# THE WEIGHT OF CITIES

## RESOURCE REQUIREMENTS OF FUTURE URBANIZATION

# Acknowledgements

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# About the International Resource Panel

This report was prepared by the Working Group on Cities of the International Resource Panel (IRP). The IRP was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and its environmental impacts over the full life cycle and contribute to a better understanding of how to decouple economic growth from environmental degradation. Benefiting from the broad support of governments and scientific communities, the Panel is constituted of eminent scientists and experts from all parts of the world, bringing their multidisciplinary expertise to address resource management issues. The information contained in the International Resource Panel's reports is intended to be evidence based and policy relevant, informing policy framing and development and supporting evaluation and monitoring of policy effectiveness.

The Secretariat is hosted by the United Nations Environment Programme (UNEP). Since the International Resource Panel's launch in 2007, twenty-four assessments have been published. Earlier reports covered biofuels; sustainable land management; priority economic sectors and materials for sustainable resource management; benefits, risks and trade-offs of Low-Carbon Technologies for electricity production; metals stocks in society, their environmental risks and challenges, their rates of recycling and recycling opportunities; water accounting and decoupling; city-level decoupling; REDD+ to support Green Economy; and the untapped potential for decoupling resource use and related environmental impacts from economic growth.

The assessments of the IRP to date demonstrate the numerous opportunities for governments and businesses to work together to create and implement policies to encourage sustainable resource management, including through better planning, more investment, technological innovation and strategic incentives.

Following its establishment, the Panel first devoted much of its research to issues related to the use, stocks and scarcities of individual resources, as well as to the development and application of the perspective of 'decoupling' economic growth from natural resource use and environmental degradation. Building upon this knowledge base, the Panel moved into examining systematic approaches to resource use. These include the direct and indirect (or embedded) impacts of trade on natural resource use and flows; the city as a societal 'node' in which much of the current unsustainable usage of natural resources is socially and institutionally embedded; the resource use and requirements of global food systems, green technology choices, material flows and resource productivity, resource efficiency and its potential and economic implications, and the assessment of global resource use. Upcoming work by the IRP will focus on governance of the extractive sectors, the impacts of land based activities into the marine and coastal resources, land restoration, resource efficiency in circular economy, scenario modelling of integrated natural resource use, resource efficiency and climate change.

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## RESOURCE REQUIREMENTS OF FUTURE URBANIZATION

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# Preface

The first International Resource Panel (IRP) report on cities, 'City-Level Decoupling: Urban Resource Flows and the Governance of Infrastructure Transitions', produced back in 2013, provided striking figures in relation to the future of urban development. It highlighted that 60 percent of the built environment required to meet the needs of the world's urban population by 2050 still needs to be constructed.

Inspired by this reality, by the fact that China used more cement in the 2011-2013 period than the USA used during the whole 20th Century and by the absence at conferences related to cities of discussions on the implications of future urbanization on natural resources, 'The Weight of Cities' was developed.

This very timely report calls for a new strategy for 21st Century urbanization, a strategy that allows us to understand its implications, the resources being used and how different tools and interconnected interventions can help cities to better manage their resources.

The findings of the report point out that isolated actions will not result in more resource-efficient urban metabolisms, but rather that there is a pressing need for a transformative and integrated approach. In this regard, 'The Weight of Cities' shows how parallel actions in terms of urban spatial restructuring and human-scale sustainable design, resource-efficient urban components, urban infrastructure planning for cross-sector efficiency and the promotion of sustainable behaviours, would lead to improvements in well-being for all while reducing resource consumption and GHG emissions. The report also presents the entrepreneurial urban governance required to shift urbanization onto a sustainable trajectory.

'The Weight of Cities' contributes to achieving the Paris Agreement and supports the implementation of the New Urban Agenda as well as Sustainable Development Goal 11, to "make cities and human settlements inclusive, safe, resilient and sustainable", and Goal 12, to "ensure sustainable consumption and production patterns". It will also indirectly support many of the remaining Goals since the actions called for in Goal 11 are in many instances the concretization of targets across the other 16 Goals. In addition, in recognizing that 12 out of the 17 Sustainable Development Goals are directly dependent on natural resources, the report raises awareness of the new challenges related to the scarcity of resources and the environmental impacts associated with their use, including $CO_2$ emissions. Developing resource-efficient cities will not only save resources but lower GHG emissions and contribute to healthier cities.

We are very grateful to Mark Swilling, Maarten Hajer and the rest of the team for what we believe is a valuable contribution to progress towards sustainable and socially just urbanization, and for bringing the resource perspective, which should now become a central policy concern, in addition to other challenges that are already well recognized.

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# Foreword

With the world population expected to swell by almost two and a half billion people by 2050, new and existing cities must accommodate many of them. Depending on the choices we make, this could exacerbate existing problems like pollution, congestion, lack of infrastructure or public services, and marginalization of the poor. Or, if we rethink urban living and its governance, it could equally be an opportunity to develop the low-carbon, resource-efficient and socially just cities called for in the New Urban Agenda. This assessment report from the International Resource Panel, explores this transition through urban planning, investment in resource efficient infrastructure technologies and entrepreneurial governance.

The report suggests a fundamentally new approach to the way we design cities, so that people live in functionally and socially mixed neighbourhoods with better mobility options, including public transport, walking and cycling. They should have more energy efficient heating, cooling and lighting and more resource efficient components, such as vehicles, infrastructure, buildings and factories. All of which should be complemented by changing habits from consumers and producers of good and services, including better waste management or recycling.

For example, the area of Hammarby Sjöstad in Stockholm, Sweden, has been transformed from an industrial brownfield into a desirable place to live. The redevelopment created a compact area of medium-sized city blocks, small enough to walk around, with a network of green spaces, quays and walkways running through it. During development, a great deal of thought went into how people could move around their community. The use of sustainable transport is encouraged through an education centre, which provides information and promotes environmentally friendly choices and actions.

Around the world, I see more and more towns and cities determined provide such improvements for their residents. This report shows that a different urbanization, one that is sustainable and inclusive, is certainly possible. I hope it will inspire decision makers and provide a practical guide to create innovative cities that have a better relationship with nature and provide a better quality of life for residents.

Erik Solheim
Under-Secretary General
of the United Nations and
Executive Director, UN Environment

Erik Solheim

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# Glossary

### Articulated density

This refers to urban areas with strategically intensified nodes of residents, jobs, services and urban amenities.

### BAU

Business as usual

### CDS

City Development Strategy

### Cities

Urban settlements accommodating relatively large concentrations of people who are highly dependent on shared infrastructures, and where agriculture plays a minor role in the economy.

### Compactness

A property of the shape of urban footprints which is not synonymous with density. An urban shape can be compact and dense or compact and not dense.

### Density

This normally refers to the average number of people, jobs and amenities concentrated in a given city, expressed in terms of people/jobs/amenities per km2. It can also refer to the density of particular areas or 'high-density nodes' (see also strategic intensification).

### Domestic material consumption (DMC)

A measure of the total amount of materials directly used by an economy and defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports, minus all physical exports.

### Ecomobility

Travel through safe, affordable, accessible, environmentally friendly and integrated transport modes. Ecomobility gives priority to walking, cycling, wheeling, light (e-)vehicles, public transport and shared mobility, and to their interconnectivity.

### FYP

Chinese Government's Five-Year Plan

### GHG

Greenhouse gas

### Governance

The institutionalized and political configurations of power that give rise to a particular 'mode of governance' that goes beyond the mere formal structure of representation, decision-making and implementation. If government is the formal structure of power (normally represented in organograms or formal descriptions of relationships), then governance refers to the more opaque relational dynamics of everyday governing, decision-making, acting, representing, contesting and coalitioning.

### High-density nodes

This refers to particular areas in cities where there is a high concentration of people living in the area (number of people or households per $km^2$) and/or a high concentration of jobs/livelihoods (per $km^2$)

## Imaginaries

Representations of possible futures, often via a combination of images, compelling narratives and calculations. Powerful imaginaries have transformative capacity and can actively shape decisions in the present.

## Industrial symbiosis

A local collaboration between private and/or public enterprises to buy and sell their residual products for mutual economic benefit, thereby reducing environmental impact.

## Informational development/ informationalism

A new technological paradigm in which informationalism, not industrialism, is the primary driver of productivity.

## Infrastructure

The technologies and processes involved in delivering a particular service, including the administrative and regulatory arrangements within which these technologies and processes are embedded. For the purposes of this report, infrastructure primarily refers to energy, waste, water, sanitation and transit (including roads, pavements, rail, vehicular and non-motorized transit modes) infrastructures, but it can also, at times, refer to food delivery infrastructures, which are much more of a hybrid of public and private systems.

## Life-cycle assessment (LCA)

A tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle.

## Material footprint

An indicator of resource use that attributes global *material* extraction to domestic final demand.

## Material intensity

An intensive measure that is related to the density of infrastructure, buildings and activity in the urban space.

## Material requirements

An extensive measure that responds to total population or total land use.

## Metabolic configuration

The actual specific flow of resources through an existing urban system that a particular set of infrastructures makes possible within a given spatial formation and in accordance with allocative logics set by the prevailing mode of governance.

## Metabolic imaginary

An ideology, discourse or culturally accepted world view that provides the logic of legitimation (who benefits and loses and why), technical justification (why it is low risk, viable and efficient), financial rationale (most affordable given the resources available) and consumption necessity (why a particular service is needed/desired) for the particular spatial and infrastructure dimension of a given metabolic configuration.

## Metabolism

The flow of resources through a particular system, including where they originate, how they are processed and where they go after use (i.e. into waste systems or into re-use systems).

## Mixed use

A form of development that combines residential and commercial use and provides amenities at the neighbourhood, block and building level to guarantee proximity to amenities in residential areas.

## Modes of urban governance

Governance takes particular forms in particular urban contexts—these forms can be characterized as ‘modes of urban governance’, which in this report are described as clientelist, populist, managerial, corporatist, entrepreneurial and pluralist.

## NUP

National Urban Policy

## Resilience

This refers mainly to urban resilience the capacity of individuals, communities, institutions, businesses and systems within a city to survive, adapt and grow, no matter what forms of chronic stress and acute shocks they experience.

## Resource-efficient urban systems or resource-efficient urbanism (sometimes referred to as 'resource efficiency')

This refers to urbanisms/urban systems in which the resources required per capita to achieve a given level of human well-being and/or economic output (e.g. 8 tonnes per capita where gross domestic product (GDP) per capita is US$20,000 per annum) are less than what is achieved in conventional resource-intensive urbanisms/urban systems.

## Resource-intensive urban systems or urbanisms

Urbanisms/urban systems in which densities are low and business-as-usual infrastructures are used, resulting in resource use per capita to achieve a given level of human well-being and/or economic output that is relatively high.

## Resource productivity or resource-productive urban systems

This concept is used interchangeably with resource efficiency or resource-efficient urban systems/urbanism.

## Slum

An urban area that lacks one or more of the following: (1) durable housing of a permanent nature that protects against extreme climate conditions; (2) sufficient living space, which means not more than three people sharing the same room; (3) easy access to safe water in sufficient amounts, at an affordable price; (4) access to adequate sanitation in the form of a private or public toilet, shared by a reasonable number of people; (5) security of tenure that prevents forced eviction.

## Smart city

This term is typically used to describe an urban development that integrates information and communications technology (ICT) and Internet of things (IoT) technology to manage a city's assets more effectively. It is sometimes also used in a manner that encompasses intelligent, creative, knowledge-based solutions that go beyond an information technologies (IT) focus. Although 'smart' technologies can be used to improve resource efficiencies, a smart city is not synonymous with a sustainable city.

## Sociotechnical systems

This refers to urban infrastructures and tends to be used when emphasis is being placed on more than just the technologies, i.e. infrastructures in the sense of a combination of technologies, processes, market structures, regulatory regimes and governance arrangements.

## Strategic intensification

This refers to the process of intensifying the number of jobs/people/amenities located within a network of primary and secondary high-density nodes that are well-connected by efficient and affordable mass transit systems (bus, rail, non-motorized).

## Transit-oriented development (TOD)

Public sector development strategies aimed primarily at urban regeneration and transformation centred on public transport. Unlike transit-related development (TRD), TOD uses public-private partnerships to capture a portion of the improved land values to contribute towards the costs of the public transport infrastructure.

## Urban

This refers to an area where households are clustered together in coterminous neighbourhoods, which altogether form a recognizable, socio-physical space that is distinct from the surrounding rural area. In particular, they tend to have higher densities, greater access to various shared services and are partly or wholly dependent on various types of non-agricultural production.

## Urbanism

A broad term that refers to a general pattern of urban dynamics and development trajectories. Inclusive urbanism tends to be welfarist, socially mixed and inclusionary; splintered urbanism emerged during the neo-liberal era and denotes when richer enclaves are developed separately from poorer areas as a result of reduced cross-subsidization and application of full cost-recovery systems; green urbanism (illustrated most clearly by the 'green building' movement) involves making urban systems and development approaches (for energy, waste, transit, resources, food, etc.) more sustainable in some way; slum urbanism refers to the growth of cities via the spread of informal settlements; sustainable or liveable urbanism refers to the construction of bioeconomic regions that are expressly committed to restoring the ecosystems within which they are embedded, minimizing resource and fossil fuel use, and maximizing recycling.

## Urban form

The design and physical layout of a city.

## Urban metabolism

The flow of resources through urban systems (including sourcing, processes and outputs into waste or re-use systems) with reference to either urban systems as a whole (globally, nationally, regionally) or at the subsystem (a particular area) or sector (e.g. transport, energy, food) level.

## Urban morphology

The study of the form of cities and their component parts, and the processes involved in their growth and transformation, in order to understand their spatial structure and character.

## Urban productivity

This refers to the total economic value (measured in terms of GDP per capita of Gross Value Added [GVA]) generated by a given area of urban space (usually measured in hectares or km$^2$) with specific urban characteristics (usually density, measured in terms of population or jobs per hectare or km$^2$). For example, the GVA of an urban area with a density of, say, 15,000 people per km$^2$ measured in terms of GVA per capita may be higher than for an area with an equivalent size but with a population density of 5,000 people per km$^2$.

## Urban settlement

This refers to any form of settlement across a wide spectrum, from small town to megacity. At one end of the spectrum are settlements of roughly 2,000 people who live in a relatively concentrated area and are co-dependent on a minimum number of shared services, facilities, amenities and infrastructures (and may still be dependent on agriculture). At the other end are large-scale metropolitan systems in which agriculture plays a minimal economic role. All cities are urban settlements, but not all urban settlements are cities.

## Urban systems

A general term that refers to the configuration of spaces, infrastructures, patterns of development and consumption, behaviours and movements of particular urban settlements and cities.

## Urban transition

Major systemic changes to the nature of the urban system, specifically city-wide changes to the nature of sociotechnical (infrastructure) systems (e.g. introduction of sanitation systems or the mid-20th Century highway revolution) and/or spatial changes in densities (de-densification or densification) that have economic, social and environmental implications.

## Well-grounded cities

An approach that focuses on the real foundational economy—an economy that relates to the livelihoods of the majority of citizens and what is required to improve their well-being and overall productivity. This includes all aspects of social policy (housing, welfare, education and health) as well as public open space, mobility, food and safety. The overall aim is to reduce inequalities by maximizing benefits for all rather than focusing on elite property development investments.

# Executive summary

How do we prepare for the doubling in size of the urban population between 2010 and 2050? This report by experts from the International Resource Panel (IRP) draws on a range of methodologies, both qualitative and quantitative, to answer this question. The report is the first of its kind, with three interconnected aims: (1) to assess the resources required, (2) investigate the possibility of sustainable alternatives and (3) offer a perspective on governance—how to transition to socially inclusive, resource-efficient and sustainable urban development.

The report presents the first assessment of the resources required at a global scale for the coming wave of urbanization. Using material flow analysis, the analysis of urban form and city organization, the assessment of the potential contribution of known sustainable technologies, as well as case study methodology, it reveals the possibility of an alternative, resource-efficient urban management strategy. The report identifies the proliferation of the sustainability-oriented 'urban experiments' as a basis for a new form of resource-efficient urbanism. This emergent mode of urban governance can be aligned with the potential of networks of knowledge-based economies that will change industrial activity in cities over the coming decades.

The report seeks to address the complex interrelationships between (1) urban population growth and demographic change, (2) spatial change and development (with particular reference to (de-)densification), (3) infrastructure planning and development, and (4) resource flows into, through and out of urban systems, and consequently the complex interrelationships between cities and the wider ecosystems within which they are embedded. It presents urban resource flows as being key to understanding what it will take to promote a transition from resource-intensive urban metabolism towards alternatives that manage resources more carefully. Unless alternative urban metabolic configurations are imagined, it will not be possible to develop strategies for achieving more sustainable and socially just (inclusive) metabolic configurations. Implementing an infrastructure transition is an achievable goal, considering that the level of upfront investment required in infrastructure between 2015 and 2030 would only need to increase by 5 percent to shift from a carbon-intensive approach to a low-carbon alternative.

The report cites urban morphology as a key lever to improving urban resource management and reducing inequity. Over the last hundred years urban spatial formations have tended to de-densify, with significant implications for available arable land and food production. Spatial expansion has promoted certain business-as-usual (BAU) infrastructure solutions that have tended to focus on extension within an engineering context, while the supply of resources at cheap rates has been presumed to be unconstrained. This can be referred to as the conventional or 'modernist' metabolic configuration, which is 'locked in' by a set of infrastructures and spatial arrangements that are supposedly tried and tested and therefore low risk. However, this metabolic configuration is fundamentally unsustainable.

There is a realization that more sustainable metabolic configurations will be needed, however, the underlying metabolic shifts required are rarely made explicit, and effects on the social inclusiveness of cities are not a consideration. This report presents the first systematic assessment of why conventional, urban metabolic configurations are resource inefficient and unsustainable, and how alternative urban metabolic configurations can be analysed and conceptualized with respect to alternative infrastructures, technologies and spatial patterns.

The report contains seven chapters, which aim to answer the following key questions:

## 1. Why should cities focus on improving their management of resources?

Chapter 1 sets the context for the report by outlining the nature of the urban challenge over the next three and a half decades. With urbanization set to rise from 54 percent in 2015 to 66 percent in 2050, the global urban population is likely to grow by 2.4 billion people (UN-DESA, 2014). The bulk of urban growth will happen in the cities of the Global South, particularly in China, India and Nigeria. With material consumption predicted to grow faster than urban populations, global urban material consumption is projected to reach approximately 90 billion tonnes by 2050. The types of cities that develop will differ from region to region, and will reshape the global economy and demand for resources. Most of the economic growth and demand for resources will come from cities with populations of less than 10 million (Dobbs *et al.,* 2011).

Domestic material consumption (DMC)—expressed here in tonnes per capita per annum—is a useful metric for estimating direct resource use in a particular region, and can be used to monitor changes in resource consumption at the city level. A DMC range of 6–8 tonnes per capita per year has been proposed as an indicative target for sustainable consumption (UNEP, 2011) and could be used by cities wanting to limit the resource and environmental impacts of their inhabitants. Urban metabolism can be used to bring different disciplines together to monitor and understand resource consumption patterns, and identify areas for intervention that could help cities meet this target.

Innovation is required in order to move urban metabolic patterns away from an unsustainable baseline. In the past, coalitions of interests have promoted innovation (e.g. in waterborne sanitation) and there are signs that international and local-level interest groups are already starting to engage in a significant way to move urban metabolic configurations in a more sustainable direction.

## 2. What are the implications of current trends on urban resource demand?

Chapter 2 uses available data to forecast how urban resource use is likely to grow until 2050, based on estimates of urban DMC for different world regions. To date, global databases have failed to distinguish between the DMC of nations and DMC within urban areas. The baseline estimates for DMC provided in this chapter are based on the assumption that infrastructures will result in metabolic configurations that will be as resource intensive by 2050 as they were in 2000, and that average densities will continue their long-term decline by an average of –2 percent per annum. The result is a convergence corridor of an urban DMC of 8–17 tonnes per capita per year, modeled using a logistic equation that implies saturation in DMC for both developed and developing nations, although at different levels. If urban DMC can be reduced from a range of 8–17 tonnes per capita per year to a range of 6–8 tonnes per capita per year, this would contribute significantly to achieving the IRP indicative decoupling target of keeping the domestic extraction level equal to what it was in 2000 (UNEP, 2011), suggesting a target of 50 percent reduction in DMC. A first-order estimate of what could be achieved if cities were more resource efficient in three sectors—transport, commercial buildings and building heating/cooling—is a reduction of about 46–67 percent. This percentage reduction in the three sectors is in line with the 50 percent resource-saving target. The more detailed assessments of specific resource efficiencies in subsequent chapters using different methodologies should be contextualized by this ballpark improvement in urban resource efficiency by a factor of two.

## 3. How can spatial planning help cities to manage their resources better?

Chapter 3 identifies the interventions that are key to better resource efficiency and greater social inclusion within more equitable space economies and urban metabolic configurations. These interventions include spatial restructuring of the urban morphology to reverse the century-long trend towards de-densification and promote compact urban growth, liveable neighbourhoods, resource-efficient buildings and urban systems, and behavioural change. Evidently, this implies a markedly different orientation to the current sociotechnological orientation towards smart cities, which is based on a privately-owned car fleet and the tendency to use the policy tools of land use, land rights and zoning to benefit middle- and upper-income property owners. The primary significance of urban morphology interventions is that they are, on the whole, controllable by local governments, especially those with the capacity for integrated planning (which is addressed in more detail in Chapter 6).

As argued in Chapter 3, it is possible to radically improve urban productivity by a factor of 10. The design of cities constitutes the greatest potential source of savings at zero or negative cost. Denser, better-connected cities designed to be more open to light, the sun and wind will improve well-being and social and economic exchanges, while economizing on the square kilometres of asphalt, the concrete, the electricity and the water that are currently wasted in the overly long and scattered networks of our sprawling contemporary cities. If the productivity of the urban system was multiplied by 10, humankind could continue to urbanize, creating wealth and eliminating poverty while halving the pressure exerted on the planet.

There is a substantial body of evidence that supports the contention that it is indeed possible to radically improve urban productivity (otherwise known as resource-efficient urbanism). However, if the long-term trend of de-densification is not reversed, the introduction of resource-efficient infrastructures and buildings will not result in more resource-efficient urban metabolic configurations. The analytical and policy focus must therefore not be on achieving an increase in average density across a given space economy. Instead, the focus must be on what this report will refer to as ‘strategic intensification’ of the urban space economy, which can, in turn, be defined as a well-articulated network of high-density nodes that are connected by efficient and affordable ecomobility options.

