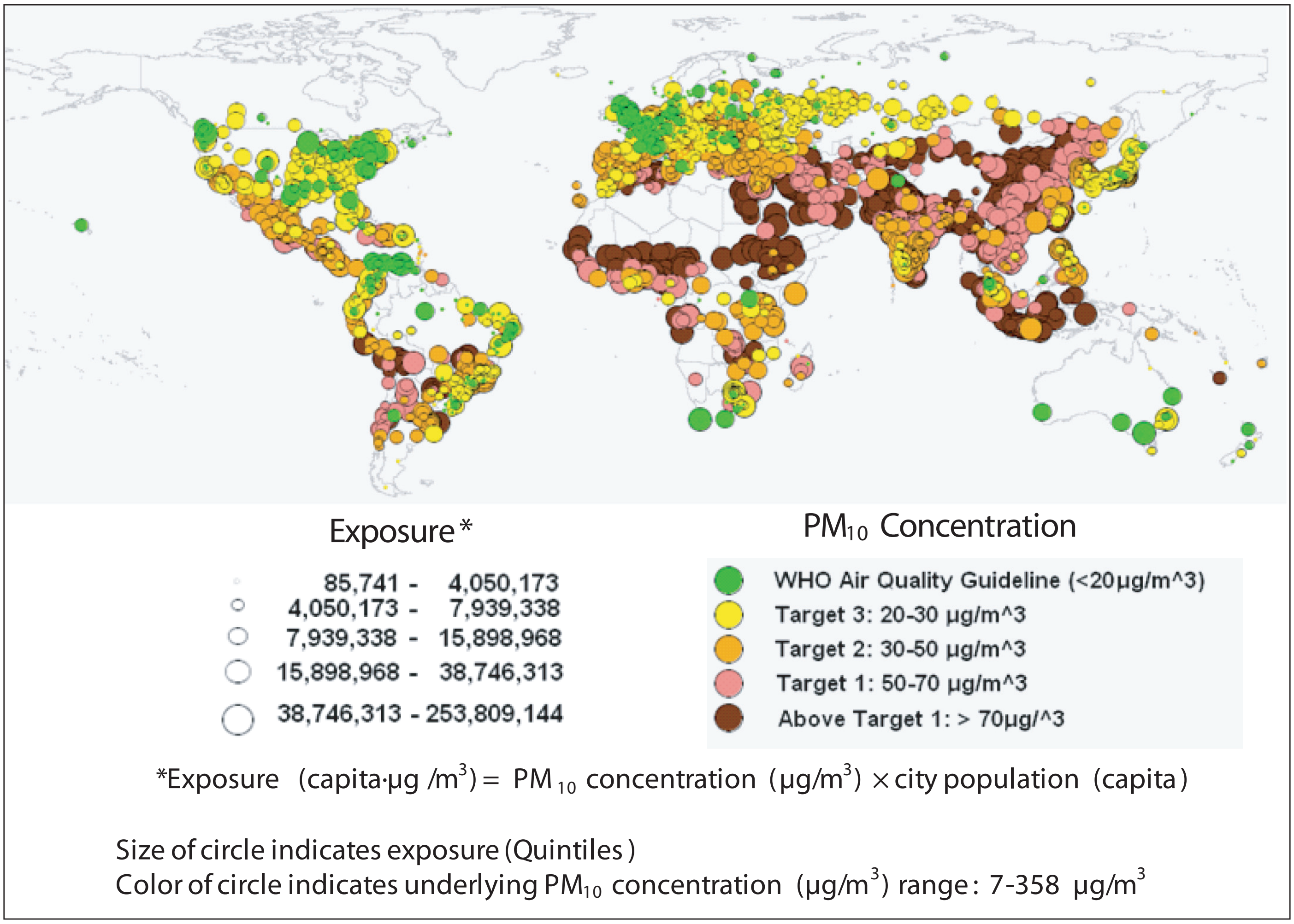
[37] As discussed in Section 18.6.2, global market integration and economic structural change can result in relocations of industrial activity and hence exercises an additional effect on local pollution.



*Exposure (capita·µg /m^3) = PM$_{10}$ concentration (µg/m^3) × city population (capita)

Size of circle indicates exposure (Quintiles)
Color of circle indicates underlying PM$_{10}$ concentration (µg/m^3) range: 7-358 µg/m^3

Figure 18.34 | Human risk exposure to PM-10 pollution in 3200 cities worldwide (For a numerical summary see Table 18.20). Source: Doll, 2009; Doll and Pachauri, 2010, based on World Bank data.

that NO$_x$ pollution is of special concern for Asia megacities. The reason is the rising number of private automobiles in cities of the developing world as a result of rising affordability, rising mobility demand, and slow development of public transport infrastructures. Over the years, the fuel efficiencies of new automobiles have improved considerably, the sulfur content of fuels are on a constant decline, and the emission standards have tightened (Figure 18.36), but the high volume of automobile travel demand has far overwhelmed vehicle-efficiency gains and the impacts from cleaner fuels. This confirms that urban air-quality management especially needs to address transport-related emissions from a much more systemic perspective, including transport policies that influence the urban modal split toward a reduced automobile dependence in addition to traditional vehicle efficiency, and exhaust emission and fuel standards measures.

While the majority of air pollution is associated with energy use, in many cases other sources also play an important role. Natural factors, such as dust and fine sand particles, flow across the boundary between the natural and anthropogenic sources, and also contribute to urban air pollution. The role of transboundary air pollution is particularly important for SO$_x$.

18.5.5.2 Examples of Air Pollution Control Measures and Urban Energy

A wide variety of air-pollution control policies and measures are in place globally. Some are system-wide and comprehensive measures, while others address a specific sector or technology depending on the prevailing sources of the air pollutants. Some of these measures are regulatory, while others are technological, managerial, or a mixture. Here a few representative examples are illustrated that touch a broad range of such measures, namely legislation, market, court rulings, and technology. Each has different implications on urban energy systems.

United Kingdom 'smoke control area' regulation

The United Kingdom started air-pollution control with a strictly source-control approach. It gradually shifted to a complex, but integrated, and risk management effects-based approach (Longhurst et al., 2009). Intense pollution from domestic coal use persisted in the United Kingdom until the 1950s and 1960s. Heightened concerns after London's Great Smog episode of December 1952 led to the introduction of The Clean Air Act of 1956 as an emergency measure. Significantly,

Table 18.20 | Number of cities and residing population categorized by ambient PM-10 WHO air quality standards (ACQ = WHO air quality guidelines met (less than 20 μg/m^3), for definition of Target 1 to 3 concentration standards see Figure18.34) for a sample 3200 cities globally and by three regions (ALM = Africa, Middle East, Latin America and the Caribbean).

Global	# of Cities	Population (millions)
ACQ	446	164
Target 3	809	385
Target 2	777	409
Target 1	362	260
Above Target 1	803	739
Annex-1	**# of Cities**	**Population (millions)**
ACQ	325	121
Target 3	610	314
Target 2	371	183
Target 1	51	41
Above Target 1	26	12
ALM	**# of Cities**	**Population (millions)**
ACQ	115	41
Target 3	160	60
Target 2	228	126
Target 1	132	103
Above Target 1	205	160
Asia	**# of Cities**	**Population (millions)**
ACQ	6	2
Target 3	39	11
Target 2	178	101
Target 1	179	116
Above Target 1	572	567

Source: Doll and Pachauri, 2010 based on World Bank data.

some key industrial cities had already taken pre-emptive action, but the politics of a national measure proved more difficult. The Clean Air Act enabled local authorities to control pollution by declaring Smoke Control Areas ('smokeless zones' in which the burning of coal was banned) to whole or part of the district. Various measures were also used to ease compliance with the regulation, such as subsidies for furnace switching. In this regime, each local authority publicized the fuels that could be used and a list of exempt appliances. The Clean Air Act was further extended in 1968 to address the question of unevenness in the implementation, because in wealthier cities it was progressive while in other cities the implementation was less than that desired. The major feature of this regime was to induce a shift from coal to electricity, natural gas, and other cleaner forms of energy and implied a major transformation in energy esnd-use patterns and systems. However, with increasing levels of transport-related pollution in UK cities, NO$_x$ concentration levels can be high and close to the statutory limits. This, in turn, may restrict further expansion of CHP systems in urban areas.

The regional clean air incentives market

The California South Coast Air Quality Management District (SCAQMD) has used a market-based system since January 1994, known as RECLAIM (Regional Clean Air Incentives Market), to reduce system-wide air pollution. SCAQMD covers 27,125 km^2 (10,473 square miles). At the launching of RECLAIM, it was expected to reduce the cost of achieving the same emissions reduction through a traditional command and control approach by some 40% (Harrison, 2004). Under this system, each facility participating in the RECLAIM program (facilities that emit 4 tonnes/year or more of NO$_x$ and/or SO$_x$ in 1990 or any later years) are allocated RECLAIM trading credits (RTCs) equal to their annual emission limits for SO$_x$ and NO$_x$. The facilities must meet these allocated emissions limits. If a facility can reduce emissions more than required, they can sell surplus trading credits to the credit market, which can be bought by facilities that could not meet their own emission-reduction targets. The system is designed in such a way that the total allowable emission cap was reduced over time until 2003 after which it remained stable. It requires facilities to cut their emissions by certain amounts each year. By 2003, the program anticipated to reduce the total emission load for NO$_x$ and SO$_x$ in SCAQMD by 70% and 60%, respectively (Anderson and Morgenstern, 2009). In January 2005, RECLAIM decided to reduce cumulatively the emissions further, by 7.7 tonnes/day or about 20% by 2011 (Figure 18.37).[38]

Introduction of compressed natural gas vehicles in New Delhi

To address high concentrations of air pollutants in Delhi, the Supreme Court of India, acting on public interests litigation filed at the behest of civil society, directed the government of the National Capital Territory of Delhi and other authorities in Delhi to act on mitigating air pollution through specific technological interventions. The legal deliberations began as early as 1990, but the key court decisions were made in 1998. The cornerstone was the conversion of all diesel public transportation into compressed natural gas (CNG) vehicles, which began implementation in April 2001. Along with the implementation of these directives, authorities enacted a series of other measures, such as expansion of the scope of CNG coverage, scrapping of older vehicles, improving fuel quality, implementing stringent emission standards for vehicles, and improvements in the infrastructures. The implementation involved a series of policy instruments, such as penalties for noncomplying vehicles, sales-tax exemption, interest subsidy on loans to replace three wheelers, making CNG retrofitting kits available, expansion of CNG fueling stations, and others. The literature shows an ambiguous picture of the impact of CNG conversion on air pollution, but generally agrees that CNG conversion was one of the several key factors and that it triggered other measures that led to improvements in the air pollution of Delhi (Goyal and Sidhartha, 2003; Kathuria, 2004; Jalihal and Reddy, 2006; Ravindra et al., 2006; Kandlikar, 2007; UNEP, 2009).

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[38] For further updates see www.aqmd.gov/RECLAIM/index.htm.