Four systemically interrelated interventions are discussed in detail in Chapter 3:

- spatial restructuring of the urban morphology to achieve strategic intensification, i.e. the formation of a well-articulated network of high-density nodes and within these nodes, the fostering of a richer mix of housing, jobs and amenities at the neighbourhood level. It is worth noting, however, that although an increase in average density across a given space economy may be the emergent outcome of successful strategic intensification, it should not be the analytical and policy focus;

- human-scale sustainable design that creates conditions for liveable functionally and socially mixed-use neighbourhoods, with options for ‘soft’ mobility (pedestrianization, cycling) at the city/neighbourhood level and ‘passive’ heating, cooling and lighting at the building level;
- resource efficiency of all urban components, such as vehicles, infrastructures, buildings, factories;
- promotion of sustainable behaviour, specifically the separation of waste at source for recycling, use of public transport, walking or cycling, use of public spaces, etc.

As demonstrated in Chapter 3, the actual improvements in energy and resource productivity from each of these interventions are not simply the sum of each intervention, but are ‘multiplicative’ if they are implemented in mutually reinforcing ways. The evidence indicates that higher densities and compact urban forms could reduce greenhouse gas (GHG) emissions by a factor of two or more, human-scale functionally mixed neighbourhoods could reduce energy consumption by a factor of two or more, energy-efficient buildings could reduce energy demand by a factor of two or more, efficient systems could achieve a further 20 percent energy saving and behavioural changes could reduce energy demand by a factor of two. Altogether, this would result in a tenfold reduction in energy use, which significantly exceeds the Factor 5 target that is usually referenced.

## 4. How can alternative infrastructure choices help cities to manage their resources better?

Chapter 4 uses an integrated life-cycle assessment (LCA) framework to assess how the introduction of more resource-efficient technologies in key sociotechnical systems could influence the overall environmental and natural resource impacts of providing key urban services by 2050. Empirical data from a sample of 84 cities and available literature was used to project the demand for vehicular passenger transportation, commercial buildings and heating/cooling energy from the present to the year 2050. This baseline scenario assumed an urban metabolic configuration characterized by growth in population and income, decreasing urban density and marginal technological changes in the production of energy and materials.

The standard resource-efficient scenario assumes an urban metabolic configuration in which the same population, income and density scenarios apply as in the baseline scenario, but which incorporates high penetration of resource-efficient technologies[1]—namely Bus Rapid Transit (BRT), green-certified commercial buildings and district energy systems—coupled with a transition to a low-carbon electricity supply consistent with 2°C climate mitigation scenarios. In addition to the improvements assumed by the standard resource-efficient scenario, the strategic intensification scenario considers increasing urban population density from the present to 2050, in reverse of observed trends.

The results show that with high penetration of BRT in transportation, green commercial buildings and district energy in heating and cooling, a 24–47 percent reduction in resource impacts can be achieved by 2050. In the strategic intensification scenario, the results show an additional 3–12 percent reduction in resource impacts, that is, resource efficiencies ranging from 36–54 percent compared with the baseline scenario. This is within the Factor 2 target of halving urban DMC by 2050. The findings indicate that existing sociotechnological systems, when combined with the type of strategic intensification described in Chapter 3, can take us to the future of resource-efficient and liveable cities.

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[1] Although an LCA of BRT systems was conducted, the BRT is only one option within a much wider range of structurally integrated mass transit systems that serve the same purpose. Similarly, the LCA of district energy systems reveals what is possible if energy were used more efficiently within the urban system.

## 5. How can integrated planning of infrastructure projects help cities to manage their resources better?

Whereas Chapters 2, 3 and 4 are based on top-down analyses using global databases, Chapter 5 draws on detailed, empirical case study material from three contexts: Minneapolis, USA; Beijing and the highly industrial northern city of Kaifeng, China; and Ahmedabad and Delhi, India. It considers the potential impacts of implementing policies already approved or generally supported by governments at the local, regional and national levels in each of the three countries, and finds that there are significant resource efficiencies to be achieved through resource sharing, by way of intersectoral infrastructure interventions in the following sectors:

- building and construction;
- energy supply sector, focusing on electricity services;
- heat energy supply, incorporating reutilization of waste heat from industrial resources;
- travel behaviours and transportation;
- waste management, including waste-to-energy.

The Minneapolis case study (Chapter 5) reveals that significant resource efficiencies can be achieved by 2050 if the following combination of interventions are implemented: strategic intensification and infill in transit-related nodes, energy-efficient buildings, 65 percent of all energy provided by 2050 from non-fossil fuel resources (including both nuclear and renewables), extended mass transit services, fourth-generation district energy systems and advanced timber construction to replace cement-based building systems. The result would be a 33 percent reduction in GHGs by 2050, a 62 percent saving in mineral construction materials in mid-rise buildings and a 40 percent reduction in building energy for heating and cooling.

In contrast to the stable population scenario in Minneapolis, the implications of rapid population growth in industrializing cities were assessed in the case studies of Beijing and Kaifeng. Significant resource efficiencies could be achieved over a shorter time-frame of approximately five years if the following policy-approved interventions were implemented in a coordinated manner: industrial efficiency in accordance with the ‘Top 10,000 Program’, fourth-generation district energy systems, industrial waste heat reutilization, energy-efficient buildings, combined heat and power (CHP), waste-to-energy and material exchange/substitution (with respect to fly ash and slag content in building materials to reduce cement content). The results show that material savings would be considerable and GHG emissions could be slashed by 40 percent in four years. This presents a case for optimism, in that rapid urbanization can also offer a greater pace of resource efficiency.

The Ahmedabad and Delhi case studies focus on the in situ rehabilitation of slums by building multi-storey buildings in the inner city. It was found that this could reduce material use by 36 percent (compared with single-storey construction) while reducing motorized travel demand and improving access to employment which, in turn, would reinforce higher densities. It was also found that if the poorest 50 percent of Delhi’s population were given access to electricity above today’s consumption levels, this would only increase total energy demand by 13 percent.

In short, the three detailed case studies reinforce the conclusion that inclusive strategic intensification within key nodes, plus resource sharing via coordinated, intersectoral infrastructure interventions can contribute to a 30–50 percent resource-use reduction in key infrastructure sectors.

## 6. What types of governance and planning are required for cities to transition towards improved resource management?

Accelerating urban productivity by restructuring the morphological form of neighbourhoods, investing in city-wide transit systems, building inclusive, renewable energy grids and energy-efficient buildings, reducing waste to zero and resource sharing will all depend on the emergence of appropriate modes of urban governance. These modes, however, are not the outcome of clean-cut policy processes, but rather emerge as new ecologies of urban actors create leadership coalitions to realize the potential of accelerated urban transitions. The form this takes will vary greatly depending on the context. In cities of the Global North with well-developed urban infrastructures, city-level leadership will face the challenge of lock-in and sunk costs if they are seriously committed to retrofitting; whereas in cities of the Global South that have not yet locked in 19th or 20th Century technologies, the challenge will be to secure and build up the necessary institutional capacity for implementation and also, the need to overcome the modernist aspiration to 'be like the West' (which has been the cause of some unsuccessful urban developments in China's vast new urban agglomerations). The approximate $90 trillion that is estimated to be spent on new or renewed urban infrastructure between now and 2050 can either reinforce a BAU paradigm of the car-oriented '100-mile city' or, alternatively, promote densities and infrastructure solutions that make it possible to have a good quality of life without emitting more than 2 tonnes of $CO_2$ per capita per annum, and without using more than 6–8 tonnes of resources per capita per annum.

To be both guiding and responsive in ways that enable experiments in sociotechnical change and strategic intensification to be upscaled, Chapter 6 argues that in order to address the challenge of the urban transition, there must be a balance between informational development, human development and sustainable development. To this end, entrepreneurial governance of urban experimentation that maximizes the potential of new information and communication technologies will be needed, but not within a smart city paradigm. For cities and urban settlements to be economically inclusive and resource efficient, the 'competitive cities' governance approach to urban economies will need to be replaced by the 'well-grounded cities' approach (see glossary) that serves the interests of all citizens. Without this paradigm shift, a balance between informational, human and sustainable development will not be possible. Furthermore, integrated urban planning holds the key to achieving strategic intensification of urban space economies, especially with respect to setting flexible frameworks for guiding the spatial evolution of high-density, mixed-used neighbourhoods with access to affordable and efficient transit and multi-purpose public spaces. Given the uneven geography of urbanization patterns, the diversity of urban regulatory regimes must be recognized when conceptualizing the future of urban governance—these range from the structurally formal, highly regulated regimes in cities of developed countries to the highly informal and unregulated regimes in many poorer cities. Hybridized and diverse urban service delivery systems in Southern cities reflect their heterogeneity. Finally, there are a multiplicity of state-led, market-led, technology-led and citizen-led urban experiments already under way around the world that reinforce the notion that urban experimentation is, indeed, emerging as a mode of urban governance fit for the complexities of the 21st Century. Case study examples from cities around the world are used to illustrate these concepts in action.

## 7. What is required to improve urban resource management?

A new strategy for urbanization is proposed, one which focuses on resource efficiency and social inclusion at the city level. City stakeholders from academia, policymakers, community leaders, designers and the business community need to reconnect and rethink the relationship between cities and the natural environment. This is envisaged as a movement propelled by strong imaginaries of current and possible success, capturing the productive energy of policymakers, insights from academics, initiatives from civil society, designers, business and finance to rethink existing cities as well as create new ones. Urban metabolism provides a powerful language to facilitate collaboration between distinct but intersecting world views, as has been done with this report.

The task ahead is to rethink the city for the era without cheap fossil fuels. We suggest combining 'post-fossil' strategies with those aimed at achieving socially inclusive cities. The push to really break away from fossil fuels and the current rates of material resource consumption should create a spike of sustainability-oriented innovations. If done well, sustainability will become an aspirational good in itself.

The following recommendations are proposed:

**1. Urban metabolisms must shift from 'linear' to 'circular':** We recommend a shift from linear urban economies to circular ones, by extracting more utility from so-called 'waste' streams. This implies new approaches to managing the movement of resources through the city, both in terms of stocks (e.g. building materials) and flows that service the city (e.g. water).

**2. Urban metabolisms must be monitored to assist strategic planning at local government level:** Awareness of resource use is a significant driver of change towards resource efficiency. The urban metabolic configuration of cities must be understood, and local governments must use this to develop resource strategies. We recommend the introduction of a system of 'green accounting' as a first step to rethinking the resource balance sheet in business and public service.

**3. The relationship between GDP and material flows, global land use and GHG emissions must be measured and targets must be set:** The negative externalities of various resource uses must be priced in. Pricing of carbon emissions and scarce resources such as water will provide economic incentives for behavioural change. Attention should also be given to the economics of land; we recommend further investigation into value-added taxes that help local governments to recoup the money they spend on maintaining public infrastructure.

**4. City planning 'defaults' must be changed:** Cityscapes need to be designed for people rather than cars, and must enable the poor, in particular, to access the opportunities on offer in the city. We recommend a radical change in default approaches to urban planning to prevent uncontrolled sprawl. Specifically, we recommend creating a well-articulated network of strategically intensified nodes, connected by efficient and affordable mass transit systems; liveable, functionally and socially mixed neighbourhoods; resource-efficient smart buildings and urban energy, waste and water systems; and changing values and behaviour to support this.

**5. Use urban infrastructure as a catalyst for sustainable cities:** For cities to shift their defaults towards sustainability, it is essential to channel existing infrastructure budgets in new directions. A low-carbon scenario would require adding only 5 percent to infrastructure spending.

**6. Urban infrastructure and land-use policy must be strategically linked to achieve sustainability goals:** Transit-oriented development (TOD) has the potential to significantly change the way people and goods move through the city, thus reducing dependence on fossil fuels and potentially improving quality of life for city inhabitants in many ways. We recommend approaching TOD and area development as integrated portfolios.

**7. Develop appealing mixed-use and socially mixed, inner-city neighbourhoods:** Enclave urbanism stands in the way of achieving socially inclusive cities. We recommend investing in developing mixed-use neighbourhoods that are attractive and remove the incentive to escape ‘urban blight’, and in the urbanization of the suburb, focusing development around high-access nodes of the transport network. This requires an integrated approach in which such mixed-use and socially mixed neighbourhoods also have top schools, cultural amenities, sporting and recreation facilities, and pavements that are safe and clean.

**8. The power of design can be used to actively develop appealing visions of vibrant, green and socially inclusive cities to guide strategic planning:** We recommend using the power of imaginaries to create an appetite for the sustainable city. We also recommend using good presentations of successful case studies to generate interest among both investors and politicians for sustainable urban futures.

**9. A politics of experimentation can provide hope for a better future:** Concepts such as ‘living labs’, city deals, innovation hubs and special zones indicate that cities are now thinking much more in terms of learning by doing than focusing on one solution and trying to apply it everywhere. Most likely, it is this politics of experimentation that will provide the inspiration and mutual learning that can really propel a broader transition.

**10. Cities must learn from the experiences of other cities to hasten transition:** We recommend accelerating learning by investing in city networks and ‘twin town’ or ‘sister city’ initiatives, which function as horizontal communicative and learning platforms. The learning capacity of cities can be enhanced by investing in networks of cities at various scales—nationally, internationally or even globally. Investments must be made to build institutions that help these networks to function better and build solidarity among cities.

Each city is unique, so we recommend combining analysis at the global level with constant ‘deep dives’ into local and regional strategies. We therefore promote an approach that mobilizes local ingenuity in a manner that appreciates local contexts and allows for the creation of new, forward-thinking engines of growth and development.

**11. Higher levels of government must support city-level innovation for resource efficiency:** Collaboration with higher levels of government is essential if cities and networks of cities are to overcome regulatory barriers and access funding. Reinforcement, inspection and compliance are mostly national responsibilities, and should serve to support cities in achieving resource-efficiency goals. Similarly, prices and taxes set at the national level can contribute significantly to providing incentives and disincentives for behaviours that support resource efficiency.

A politics of experimentation can be fostered by higher levels of government by way of setting overarching goals, establishing the right conditions for city-level experimentation and providing relevant stakeholders with the resources, space and flexibility they need to experiment and share what their learnings with other cities. A two-way interaction between cities and national governments helps to ensure that experiments achieve policy goals, and that policies are refined based on practical experience.

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# Introduction

This report has been prepared by the Cities Working Group of the International Resource Panel as a successor to the City-Level Decoupling report (see UNEP, 2013a). It has brought together a global team of experts from different disciplines to address one of the great challenges of our age: how to prepare for the doubling in size of the urban population during the period 2010–2050 by promoting a transition to socially inclusive, resource-efficient and sustainable modes of urban development. To address this challenge, an understanding of its dimensions and potential policy-relevant solutions is required. To this end, this report provides an assessment of the following:

- the nature and extent of the urbanization challenge, with special reference to the current second urbanization wave taking place mainly in developing countries (especially China, India and much of Africa);
- the resource implications of future urbanization if the existing infrastructures and densities in cities remain unchanged;
- the potential resource efficiencies of a strategy based on higher urban densities supported by efficient mass transit, energy efficiency and renewable energy;
- the evidence from life-cycle analyses of the resource efficiencies of specific urban infrastructures when compared with BAU approaches;
- case studies of infrastructure interventions in cities in China, India and the USA that can facilitate resource sharing and resource efficiencies, illustrating efficiencies through cross-infrastructure interactions in cities;
- the type of governance and planning strategies required to deliver on a global shift from unsustainable to more socially inclusive, resource-efficient urbanism.

The report is highly relevant given the rapid pace of urbanization and its impact on resource and land use. Sustainable cities have been included among the 17 global ambitions captured in the Sustainable Development Goals (SDGs), which set the global agenda for sustainable development from 2015 to 2030. Goal 11 aims to create “inclusive, safe, resilient and sustainable cities” and has helped to shift attention towards cities as loci for strategic actions that promote economic, social and environmental well-being. Strategies for sustainable urbanism in the 21st Century must not only address ongoing urban challenges, but also account for newer trends such as climate change, rising inequality and exclusion, decreasing security and an upswing in international migration (UN-Habitat, 2016). The New Urban Agenda of 2016 elaborates how sustainable development should manifest in cities, and calls for systemic interventions to promote inclusion, resource efficiency and resilience (United Nations General Assembly, 2016). In line with the New Urban Agenda, a number of countries are formulating and implementing National Urban Policies (NUPs) and cities are developing City Development Strategies (CDS) in order to harness the potential of urbanization to achieve national and global goals (OECD, 2017; Cities Alliance, 2017). This is the first report to provide a policy-relevant, global-level material flow analysis that can be used by national governments to formulate comprehensive NUPs, which address the challenge of decoupling urban development from rising rates of resource use.

This report’s focus on resource management at the city level provides a useful lens through which to understand urban systems and how urban resources can be best used. Improving resource efficiencies and reducing waste helps to save energy (European Commission, 2016) and reduce GHG emissions (IRP, 2016) while creating opportunities for cities to save money on operating costs, which can be redirected towards addressing urban social challenges. Improving resource efficiency can also contribute to improving urban resilience, although some tensions between the two concepts exist (UNEP, 2017). By achieving more with less and by using more renewable resources, the environmental damage associated with resource extraction and waste disposal can be slowed and ideally reversed over time. Of course, as already indicated, this could happen in a way that is not socially inclusive if state intervention is absent and the financial benefits of resource-efficient urbanism are not captured and redistributed.

Drawing on complexity thinking, this report brings together a range of urban perspectives and related methodologies to improve our understanding of the challenges and opportunities. However, these perspectives and methodologies do not fit neatly together to create a 'science of cities', nor do they follow a clear, linear logic from one to the next. Instead, these perspectives and methodologies can be seen as layers of analysis or 'framings' superimposed on top of one another to enable the reader to comprehend the complexity of the challenges and opportunities that need to be addressed. This is different to a more integrated, 'cybernetic' trend in urban studies to discover a kind of algorithmic essence of the urban dynamic, which can then be modeled to drive particular policy solutions (see, for example, Batty, 2013).

## 1. Context and focus

There is a growing awareness across the world's policy communities that the global economic crisis, which began in 2007, may mark the end of an era and the start of some sort of global transition, which is likely to differ in scope and scale from region to region. What is certain is that the crisis brought to an end the post-Second World War long-term development cycle—2009 was the first year since the Second World War that the global economy actually shrank (as measured in terms of GDP) (Gore, 2010). After Second World War, the Bretton Woods Conference was convened to agree on a new world economic order, yet this latest global economic crisis has not prompted any global gathering of this nature. Instead, a prolonged, highly unstable interregnum persists, reinforcing short-termism, insecurity and fears of another crash in the not-too-distant future.

There is, however, a certain inevitability about a convergence of forces that could result in a transition to the next long-term development cycle (Perez, 2013; Swilling, 2013). Given the current consensus that this long-term development cycle will have to occur within what some refer to as more sustainable planetary boundaries, which define the Anthropocene (Rockström, 2009), the chances are high that the next cycle will depend on a 'green transformation' of some kind (Scoones *et al.,* 2015; United Nations, 2011). How radical this will be is subject to intense contestation. The adoption by the United Nations of the SDGs is the clearest marker of a political recognition that economic and social development must be conceived as taking place within ecological systems that need to be sustainably managed. Whatever comes next will have to be justified, in one way or another, as being more ecologically sustainable and developmentally inclusive than the era that preceded the crash. This is increasingly being referred to as the next 'great transformation' (see, for example, German Advisory Council on Global Change, 2011).[2]

At the same time, it is also generally accepted that we face the challenge of the next (potentially more sustainable) long-term development cycle within the wider context of a great transformation just when the majority of the world's population is living in urban settlements ranging from a few thousand to over 10 million people. Indeed, according to United Nations population projections, the urban population is set to nearly double in size between 2010 and 2050, by which time as many as 7 billion out of 9.5 billion people may be living in urban settlements. While progress at the global level to position the next long-term development cycle within planetary boundaries is low, there is an outburst in cities and urban settlements across the world of sustainability-oriented urban experiments (Evans *et al.,* 2016; Guy *et al.,* 2011; Hodson & Marvin, 2016; Joss, 2010; LSE Cities *et al.,* 2013). These occur within the context of a global shift from industrialism to informational development, as microelectronics-based digital information and

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[2] This also resonates somewhat with the 2016 World Economic Forum theme of the 'fourth industrial revolution'.

communications are becoming the all-pervasive technological foundation of a knowledge-based economy, organized via networks (Castells & Himanen, 2014). The evolutionary potential of these existing urban experiments might be just as significant as any agreement at the global level (Hajer *et al.,* 2015). Their potential for collaborative learning, sharing and scaling within an informational development context may be significant enough to justify the argument that they possibly represent the emergence of a new mode of urban governance, aligned with the potential of networks of knowledge-based economies. These types of knowledge-based networks will also change the industrial activity in cities over the coming decades.

The dynamics of urban change are crucial because the global economic crisis of the last decade was distinctly urban in character. After all, it was triggered by the sub-prime crisis, which was, in turn, a crisis created by the massive flow of cheap credit into urban property during a period of declining resource prices up to 2002, and thereafter during a period of rising resource prices. This all happened in the context of rising urban property prices across almost all major urban centres globally, albeit confined to enclaves within these cities, which were, in turn, a distinctive characteristic of the financialization of the global economy promoted by the economic policies adopted by Western governments from the early 1980s onward, and by the global multilateral financial institutions (Harvey, 2012). Here, urban change and global economic developments are intricately interrelated. It was rising urban property prices that created the security needed for extending credit to mainly middle- and lower-middle-class households in cities around the world, connected to the sonic flows of finance that fuelled the consumption boom and the rise of China as the world's leading manufacturer. Indeed, it was the Chinese surpluses invested in Western government bonds that made the credit bubble after the dot-com crisis of 2000/2001 possible. However, the key difference between cities with more developed economies and cities with developing economies is the fact that in the latter, massive quantities of resources have been deployed to rapidly expand the building stock (infrastructure and housing). This means that the rise and fall of resource prices will have quite specific effects on cities in developing countries.

In short, global economic futures are intertwined with the way urban challenges will be addressed. Therefore, it is important to examine what is now emerging within our cities and urban settlements, to discern the potential dynamics of an emergent, resource-efficient, resilient and inclusive economic order. To this end, the evolutionary potential of the present needs to be understood, as do potential future transition pathways. Will it be possible to move away from the real estate-driven, boom-and-bust logic that increased inequality and degraded global environments, towards a more socially inclusive, resource-efficient and sustainable urbanism? If so, what are the mechanisms required for this transition? A persistent theme throughout this report is that cities are by no means homogeneous entities; they are spaces in which a complex range of social, cultural and economic divisions and inequalities often result in conflictual dynamics that make it impossible to predict with any certainty how a particular approach will manifest at the city level. Indeed, there is even a danger that a focus on resource efficiency could result in resource-efficient urbanism at the expense of social inclusion—a phenomenon already emerging in the so-called 'green enclaves' around the world, such as Masdar, or exclusive, upmarket, green suburban estates.