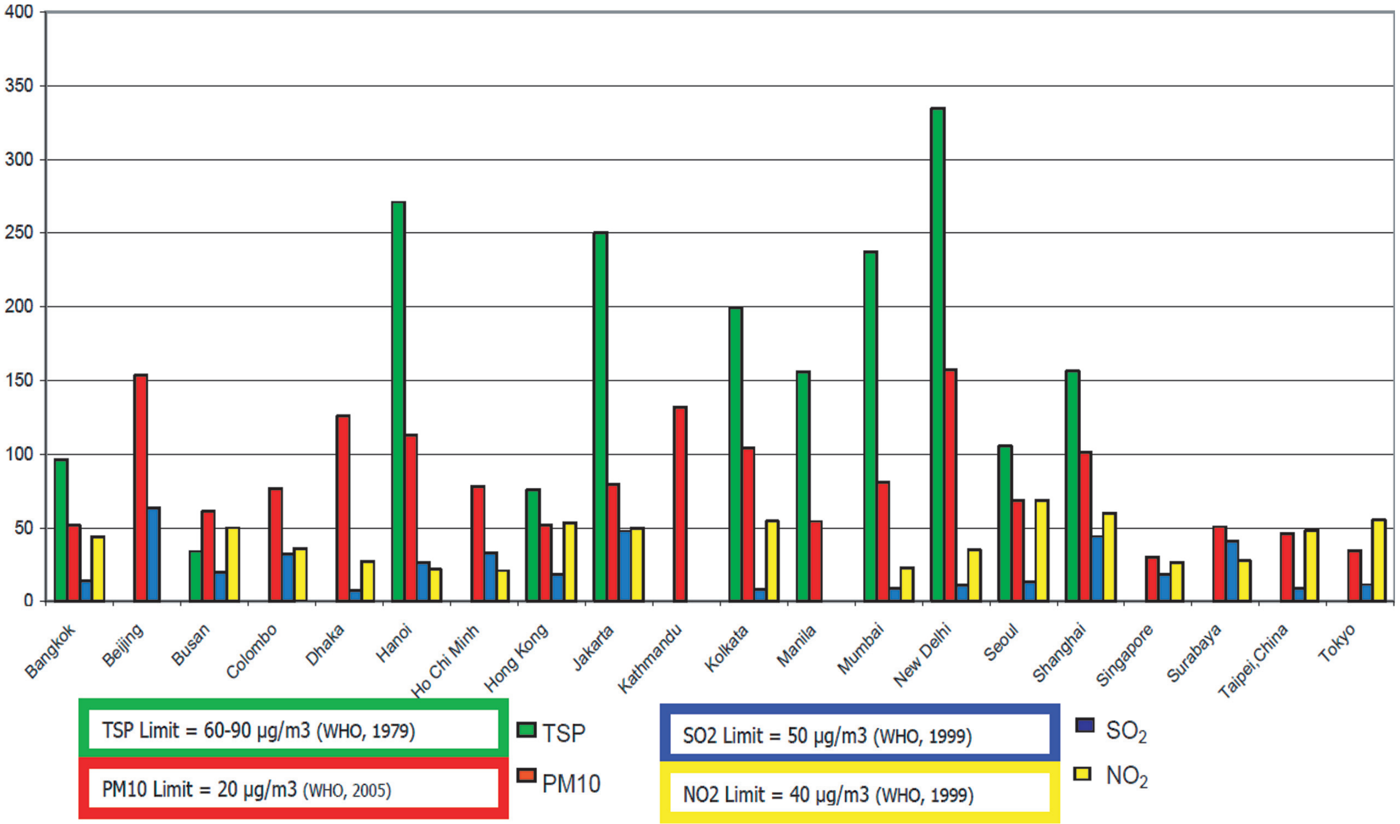
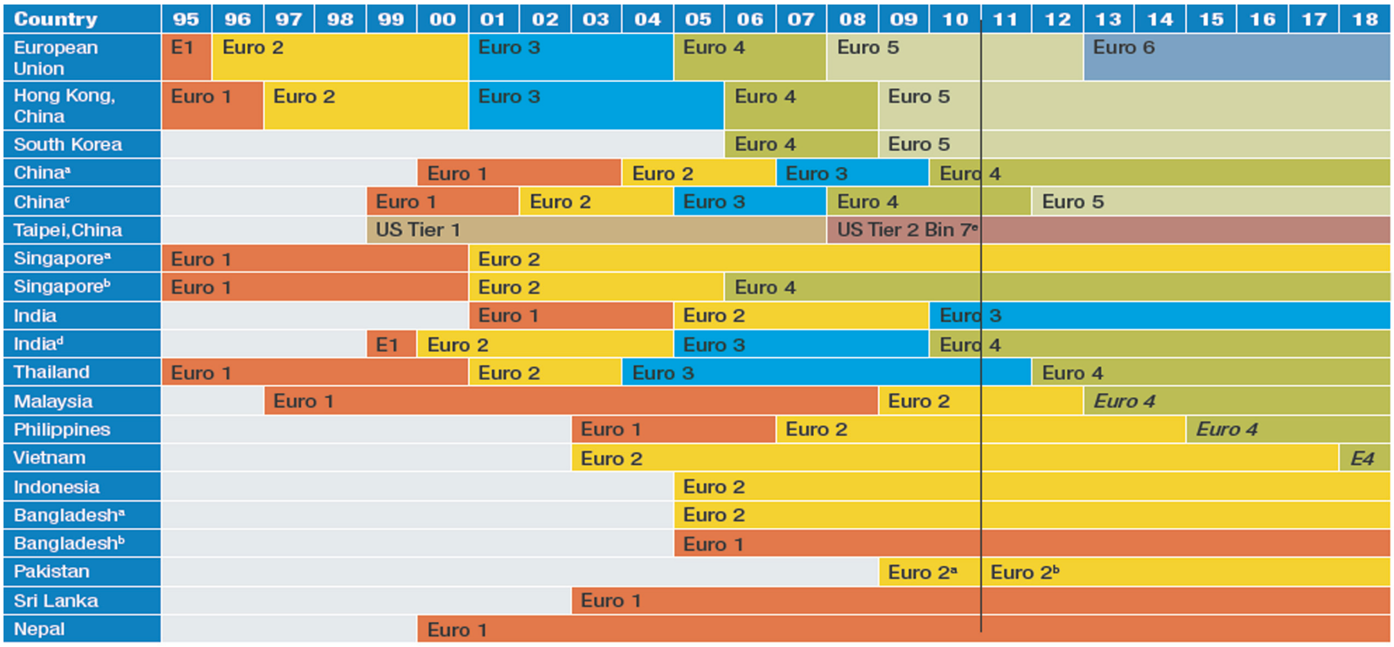


Figure 18.35 | Urban concentrations of air pollutants (μg/m^3) in Asian cities for 2005. Source: adapted from Schwela et al., 2006.



Country	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
European Union	E1	Euro 2					Euro 3				Euro 4			Euro 5					Euro 6					
Hong Kong, China	Euro 1		Euro 2				Euro 3					Euro 4			Euro 5									
South Korea												Euro 4			Euro 5									
China[a]						Euro 1				Euro 2			Euro 3			Euro 4								
China[c]					Euro 1			Euro 2			Euro 3			Euro 4				Euro 5						
Taipei,China					US Tier 1									US Tier 2 Bin 7[e]										
Singapore[a]	Euro 1						Euro 2																	
Singapore[b]	Euro 1						Euro 2					Euro 4												
India							Euro 1				Euro 2					Euro 3								
India[d]					E1	Euro 2					Euro 3					Euro 4								
Thailand	Euro 1						Euro 2			Euro 3								Euro 4						
Malaysia			Euro 1												Euro 2				*Euro 4*					
Philippines									Euro 1				Euro 2								*Euro 4*			
Vietnam									Euro 2															*E4*
Indonesia											Euro 2													
Bangladesh[a]											Euro 2													
Bangladesh[b]											Euro 1													
Pakistan															Euro 2[a]		Euro 2[b]							
Sri Lanka									Euro 1															
Nepal						Euro 1																		

*The level of adoption vary by country but most are based on the Euro emission standards
Italics – under discussion; a – gasoline; b – Diesel; c – Beijing [Euro 1 (Jan 1999); Euro 2 (Aug 2002); Euro 3 (2005); Euro 4 (1 Mar 2008); Euro 5 (2012)], Shanghai [Euro 1 (2000); Euro 2 (Mar 2003); Euro 3 (2007); Euro 4 (2010)] and Guangzhou [Euro 1 (Jan 2000); Euro 2 (Jul 2004); Euro 3 (Sep-Oct 2006); Euro 4 (2010)]; d – Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Bangalore, Lucknow, Kanpur, Agra, Surat, Ahmedabad, Pune and Sholapur; e – US Tier 2 Bin 7 is equivalent to Euro 4 emissions standards

Figure 18.36 | Overview of vehicle emissions standards, Europe versus Asia. Source: CAI-Asia, 2009.