Building on the first IRP report on cities, 'City-Level Decoupling: Urban Resource Flows and the Governance of Infrastructure Transitions' (UNEP, 2013a), this report seeks to address the complex interrelationships among four primary global drivers of urban change:

- urban population growth and demographic change;
- spatial change and development, with special reference to (de-)densification;

- infrastructure planning and development;
- resource flows into, through and out of urban systems, and therefore the complex interrelationships between cities and the wider ecosystems within which they are embedded.

Unlike most other reports on cities and urbanization, the point of departure for the first City-Level Decoupling report and for this report is that urban resource flows are key to understanding what it will take to promote a transition from resource-intensive, urban metabolisms towards alternatives that manage resources more carefully. An *urban metabolic configuration* consists of the actual specific flows of resources into, through and out of an existing urban system, which a particular set of infrastructures makes possible within a given ecological and spatial formation, and in accordance with the allocative logics set by the prevailing mode of governance. Unless alternative urban metabolic configurations are imagined, it will not be possible to develop strategies for achieving more sustainable and socially just (inclusive) metabolic configurations or their associated infrastructure and spatial solutions. Implementing an infrastructure transition is an achievable goal, considering that the level of upfront investment required in infrastructure between 2015 and 2030 would only need to increase by 5 percent to shift from a carbon-intensive approach to a low-carbon alternative (i.e. from $89 trillion to $93 trillion) (Global Commission on the Economy and Climate, 2014).

In addition to elaborating on the urban infrastructure argument established in the City-Level Decoupling report, this report includes urban morphology as a key lever to improving urban resource management and reducing inequity. To date, aside from certain exceptions in land-constrained societies (e.g. South Korea, Singapore and some European countries), urban population growth has occurred in urban spatial formations that have tended to de-densify in the long run. Wealthier households sprawl outwards into suburbia, and the urban poor are increasingly marginalized to the periphery by a combination of forced relocations and the dynamics of the property market. This has significant implications for land and agriculture, as a 1 percent per annum decline in densities in developing countries between 2000 and 2050 would result in a quadrupling of the urban land area (UN-Habitat, 2016).

Spatial expansion has, in turn, driven infrastructure solutions (in particular the BAU centralized energy systems, highways as key infrastructure for transport, waste incineration and landfills, water and sanitation solutions) that have tended to focus on extension within an engineering context, while the supply of resources at cheap rates has been taken for granted and presumed to be unconstrained by biophysical realities. This can be referred to as the conventional or modernist, unsustainable metabolic configuration, which is locked in by a set of infrastructures and spatial arrangements that are supposedly tried and tested and therefore low risk. Governance arrangements that reproduce these unsustainable metabolic configurations focus on middle- and elite-class interests, while marginalizing the urban poor.

The increasingly prominent discussions about infrastructure alternatives (e.g. transit-oriented development (TOD), district energy systems, smart cities) and the need for strategic intensification of urban space economies reflect a realization that more sustainable metabolic configurations will be needed. However, the underlying metabolic shifts that are needed are rarely made explicit, and effects on the social inclusiveness of cities are not a consideration. Infrastructure options are often considered from a technocratic perspective with no reference to their preferred metabolic outcomes and social impacts; quite often, they are also considered without reference to the need for spatial restructuring (specifically, the implications of strategic intensification).

This report presents the first systematic assessment of why conventional urban metabolic configurations are resource inefficient and unsustainable, and how alternative urban metabolic configurations can be analysed and conceptualized with respect to alternative infrastructures, technologies and spatial patterns. Once it is accepted that resources are not readily available and are subject to increasing and volatile prices, it follows that accommodating a doubling of the urban population in the four decades from 2010 to 2050 will require a more sustainable metabolic configuration. This will mean fundamentally rethinking the infrastructures that conduct resources through urban systems, and the forms and relative densities of urban built environments. This, in turn, will create opportunities for addressing the challenge of informality in the cities of the Global South, where millions of urbanites remain without dignified access to urban services.

This report utilizes a set of terms that are defined in the glossary.

The report is structured as follows:

**Chapter 1** provides an overview of recent literature on urban population and economic trends, and the implications they have for resource consumption. Urban metabolism is introduced as a tool for facilitating decision-making about regional and global resource issues at a local level.

**Chapter 2** provides a quantitative estimate of the resource requirements of future urbanization if existing metabolic configurations remain unchanged (i.e. because current infrastructures and densities are replicated in the future) and the urban population doubles in size.

**Chapter 3** assesses the resource implications of future urbanization if a much denser metabolic configuration is created, by reversing the long-term trend of de-densification in order to create well-articulated, high-density nodes connected by efficient and affordable ecomobility options.

**Chapter 4** assesses the resource implications of sector-specific metabolic configurations arising from more sustainable sociotechnical systems, specifically Bus Rapid Transit (BRT) systems, green buildings, district energy systems and integrated waste systems.

**Chapter 5** assesses the metabolic efficiencies arising from cross-infrastructure synergies and new infrastructure alternatives that are being implemented in several Chinese, Indian and US cities.

**Chapter 6** assesses the governance implications of a shift from unsustainable, resource-intensive metabolic configurations to more sustainable, resource-efficient metabolic configurations, paying specific attention to the dynamics of informational development, urban experimentation, urban economies, regulation of urban service delivery systems and integrated planning.

**Chapter 7** offers a conclusion that draws out the policy implications of the need for a global transition from unsustainable, resource-intensive urbanism to sustainable, resource-productive urbanism in the developed and developing world.

This report proposes an urban transition with three overriding policy goals to achieve a sustainable metabolic configuration: resource-efficient urban infrastructure systems, strategic intensification of urban morphologies via well-articulated hierarchies of high-density nodes and the use of resource-efficient and more spatially functional urban morphologies to achieve social inclusion. Furthermore, a key conclusion is that an appropriate mode of urban governance, which stimulates urban experimentation in this direction, will be required to address this agenda. A one-size-fits-all approach will not work in an increasingly complex world. Instead, a coordinated search for working alternatives combined with a new push to find ways of sharing solutions and learning from failures will be required. This is likely to be both a precondition for urban transition and an emergent outcome in the long run.

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# Chapter 1

# Global urbanization, resource consumption and urban metabolism

## 1.1. Introduction

The need for this report arises from the dual challenges of urbanization and increasing resource consumption on a resource-constrained planet. To set the context, this chapter provides an overview of the trends in urban population and economic growth, and the implications they have for resource consumption. Urban metabolism is introduced as a framework for thinking about urban resource management, which facilitates decision-making on regional and global resource issues at the local level. In particular, it draws attention to the rising resource demands related to servicing both underserviced and increasingly affluent populations. In this way, cities that improve citizens' access to essential services while managing resources wisely and producing minimal waste may keep their ecological and carbon footprints small, thus reducing the potential impact of urban lifestyles on the planet.

## 1.2. Urbanization patterns

The 2014 revision of the World Urbanization Prospects report (UN-DESA, 2014) estimates that with population growth and urbanization, the current global urban population will have increased by 2.4 billion by 2050. The proportion of the population living in cities and towns is expected to rise from 54 percent in 2015 to 60 percent by 2030, and to 66 percent by 2050 (UN-DESA, 2014). Nearly 37 percent of the projected urban population growth by 2050 is expected to come from just three countries: India, China and Nigeria. It is estimated that they will contribute 404 million, 292 million and 212 million urban dwellers respectively (UN-DESA, 2014). Africa's urban population is expected to grow from 400 million in 2010 to 1.2 billion in 2050 (Parnell & Pieterse, 2014). This is what is generally known as the second urbanization wave, which describes the phase of urbanization that began in 1950 and has largely taken place in the Global South. By contrast, the first urbanization wave took place between 1750 and 1950 and resulted in the urbanization of only 400 million people, mainly in the Global North.[3]

One fact that helps to illustrate the enormous significance of this process of social transformation on natural resources is the following: in the three-year period from 2011 to 2013, China used more cement than the USA used over the course of the entire 20th Century (Smil, 2013). Given that China is halfway through its urbanization process, India is only a quarter of the way through, and the African continent's urban population is projected to increase by 800 million by 2050, it is clear that the increased resource demands of urbanization are highly significant.

In 1700, only 2 percent of the world's population lived in cities and by 1900, 15 percent were urbanized (Clark, 1996; Grant, 2004). Since 2008, more than 50 percent are living in cities (UN-DESA, 2014), marking a key point of transition in human history. Of nearly 3.6 billion urban dwellers in the base year of 2010, 1.86 billion lived in Asia, 538 million in Europe, 468 million in Latin America and the Caribbean, 395 million in Africa, 280 million in North America and 26 million in Oceania.

While significant growth in the urban portion of the world population is expected over the next few decades, there are large differences in urbanization levels among regions (see Figure 1.1). At one extreme, South America has the largest proportion of population living in urban areas, at 83.7 percent in 2010, while at the other extreme, Eastern Africa ranks last, with only 23.7 percent of urban population in 2010.

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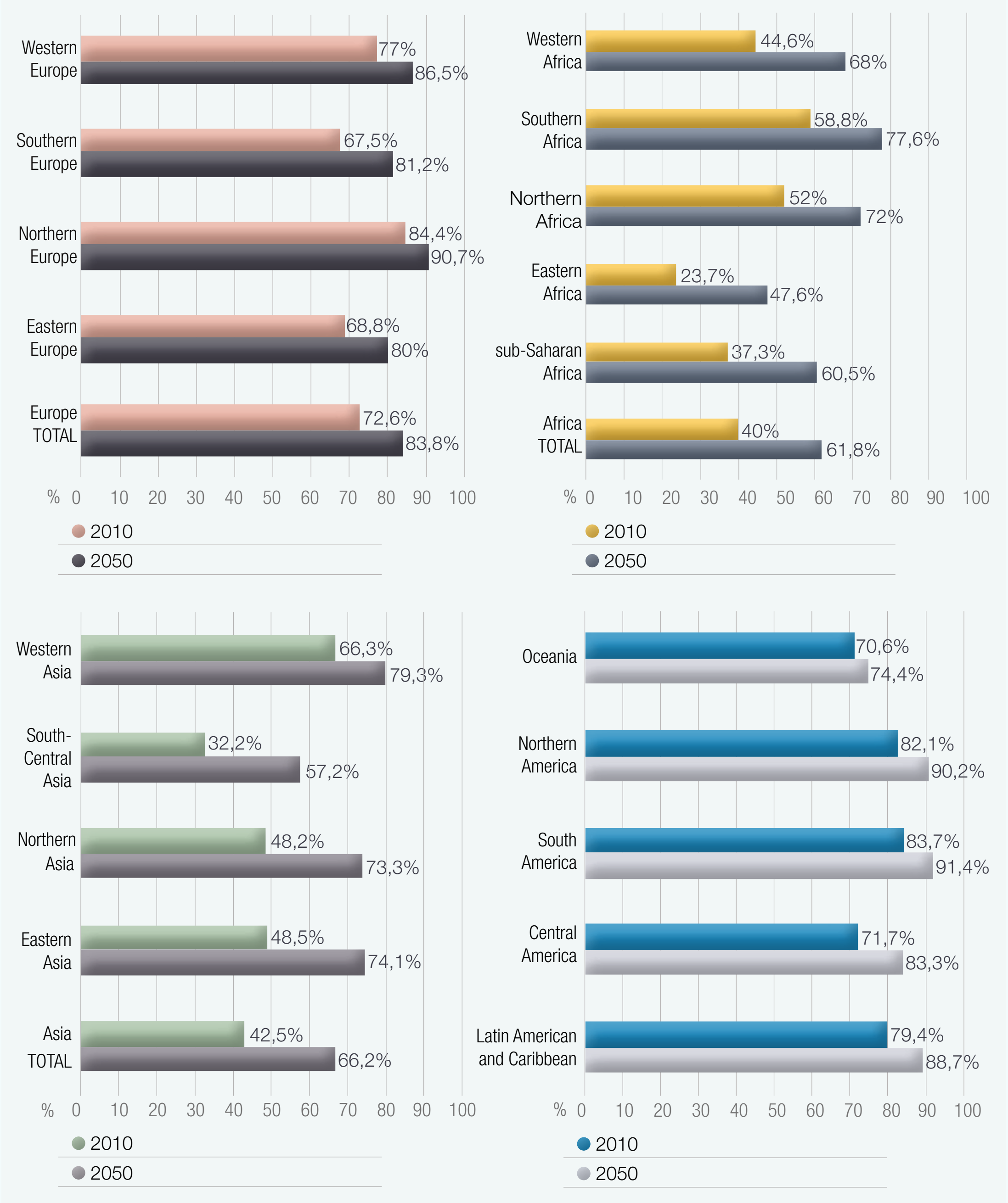
[3] Although populations are observed to be urbanizing in greater gross numbers than ever before, the decade when urban demographic expansion was at its fastest relative rate across the world was during the 1950s (UN-Habitat, 2010). This global statistic, which may appear at odds with the popular view that current growth rates are the fastest ever, arises because 'global urban growth' is an average of the low (and even negative) urban growth rates in developed nations and the high urban growth rates in developing nations (especially in Asia) since 1990. This underlines the point that 'global' urbanization can be misleading: urban populations are not only changing at different rates in different regions but also living in vastly different urban settings.

There are three distinct contributors to urban population growth: (i) migration of people from rural areas (or urban areas elsewhere) to existing urban areas; (ii) natural growth, where birth rates are higher than death rates in existing urban areas; and (iii) expansion of urban development into rural areas (Gatson, 2011). The way urban boundaries are delineated has a direct bearing on how governments administer their cities, and changes to these administrative boundaries also have implications for how urban growth is measured. The factors resulting in demographic changes vary significantly among the world's regions. Migration is expected to be a major contributor to urban population growth in countries of the Global North, while for countries of the Global South, urban population growth will be driven primarily by natural growth.

**Figure 1.1**: Urban population proportion by region in 2010 and 2050

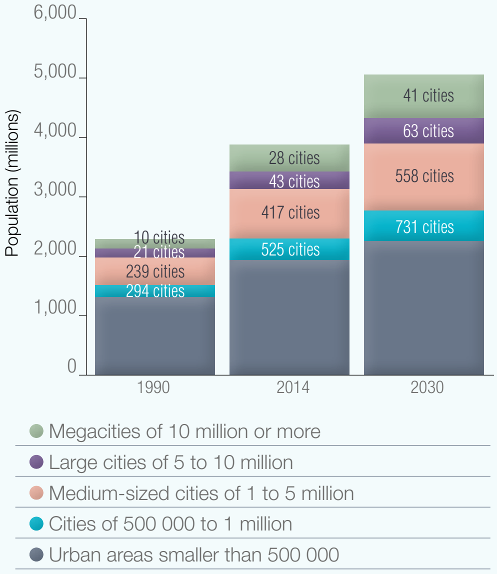


There are significant spatial variations within countries and across global regions in terms of how urbanization is realized (UN-Habitat, 2008). In Japan, approximately half the urban population lives in megacities of 10 million people or more; in Korea, half the country lives in the Seoul metropolitan area. In the UK, nearly a fifth of the urban population lives in London; and in North America, a quarter of the urban population lives in cities of more than 5 million. Southern Asia has the same proportion in cities over 5 million but a little further south-east in Indonesia, city dwellers are in the minority and only 4 percent of the national population is in its major city, Jakarta. By contrast, Latin America and the Caribbean is the most urbanized region in the developing world, with 77 percent of its population living in urban areas. Africa's urban population is over 400 million, the vast majority of whom live in small but growing cities rather than megacities. Approximately 60 percent of sub-Saharan city dwellers live in slums—the highest proportion compared with all other world regions (UN-Habitat, 2014b). The population 'state' of global cities differs significantly with variations in the culture, geography, climate, development phase and history of each context.

Globally, cities of various sizes are expected to expand as urban population positive growth rates continue in most parts of the world, but by no means all (see Figure 1.2). Currently, megacities are most prevalent in the Asian region, including the likes of Tokyo, Delhi and Shanghai. China alone has 15 megacities (OECD, 2015). By 2030, the Asian region will have no less than 22 megacities (UN-Habitat, 2015b), largely due to four large cities in India that are expected to become megacities by 2030. Currently, Africa hosts three megacities—Cairo, Lagos and Kinshasa—and three new megacities will be added by 2030—Dar es Salaam, Johannesburg and Luanda (UN-DESA, 2014).

In all regions except Northern America and Oceania, urban areas with less than 1 million inhabitants account for more than half the urban population. In South-Eastern Asia, 65 percent of the urban population lives in centres of 500,000 people or less. In Western Europe, this is the case for 71 percent of urban dwellers. By 2050, small but growing cities will absorb nearly 3 billion people worldwide (UN-DESA, 2014). Not all cities will contribute to the world's urban growth, as some will experience a slow or negative population growth rate (e.g. in parts of Europe, where many urban settlements have experienced declining population growth over the past decade and a half).

**Figure 1.2**: World megacities in 1990, 2014 and projected for 2030



(Source: UN-DESA, 2014)

Credit: yuttana Contributor Studio/shutterstock.com

## Different growth

### Not all cities in developing countries are experiencing rapid population growth

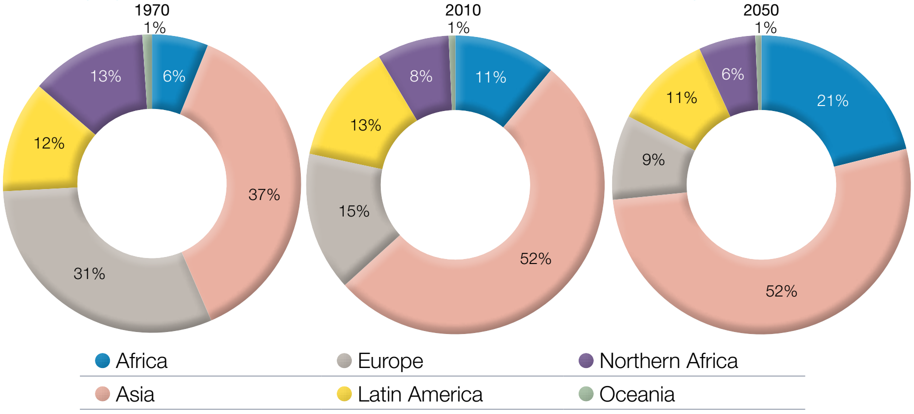
Cities such as Kolkata, Chennai, Recife, Santiago, Monterrey, Algiers, Alexandria, Maputo and Lusaka are experiencing relatively low population growth rates per annum, of approximately 1–2 percent. Growth rates of over 4 percent per annum have mostly been experienced in cities of West African countries, such as Abuja, Bamako and Ouagadougou. Some Chinese cities saw explosive annual growth rates of over 17 percent in the 1990s.

### Some city populations are expected to decline

Other cities in developing countries are experiencing population decline, for example, Rabat, La Paz, Manila and Bandung. The population of Tokyo is also expected to decline, although it will remain the world's largest agglomeration. Other megacities such as New York, Newark will fall in rank in terms of their population sizes.

Cities in Europe will particularly continue to feature low fertility rates and rapidly aging populations. This is a key demographic characteristic and points to the overall decline in population size. The low growth or decline in Europe and Northern America and the ascendancy of Asia and Africa can be seen in the regional distribution of the world's urban population shown in Figure 1.3.

**Figure 1.3**: Relative proportion of the world's urban population in global regions for 1970, 2010 and that projected for 2050 in the United Nations World Urbanization Prospects report



(Source: UN-DESA, 2014 https://esa.un.org/unpd/wup/CD-ROM/)

### New city types may emerge

New types of cities are also expected to emerge in various regions. They present opportunities to implement novel designs and bypass technologies that older cities are locked into. In China, the city of Rizhao combines incentives and legislative tools to encourage the large-scale, efficient use of renewable energy, especially solar energy. Saudi Arabia is developing several 'economic cities' to prevent sprawl: King Abdullah Economic City, Prince Abdulaziz bin Musaid Economic City, Knowledge Economic City and Jazan Economic City. Sprawl is prevented by imposing strict urban edges, ensuring buildings are multi-storey and via the control of land.

Sources: Grant (2004); UN-Habitat (2010:15); UN-Habitat (2012); and Saudi Arabia General Investment Authority (Undated)

The economic growth of countries is intrinsically linked to the prosperity of their cities, which typically act as agglomeration points for economic activity (UN-Habitat, 2012). In the last two decades, cities have increasingly become global economic platforms for trade, production and innovation. Urbanization has lifted millions out of poverty due to sizeable investments in infrastructure and services, increases in productivity and employment opportunities, and improvements to quality of life (UN-Habitat, 2016), so it is unsurprising that the extent of urbanization[4] is correlated with the wealth of nations. During the period from 1960 to 2010, the

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[4] Urbanization is measured as the proportion of urban population in relation to a nation or region's total population.

world proportion of urban populations increased from 33 percent to 51 percent, while per capita income increased by 152 percent, from $2,382 to $6,006 (UN-Habitat, 2012). However, the connection between urbanization and economic prosperity is not inevitable and this correlation varies across and within regions, indicating that a multiplicity of factors affects this phenomenon (UN-Habitat, 2012). Generally, countries with a high per capita income are the most urbanized, while those with a low per capita income are the least urbanized. Managing the benefits of agglomerative economies (proximity of labour, employment housing and services) against the diseconomies of, for example, disease, congestion, poverty or crime is necessary to enable prosperous cities (Turok, 2014).

Whether more people *can* live in cities depends on a number of factors including: economic opportunities in cities and, more broadly, in trade; stable government; available technology and infrastructure; rural productivity; and resource availability (in particular, food, energy and water). Even in stable developing countries, urbanization is delayed where agriculture and resource extraction are still labour intensive, technology is too expensive and the terms of trade are unfavourable.

Although half of the world's population living in cities generates more than 80 percent of global GDP, just 380 of the largest cities generate 50 percent of global GDP (Dobbs *et al.,* 2011). Regionally, Eastern Asia now produces the largest share of global urban GDP and Africa the smallest (see Figure 1.4). While Northern America, Europe and Oceania enjoy the highest per capita income, developing countries in Eastern Asia and the Pacific have seen their per capita GDP double every 10 years since 1990 and this looks set to continue until 2020. By way of comparison, Organisation for Economic Co-operation and Development (OECD) nations and Latin America and the Caribbean have experienced a 40 percent increase in GDP per capita since 1990, while the Middle East and North Africa have increased their GDP per capita by a third over the same period.