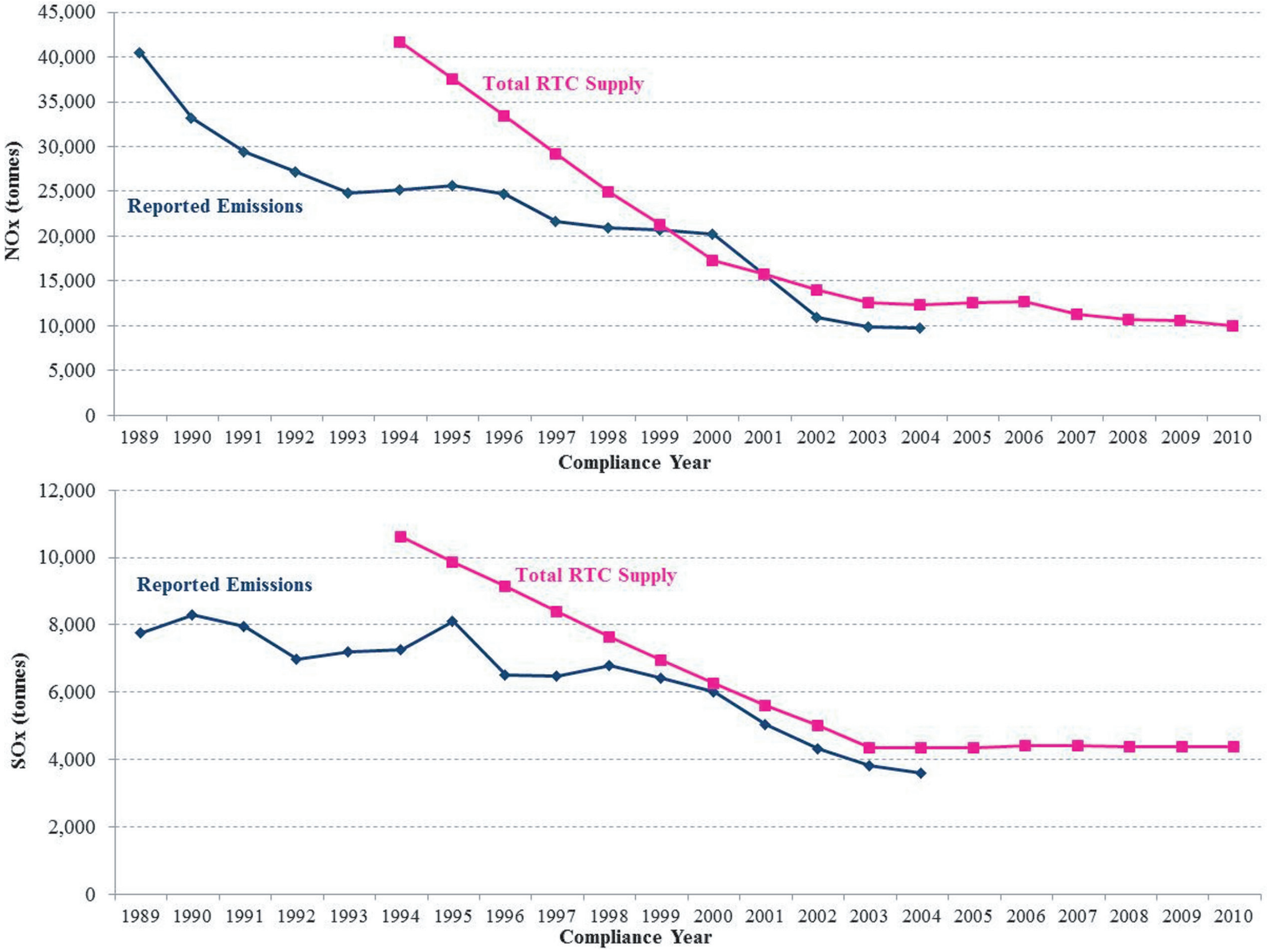


Figure 18.37 | RECLAIM's impacts on emissions in South Coast Area of California on NO_x (top) and SO_x (bottom) emissions versus allowable emission cap (RTCs) (in tonnes). Source: Anderson and Morgenstern, 2009.

18.5.5.3 Key Policy Issues

The ways and methods adopted to mitigate urban air-pollution impacts in urban energy systems differ widely. In Delhi, deliberate CNG introduction to reduce air pollution created a new urban energy supply, demand, and infrastructure, largely following a technology strategy. The ban on coal-fired boilers in Chinese cities such as Beijing and Shanghai, led to greater use of electricity and natural gas (Dhakal, 2004). As an example of a regulatory approach to urban air pollution, it largely follows the historical United Kingdom 'smokeless zone' regulatory model. City energy-system decisions in China are influenced by air-pollution mitigation, public transport improvements, and energy-security concerns (Dhakal, 2009). The will to control PM-10 prompted many cities in Asia, America, and Latin America to move progressively toward discouraging diesel. Europe is moving more on the path of dieselization with stricter control of the sulfur content of diesel combined with particulate filters in automobiles.

Despite improvements in both vehicle technology and fuel quality, the high growth rates in private automobile ownership and usage with rising income is proving a challenge to the control PM-10, suspended particulate matter, and NO_x pollutants in cities of developing countries (Dhakal and Schipper, 2005). The key policy challenges for air pollution that have direct bearing on urban energy systems are (adapted from Schwela et al., 2006):

- Comprehensive assessment of the effectiveness of different options is needed in cities, but requires adequate institutional capacity, which remains comparatively weak in many large cities (Table 18.21), not to mention smaller ones. Often problems are addressed on a piecemeal basis without considering the complete system and thus rebound effects are prevalent.

- Development of more reliable inventories of air-pollution emissions is essential. Cities are not regularly updating their inventories

Table 18.21 | Classification of urban air-quality management capacity in Asian cities.

Capability Classification	Cities
Excellent I	Hong Kong, Singapore, Tapei, Tokyo
Excellent II	Bankgkok, Seoul, Shanghai
Good I	Beijing, Busan
Good II	New Delhi
Moderate I	Ho Chi Minh City, Jakarta, Kolkata, Metro Manila, Mumbai
Moderate II	Colombo
Limited I	Hanoi, Surabaya
Limited II	Dhaka, Kathmandu
Minimal	–

Source: Schwela et al., 2006.

and often there are serious ambiguities in emission volume and sources data.

- The need to adopt more stringent vehicle-emission standards is evident. The pace of adopting new emission standards in the face of rapidly rising private transportation is very slow. In addition, a reasonable global harmonization of air-quality and technology standards is needed. Currently, decision makers are torn between the Euro Standards and the USEPA standards, which affects technology choice and fuel regimes differently.
- Introducing cleaner fuel more actively for motor vehicles, industries, and power plants is necessary.
- Transport polices that affect urban mobility choices need to complement vehicle- and fuel-specific policy measures. In their absence, any air-quality improvements are likely to be quickly overwhelmed by continued motorized transport growth.
- Despite good policies on technology and fuel, inadequate emphasis on inspection and maintenance of systems remains one of the key challenges. Much of the existing air-pollution problems can be addressed by simple *implementation and stricter enforcement* of existing legislations, standards, and inspection and monitoring regimes for air quality.
- For transboundary air-pollution issues, such as acid rain and black carbon (emerging as key problems, particularly in Asia), regional approaches and regimes are needed, but such regional coordination emerges only very slowly in many world regions.
- To harmonize many environmental issues within common policy responses, estimation of the co-benefits of air-pollution management with respect to human health, urban energy system improvement, energy security, climate change mitigation, and ecosystems in general is essential. In developing countries such a co-benefit approach can help devise limited resources more efficiently, and also broaden the technology and financial resources available for air-pollution control.

18.6 Summary and Conclusion

18.6.1 An Urbanizing World

The world is already predominantly urban, with the urban environment housing more than 50% of global population and accounting for even larger shares in economic and energy activities. Almost all future population growth of some three billion people to 2050 will be absorbed by urban areas. This urban growth is the combined result of natural increases in urban populations plus migration from rural to urban areas such that the increase in rural population in many developing countries will be overshadowed by population flows to the cities.

In contrast, rural populations globally will peak at around 2020 at a level of 3.5 billion people and decline thereafter. This global result masks heterogeneity in regional trends: whereas rural populations in Asia are projected to decline rapidly after 2020, the African rural population will continue to grow at least to 2040, before also declining.

Patterns of urban population growth have been and will remain heterogeneous. Most of the growth will continue to occur in small- to medium-sized urban centers, which explains the remarkable robustness of the distribution of city-size classes over time and across different regions. Growth in small cities poses serious policy challenges, especially in the developing world. In small cities, data and information to guide policy are largely absent, local resources to tackle development challenges are limited, and governance and institutional capacities are weak. Despite much public attention, the contribution of 'megacities' to global urban-population growth will remain comparatively small.

Shrinking cities in the developed world are an increasing phenomenon in urban dynamics, and could continue as below-replacement fertility levels outstrip increased longevity and so lead to declining populations in almost all high-income countries (and potentially in low-income countries in the long-term). The impacts of population contraction on urbanization remain a major unknown.

Cities of the future will have significantly older populations. Cities in developing countries will approach the age structures already prevalent in some cities of the industrialized world, with more elderly than young residents. This urban aging effect is likely to be mitigated temporarily by continued rural-urban migration as migrants comprise predominantly younger and more enterprising age cohorts, both nationally and internationally. Conversely, this demographic pattern suggests that aging will also be significant for rural settlements in low- and high-income countries alike. 'Graying' rural villages are probably the logical counterpoint of continued urbanization combined with a continued unfolding of the demographic transition worldwide.

18.6.2 Urban Energy Use

The urban share in current world-energy use varies as a function of system boundaries in terms of spatial scales (cities versus agglomerations), energy-systems definition (final commercial, total final, and total primary energy), and the boundary drawn to account for embodied energy in a city's goods and services, both imported and exported. The direct transfer of national energy (or GHG emissions) reporting formats to the urban scale is often referred to as a 'production' approach, and contrasts to a 'consumption' accounting approach that pro-rates associated energy uses (or GHG emissions) per unit of expenditure of urban consumer expenditures, thus accounting for energy uses irrespective of their form (direct or embodied energy) or location (within or outside a city's administrative boundary). Both approaches provide valuable information and should be used as complementary tools to inform urban policy decisions. However, to be useful, urban studies need to adhere to much higher standards in terms of clarity and documentation of the terminology, methodology, and underlying data used. To improve comparability, this assessment recommends specifically that all accounts based on the consumption approach (which are data- and time-intensive to prepare, and so exist only for a very limited set of megacities) be complemented by corresponding production-based energy accounts (which are much simpler and easier to determine). To ensure reproducibility, this assessment also recommends explicitly that no urban GHG-emission inventory be published without the underlying energy data used in the assessment.

Available estimates of current urban energy use based on a production approach (direct final energy use, or primary energy use, i.e., including pro-rated upstream energy sector conversion losses) suggest that urban energy use accounts for between 60% and 80% of global energy use. Total energy use is therefore already predominantly urban. Mirroring the growing importance of urban areas in demographic and economic development, urban energy use will continue to grow further as a fraction of total global energy needs. This implies that energy sustainability challenges need to be addressed and solved primarily by action in urban settings.

There is great heterogeneity in urban energy-use patterns, especially when manufacturing and transport energy uses are included. In many developing countries, urban dwellers use substantially *more* energy than their rural compatriots, which primarily reflects higher urban incomes. Conversely, in many industrialized countries per capita urban final energy use (i.e., based on a production-accounting approach) is often substantially *lower* than the national average, which reflects the effects of compact urban form, settlement types (multi- versus single-family dwellings) and availability and/or practicability of public transport infrastructure systems compared with those in the suburban or rural sprawl. The few available data, however, suggest that urban energy use in high-income countries is not substantially different from national averages using a consumption-based accounting approach that also includes energy embodied in imports. So, the effects of lowered direct final energy use through a more service-oriented urban economy, urban form and density, and resulting lower transport energy use are largely compensated by higher embodied energy use associated with higher urban incomes in high-income countries. For low-income countries, available data are too sparse to allow a similar comparison. However, it is highly likely that, because of the much higher income differential between urban and rural populations in low-income countries, their urban energy use is significantly higher on a per capita basis compared to national averages in a consumption-based accounting framework as well. Levels and structure (access to electricity, clean fuels for households, private motorized transport) of urban energy use in low-income countries are therefore a powerful leading indicator of future developments to come with rising urbanization and income growth in the developing world.

Drivers of urban energy use include geography and climate, resource availability, socioeconomic characteristics, degree of integration into the national and global economy (imports/exports), and urban form and density. Not all of these can be influenced by local governance and decision making. Priorities for urban energy and sustainability policies, therefore, should focus where local decision making and funding also provides the largest leverage effects: urban form and density (which are important macrodeterminants of urban structures, activity patterns, and hence energy use), the quality of the built environment (energy-efficient buildings in particular), urban transport policy (particularly the promotion of energy efficient and 'eco'-friendly public transport and non-motorized mobility options), and improvements in urban energy systems through cogeneration or waste-heat recycling schemes, where feasible. Local action, however, also requires local capacities and responsibilities in addressing urban energy and environmental problems, including a mediating role among the multiple stakeholders characteristic of decentralized urban decision making.

Conversely, the promotion of local solar or wind renewables will, at best, have a marginal impact on the overall energy use of larger cities (typically <1%)[39] because of the significant energy-density mismatch between (high) urban energy use and (low) renewable energy flows per unit land area available in urban areas. Smaller cities, however, could provide more avenues to integrate renewable energy into urban energy systems than large cities. Cities could also play an important role as consumers of renewable energies, creating niche market impulses as well as potentially exerting leverage on the application of sustainable social and ecological production criteria for their renewable energy suppliers.

Nonetheless, urban energy and climate policy should recognize that the most productive local decisions and policies influence the *efficiency* of urban energy use that is the demand side of the energy system, rather than its supply side.

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[39] Important exceptions include utilization of urban wastes and, where available, geothermal resources, both of which are characterized by a high energy density.