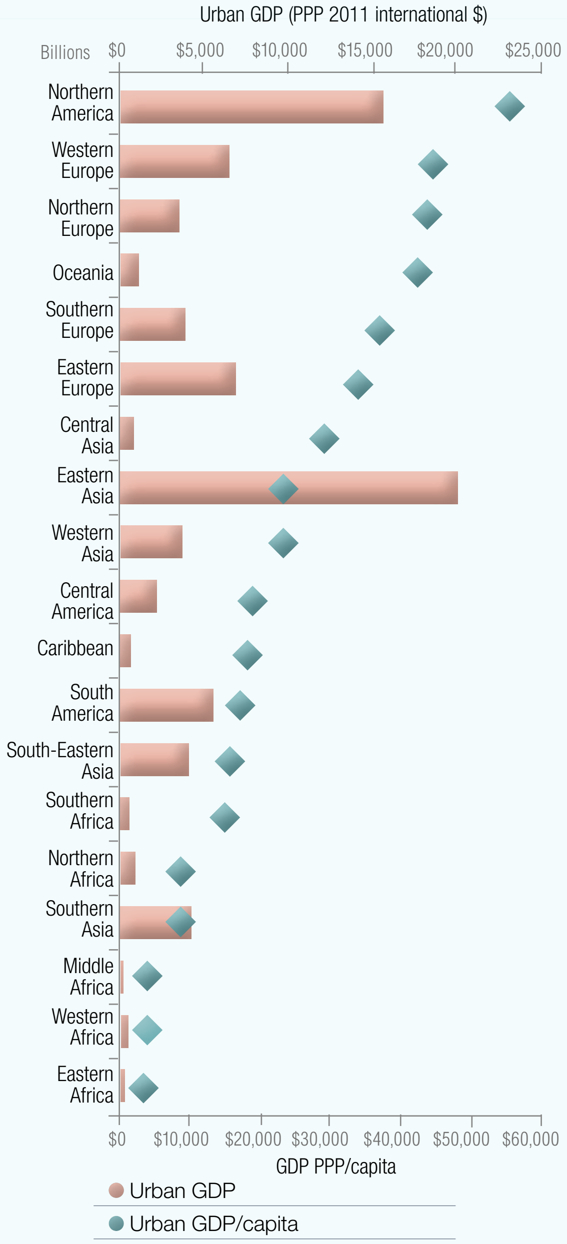

**Figure 1.4**: Comparison of estimated urban GDP (red columns – top) ordered by GDP per capita (blue diamonds – bottom) for United Nations major global regions at 2010 (all measures are GDP at purchasing power parity (ppp) in 2011 international dollars). Regional estimations based on collected data from the Brookings Institution[5] supplemented with data from PricewaterhouseCoopers (2009)—sample of 332 globally distributed cities representing 1.475 billion urban dwellers in 2010 (approximately 40 percent of world total)

There is also a differential contribution to global urban income from cities of different sizes. In 2010, the world's megacities produced nearly 15 percent of global GDP (Kennedy *et al.,* 2015)

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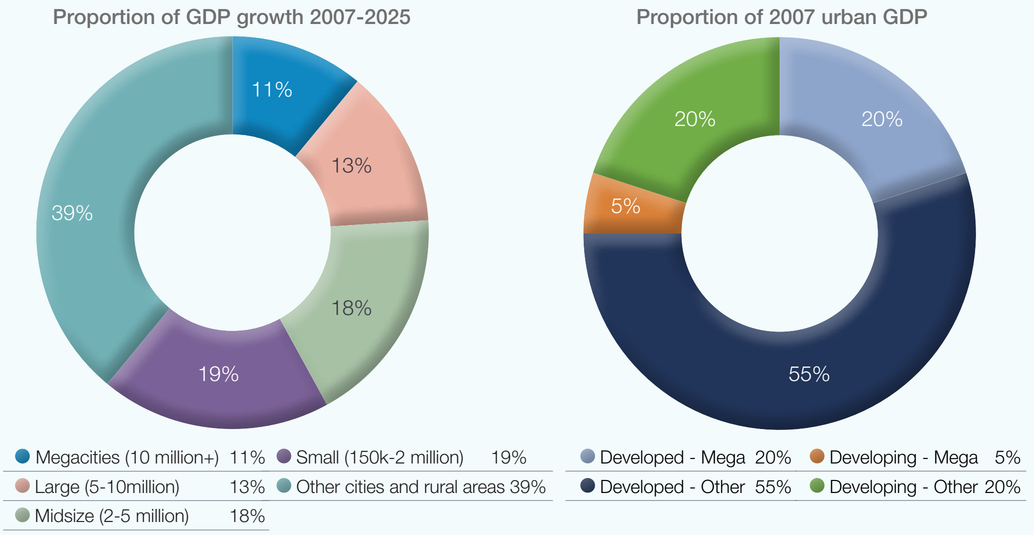
[5] http://www.brookings.edu/research/reports2/2015/01/22-global-metro-monitor

**Figure 1.5**: Contribution to urban GDP from cities of different sizes



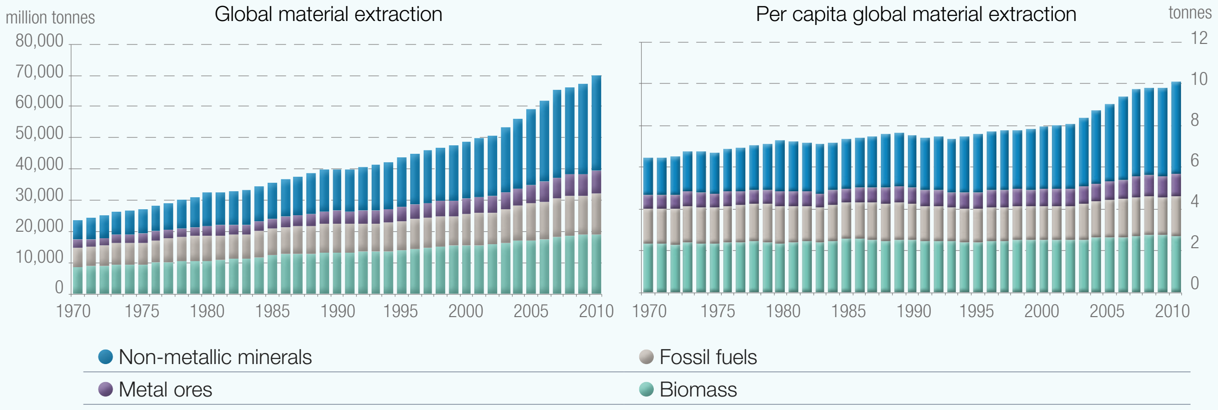
(Source: Dobbs et al., 2011)

but it is the smaller cities in developed nations that produce more than half of global urban GDP (see Figure 1.5). The economic growth of megacities over the last quarter century has varied with respect to that of their host nation—London, Mexico City, Moscow and Buenos Aires all exceeded the growth of their host countries whereas Beijing, Mumbai, Tokyo, São Paulo and Delhi did not. Over the next 10 years, the McKinsey Global Institute Cityscope 1.0 model[6] anticipates that 75 percent of global economic growth will be attributable to cities, and that cities smaller than 10 million people will deliver more growth than all the megacities in the developed and developing worlds combined.

## 1.3. Urban resource consumption

Improvements in GDP and quality of life typically lead to increased resource consumption, and as cities grow in terms of population and prosperity, they become global nodes of consumption. Domestic material input (DMI) represents all the materials used within a region or city, including domestic extraction of resources (DE), imported resources and any resources that will be

**Figure 1.6**: (Left) Global material extraction (DE) by four material categories, 1970–2010, million tonnes. (Right) Per capita global material extraction (DE) by four material categories, 1970–2010, tonnes



(Source: UNEP, 2016:32–33)

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6. http://www.mckinsey.com/global-themes/urbanization/urban-world-mapping-the-economic-power-of-cities

exported. Domestic material consumption (DMC), on the other hand, only considers the resources consumed by a city or region, and subtracts those that are exported. DMC is expressed in tonnes consumed per capita per annum and can be used to track changes in the resource consumption of a region—in this case the city. DMC also relates to the use of energy resources in terms of the mass of energy carriers (flows of coal, oil and gas) and embodied energy in energy-intensive materials: concrete, aluminium and steel. According to the most recently published data by the IRP, global DE reached 70 billion tonnes in 2010, which translated into an average of 10 tonnes per capita. Total DE doubled during the 25 years up to 2010.

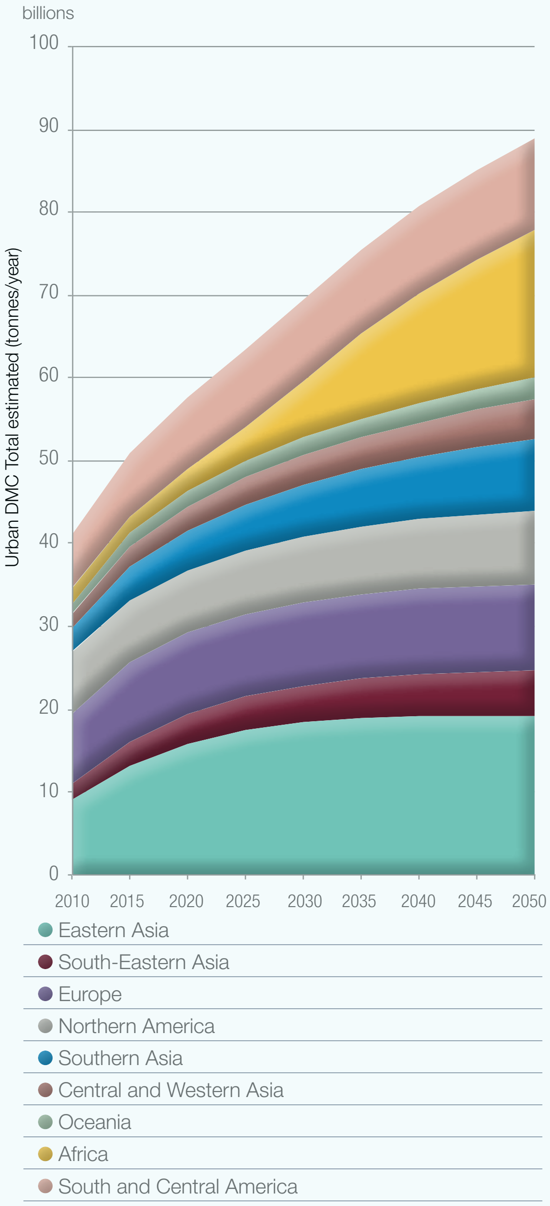
By 2010, urban DMC accounted for approximately 60 percent of total global DMC (see Chapter 2). Global urban material consumption is projected to grow faster than the global urban population. The total global urban material consumption is projected to reach approximately 90 billion tonnes by 2050 (see Figure 1.7). This represents an approximate increase of 116 percent in global urban material consumption for a 78 percent increase in size of the global urban population over the period 2010–2050. The end result would be an average urban DMC of approximately 14 tonnes per capita by 2050.

As far as land use is concerned, if the long-term, historic de-densification trend continues until 2050, global urban land use could increase from just below 1 million km$^2$ to over 2.5 million km$^2$ (see Figure 1.8). Significantly, if urban areas expand in this way, some of the world's most productive food-producing areas will be eliminated (Bringezu *et al.,* 2014).

## 1.4. Sustainable Development Goals for resource consumption

During the lead-up to the approval by the United Nations of the SDGs, the IRP proposed the following SDG: the "efficient use of natural resources in an equitable and environmentally benign manner for human well-being and future generations" (Bringezu, 2015). Two possible targets were proposed: Target A— "To double the yearly rate of resource productivity increase". GDP in relation to material flow indicators, global land use and GHG emissions were suggested as possible indicators. Target B— "Decoupling economic growth rates from escalating use of natural resources to achieve the average material intensity of consumption per capita of 6–8 tonnes per capita per year in 2050" (IRP,

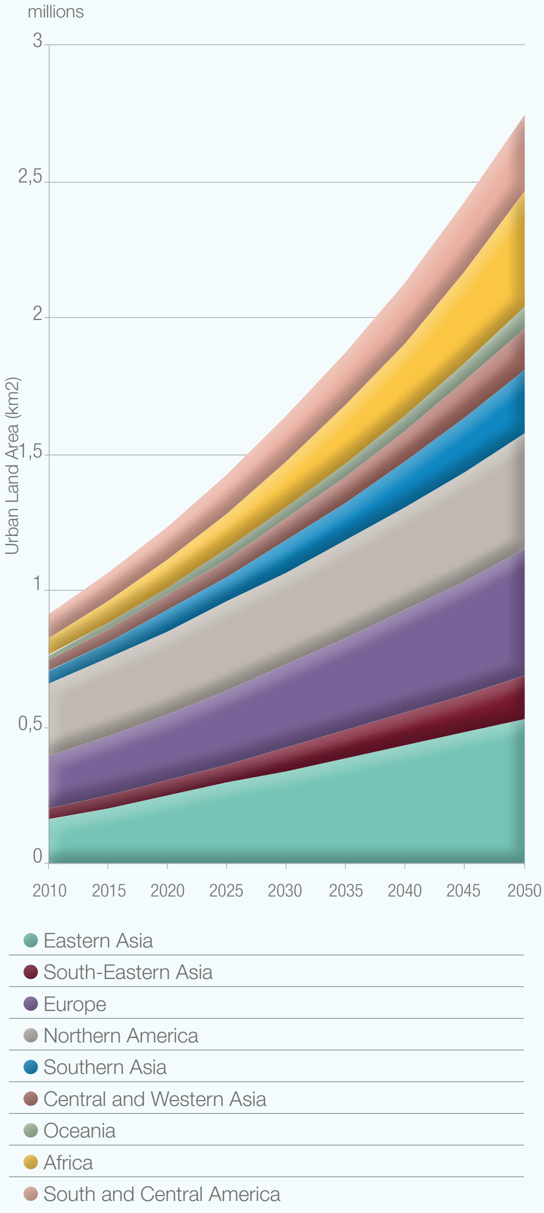
**Figure 1.7**: The composition of aggregate global urban DMC by major world regions



(Source: Calculations for Chapter 2)

2014). Although target B was not ultimately included in the SDGs, a recent review of similar indicators (Bringezu, 2015) acknowledged that this target was consistent with a possible "target corridor for sustainable use of global resources" by 2050, and proposed that this should be understood using a different indicator to DMC, namely, total material consumption (TMC). A TMC of 10 tonnes per capita per year of abiotic resources (within a range of 6–12 tonnes per capita per year), 2 tonnes per capita per year of biotic resources and raw material consumption of 5 tonnes per capita per year (within a range of 3–6 tonnes per capita per year) was potentially sustainable (Bringezu, 2015). Given that urban DMC accounts for approximately 60 percent of total global DMC, the transition that will enable these more sustainable global consumption levels to be achieved will need to take place primarily in cities. To this end, understanding how cities process resources is a necessary first step to reducing or reshaping resource consumption and its associated impacts.

**Figure 1.8**: Growth in urban land area by region and globally, 2010–2050, if historic trend of de-densification of –2 percent per annum continues



(Source: Calculations for Chapter 2)

## 1.5. Integrating an urban metabolism perspective

Within cities, specific areas of action need to be identified to optimize resource consumption, while ensuring service access for the poor. The City-Level Decoupling report introduced urban metabolism as a lens through which cities can be studied in order to understand major resource and energy flows, and identify infrastructural investments that would enable cities to shift from a linear (i.e. wasteful) metabolism towards a more resource-efficient urban metabolism (UNEP, 2013a).[7]

Urban metabolism refers to the multitude of interrelated exchange processes that shape the urban environment (Castán Broto *et al.,* 2012). Traditional explorations have made use of urban metabolism as an analogy, which likens a city either to an organism (Gandy, 2004; Rosado *et al.,* 2014), superorganism (Girardet, 2004) or ecosystem (Newman, 1999; Grimm *et al.,* 2008; Bristow and Kennedy, 2013), enabling researchers to draw parallels and similarities. However, an urban metabolism is also a very real, tangible characteristic of a city, which is

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7. We prefer to use the notion of resource-efficient urban metabolism than the more common notion of circular metabolism. The latter implies that it would be possible to reach a stage where all outputs become inputs and therefore no additional inputs are needed. There is no evidence to suggest that this will ever be true. For example, cement will always be needed, although this need not be Portland cement because there are now low-carbon alternatives. Irrespective, virgin materials from external sources will still be needed to make it.

influenced or shaped by multiple social actors, sociotechnical infrastructure systems, resource flows and natural occurrences. In this way, urban metabolism assessments aim to understand the processes by which a city might access and consume resources from its local and global hinterland, digest them to execute its various functions, as well as produce waste and dispose of it in the hinterland (Kennedy *et al.,* 2007; Currie & Musango, 2016). Such assessments are directly applicable when comparing sustainability indicators, setting and monitoring GHG emission targets, testing or modelling planning or policy implications and as visioning or design tools (Kennedy *et al.,* 2011).

The concept of urban metabolism has been used by various groups to serve diverse agendas over the years, and new ways of bridging these disciplinary foci are being widely explored (Castán Broto *et al.,* 2012; Chen and Chen, 2015; Newell and Cousins, 2015; Bai, 2016). The differing perspectives on urban metabolism emerge from four different 'ecologies'. The 'human ecology' of the Chicago School initially investigated urban metabolism to understand social change within the city, treating the natural environment as an external, non-social backdrop (Wachsmuth, 2012). 'Industrial ecology', the field that most utilized and popularized the term urban metabolism until recently, analyses the stocks and flows of energy and materials, understanding nature as an external source of resources and as a waste sink for the city's by-products (Bai, 2007). 'Urban ecology' understands cities as complex, socio-ecological systems and investigates the effects of interrelationships within cities and at other scales or levels, particularly in the context of global sustainability imperatives (Grimm *et al.,* 2008; Du Plessis, 2008). Attempts have been made to connect the notion of the urban nexus with urban metabolism studies, to examine the "mutual dependency of multiple elements in terms of coupled material and energy flows being interlinked and conversion processes embedded in intertwined chains at multiple scales" (Chen & Lu, 2015). 'Urban political ecology' (UPE) has attempted to explain these complex, socio-natural processes in cities as products of history, geography and politics (Swyngedouw & Heynen, 2003; Wachsmuth, 2012). In particular, UPE demonstrates "how the material conditions of urban environments are controlled by and serve the interests of elites, at the expense of marginalized populations" (Castán Broto *et al.,* 2012).

These disciplines have tended to produce research in parallel, but there have been recent attempts to find points of interaction among disciplines through transdisciplinary engagement (Castán Broto *et al.,* 2012), which could make use of urban metabolism as a boundary metaphor[8] (Newell and Cousins, 2015) for linking the key foci of industrial ecology (quantification of material and energy flows), political ecology (social inequality) and urban ecology (systems thinking).

Aspects of resilience thinking, notably the Planetary Boundaries framework (Rockström *et al.,* 2009; Steffen *et al.,* 2015), have been applied to the city level (Hoornweg *et al.,* 2016) in an attempt to connect city decisions with global processes.[9] Further, the "sustainability of cities should be a complex and comprehensive indicator with the consideration of the nexus between different factors we concern, such as economics, energy, water and human health" (Chen and Chen, 2015). Similarly, as the understanding of resources extends beyond materials and energy to include finance, time, people and information, the scope of urban metabolism assessments must inevitably grow. This cross-pollination of concepts is important as, to grasp the role that cities play in accelerating global transformation, it is necessary to integrate urban metabolism (UM) into a wider conception of the political economy of urban governance (Pincetl *et al.,* 2012). In other words, an understanding of "*who*-is-using-*what*-flows-*where*-to-do-*what* (and the concomitant waste

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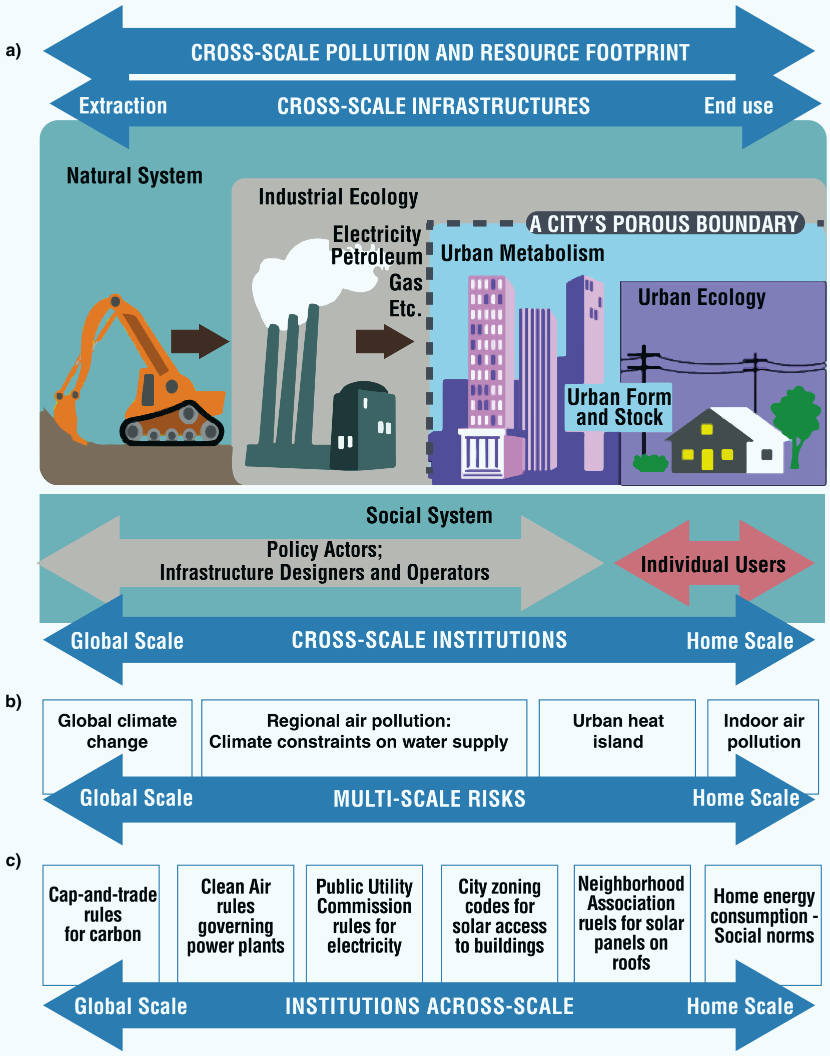
[8] This term is derived from the notion of a boundary object, described originally by Star and Griesemer (1989) as an object that is adaptable enough to be used in different ways by various actors, but robust enough that it retains its common identity, and can be used to maintain coherence among these actors.