18.6.3 Facing the Challenges

18.6.3.1 Urban Poverty

Several hundred million urban dwellers in low- and middle-income nations lack access to electricity and are unable to afford the cleaner, safer fuels. Most are in low-income nations in southeast Asia and sub-Saharan Africa. In many low-income nations, more than half the urban population still rely on charcoal, fuelwood, straw, dung, or wastes for cooking, with significant adverse consequences for human health and urban air quality. A large part of the poor urban population that lacks clean fuels and electricity not only cannot afford these, but also faces political or institutional obstacles to accessing them.

In many middle-income and all high-income nations, nearly all low-income urban dwellers have legal electricity connections and access to clean fuels. The shift to clean fuels and the availability of a reliable electricity supply bring many advantages in terms of health, convenience, and time saved in accessing and using energy.

The costs of connection to an electricity grid and the use of electricity can be beyond the reach of low-income groups, but innovations have reduced these costs – for instance, rising tariffs with low prices for 'lifeline' electricity use, pay-as-you-use meters, and standard 'boards' that remove the need for individualized household wiring.

The constraints on supporting the shift to clean fuels and providing all urban households with electricity are less to do with energy policy than with authorities' handling of issues of informal settlements. A large part of the population that lack clean energy and electricity live in informal settlements. It is mostly in nations where this antagonistic relationship between local government and the inhabitants of such settlements has changed, through widespread public support to upgrade 'slums' and squatters, that clean energy and electricity reaches urban poor groups.

Housing, infrastructure, energy, and transport services are the key sustainability challenges to accommodate some three billion additional urban dwellers in the decades to come, especially in low-income countries. Informal settlements will be one of the transitional forms of settlement for many of these new urban dwellers and will require a much more proactive, anticipatory policy approach, especially with respect to the location of informal settlements and subsequent infrastructure connections and upgrading programs.

Energy-wise, low-cost and fast implementation options will take precedence over 'grand' new urban designs that require unrealistic capital provision over long periods. In low-income countries access to clean cooking fuels and electricity, as well as pro-poor transport policies, which include safer use of roads by non-motorized modes (walking and bicycling) and making public transport choices available (e.g., through BRT systems) need to receive more attention.

18.6.3.2 Livable Cities: Urban Density and Form

Urban density and form are not only important determinants for the functionality and quality of life in cities, but also for their energy use. Historically, the diversity of activities and ensuing economic and social opportunities that are the major forces of attraction to urban settings were provided by high density and co-location (mixed land-uses) of a diversity of activities that maximize the 'activity zone' of urban dwellers while minimizing transport needs. This urban history contrasts with decades of trends toward lower urban densities, which include widespread urban sprawl, and even 'ex-urban' developments.

It is widely agreed that there is no theoretical or practical argument for defining a universal 'optimal' form or density for a city. In theory (and often also in practice) higher densities increase the *economies of scope* (i.e., of activity variety) in a city. These are the main locational attractions of urban places in terms of potential number of jobs, breadth and variety of specialized trades and economic activities, along with cultural and many other attractions, usually summarized as *positive agglomeration externalities* that also extend to urban infrastructures (e.g., communication and transport networks). Conversely, higher densities can entail negative externalities as well, such as congestion, high land prices that limit the quality of residential living space for urban dwellers, or environmental problems (noise, air pollution).

Nonetheless, empirical data strongly suggest that the *net balance* of these positive and negative agglomeration externalities remained stable for extended periods of time, as illustrated by the remarkable stability of the rank-size distribution of cities (with dominating positive or negative net agglomeration externalities the growth of the *ensemble*[40] of larger cities should be above or below that of smaller cities, which is not the case). The historical evolutionary processes that govern urban growth have played out differently over time and space, which results in *path dependency*. Cities that evolved along alternative pathways have alternative density levels from high-density 'Asian' (e.g., Tokyo, Shanghai, Mumbai) and 'old European' (e.g., London, Madrid, Warsaw) to low density 'new frontier' (e.g., Los Angeles, Brasilia, Melbourne) pathways, each of which have different structural options available to improve energy efficiency and optimize urban energy and transport systems in terms of sustainability criteria.

Despite this diversity, two important generalizations can be drawn. First, the implications of urban density on the requirements of urban energy systems are that they need to be basically *pollution free*, as otherwise even relatively clean energy forms can quickly overwhelm the assimilative capacity of urban environments. This especially applies to the million, decentralized energy end-use devices (stoves, heating systems, vehicles) for which end-of-pipe pollution control is often not an option. Thus, in

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[40] Evidently, ***individual*** cities can forge ahead or fall behind the overall distributional pattern of aggregate uniform urban growth rates as outlined by the rank-size rule.

the long-term all end-use energy fuels consumed in urban areas need to be of zero-emission quality, as exemplified by electricity or (eventually) hydrogen, with natural gas as the transitional fuel of choice in urban areas. (Evidently, pollution levels also need to be minimized to the maximum technologically feasible at the point of production of these fuels.) This 'zero-emission' requirement for urban energy transcends the customary sustainability divide between fossil and renewable energies, as even 'carbon-neutral' biofuels when used by millions of automobiles in an urban environment will produce unacceptable levels of NO_x or O_3 pollution.

Second, the literature and above discussion repeatedly has identified important size and density thresholds that are useful guides for urban planning. The importance of these urban thresholds extends to specialized urban infrastructures, such as underground (metro) transport networks that are, as a rule, economically (in terms of potential customers and users) not feasible below a threshold population size of less than one million. It also extends to energy (e.g., cogeneration-based district heating and cooling) and public transport networks, whose feasibility (both for highly centralized and decentralized, distributed 'meso'-grids) are framed by a robust gross[41] density threshold between 50 and 150 inhabitants/ha (5000–15,000 people/km^2). Such density levels of 50–150 inhabitants/ha certainly do *not* imply the need for high-rise buildings, as they can be achieved by compact building structures and designs, both traditional and new, including town or terraced houses, while still allowing for open public (parks) or private (courtyard) spaces – but they do preclude unlimited (aboveground parking) spaces for private vehicles. Zoning and parking regulation, combined with public transport policies and policies that promote non-motorized transport modes and walkability thus constitute the essential 'building blocks' of urban energy efficiency and sustainability 'policy packages.'

18.6.3.3 Mobile Cities: Urban Transport

Urban transport is a key policy concern, both for its high visibility (potential opposition to 'top-down' policies) and its crucial importance to the very functionality of cities. Two fundamental observations need to guide urban transport policies.

First, on a sustainability metric there is a clear contradiction between growing private motorized transport and growing energy use and pollution. This contradiction relates not primarily to the technological artifacts *per se* (automobiles or scooters), but rather to the *organizational form* of their *usage* as privately owned vehicles with correspondingly low occupancy rates (and thus high energy/emissions per unit service delivered). Well-designed taxis or automobile-sharing schemes are excellent examples that the (selective) use of automobiles as modes of individual transport when needed (as opposed to their preordained use, despite congestion, simply because of a lack of alternatives) can be reconciled with the prerogatives of an energy-efficient city. Conversely, along the same sustainability metric, non-motorized mobility (walking and bicycling) and public transport schemes that function well and have high occupancy rates are the options of choice for urban mobility and should receive corresponding priority.

Second, the fundamental interrelations between demand and supply often create a 'vicious circle' for urban transport planning: more automobiles lead to congestion, which improved urban road infrastructures aim to alleviate. But more (road infrastructure) supply *induces* yet more demand (individual mobility and land-use changes) in an ever-spiraling 'rat race' of 'supply following demand' growth. A new public policy paradigm for urban transport needs to break this cycle of rebound effects through integrated urban energy transport policies that deal with both demand and supply.

The wide variation in urban transport choices observed in the modal split across cities illustrates that urban mobility patterns are not *ex ante* given, but rather result from deliberate choices of individuals and decision makers. Urban transport choices can be changed, if both a strong determination for sustainable transport policy *and* a corresponding wide public acceptance of the overall goals of such a policy exist. This wider acceptance of the overarching goals is also required to implement some individual measures (e.g., traffic calming, pricing schemes (for roads and parking, etc.)) that often face lobbying opposition. Restrictive measures that limit individual mobility by automobiles need to be complemented by proactive policies that enhance the attractiveness of non-motorized and public transport choices, and 'soft' policy measures (e.g., fees, tariffs) also need to be complemented by 'hard' (i.e., infrastructural investment) measures. The overriding goal is to turn the often automobile-dependent 'vicious' policy cycle into a 'virtuous' cycle that favors non-motorized and public transport choices.

One key measure in this context will be the progressive internalization of external costs of motorized private transport along with the provision of high-quality alternative public and non-motorized transport. Estimates for Europe suggest that these external costs are at least in the order of 6–10 cents per passenger-km (see Table 18.16), which when fully internalized would double private motorized transport costs. Comparable estimates for low-income countries are not available, but given their generally much higher road-accident rates, external costs are likely to be even larger. However, accompanying measures and strong leadership will be needed to increase the political acceptability of this invariably unpopular measure. Recent experiences with the introduction of road prices and congestion charges in cities across a wide political spectrum suggest that such policy approaches are both feasible and have the ability to alter urban transport behavior.

Attractive public transport systems require a dense public transport network and a high service frequency with short intervals, which are only

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[41] i.e. a minimum density level over the entire settlement area that comprises residential zones of higher density with low density green spaces.

feasible with a minimum threshold of urban density. A rule-of-thumb goal might be to have only urban settlements within easy walking (<500 m) access to a viable public transport service. Investments in public transport systems need to find an appropriate balance between improvements that are less capital intensive and faster to implement, and radical solutions. BRT systems are, therefore, a much more attractive option for many cities in low-income countries than are capital-intensive subway systems, even though, in the long term, the latter offer the possibility of higher passenger fluxes and greater energy efficiency. Often there is no contradiction between incremental versus radical public transport policy options: for instance, BRT can also be considered as a transitional infrastructure strategy to secure public transport 'rights of way,' which offer subsequent possibilities for infrastructure upgrades, for example in putting light rail systems in BRT lanes. Many of the new urban settlements being formed easily meet these density targets. The policy issue is to exploit the advantages before 'lock-in' into private transportation takes hold.

18.6.3.4 Efficient Cities: Doing More with Less Energy

From all the major determinants of urban energy use – climate, integration into the global economy, consumption patterns, quality of built environment, urban form and density (including transport systems), and urban energy systems and their integration – only the final three are amenable to an urban policymaking context and therefore should receive priority.

Systemic characteristics of urban energy use are generally more important determinants of the efficiency of urban energy use than those of individual consumers or of technological artifacts. For instance, the share of high occupancy public and/or non-motorized transport modes in urban mobility is a more important determinant of urban transport energy use than the efficiency of the urban vehicle fleet (be it buses or hybrid automobiles). Denser, multifamily dwellings in compact settlement forms with a corresponding higher share of nonautomobile mobility (even without thermal retrofit) use less *total energy* than low-density, single-family 'Passivhaus'-standard (or even 'active,' net energy generating) homes in dispersed suburbs with two hybrid automobiles parked in the garage and subsequently used for work commutes and daily family chores. Evidently, urban policies need to address both systemic and individual characteristics in urban energy use, but their different long-term leverage effects should structure policy attention and perseverance.

In terms of urban energy-demand management, the quality of the built environment (buildings efficiency) and urban form and density that, to a large degree, structure urban transport energy use are roughly of equal importance. Also, energy-systems integration (cogeneration, heat cascading) can give substantial efficiency gains, but ranks second after buildings efficiency and urban form and density, and associated transport efficiency measures, as shown both by empirical cross-city comparisons and modeling studies reviewed in this chapter.

The potential for energy-efficiency improvements in urban areas remains enormous, as indicated by corresponding urban exergy analyses that suggest urban energy-use efficiency is generally less than 20% of the thermodynamic efficiency frontier; this suggests an improvement potential of more than a factor five. Implementing efficiency improvements (including systemic measures) should therefore receive highest priority. In the built environment, there is considerable inertia and irrational behavior, given the relatively low or even negative cost of GHG abatement through refurbishment of buildings. There is therefore a strong argument for prescription and regulation regarding building standards.

Conversely, the potential of supply-side measures within the immediate spatial and functional confines of urban systems is very limited, especially for renewable energies. *Locally harvested* renewables can, at best, provide 1% of the energy needs of a megacity and a few percentage points in smaller, low-density cities because of the mismatch between (high) urban energy demand and (low) renewable energy supply densities. Without ambitious efficiency gains, the corresponding 'energy footprint' of cities that import large-scale, centralized renewable energies (biofuels for electricity) will be vast and at risk of producing 'collateral' damages caused by large-scale land conversions (e.g., soil carbon perturbations and albedo changes), and competition over food and water. Given that all city systems are subject to uncertainty and change, there is also a need for option-based design techniques that allow for city growth and technological evolution, and that avoid strongly path-dependent solutions and 'lock-in' into urban energy-supply systems based on current- or near-term renewable options that, ultimately, will be superseded by third and fourth generation renewable supply technology systems. Improved urban energy-efficiency leverages supply-side flexibility and resilience, and thus adds further powerful arguments for strategies that focus on urban energy-efficiency improvements.

Finally, *energy security* is a re-emerging issue for many cities because energy security declined over recent decades and security concerns need to be integrated increasingly into urban energy policies and sustainability transition analysis. Better efficiency and improved energy systems integration will also benefit urban energy security, although a further assessment of energy security is beyond the scope of this urbanization chapter (as dealt with in the energy security Chapter 5).