[9] This is part of a larger project to collect city-level sustainability data: https://city-sustainability.com/

produced) needs to be added to UM analyses" (Pincetl *et al.,* 2012).

The social-ecological-infrastructural systems (SEIS) framework (Figure 1.9), developed by Ramaswami *et al.* (2016) is a good example of a wider urban metabolism perspective, particularly as it incorporates social actors as influencers of the city's metabolism and contends with questions of scale and city boundaries. The framework focuses on analysing the provision of seven key infrastructures that are essential for all cities: food, energy, water, shelter, transportation-communication, sanitation and waste, and green spaces. It recognizes that: (i) the scale of cities is typically smaller than the scale at which infrastructures are provided, requiring transboundary infrastructure provision; (ii) users of infrastructure are connected with producers across city boundaries and larger scales, resulting in multiple impacts, such as system-wide energy use and GHG emissions, water use and more; and (iii) due to these transboundary realities, the governance of infrastructure systems transcends the city scale and includes diverse actors, such as the users, infrastructure designers and operators, and policy actors across larger scales. The SEIS

**Figure 1.9**: Pictorial illustration of the socio-ecological-infrastructural systems (SEIS) framework depicting: a) integration across the spatial scale of infrastructures, urban metabolism, industrial ecology, and urban resource/pollution footprints with social actors and institutions; (b) multiple and multi-scale risks posed to cities by infrastructure-environment interactions across scales; (c) select examples of institutions that shape energy use and greenhouse gas (GHG) emissions across scales.

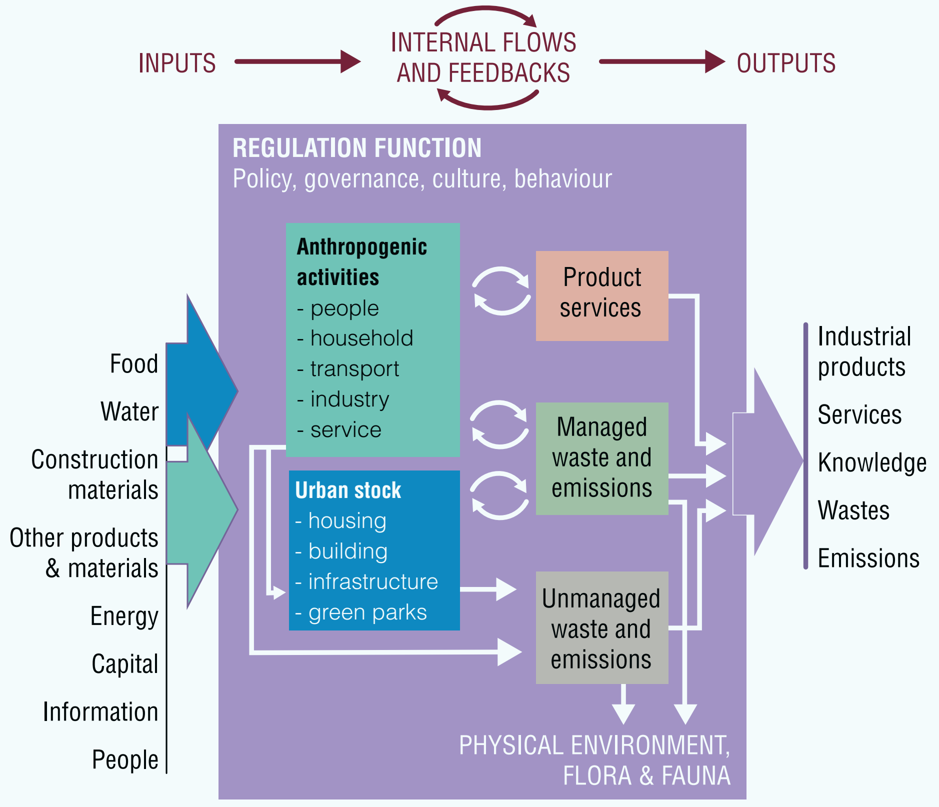


(Source: Ramaswami et al., 2012)

framework identifies three clusters of societal actors that shape the discursively constructed, built material systems: infrastructure designers and operators who derive designs and systems directly from idealized visions of the way urban systems should work; policy actors who set the regulatory and land-use frameworks for resource use within specific infrastructure configurations; and individual users (home dwellers, businesses and facilities) who are the primary resource users and effectively 'buy into' the applied visions of the designers. "Social actors are the primary agents of change, and institutions are the instruments through which actors shape the current and future trajectory of urban infrastructures in terms of resource use, pollution, climate risks, and health impacts. Any study of resource-efficient, environmentally sustainable and healthy cities must necessarily incorporate transboundary infrastructures serving cities, along with associated cross-scale social actors and institutions that govern these infrastructures." (Ramaswami *et al.,* 2012:802)

The growing need to understand not just the resource interactions at the boundaries of cities, but also their internal dynamics, requires an understanding of how urban ecosystems behave. Bai (2016) suggests that an urban metabolism (visualized in Figure 1.10) "encompasses four elements: the total input (e.g., energy, material, money, information), distribution of the input within city to drive urban functions, the total output (e.g., products, emissions, knowledge), and the regulating function that shapes such flows and distributions." Moreover, Bai enumerates eight characteristics of urban ecosystems derived from urban metabolism studies as "energy and material budget and pathways; flow intensity; energy and material efficiency; rate of resource depletion, accumulation and transformation; self-sufficiency or external dependency; intra-system heterogeneity; intersystem and temporal variation; and regulating mechanism and governing capacity" (Bai, 2016:8), each of which pose specific questions and implications for sustainability.

**Figure 1.10**: Conceptual diagram of urban metabolism



(Source: Bai, 2016)

To study these internal system processes, Ferrão and Fernández (2013) suggest a multilayer conceptual framework which makes use of different urban metabolism assessment methods and provides urban decision makers with specific sustainability indicators, as well as identifying leverage points that shape their city's metabolism. This framework proposes seven layers of examination: (i) urban bulk mass balance, (ii) urban material flow analysis, (iii) product dynamics, or life-cycle assessment (LCA), (iv) material intensity by economic sector, (iv) environmental pressure of material consumption, (vi) spatial location of resource use, and (vii) transportation dynamics (Ferrão and Fernández, 2013). These layers range from simple analyses of typically available data, to more time- and resource-intense forms of analysis.

The main difficulties related to assessing urban metabolism include: (i) a dearth of available city-level data required to undertake assessments (Currie *et al.,* 2015); (ii) difficulty in estimating informal flows, predominant in much of the Global South (Currie, 2015; Smit and Musango, 2015; Kovacic *et al.,* 2016); (iii) lack of consensus around which methodologies best estimate urban metabolism (Kennedy *et al.,* 2011; Currie *et al.,* 2015)—standardizing a method for analysis is made more challenging by the disciplinary widening of urban metabolic assessments, as described above; and (iv) the open nature of the city system (Odum, 1996; Ferrão and Fernández, 2013). Studies of resource flows have typically been undertaken at the national level, where boundaries are clearer and data are more readily available, and most city-level metabolic studies have been completed in the Global North (Barles, 2009; 2010).

Despite these challenges, the last decade has seen a rapid increase in urban metabolism studies (Bai, 2016; Musango *et al.,* 2017), with growing representation in the Global South. These studies have brought forth a wide range of methods for examining urban metabolism, which include:

i. basic urban metabolism assessments, which attempt to provide an urban baseline in relation to context, biophysical characteristics, resource flow parameters, the role of utilities and policy frameworks (see, for example, Kennedy *et al.,* 2014; Musango *et al.,* 2017);

ii. energy and material accounting methods, such as material flow analysis, substance flow analysis and exergy or emergy analyses, which estimate the inputs and outputs of the city system (see, for example, Rosado *et al.,* 2014; Hoekman, 2015; Lei *et al.,* 2016);

iii. input-output analysis, which allows sectoral analysis of urban functions (see, for example, Li *et al.,* 2015);

iv. footprinting methods, such as ecological or carbon footprints, which present a singular metric of a city's impact, typically as a land-use function (see, for example, Gasson, 2002; Chen *et al.,* 2016);

v. life-cycle analysis, which estimates the direct and embodied impact of resource flows at each stage of a city's life cycle, mostly for comparative purposes (see, for example, Goldstein *et al.,* 2013);

vi. simulation methods, such as system dynamics modelling or agent-based modelling, which examine internal behaviours within the city system (see, for example, Abou-Abdo *et al.,* 2011; Musango *et al.,* 2016);

vii. hybrid methods, which importantly attempt to connect the multiple perspectives of urban metabolism, but include more socio-economic indicators, or investigating resource interrelations (see, for example, Newman, 1999; Giampietro *et al.,* 2009; Mostafavi *et al.,* 2014; Manley *et al.,* 2014).

These methods, as well as their uses and shortcomings, are described in a recent report by Musango *et al.*, (2017). The report also includes a list of published urban metabolism studies, and Metabolism of Cities[10] has developed a constantly updating database of publications and city-level data derived from

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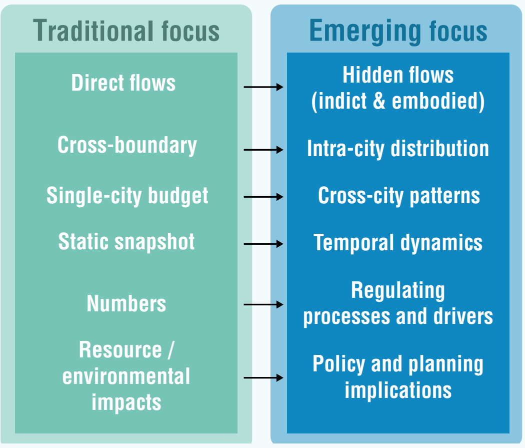
[10] https://metabolismofcities.org

these publications. Thorough reviews of urban metabolism methods have also been undertaken by Kennedy *et al.* (2011) and Zhang (2013), and Beloin-Saint-Pierre *et al.* (2016) offer a useful tool for determining which method to utilize based on target audience, data availability, desired indicators, scope and scale to be examined and desired detail of internal urban functions.

Castán Broto *et al.* (2012) identify six key themes emerging from urban metabolism research, shown in Table 1.1. This report, while acknowledging the importance of addressing each theme, retains the focus of the City-Level Decoupling report on themes 2 and 3, primarily making use of material flow accounting techniques to understand the wider interrelations among, and implications of, urbanization, economic activity and material and energy consumption. In addition, based on Bai's (2016) assessment of the trajectory of urban metabolism research (Figure 1.11), this report makes contributions to the emerging foci of (i) cross-city patterns, (ii) temporal dynamics, (iii) regulating processes and drivers, and (iv) policy and planning implications. In the subsequent chapters of this report, a variety of quantitative methods from various disciplines will be used to better understand how urban metabolisms could be optimized for resource efficiency and inclusivity through changes in infrastructure and spatial planning.

**Figure 1.11**: Comparison of traditional and emerging focus in urban metabolism studies



(Source: Bai, 2016)

**Table 1.1**: Six themes emerging from urban metabolism research

| Theme | Key question | Emphasis on |
|---|---|---|
| 1. The city as an ecosystem | What lessons from the functioning of ecosystems can be applied to design and plan better cities? | Nature-inspired models of development in urban planning and design |
| 2. Material and energy flows in the city | What methods can account for material and energy flows through the city and can these provide suggestions for their optimization? | Comparative analyses of cities and models of urban planning in relation to their efficiency in allocating materials and energy |
| 3. The material basis of the economy | What policy measures can break the link between urbanization, economic growth and resource consumption? | The material limits of the economy and macroeconomic models to achieve economic and resource stability |
| 4. Economic drivers of rural-urban relationships | How do economic relations shape the distribution of flows between urban regions and their surroundings? | Forms of territorial organization in relation to different modes of economic circulation |
| 5. The reproduction of urban inequality | How do existing urban flows distribute resources across the city and who controls these processes? | Patterns of unequal access to resources and the control of these patterns by urban elites |
| 6. Re-signifying socio-ecological relationships | What socio-ecological practices have the potential to reimagine and reconfigure existing socio-ecological flows? | Alternative visions and models of socio-ecological flows in cultural production, everyday practices and policy innovations |

(Source: Castán Broto et al., 2012)

## 1.6. Towards inclusive, resource-efficient and resilient urbanism

The Habitat III Conference in October 2016 saw the adoption of the New Urban Agenda, which sets a new global standard for sustainable urban development for the coming two decades. It represents an evolution of the previous Habitat declarations in that it considers the challenge of urban poverty more systematically than ever before, and recognizes that it is unlikely to be overcome without integrated urban systems that align to promote inclusion, resource efficiency and resilience.[11] It places a strong emphasis on infrastructure and spatial planning as levers to help cities manage their resources more effectively and integrate the poor into the economy. Notably, it recognizes that "…urban form, infrastructure and building design are among the greatest drivers of cost and resource efficiencies…". When it comes to making choices between infrastructure alternatives, signatories commit to ensuring that they consider "…innovative, resource-efficient, accessible, context-specific and culturally sensitive sustainable solutions", and there is repeated mention of the importance of innovation and knowledge-sharing in achieving this.

Innovation and experimentation are already emerging in cities across the world in the form of extensive investments in innovative, sociotechnical infrastructures and spatial reorientations (Castán Broto & Bulkeley, 2013; Evans *et al.,* 2016). This results in metabolic reconfigurations of varying degrees of significance, from minor adjustments, such as shifting water heating from electric to solar systems, to major densification interventions coupled with mass transit. Although sustainability-oriented urban experimentation has become a focus in international local governance networks and associations and is increasingly gaining attention among researchers, there is relatively limited literature that interprets these experiments through the lens of resource-efficient, urban metabolic configurations, with a view to supporting the implementation of the resource targets of SDG 11 and the New Urban Agenda.

Although the learning curves for pioneering cities are steep, insights can also be acquired from previous eras of urban innovation. The urban visionaries who promoted sanitation during the late Victorian era, and those who promoted the mid-20th Century highways of urban modernity built formidable coalitions to guarantee funding and implementation of their respective urban visions (Hajer, 2014). The sanitary movement of the Victorian era comprised of scientists, politicians, human rights campaigners, leaders from business, engineers and visionary urban planners. The protagonists of the modern movement that transformed cities with an emphasis on suburbs and highways from the 1930s onward included industrialists, designers, real estate tycoons and liberal politicians. In both cases, their visions anticipated the cities that would eventually provide the spatial coordinates for the metabolic configurations and patterns of economic accumulation that followed. Think of Baron Haussman's Paris and the New York that Robert Moses built. Today, the transformation of cities in pursuit of global sustainability goals is being driven by the likes of the World Business Council for Sustainable Development (WBCSD), C40 Cities, ICLEI – Local Governments for Sustainability, Global Green Growth Institute (GGGI), United Cities and Local Governments (UCLG), the Covenant of Mayors for Climate and Energy and the many networks that strive to achieve low-carbon or more resource-efficient cities (usually with reference to a key resource such as water, food or energy). Alternatives to these more mainstream networks are those that articulate the needs of the urban poor, such as the Water Justice movement in Latin America or Shack/Slum Dwellers International (Swilling, 2016).

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[11] This report considers resource custodianship to be an important component of building resilience. The United Nations International Strategy for Disaster Reduction (UNISDR) Making Cities Resilient campaign and the 100 Resilient Cities project consider the broader issue of building resilience at the city scale, in response to the Sendai Framework for Disaster Risk Reduction 2015–2030.

## 1.7. Conclusion

This chapter provides a framing for the report that follows by outlining the nature of the urban challenge in the decades ahead. The global urban population is likely to grow by 2.4 billion by 2050, and the bulk of this growth is likely to happen in the cities of the Global South. As cities around the world grow at different rates, they will reshape the global economy. With material consumption predicted to grow faster than urban populations, these shifts will have serious repercussions for global resource consumption and the associated environmental impacts. The challenge will be to support improvements in quality of life in cities in current developing regions while remaining within the limits of sustainable consumption. DMC can be used to monitor changes in urban resource consumption, and a range of 6–8 tonnes per capita per year has been proposed as a target for sustainable consumption in developed and developing nations. Urban metabolism provides a useful way of understanding how cities consume, and can be used as a boundary metaphor to bring different disciplines together to address the challenge of accommodating greater urban populations in a manner that reduces inequality while remaining within sustainability limits. The New Urban Agenda calls for spatial planning and infrastructure investments that promote inclusion, resource efficiency and resilience, and acknowledges the importance of knowledge and innovation in achieving this. Urban metabolism assessments are useful quantitative and qualitative tools to aid urban planning and decision-making, specifically as they improve system knowledge and enable identification of high-leverage interventions for redirecting existing resource flows or introducing new ones. In this way, the study of urban metabolism can be leveraged by multiple disciplines and practitioners to address the challenges of accommodating greater urban populations, while reducing inequality and remaining within global resource limits.

The following chapters will show that context-specific, urban metabolic transitions are not only required if the goals of the SDGs and the New Urban Agenda are to be achieved in a mostly urban world, but that many are already under way, as illustrated by the outburst of multiple urban experiments. This report triangulates five modes of analysis: (i) the projections made possible by an urban metabolic analysis of future urbanization patterns, based on the assumption that little will be done to improve resource efficiency or increase density (Chapter 2); (ii) an analysis of the improvements in urban productivity made possible by a range of integrated, systemic city planning interventions that contribute, in particular, to strategic intensification of the urban space economy (Chapter 3); (iii) life-cycle analyses of a suite of sociotechnical systems that could be reconfigured in context-specific ways to manage the transition to resource-efficient urbanisms (BRTs, green buildings, district energy systems, zero-waste systems) (Chapter 4); (iv) comparative case studies of sociotechnical system change in cities in China, India and the USA (Chapter 5); and (v) a governance analysis aimed at ascertaining the most appropriate mode of urban governance for the era of urban transitions that we now face (Chapter 6).

Credit: ABB Photo/shutterstock.com

# Chapter 2

# Resource requirements of future urbanization — Baseline scenario

## 2.1. Introduction

In order to understand the magnitude of the urban resources challenge, this chapter estimates the resource requirements of future urbanization based on the assumption that the population will increase and urbanize in line with United Nations estimates. DMC is used to quantify estimated future resource requirements at global and regional levels, calculated using data from the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Material Flows database, United Nations urban population projections and selected data from cities in various world regions. The CSIRO Material Flows database is a compilation of national data on international, economy-wide material flows that have been systematically harmonized into a consistent and globally comprehensive time-series data set. This has been used in previous studies of global regional material flows (West & Schandl, 2013a; West *et al.,* 2014; UNEP, 2016).

The initial survey of data available for this Baseline Scenario revealed a large amount of information about the performance of a subset of global cities, but also that there are substantial gaps in the data. A pervasive challenge is that global data on material resource use are rarely available at the urban level. The urban data that are available represent a limited sample of cities, which may not correspond with the sample cities for other data topics (e.g. density). Conversely, global data on urban trends (such as long-term population change) are available at a regional level but not always for specific cities. Although a bottom-up, data-driven approach would be ideal, it was not feasible given the scope and scale of this project. One common element that we were able to use across various data was a definition of a city. For statistics on population, economic measures or resource flow accounting, we refer to the urban or metropolitan jurisdictional boundary. For measuring area, we use the measure of 'built-up area' from the Universe of Cities data set.[12] This is based on an analysis of satellite image data of the built-up, impervious area within the jurisdictional boundary. It includes any built-up area within 1 km of another built-up area, thus including suburbs and peripheral development but excluding large areas of agriculture and parks, which may be within a metropolitan area. This is our basis for defining average population density.

The point of departure for this chapter is the urbanization processes and patterns summarized in Chapter 1. Building on this demographic and income data, the first section of this chapter discusses land use and density patterns, the second section discusses the drivers of change to 2050 that have informed the assumptions of the Baseline, and the third section presents the Baseline Scenarios and the assumptions that were adopted. Note that the term 'Baseline' in this chapter is used with deliberate capitalization because this relates to the specific scenario assumptions that create a reference with which to compare alternatives in subsequent chapters.

## 2.2. Land use and density

### 2.2.1. Land use and density

One of the impacts of urbanization has been the increasing need for land to provide for a growing population and its economic activities. Globally, cities occupy less than 2 percent of the world's land area (Seto *et al.,* 2012). Urban form and the spatial pattern of land use influence the way cities use and generate resources and waste, and ultimately the quality of life of city dwellers (Dempsey and Jenks, 2010).

There are several estimates for global urban land coverage in the literature and different approaches are used to model future urban expansion (Angel *et al.,* 2011; Seto *et al.,* 2012). Estimates shown in Figure 2.1 are based on average densities from a large sample of city data and data on urban populations.[13]

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[12] http://www.atlasofurbanexpansion.org/data

[13] 1,728 cities from www.demographia.com

For comparison with other calculations, see Table 2.1. Note that Angel and colleagues assumed a high estimate for de-densification in North America that even their own research suggests is unlikely. For these calculations, we have specifically assumed that the USA will retain its current average urban density for the scenario period. Additionally, we have used an updated revision of United Nations urban population projections, which were unavailable before 2014. These factors contribute to the differences seen among the results in Table 2.1.

**Figure 2.1**: Comparison of urban land area (green columns – bottom scale) ordered by average urban density (blue diamonds – top scale) for United Nations major global regions as at 2010 (all area measures are in km²)

**Table 2.1**: Comparison of estimates for current and future global urban land area in the analysis used here (refer to Section 2.4.3) with calculations from the literature (km²)

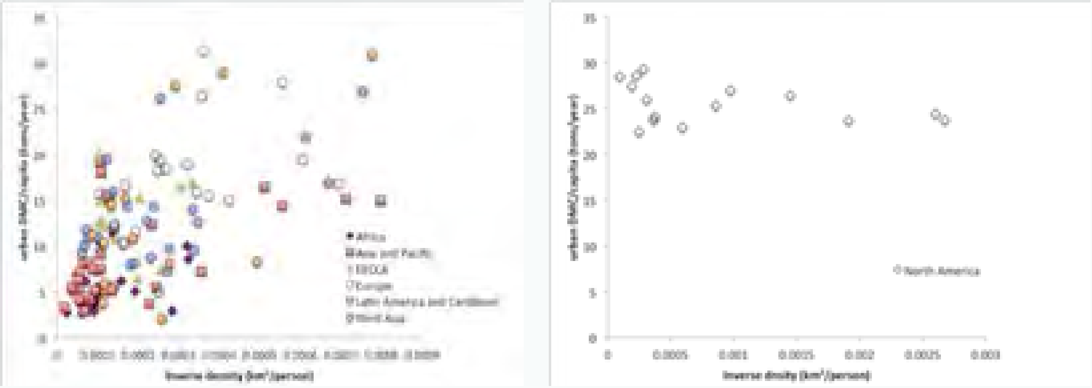
| Year | 2000 | 2010 | 2030 | 2050 |
|---|---|---|---|---|
| Estimate of total | | 912,000 | 1,640,000 | 2,746,000 |
| Angel *et al.* (2010; 2011) | 602,846 | 902,048 | 1,763,828 | 3,181,952 |
| Seto *et al.* (2012) | 652,825 | | 1,863,300 | |

## 2.2.2. Resource use and density

The magnitude of material requirements for cities is related to their populations and occupation of space, but the direct material intensity of cities (tonnes per km² or tonnes per hectare) is related to the way that space is filled and connected with infrastructure (buildings, transport and communications infrastructure) and in the provision of basic services. However, the relationship is not clear-cut as there are intervening factors, such as the importance of industry or services in the local economy, the development stage of the city and its host country, and the geography and culture of a city. As far as urban cultures are concerned, there is acceptance of high-rise apartment living in Hong Kong, which is very different from the norm in Nairobi or Sydney. These factors confound a simplistic relationship between material requirements and space per capita. A general pattern of high population density cities having lower urban DMC per capita is apparent in Figure 2.2, but there is considerable scatter in the data at global and regional levels and North America appears to be a special case, where urban DMC per capita has no relationship with urban density.