18.6.3.5 Clean Cities: Air Pollution

To a degree, the observed significant improvements in urban air quality caused by the elimination of traditional air pollutants, such as soot, particles, and SO_2, in cities of high-income countries are a powerful illustration that cities act as innovation centers and hubs for environmental improvements that lead to a sustainability transition path.

The first signs of progress in these traditional air pollutants are evident in countries of lower income as well, and are illustrated by the recent decline in the emissions of some traditional pollutants in Asian megacities. Nonetheless, an exceedingly high fraction of urban dwellers worldwide are still exposed to high levels of urban air pollution, especially TSPs with fine particle emissions (PM-10s) continuing their upward trend.

A wide portfolio of policy options is available, ranging from regulatory instruments such as mandated fuel choice ('smokeless zone' regulations), air-pollution standards, regulation of large point-source emissions and vehicle exhaust standards, to market-based instruments (or hybrid) approaches that incentivize technological change. An important feature of these regulatory or market-based approaches is *dynamic target setting* to reflect changing technology options and to counter the consequences of urban growth and potential consumer 'take-back' effects. The tested experiences in a diversity of settings from the United Kingdom through California to New Delhi provide valuable lessons for policy learning. However, an institutional locus on the exchange of policy lessons and capacity building (including pollution monitoring), particularly in small- and medium-sized cities in low-income countries, remains sorely lacking.

Air pollution is also the area of urban environmental policy making where the most significant co-benefits of policies can be realized: improving access to clean cooking fuels, for example, improves human health and lowers traditional pollutant emissions, and also has (through reduced black carbon emissions) net global warming co-benefits. (See also Chapters 4 and 17 on illustrations of co-benefits). Similarly, improved energy efficiency and public transport options (e.g., New Delhi's transition to CNG buses) can also yield co-benefits on a variety of fronts (lower energy and transport costs for the poor, cleaner air, improved urban functionality) and should therefore be higher on the policy agenda than more single-purpose policy measures (e.g., renewable portfolio standards for urban electricity supply). Examples of the management of urban heat island effects also illustrate well the potential significant co-benefits between mitigation and adaptation measures.

Realization of the significant potential co-benefits, however, requires more holistic policy approaches that integrate urban land-use, transport, and energy policies with the more traditional air-pollution policy frameworks. Cities in low-income countries, where the growth trends of urbanization and air pollutants are the most pronounced (to the extent that they will determine global trends), are also where institutional capacities and information needs are largest. These must be improved to be able to reap the multiple co-benefits of more integrated urban policies. A renewed effort to improve measurement and monitoring as well as planning and modeling of urban environmental quality, with a particular focus on urban energy and urban transport policy, is urgently needed. This needs to be coupled with the development of institutional capacity for the design, implementation, and enforcement of policies and plans.

18.6.4 Policy Leverages, Priorities, and Paradoxes

The highest impacts of urban policy decisions are in the areas where policies can affect local decision making and prevent or unblock spatial irreversibilities or technological 'lock-in,' or to steer away from critical thresholds.

Examples include preventing the further development of low-density, suburban housing and of shopping malls, or promotion of the co-location of high energy supply and demand centers within a city that enable cogeneration and waste-heat recycling for heating and cooling purposes (e.g., in business districts). Buildings energy-performance standards are also a prime example of policy interventions that need to be implemented as early as possible to reap long-term benefits in terms of reduced energy use and improved urban environmental quality. New technologies, like smaller micro- and mesogrids are particularly attractive options that are also suitable for deregulated market environments. The literature on urban energy use, particularly with respect to transport, also identifies a critical 'threshold' of between 50 and 150 inhabitants/ha below which public transport (or energy cogeneration) options become economically infeasible, which thus leads to overproportional increases in energy use (e.g., longer trips using private automobiles). To avoid such critical thresholds being crossed should be a high priority for urban administrations.

Given capital constraints, it is entirely unrealistic to expect 'grand' new urban 'ecodesigns' to play any significant role in integrating some three billion additional urban dwellers to 2050 into the physical, economic, and social fabric of cities. Building cities for these three billion new urban citizens along the Masdar (Abu Dhabi) model would require an investment to the tune of well above US$1000 trillion, or some 20 years of current world GDP![42] The role of such new, daring urban designs is less a template for development, but rather a 'learning laboratory' to develop and test approaches, especially to low-cost options for sustainable urban growth in low-income countries and to retrofit and adapt existing urban structures and systems across the globe.

To address urban energy sustainability challenges will also require a new paradigm for drawing systems or ecosystems boundaries that extend the traditional place-based approach (e.g., based on administrative boundaries or ecosystems such as regional watersheds or air-quality districts). Sustainability criteria need to be defined on the basis of the functional interdependence among different systems, which are not necessarily in geographic proximity to each other.

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[42] This extreme estimate does not suggest that energy efficient cities are prohibitively expensive. A wide range of measures in building retrofits and low-cost new energy efficient housing as well as in public transport policies can result in significant reductions of energy use at modest investment levels. For estimations of the investment needs of the GEA transition pathways, see Chapter 17.

System analytical and extended LCA methods are increasingly available to address the question of the social, economic, and environmental sustainability of urban energy systems that almost exclusively rely on imports. However, clear methodological guidelines and strategies to overcome the formidable data challenges are needed, a responsibility that resides within the scientific community, but that requires support and a dedicated long-term approach for funding and capacity building.

A common characteristic of sustainable urban energy system options and policies is that they are usually systemic: for example, the integration of land-use and urban transport planning that extends beyond traditional administrative boundaries; the increasing integration of urban resource streams, including water, wastes, and energy, that can further both resource (e.g., heat) recovery and improve environmental performance; or the reconfiguration of urban energy systems toward a higher integration of supply and end-use (e.g., via micro- and mesogrids) that enable step changes in efficiency, for example, through cogeneration and energy cascading. This view of more integrated and more decentralized urban infrastructures also offers possibilities to improve the resilience and security of urban energy systems.

And yet this systemic perspective reveals a new kind of 'governance paradox.' Whereas the largest policy leverages are from systemic approaches and policy integration, these policies are also the most difficult to implement and require that policy fragmentation and uncoordinated, dispersed decision making be overcome. This governance paradox is compounded by weak institutional capacities, especially in small- to medium-sized cities that are the 'backbone' of urban growth, as well as by the legacies of market deregulation and privatization that have made integrated urban planning and energy, transport, and other infrastructural policy approaches more difficult to design and yet more difficult to implement.

However, there are good reasons for (cautionary) optimism. Urban areas will continue to act as innovation centers for experimentation and as diffusion nodes for the introduction of new systems and individual technological options (Bai et al., 2010) by providing critical niche market sizes in the needed transition toward more sustainable urban energy systems. The task ahead is to leverage fully this innovation potential of cities and to scale-up successful experiments into transformative changes in energy systems. Individual and collective learning, transfer of knowledge, and sharing experiences and information across cities and among stakeholders will, as always, be key objectives to which this chapter hopes to contribute.

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