Even within developed countries, starkly different material intensities for particular substances are apparent. For example, in the stock of aluminium, most developed countries have shown a recurring development pattern of a slow build-up to 50 kg per person, followed by a linearly increasing trend. However, this trend varies across different countries. Even if attempts are made to control for economic structure, development phase, culture and somewhat similar geography, it is observed that a UK citizen requires just over 200 kg per capita,

**Figure 2.2**: DMC per capita data obtained or derived for 152 cities plotted against space per capita measured as inverse density (km$^2$ per person) and income per capita (GDP at purchasing power parity in 2011 international dollars).



(EECCA refers to Eastern Europe, the Caucasus and Central Asia)
(Source: Data from Saldivar-Sali, 2010)

## Declining urban densities

In a survey of 120 global cities, Angel *et al.* (2010) found that average density declined at a mean annual rate of 2.0 ± 0.4 percent between 1990 and 2000, with no significant difference in the rate of decline between more and less developed countries.[14] For 30 cities for which data was available since 1800, a 1.5 percent long-term historical decline in density was noted.

According to Angel *et al.* (2005): “If average densities continue to decline at the annual rate of 1.7 percent as they have during the past decade, the built-up area of developing-country cities will increase from 200 000 km$^2$ in 2000 to more than 600 000 km$^2$ by 2030, while their population doubles.”

To translate into global land-area terms, if density were not to decline, compared with a steady 2 percent decrease until 2030, the amount of land saved from urban development between 2000 and 2030 would approximately equal the entire planet’s urban land area in the year 2000 (650,000 km$^2$).

### The importance of density and its structure within cities

Compact and contiguous cities offer efficiencies in transport and infrastructure and in the World Bank’s Urban and Local Government Strategy (World Bank, 2010), they argue that “…density, agglomeration, and proximity are fundamental to human advancement, economic productivity, and social equity”.

Average density of cities is a gross statistic that has been used to show economies of agglomeration regarding per capita transport energy needs, road length, water and wastewater servicing requirements (Müller *et al.*, 2013). Yet within cities, there is an intra-urban density distribution. Salat and Bourdic (2012) and Bourdic *et al.* (2012) contend that the more hierarchical the density distribution, the more efficient the urban structure, and the more homogeneous the density distribution, the higher the energy consumption for transportation per capita. Raising average density is thus not always an appropriate means of improving urban resource efficiency. For a more nuanced discussion on the role of density in urban resource consumption, see Chapter 3.

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[14] For a consistent measure of urban area, the authors used satellite data on the built-up, impervious area of cities.

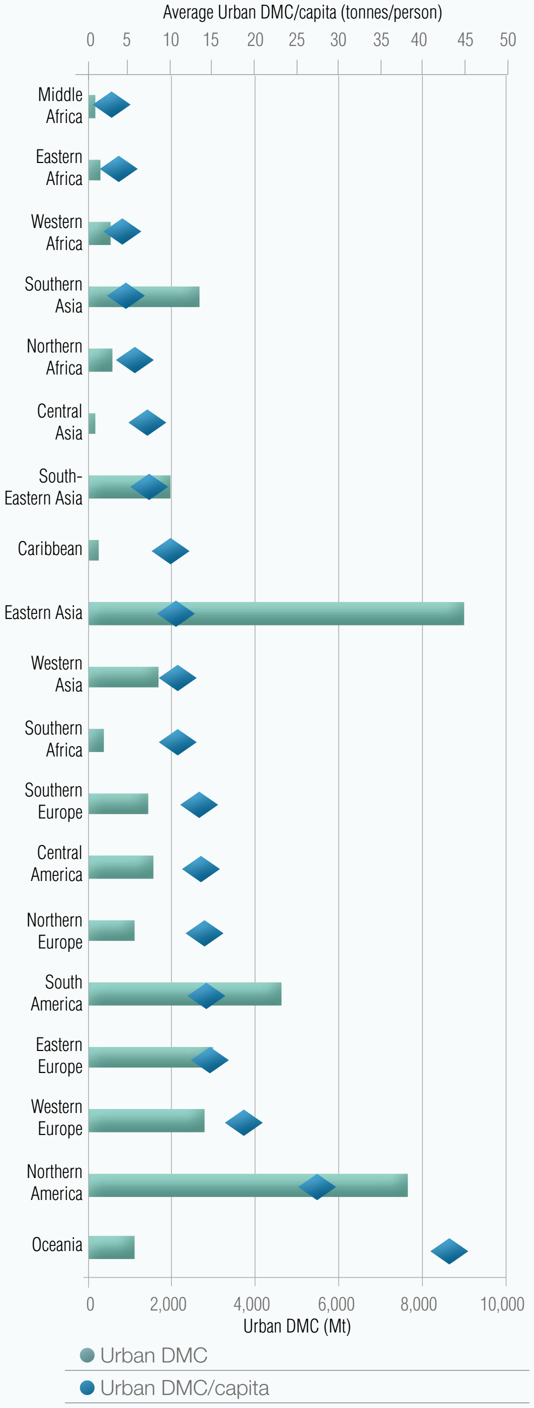
the average Australian more than 350 kg per capita and the average US citizen needs nearly 550 kg per capita of aluminium per year (Liu *et al.,* 2013).

It should be mentioned that *direct* material intensity, according to the standards of material flow accounting (Eurostat, 2001), is being referred to here, and by these definitions, developed countries have apparently decoupled their economic growth from growth in their material needs. This is partly because developed nations have already passed the construction phase in which their societies installed much of the material-intensive infrastructure. This is only part of the story. When the *indirect* material impact, embedded in the extended supply chains for products and services consumed in developed countries, is included in a 'material footprint', the apparent decoupling ceases to be the case (Wiedmann *et al.,* 2015). In this sense, wealth and income very much relate to society's material impact, but currently, this indirect analysis is only globally available at the scale of nations, not cities.

Generally, material consumption is highly uneven across the different world regions. In terms of material footprint, the world's wealthiest countries consume 10 times as much as the poorest and twice the global average (UNEP, 2016). As the population in developing regions has become wealthier, their material consumption has also increased, although in an uneven manner. In the Asian region, absolute consumption increased in all regions for the period 1980–2009, except for Central Asia.[15] Eastern Asia showed the largest increase, in particular China and India, with less dramatic changes in Indonesia and Thailand (Asian Development Bank and Inter-American Development Bank, 2014). The per capita consumption has also declined or remained almost level in regions such as Central America, Northern America and Africa (Dittrich *et al.,* 2012).

Based on Saldivar-Sali's (2010) DMC per capita estimates, there is a general distinction between African and Asian regions with an urban DMC per capita of less than 10 tonnes per person, and European and American regions with urban DMC per capita of over 10 tonnes per person (see Figure 2.3).

**Figure 2.3**: Comparison of total urban DMC in million tonnes (green columns – bottom scale) ordered by average urban DMC per capita (blue diamonds – upper scale) for United Nations major global regions at 2010. Urban DMC data obtained or derived for major global regions based on Saldivar-Sali (2010)



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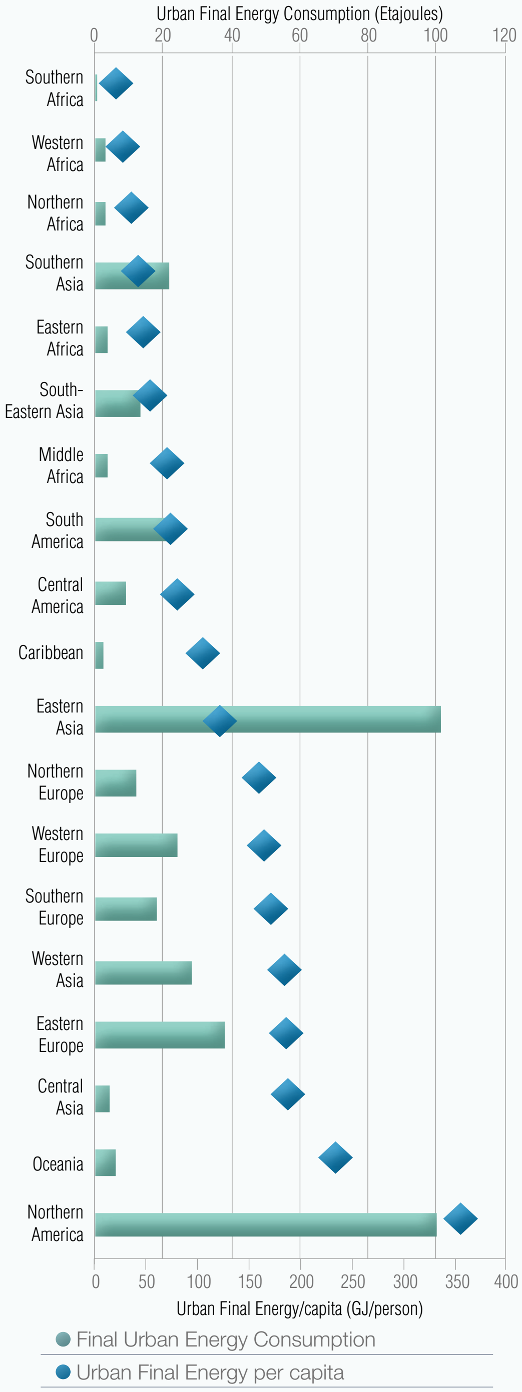
[15] This is associated with the collapse of the former Soviet Union, which resulted in a decrease in aggregate material consumption.

A global survey of urban energy consumption appeared in Chapter 18 of the Global Energy Assessment (Grubler *et al.,* 2012). The authors acknowledged the problems of obtaining urban energy data for a study of this scope and we find that the situation has scarcely changed since that publication.[16] In the Global Energy Assessment (as is the case here), analysis was restricted to direct or 'final' energy consumed i.e. all energy supplied to the final consumer for all energy uses. This is to be distinguished from the more comprehensive 'total primary energy supply' metric, which would include energy lost in transformation and transmission and the upstream primary fuels used to generate electricity. It is an open question as to whether the choice of technology and fuel to generate electricity is a decision made at the metropolitan level or at that of the state. Depending on the answer, upstream primary energy requirements can be attributable to cities. What is certain is that the point of end use of the final energy form does occur in cities and this enables a global comparison.

**Figure 2.4**: Estimations of urban final energy consumption in Etajoules = $10^{18}$ joules (light blue columns – upper scale) ordered by average urban final energy per capita (blue diamonds – bottom scale) for United Nations major global regions at 2010



Using the latest national data from U.S. Energy Information Administration (EIA),[17] data from the Global Energy Assessment and United Nations urban population data, it has been possible to produce a final urban energy consumption estimate for major global regions as at 2010 (see Figure 2.4). While total urban final energy consumption in Etajoules for Eastern Asia is comparable to that of Northern America, the urban final energy per capita is half that of the Northern America region.

On the contrary, regions such as Central Asia and Oceania depict low total urban final energy consumption (in Etajoules) but higher per capita urban final energy. All the regions in Europe have a higher per capita urban final energy than in Eastern Asia, despite having lower total urban final energy. This clearly illustrates the challenges in framing energy indicators, which although acknowledged in this report, is beyond its scope

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16. Urban material and energy needs are surprisingly absent from otherwise comprehensive data sets e.g. http://urbandata.unhabitat.org/
17. http://www.eia.gov/forecasts/ieo/ieo_tables.cfm

## 2.3. Drivers of change

The premise of the Baseline Scenario is the continuation of the status quo, however, explicitly or implicitly, this involves more than simply fixing the numerate parameters of urban performance for the scenario period. This section provides some background on the reasoning and narrative of the Baseline Scenario which, despite its reference to the existing state of cities, still involves some drivers of change. Part of the discussion here is also an acknowledgement of the unknown or uncertain elements that have been excluded from the Baseline Scenario: elements of urban development that may well instigate change but for which there is neither the data nor the means to simulate a future.

### 2.3.1. Population growth and demographic change

Based on the projections available in the World Urbanization Prospects data (UN-DESA, 2014) there will likely be an additional 2.4 billion people living in cities by 2050. The bulk of this growth will occur in the developing world, with nearly 37 percent occurring in China, India and Nigeria alone. Estimates suggest that Africa's urban population could increase by about 800 million—an amount greater than the combined current urban populations of Southern Asia and Europe at 2010.

In terms of scale, the absolute increase in the size of the urban population is *the* most important quantitative driver, but at the same time, there will be a significant shift in the age structure of populations in less developed regions (see Figure 2.5). Although detail on demography is not included in this scenario, as life expectancies increase, there will be sustained demand for housing and access to basic services, and relatively greater demand on medical services in cities as their populations age.

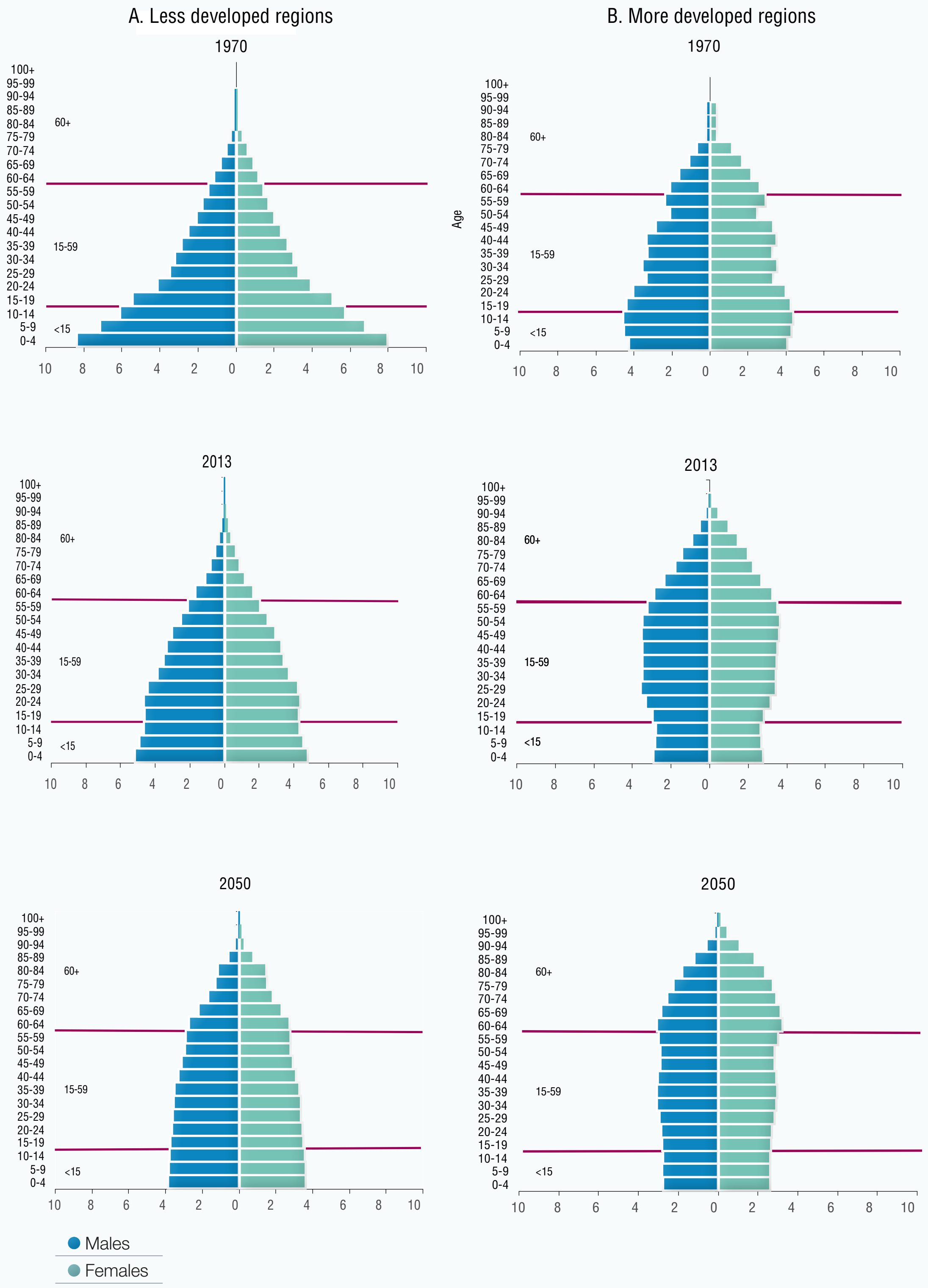
In 2050, it is likely that a far greater proportion of the population will be over the age of 35 than at present. This qualitative shift will affect the overall lifestyle and consumption profile of the population, and therefore, the per capita resource footprint. This issue needs to be addressed when thinking about urban design for accessibility, but also in terms of the changing needs of the (currently) young cohort in developing countries as they age. Initially, high-density apartments will provide for young adults and couples engaging in new urban economies and enable mass transport options. However, if implemented without regard for green spaces and educational facilities, the subsequent generation will grow up in very different circumstances to their parents. It is worthwhile considering the multigenerational use of urban space and what this means for the pace and path of urban growth, particularly in developing countries where there is so much potential for positive intervention at the beginning.

### 2.3.2. Affluence and economic transitions

Cities tend to generate more income per capita as they increase in size (Bettencourt *et al.,* 2007). Furthermore, there is a strong correlation between rising income and consumption patterns of citizens, how much energy they use and hence, their GHG emissions per capita (Lenzen *et al.,* 2004). The long-term national GDP growth projections from the OECD anticipate that GDP in developing countries will increase fourfold between 2015 and 2050 (OECD, 2016) and it is expected that the 600 largest cities will expand 1.6 times as fast as the global population and produce 60 percent of global GDP by 2025. This translates to 735 million households with an average annual income of $32,000 (Dobbs *et al.,* 2011).

Cities produce 80 percent of global GDP and just 100 cities may account for 35 percent of global GDP *growth* by 2025, while the overall group of more than 2,000 metropolitan areas will be responsible for 75 percent of global economic growth by the same year (Dobbs *et al.,* 2011). As many middle-size cities increase in population, their economic importance will also grow, and their income will increase at a faster rate than the population. Consequently, the per capita affluence will steadily increase by 3 percent per year for a new class of mid-size, economically

**Figure 2.5:** Demographic shifts in the age structure of major global regions from UN-DESA (2013). See also data here: http://esa.un.org/unpd/popdev/Profilesofageing2015/index.html



robust cities. Cities in the developing world will increasingly feature in this class.

Economic events and transitions affect resource use. The USA had the world's largest total primary energy supply and a long-term increasing trend from 1960 until the Global Financial Crisis in 2009, after which China became the largest total primary energy generator. Since the Crisis, economic conditions, among other factors, have seen a decline in both the per capita and overall energy needs of the USA (OECD/IEA, 2014). The International Energy Agency (IEA) estimates that although China will remain the largest producer and consumer of coal and overtake the USA in oil consumption, its transition to a more service-based economy will require 85 percent less energy to produce each future unit of economic growth (OECD/IEA, 2015).

Urbanization is associated with increases in overall and per capita income. At the national level, higher incomes have been shown to be related to the direct and indirect urban consumption of energy and production of GHG emissions (Lenzen *et al.,* 2004; Lenzen *et al.,* 2008; Lenzen and Peters, 2010; Grubler *et al.,* 2012; Wiedenhofer *et al.,* 2013; Kalmykova *et al.,* 2015). Wealth and the consumption of electricity in particular, are closely connected (Ferguson *et al.,* 2000). However, the energy impacts of urbanization are not homogeneous (Poumanyvong and Kaneko, 2010). In developing countries, urbanization contributes to greater energy efficiency through fuel switching from inefficient, traditional fuels to efficient, modern fuels and devices (e.g. heating and lighting), yet the affluence that comes from urban living—the ownership and use of more devices per person—drives energy use in the opposite direction. Urbanization in middle- and high-income countries positively influences indirect energy use through consumption of energy embedded in goods and services, while the direct energy needs per person plateau above a given threshold income level[18] (Lenzen *et al.,* 2004; Grubler *et al.,* 2012).

Economic structure influences resource needs. For example, Shanghai's industrial sector consumed more than 80 percent of the city's energy between 1990 and 2005 (UN-Habitat, 2011). Although cities such as London, Paris and New York have become predominantly service-based economies over the last 50 or more years, these activities are also resource and energy intensive, with high waste volumes. In Japan, household expenditure on services induced 14 percent of total domestic CO2 emissions in 2000, exceeding the 11 percent induced by household expenditure on electricity and public transportation combined (Nansai *et al.,* 2009).

Income per capita has been related to greater floor space in residential dwellings (Schipper, 2004; Isaac and van Vuuren, 2009), which require more material in construction and more space heating/cooling energy. Conversely, it is in the lowest-income countries where the poorest levels of access to clean water, reliable, clean energy, safe shelter and many other aspects of material well-being are found. The relationship between affluence and material needs is heterogeneous and differentiated both between and within categories of development phase (Steinberger *et al.,* 2013). This may further depend on the role of the host country in the extraction and trade of material resources (Schandl and West, 2012).

The developed world is attempting to contain environmental impacts and seeking to decouple material and energy flows from their levels of income and wealth. At the same time, developing nations are at a critical juncture—unprecedented urbanization and increasing affluence offer opportunities, but they could also lead to locked-in resource dependency and cheap but inefficient technological choices and system design. While initially less expensive, these choices can be costlier over the lifetime of the fixed capital stock invested (e.g. in vehicles, buildings, machines). Part of the narrative of the Baseline Scenario is that the choice of existing technologies, efficiencies, urban forms and systems *is* perpetuated, eschewing the opportunity for innovation.

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[18] This threshold varies depending on the national and regional economic context e.g. the local cost of housing and standard of living.

### 2.3.3. Urbanization and development

Although cities only cover 2 percent of the world's land surface, the activities within their regional boundaries consume over 75 percent of the planet's material resources (UNEP, 2013a). Continuing urbanization will accelerate the demand for the materials required to create and upgrade buildings, roads and landscapes, as well as demand for flows of water and energy to support the additional population.

In terms of global change, the situation in the developed world is one of slow growth and maintenance. Here, population change is far less than in the developing world, urbanization has already happened and major infrastructures have been constructed, although large-scale infrastructure investments do still occur (e.g. London's new massive sewage system and Crossrail project). Among the requirements for urbanization in developing countries will be a demand for materials to create new infrastructure, vehicles and buildings. Müller *et al.* (2013) estimate that if the developing world proceeds to construct new cities with the same intensity and type of infrastructure observed in developed countries, the potential carbon cost will be more than a third of the world's cumulative carbon budget to 2050.[19] While Africa and Southern Asia are entering into a construction phase, China's construction of residential buildings will probably plateau after 2035 as the centrality of its construction and manufacturing sectors is replaced by a more service-oriented economy. This has implications for material and energy flows. Between 2011 and 2013, China consumed more cement (6.6 gigatonnes) than the USA did between 1901 and 2000 (4.5 gigatonnes) (Smil, 2013). This rate far exceeds previous expectations (Fernández, 2007) and is unlikely to continue. In the past decade, the urban, built-up land area in China has grown by 78.5 percent—faster than its urban population, which grew by 46 percent—implying either an oversupply or a dramatic shift in population density in new developments. Although China is expected to add another 225 million urban dwellers, its national population will peak and start to decline in the next 10 years, setting the ultimate boundaries on China's urban expansion.

There is also a declining global trend in the size of households (persons living in a dwelling). According to the McKinsey Global Institute: "In the cities of developing regions, we expect the average size of households to decline from 3.5 people to 2.9 [between 2010 and 2050]. The regions with the largest estimated decline in the size of their urban households are Sub-Saharan Africa (from 4.1 people per household to 3.1) and the Middle East and North Africa (5.2 to 4.4)" (Dobbs *et al.,* 2011).

Isaac and van Vuuren (2009) note that there is a reasonable correlation between residential floor area per capita and income (GDP per capita), and it would be reasonable to expect that not only will there be more urban residents in developing countries in 2050, but they will also be living in smaller households and, as their affluence grows, possibly larger dwellings. The long-term saturation of China's residential market and the interaction between Africa's urbanization and rising affluence is part of the narrative behind the Baseline Scenario projections for DMC per capita up to 2050.

While studies have shown the importance of density in urban planning, it also influences resource requirements, particularly in transport, housing, water supply, energy and waste management infrastructures (Grubler *et al.,* 2012). Population density tells us something about the urban form of a city or city type, that is, how much infrastructure or what types of residential buildings are present, and information about energy use can be inferred from average density or density structure (Schiller, 2007; Tanikawa and Hashimoto, 2009; Müller *et al.,* 2013; Salat and Bourdic, 2014). In combination with data or forecasts on population, information on total urban land use can be deduced. Further, by itself, density has dependable relationships with urban wastewater, length of roads and car ownership (Müller *et al.,* 2013; Singh and Kennedy, 2015).

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[19] For further discussion on the resource impact of infrastructure choices, see Chapters 4 and 5.

Due to the overall poor relationship between urban density and DMC per capita mentioned earlier in this report, the details above are implicit in the Baseline Scenario, although it would be a worthwhile venture to use this collection of research to perform a global study on residential construction materials in relation to density.

Urbanization also has implications for the growth of slums, which will likely be one of the transitional forms of settlement for many new urban dwellers in developing countries. In 2007, the number of slum inhabitants[19] exceeded one billion, equating to one in every three urban dwellers (UN-Habitat, 2006). While the proportion of people living in slums has been declining since 1990 (see Table 2.2), the absolute numbers have been increasing. Looking at the regional or country level, this proportion has different trends, especially in developing countries. For instance, the number of slum dwellers increased from 791 million in 2000 to about 871.9 million in 2010 (UN-Habitat, 2014b). At the country level, South Sudan has the highest proportion of urban population living in slums, at 95.6 percent in 2014 (UN-Habitat, 2014b).

**Table 2.2**: Proportion (%) of urban population living in slums

| Major region | 1990 | 1995 | 2000 | 2005 | 2007 | 2010 | 2014 |
|---|---|---|---|---|---|---|---|
| Developing regions | 46.2 | 42.9 | 39.4 | 35.6 | 34.3 | 32.6 | 29.7 |
| North Africa | 34.4 | 28.3 | 20.3 | 13.4 | 13.4 | 13.3 | 11.9 |
| Sub-Saharan Africa | 70.0 | 67.6 | 65.0 | 63.0 | 62.4 | 61.7 | 55.9 |
| Latin America and the Caribbean | 33.7 | 31.5 | 29.2 | 25.5 | 24.7 | 23.5 | 21.1 |
| Eastern Asia | 43.7 | 40.6 | 37.4 | 33.0 | 31.1 | 28.2 | 26.2 |
| Southern Asia | 57.2 | 51.6 | 45.8 | 40.0 | 38.0 | 35.0 | 31.3 |
| South-Eastern Asia | 49.5 | 44.8 | 39.6 | 34.2 | 31.9 | 31.0 | 28.4 |
| Western Asia | 22.5 | 21.6 | 20.6 | 25.8 | 25.2 | 24.6 | 24.9 |
| Oceania | 24.1 | 24.1 | 24.1 | 24.1 | 24.1 | 24.1 | 24.1 |

(Source: UN-Habitat, 2014b)

Slum population growth rates tend to rise with annual growth of urban populations, while at the same time, the percentage of citizens living in slums decreases as the level of urbanization rises (World Bank, 2009). This dynamic is consistent with the Baseline Scenario, but not explicit in the calculations. Alleviating the undesirable living conditions of the urban poor will require a proactive, anticipatory policy approach, especially with respect to the location of informal settlements and subsequent infrastructure connections and upgrade programmes (Grubler *et al.,* 2012). However, the Baseline Scenario consciously avoids making assumptions about the implementation of such policies and their effect, which would certainly alter the resource intensity of habitation in cities. In other words, the Baseline Scenario does not assume that no one will be living in slums by 2050. The existing trend line is expected to continue, i.e. a percentage decline of between 2–3 percent per half decade in the relative (but not absolute) numbers of people living in slums. For more on the relationship between affordable housing typologies and resource intensity, see the case study in Section 5.5.

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20. Those living in urban areas with inadequate housing and few or no basic services.

## Mass transit

As urbanization continues, there is often a concurrent pressure to provide mass transit options in cities. While this involves significant initial monetary and material investment, it demonstrably saves energy and enables more egalitarian and effective access to the urban economy and amenities for citizens.

There is a putative intra-urban population density of about 35 persons per hectare that makes mass transit technologies logistically and financially viable (Newman and Kenworthy, 2006). Population size and density together can suggest certain technologies and infrastructures, though these may not be appropriate or may even be negated because of the climate, geography, available GDP per capita or institutional stability. The per capita transport energy savings offered by higher-density cities are not as decisive as some academic literature suggests. The uptake of mass transit is more nuanced and subject to the historical legacy of prior civic decisions, attitudes and behavioural economics and investment decisions.

There is a modest relationship between urban density and the uptake of BRT for different global regions (Cervero, 2013), although this is influenced by a particular popularity for BRT in Central and South America.[20] The fact that 'new world cities' in the USA and Australia have low densities and a high use of private vehicles is related to past urban planning decisions and corporate influence on the deliberate removal of established, mass transit infrastructure.

Recently, Australian cities have sought to re-establish or augment their light rail systems and in many medium-sized US cities, car use has been in decline since 2007—a trend that is apparent in national statistics on vehicle travel.[21] The trend is for greater uptake of public transport, despite recent drops in fuel prices. The historical shift away from mass transit during the middle decades of the 20th Century and the recent increase in investments in mass urban transit reflect a shift in policy and attitudes, more so than a shift in Australian or American urban population density.

India's impressive rail system is the world's largest single employer, but the scale and use of rail in India rests on the legacy of investment by previous generations rather than a recent reaction to urbanization and higher densities. In fact, new rail additions in India between 2006 and 2011 were eight times less than in China. Thanks to urbanization and economic growth, India's Government is now investing some $130 billion to upgrade and expand the rail system to accommodate anticipated demand that would otherwise have to turn to road transport options. It should be noted that much of this investment is in inter-city or interprovincial transport and further opportunities exist to renew or expand intra-urban rail. Elsewhere in the developing world, and especially in the growth of small cities, new transit infrastructure will augment the material consumption of citizens in tonnes per capita; however, if experience from the developed world is any guide, this will ultimately lead to greater material productivity (Krausmann *et al.,* 2009). See Chapter 4 for an analysis of the resource impact of BRT in comparison to passenger cars.

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21. See baseline information here: www.brtdata.org. BRT is available for all the major regions, however the number of cities with BRT differs between regions.
22. http://www.fhwa.dot.gov/policyinformation/travel_monitoring/14septvt/figure1.cfm

### 2.3.4. Climate

Although the effects of climate change were not modeled in this report, it is worth briefly mentioning this factor as a driver of urban change. There is already a concentration of GHGs in the atmosphere that will see a 'likely' global average temperature increase of more than 2°C (IPCC, 2014). Climate will likely be one driver of urban energy use, if not also material use, in design responses to heat stress. Material resources would also be used in adapting to other climate-related impacts, such as rising sea levels, and in building urban resilience in general. To estimate these resource quantities would require a rigorous, spatially downscaled consideration of a range of climate scenarios, which is beyond the scope of a reference scenario wherein other factors play an equal if not greater role.

There is certainly evidence of an interaction between urban design, density and the urban heat island (UHI) effect (Santamouris *et al.,* 2001; Ewing and Rong, 2008), and at least one paper found correlations between energy use and changes in heating (or cooling) degree days for global cities, depending on their geographic situation (Singh and Kennedy, 2015). However, it is the combination of population growth and affluence at a given location that has the greatest impact. Isaac and van Vuuren (2009) simulated the changes in residential space conditioning (heating and cooling) in response to climate change. The coincidence of a larger population being able to afford air-conditioning in locations where there would be a greater number of heating degree days (HDD) meant that air-conditioning energy demand increased by 72 percent. At the regional scale, considerable impacts can be seen, particularly in Southern Asia, where energy demand for residential air-conditioning could increase by around 50 percent due to climate change.

## 2.4. Baseline scenarios

This section outlines the assumptions and data sources of the Baseline Scenarios. The Baseline Scenario is essentially aimed at investigating the resource requirements of future urbanization, if the required urban infrastructures and buildings are designed, constructed and operated on a BAU basis, and if existing long-term densification trends continue.

When assuming BAU based on recent trends, it is noted that some trends cannot be expected to continue as they would lead to unfeasible outcomes (extremely high or negative values at 2050). Consequently, the general approach is modified for some trends; for instance, it is not expected that Chinese residential construction will proceed at the pace it has over the last 10 years. Although several programmes for improving the resource intensity of specific cities exist, these are not usually generalized because the effect of these programmes is not expected to be applicable to the region within which they are located or globally. Generally, values for intensive variables (e.g. energy use per capita) known at the base year (2010) were applied to scenarios of extensive variables (e.g. population).

### 2.4.1. Population

Urban population scenarios for the major global regions are shown in Figure 2.6, while Figure 2.7 shows trends over the same period for global population in urban centres with less than 1 million (from UN-DESA, 2014). The projections in Figure 2.6 show that urban populations in Africa and Southern Asia continue to grow much faster up to 2050, reaching 1.34 billion and 1.21 billion respectively. In the case of Eastern Asia, while population is increasing from 2010, this is projected to increase at a lesser rate, and begins to taper off from 2040, becoming lower than the African urban population and reaching 1.23 billion. It is significant that Africa's urban population will be the largest by 2050.

The population of urban centres less than 1 million is expected to be dominant in Africa and Southern Asia. In both the Figure 2.6 and Figure 2.7 projections, European and Northern American urban populations are generally expected to stabilize or even decline, while the major regions of urban growth are Africa and Southern Asia.

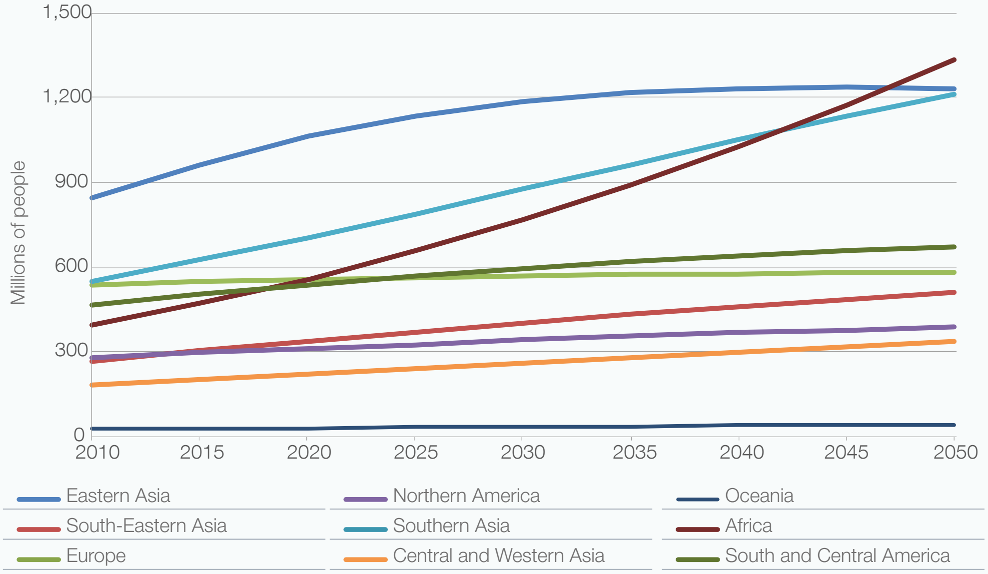
### 2.4.2. Income

Some data on gross regional product (GRP) are available for a global sample of cities (Pricewaterhouse Coopers, 2009; Dobbs *et al.,* 2011). Where city-level data is unavailable, city GDP was derived from the OECD projections of a country or from regional GDP and the fraction of that area's GDP attributed to urban areas (Dobbs *et al.,* 2011). The measure of GDP with purchasing power parity (ppp) at constant prices measured in international dollars at 2011 is used here (see Figure 2.8). From the Baseline Scenario, there is no convergence in the urban GDP. The top three regions with the highest urban GDP are Northern America, Oceania and Europe respectively, while the bottom three regions with the lowest urban GDP are South-Eastern Asia, Southern Asia and Africa. Continued growth in urban GDP is expected for all regions except for Africa and Southern Asia, which have relatively marginal change. This is due to the projected rapid increase in urban populations relative to projected growth in GDP in these two regions, as presented in Figure 2.6.

### 2.4.3. Land use and density

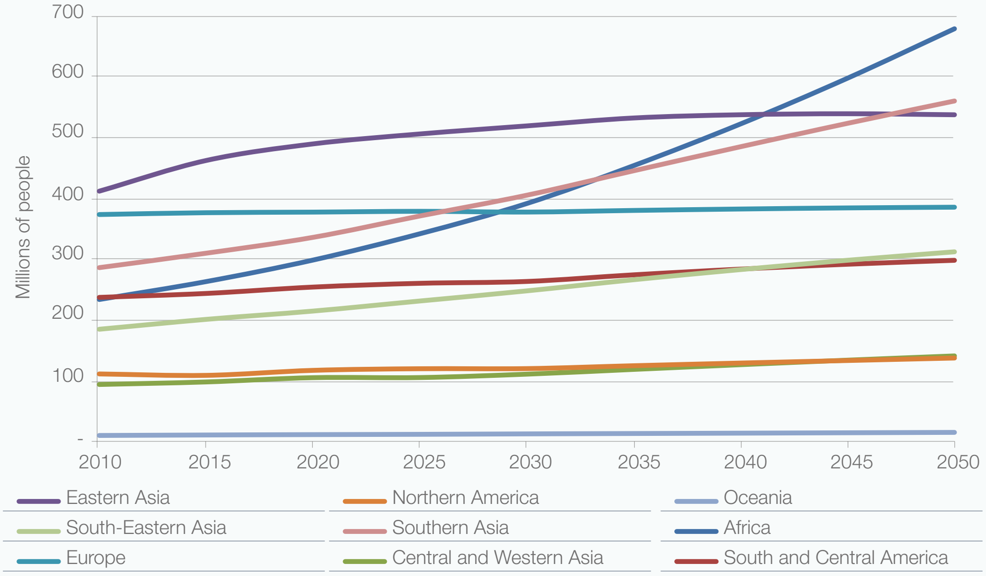
Density at 2010 was obtained from a sample of over 1,700 cities in the database at www.demographia.com and a 2 percent annual reduction rate was applied to all countries except the land-constrained states of Hong Kong, Singapore, Luxembourg, Kiribati and the Maldives. The USA was also assumed to have no change to its density over the scenario period based on

**Figure 2.6**: Global urban population by major regions



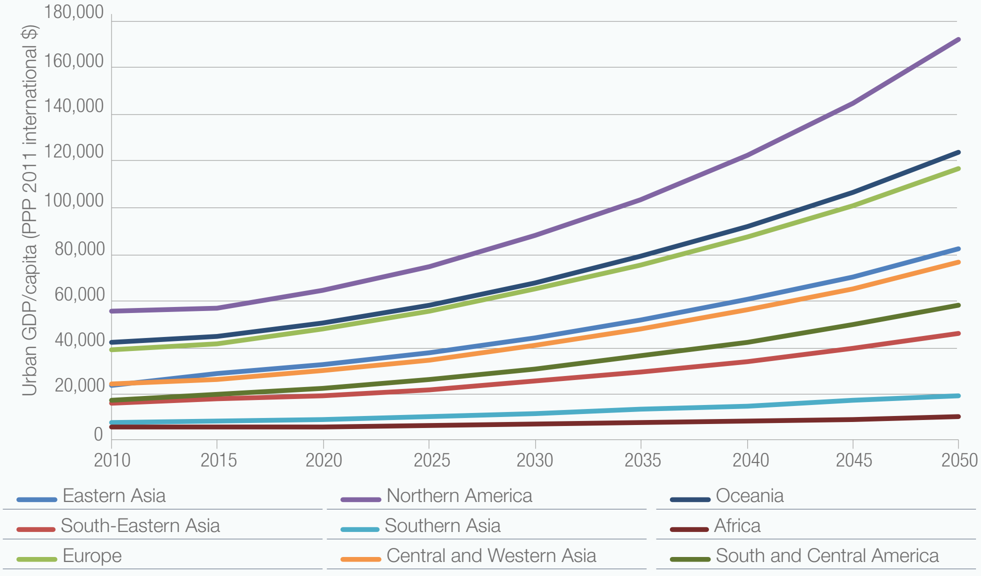
(Source: UN-DESA, 2014)

**Figure 2.7**: Global distribution of population in urban centres with less than 1 million inhabitants



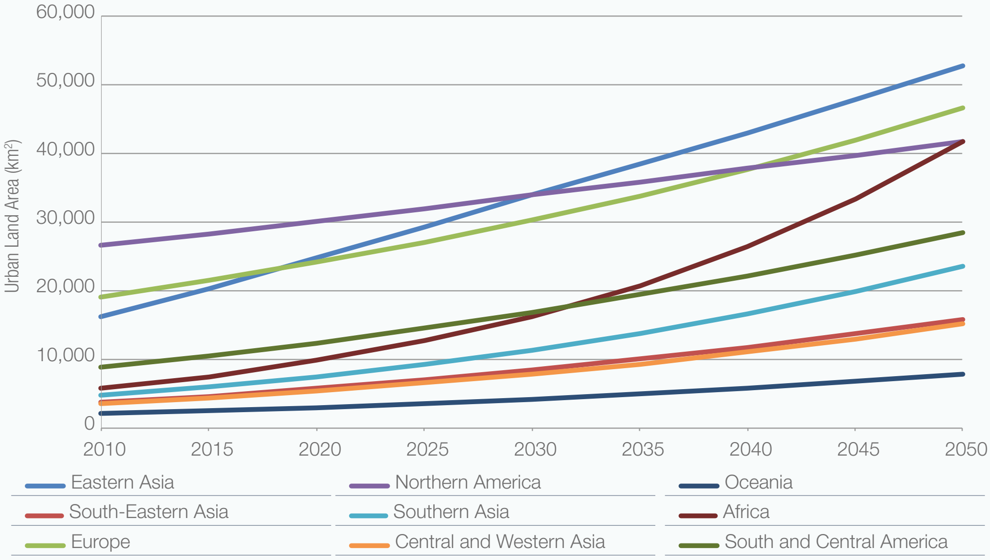
the specific recent trends in urban areas of that country, which indicate no change in density (Angel *et al.,* 2010). The urban land use by major global regions is presented in Figure 2.9. The projections indicate that the urban land area in Africa increases and becomes comparable with the Northern America region by 2050. This was projected to reach around 417,600 km$^2$ for Africa and 467,000 km$^2$ for Northern America by 2050. With urban land expanding for most regions, the urban densities for all the regions are projected to decline (see Figure 2.10), except for Northern America, which was assumed to remain constant.

**Figure 2.8**: Urban GDP in major global regions. The relative changes in OECD national GDP projections were used with estimates of regional urban GDP per capita based on data from the Brookings Institution,[22] supplemented with data from Pricewaterhouse Coopers (2009) and the regional population projections



(Source: UN-DESA, 2014)

**Figure 2.9**: Urban land use change in major global regions



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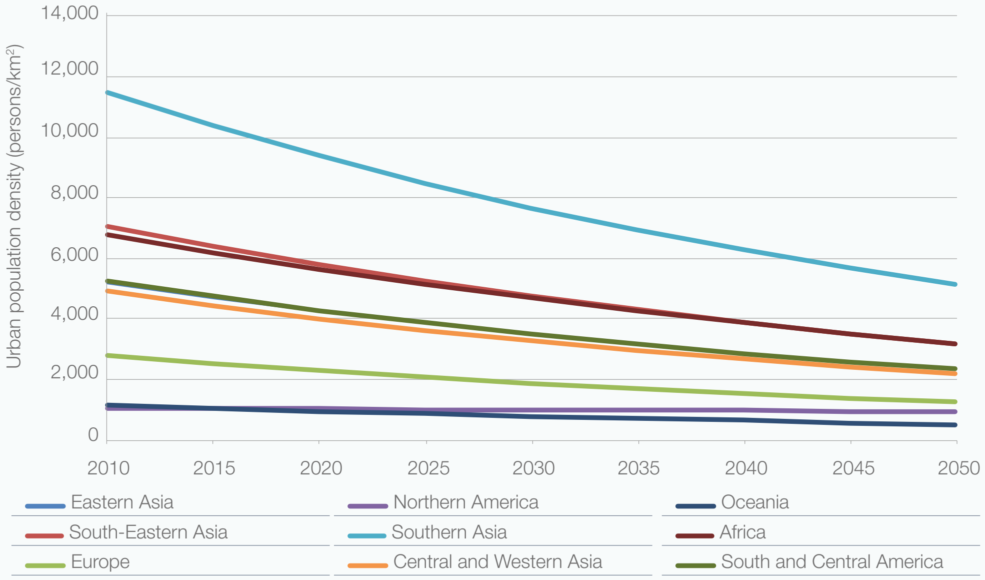
23. http://www.brookings.edu/research/reports2/2015/01/22-global-metro-monitor

**Figure 2.10**: Urban population density change in major global regions



## 2.4.4. Domestic material consumption

DMC measures the material flows consumed within a territory over a given time (often annually). DMC is defined (Eurostat, 2001) as being equal to domestically extracted raw materials plus imported materials minus exported materials.[24] As such, DMC is an imperfect measure of material consumption in cities because they often import finished goods, with the majority of the material flows and transformations happening outside the city. It is also worth noting that DMC is sometimes flawed as a *national* measure of material flow for economies that rely substantially on material extraction and trade (e.g. Chile, Australia, Canada) because the overburden of resource extraction is attributed to the extracting country, even though they do not consume said resources. The accounting of TMC[25] and the measure of 'material footprint' in raw material equivalents overcomes these limitations, but TMC is difficult and time-consuming to compile and material footprint requires a complex and globally comprehensive, multi-region input-output analysis (Wiedmann *et al.,* 2015). Neither of these measures are available in a globally comprehensive data set for urban boundaries.

Despite these caveats, DMC is considered to be a reasonable and consistently recorded indicator for comparing the material intensity in different global regions. DMC data or estimations are available for approximately 150 cities (Saldivar-Sali, 2010; Zhang, 2013; Kennedy *et al.,* 2015) and over 200 countries[26] (Schandl & West, 2010; West & Schandl, 2013b; Wiedmann *et al.,* 2015). These data sources provide a basis for attributing and presenting a historical material flow intensity—DMC per capita. However, generating future scenarios of potential change to urban DMC per capita is problematic. DMC per capita is highly contingent on resource availability at location, phase of economic development, social or political upheaval and the latent effect of historical investments e.g. in long-lived infrastructure, such as coal-fired power stations. It would be optimal to simulate urban material flows with a stock flow model that accounts for material held in long-lived stocks (buildings, vehicles, infrastructure, etc.) and the annual flows resulting from their retirement and replacement. This has been attempted for some global regions (Wiedenhofer *et al.,* 2015) or particular materials (Pauliuk *et al.,* 2013; Liu

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[24] Material inputs are defined as all solid, liquid and gaseous materials (excluding water and air, but including the water content of materials, for example) that enter the economy for further use in production or consumption processes.

[25] http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Total_Material_Consumption_percent28TMCpercent29

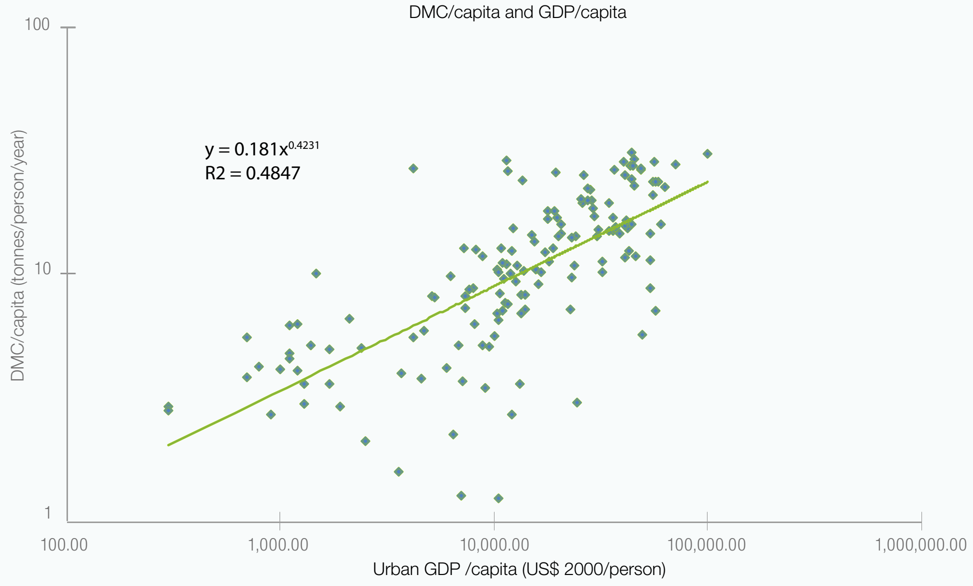
[26] http://www.materialflows.net and http://www.ces.csiro.au/forms/form-mf-la-start.aspx

*et al.,* 2013), but no globally comprehensive database or model is available. To distinguish materials in in-use urban stocks for different regions, estimations on the material intensity of a large variety of urban forms and their spatial incidence would also be required. Without an appreciation of the underlying stock dynamics, DMC still connects us to the operating material needs of stocks, changes in stock and the material requirements of their maintenance.

It might be anticipated that urban material consumption would relate to the wealth of citizens, to the extent that they can afford public infrastructures in addition to their own private material needs. Steinberger *et al.* (2010) found some relationship with national DMC and income measured in US dollars at 2000. In this work, we have stayed close to our original data sources and GDP measured in ppp terms has been used instead. We have generally found DMC per capita to be poorly correlated with city metrics, where it might otherwise be expected to relate to urban material flows: GDP measured in ppp, density, inverse density and total population. However, when we converted the GDP figures to US dollars as at 2000, a power law fitted curve shows a remarkable consistency with similar national-level observations in Steinberger *et al.* (2010) and UNEP (2011) (see Figure 2.11). A first-order global estimate of DMC per capita at 2050 based on the Baseline urban GDP per capita and this power law would be approximately 16 tonnes per capita. The fitted curve relies on the entire global data sample, and regional disaggregation does not produce such useful relationships ($R^2$ << 0.5). As we are interested in some regional differentiation, we do not use the power law regression in Figure 2.11 any further, although an enlarged global database might make the exercise worthwhile.

In the absence of globally comprehensive, regionally disaggregated, urban material flow information, we have opted to use a phenomenological approach. The top-down approach used here has been to estimate the future trends for DMC per capita of aggregate global regions using a logistic model. The underlying assumption is that regions that have experienced change in their material intensity have done so through the uptake of new infrastructure and technology. The logistic curve has been commonly observed in diffusion of innovation and technology uptake (Mansfield, 1961; Grübler, 1990). Another assumption is that all regions will reach some non-increasing equilibrium DMC per

**Figure 2.11**: Urban data on DMC per capita per year by urban GDP per capita. This graph attempts to show that DMC per capita correlates reasonably to urban GDP measured in constant US dollars as at 2000. Correlations with other metrics produce inconclusive results—original urban data on DMC per capita from Saldivar-Sali (2010)



capita value. This is based on the historical data for Europe, which has long since reached the last phase of socio-economic development and has had a stable, long-term average DMC per capita of between 12–13 tonnes per person per year for at least 40 years (see data presented in Annex A). It is important to recognize that DMC per capita is a measure of apparent consumption and if the full material footprint measured in raw material equivalents were used, the historical trend in material consumption would be upward, not stable. A corollary to these assumptions is the general expectation for major global developing regions to increase their urban metabolic rate per capita, but not to continue increasing that rate far beyond the levels seen in developed regions.

## Estimating future urban material consumption

The global sample of urban DMC per capita data supplies us with at least an average scalar value for each major global region for 2010. The difficult and highly uncertain estimation of the future relative change in those values is based on a phenomenological approach, using a logistic model fitted to regional time-series DMC per capita data. The S-shaped logistic curve has been commonly observed in diffusion of innovation and technology uptake (Mansfield, 1961; Grübler, 1990) and has the basic mathematical form as below:

**Equation 1**

$$L(t) = \frac{1}{(1+e^{-t/k})}$$

We model *L* as the material consumption per capita at a given time. *t* refers to time in yearly intervals and *k* is a parameter that modifies the scale but not the general form of the logistic function. *k* was varied for different global regions in order to fit the model to historical observations. Several other parameters have been introduced to couple the logistic model with empirical data as shown in Equation 2.

**Equation 2**

$$L_r(t) = A_r + \frac{M_r T}{(1+e^{-(t-t_{ri})/k})}$$

For each region, *r*, $A_r$ is the average DMC per capita (tonnes per person per year) at 15 years prior to $t_{ri}$, the year-date of the inflection point of the logistic curve. $M_r$ is the gradient of the least squares linear best fit to DMC per capita over 15 years previous to $t_{ri}$.

$A_r$ links the starting point of the modeled DMC per capita to historical data and $M_r$ determines the rate and polarity of change—some regions appear to be transitioning to lesser DMC per capita while others are increasing. For all regions except Africa: the inflection point, $t_{ri}$ was around 2010, meaning a good fit to historical data was obtained if we assumed that most regions have already experienced at least the first half of the logistic transition *T*. Thus, $M_r T$ sets the maximum expected change over the second half of the transition interval (ΔDMC per capita). Refer to Table 2.3.

**Table 2.3**: Parameters of the logistic modelling of future regional DMC per capita to fit historical data from the CSIRO Material Flows Database (EECCA refers to Eastern Europe, the Caucasus and Central Asia)

| | DMC/capita $A_r$(year) | ΔDMC/capita (after $t_{ri}$) | K | $t_{ri}$ | Description |
|---|---|---|---|---|---|
| Africa | 2.4(2000) | 7.6 | 4 | 2020 | 40-year transition from 2000–2040 |
| Asia and Pacific | 3.5(1990) | 10.4 | 4 | 2010 | 40-year transition from 1990–2030 |
| EECCA | 7.3(1995) | 4.3 | 4 | 2015 | 40-year transition from 1995–2035 |
| Europe | 12.7(1970) | −0.8 | 8 | 2010 | 80-year transition from 1970–2050 |
| Latin America and Caribbean | 5.1(1980) | 4.9 | 6 | 2010 | 60-year transition from 1980–2040 |
| Northern America | 19.7(1970) | −2.7 | 8 | 2010 | 80-year transition from 1970–2050 |
| Western Asia | 7.2(1995) | 7.1 | 2.5 | 2008 | 25-year transition from 1995–2020 |

The mathematics ensures that regions that have attained a consistent, long-term DMC per capita essentially maintain that stability with some potential for relatively small change (e.g. Europe). Africa is yet to experience the urban growth seen most recently, for instance, in Asia. For Africa, $t_{ri}$ was set to 2020 and $T = 40$ years, indicating that Africa's transition will occur between 2000 and 2040 with an inflection around 2020. This is at least consistent with concurrent anticipated urbanization trends in Africa (UN-DESA, 2014). Each fitted future regional DMC per capita scenario was indexed to 1 at 2010 and multiplied by the regional urban averages for that base year. Aggregate urban DMC was then estimated by multiplication with the Baseline urban population scenarios for each global region (see Annex A for an expanded explanation and sensitivity analysis).

Western Asia, which includes the Middle East, has seen a surge in construction activity over the last 10 years and this trend affects the calculation of the future urban DMC per capita for that region. The possible oversupply of built infrastructure in this region should be balanced with the projection that the urban population in this region will increase by 86 percent by 2050 (only Africa, Southern and South-Eastern Asia have greater relative growth rates). The countries of the Middle East use, and are expected to expand, their gas and oil infrastructure to generate electricity (OECD/IEA, 2015). The main difference between Western Asia and developing regions is in the latter's accelerating consumption of non-metallic minerals in construction and fossil fuels. By contrast, the two regions with comparable DMC per capita to Western Asia (Europe and North America) are conspicuously decreasing their consumption of non-metallic minerals and fossil fuels, and the Baseline Scenario continues these trends.

The Baseline DMC per capita projections are consistent with the narratives and data described in previous sections: the persistence of the long-term de-densification trend; the expansion of urban areas (notably in Africa and Southern Asia) and; the geometric rise in per capita income (notably in the smaller cities of the developing world).

Maintaining current infrastructure technology choices with future urbanizing populations, total world urban material consumption is estimated to rise from around 40 billion tonnes in 2010 to nearly 90 billion tonnes in 2050 (see Figure 2.12) for a projected urban population of 6.3 billion. This represents an approximate 116 percent increase in global urban material consumption

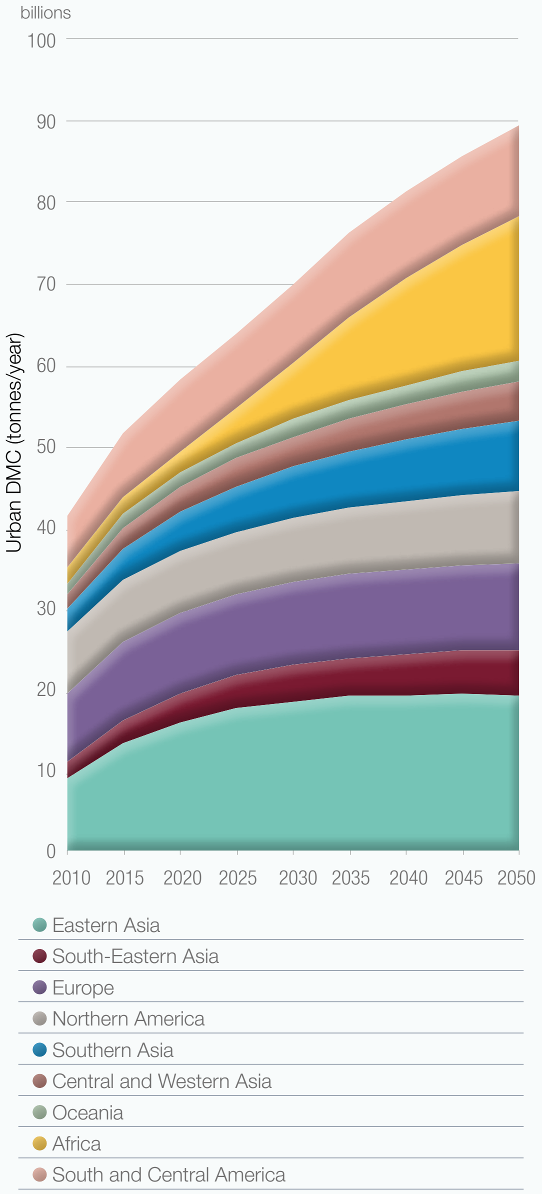
Credit: leungchopan/shutterstock.com

for a 78 percent increase in the size of the global urban population over the period from 2010 to 2050. This further translates to a global urban DMC per capita average of approximately 14 tonnes per person per year at 2050, which may be compared with the 11.6 tonnes per person per year at 2010 and contrasted to the estimate of 22 tonnes per person per year from an extrapolation of the power law regression with urban GDP per capita.[27]

Under this modelling, all major global regions see an increase in their total DMC, although there is an apparent 'contraction and convergence' of DMC per capita with all developing regions increasing, and all developed regions decreasing their DMC per capita. The range of values for average urban DMC per capita across regions is 8–17 tonnes per person per year at 2050, with higher values in Northern America, Asia and the Pacific and Western Asia, mid-range values in Europe, Eastern Europe and Central Asia, and lower values in Africa, Latin America and the Caribbean.

A previous IRP report on decoupling (UNEP, 2011) proposed three scenarios of future global material intensity or 'metabolic rate': a business-as-usual (BAU), a 'moderate contraction and convergence' and a 'tough contraction and convergence'. The BAU scenario produced an estimated global average DMC per capita of 16 tonnes per person per year at 2050 and a total of 140 billion tonnes per year. The moderate contraction and convergence scenario allowed for some catching up of the developing world, such that the global average material consumption per capita would be 8 tonnes per capita per year (still a third of the North American historical average). At this level of average consumption, total global material requirements at 2050 were estimated to be 70 billion tonnes. The tough contraction and convergence scenario assumed a per capita material consumption of around 6 tonnes per capita per year in order to arrest aggregate global material requirements at the level of 50 billion tonnes by 2050, which was the level observed at 2000. The authors conceded that this scenario would involve "…

**Figure 2.12**: The composition of global urban DMC by aggregate world regions



(Source: Historical data from the CSIRO Material Flows Database; West and Schandl, 2013a)

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[27] The calculation from the power law regression relies on current data about cities when a third of the world's urban population (and approximately a third of our sample set of cities) is in the developed world. Neither the predominance of the developed world in the urban population of 2050, nor any change in regional per capita urban DMC is represented by the power law regression. This results in an overestimate compared with the modelling of transitions in DMC per capita, which has regional resolution and uses regional urban projections to obtain the global average DMC and DMC per capita.

far-reaching absolute resource use reductions in the developed countries, by a factor of 3 to 5. In this scenario, some countries classified as 'developing' in the year 2000 would have to achieve 10–20% reductions in their average metabolic rates while simultaneously eradicating poverty…"(UNEP, 2011).

Even so, the IRP suggested an average material intensity of consumption per capita of 6–8 tonnes per capita per year in 2050 as a target for an SDG, to achieve decoupling of natural resources use from economic growth.[28] However, by 2005 global total material requirements had risen to 60 billion tonnes, by 2010 it was 79.4 billion tonnes and in a more recent BAU scenario, global material extraction was simulated to exceed 180 billion tonnes per year by 2050 (UNEP, 2016). Although the Baseline Scenario serves mainly as a reference case and is deliberately agnostic of policy interventions, the global material history of the last 10–15 years suggests that the assumptions about globally increasing resource requirements are realistic.

At 2010, urban DMC accounted for approximately 50 percent of total global DMC, and if the outcome of the BAU scenario from the previous IRP report (UNEP, 2011) is used, this ratio would increase to above 60 percent at 2050, with total global urban consumption rising to 89 billion tonnes. If *urban* DMC per capita at 2050 can be reduced from the modeled range of 8–17 tonnes per capita per year to a range of 6–8 tonnes per capita per year, this would contribute significantly to achieving the SDG resource decoupling target. A first-order estimate would be a saving of some 44 billion tonnes per year.

Looking at regional projections in Figure 2.12, Eastern Asia has the largest total urban material consumption at 2050 (19 billion tonnes per year). This is dominated by China, whose total DMC is projected to increase from 4.9 billion tonnes per year in 2010 to 13 billion tonnes per year in 2050 (approximately 170 percent). A still greater increase was modeled for India, which had an urban DMC of 1.8 billion tonnes per year in 2010, rising to over 6.7 billion tonnes per year at 2050 (approximately 270 percent). This dominates the result for Southern Asia, with the second largest increase in DMC for any global region of approximately 220 percent (see Table 2.4).

By far the largest relative change in urban DMC in the Baseline Scenario is seen in Africa. Although Africa in comparison with other regions is projected to have the lowest urban DMC per capita by 2050, urban population is projected to increase by 240 percent between 2010 and 2050, resulting in an urban population change larger than other regions. This combination places Africa as the second largest in terms of projected total urban material consumption at 2050—18 billion tonnes per year up from 2 billion tonnes per year in 2010, representing the largest increase of any global region, approximately 790 percent (see Table 2.4).

**Table 2.4**: Baseline total urban DMC by major global regions at 2050 and relative change between 2010 and 2050[29]

| Major global regions | % total urban DMC change between 2010 and 2050 |
|---|---|
| Eastern Asia | 115% |
| South-Eastern Asia | 180% |
| Europe | 25% |
| Northern America | 17% |
| Southern Asia | 220% |
| Central and Western Asia | 150% |
| Oceania | 140% |
| Africa | 790% |
| South and Central America | 70% |
| World | 116% |

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[28] http://www.un.org/sustainabledevelopment/sustainable-consumption-production/

[29] Sum of regions does not equal World due to rounding.

## 2.5. Conclusion

This chapter has provided a glimpse of the resources future that lies ahead for cities that do not take action to shift their current consumption trajectories. By combining trends in population and income, and using a phenomenological approach, DMC has been calculated for cities in the world’s major regions up to the year 2050, acting as a Baseline Scenario for this report. The key conclusion is that maintaining current infrastructure technology choices with the expected future urban populations is likely to result in an increase in urban material consumption from around 40 billion tonnes in 2010 to approximately 90 billion tonnes in 2050. During this period, the urban population is anticipated to increase by 78 percent, and global urban material consumption will increase by an even greater 116 percent. By 2050, DMC per capita is likely to converge at around 8–17 tonnes per person per year, which exceeds the range of 6–8 tonnes per capita per year required to achieve decoupling targets. This raises the question of how cities might shift their resource-intensive trajectories to achieve lower DMC figures, while also improving quality of life for their citizens. The following chapters will show how strategic interventions in infrastructure and spatial planning can help to achieve significant reductions in urban resource use, providing inspiration for sustainable urban transitions across the globe. However, it should be noted that since the real drivers of urban DMC are complex and context specific (as demonstrated in this chapter), the interventions discussed in subsequent chapters should not be seen as the only interventions that will make a difference. In particular, this chapter has demonstrated that rising average incomes are the biggest driver of rising urban DMC. While the interventions addressed in subsequent chapters are based on the assumption that there will be public policy interventions aimed at achieving the SDGs of ending poverty and reducing inequalities, what these macroeconomic interventions actually are is not the primary focus of this report.

Credit: ultramansk/shutterstok.com

# Chapter 3

# Urban form — Articulated density for efficient and liveable cities

## 3.1. Introduction

Chapter 2 analysed the resource requirements of future urbanization to 2050 on the basis existing urban configurations remain constant. One of the key assumptions of the Baseline Scenario was that density would decline at an average of 2 percent per year in all countries except land-constrained states, and that the USA would make no changes to its density over the scenario period. This chapter addresses the challenge of urban form and density, and provides a nuanced discussion on how spatial planning and an efficient distribution of people and job densities can be used strategically to optimize urban resource consumption, without claiming that densification alone will result in resource-efficient urbanism.

There is considerable evidence that the form, density and functionality of the city has considerable impacts on its resource use: first, on resources embedded for constructing the built environment (including infrastructure and buildings), and second, on resources for operating the built environment. As the complete life cycle of products and systems is addressed in other chapters, this chapter does not cover end of life, demolition, recycling and re-use of the built environment. It shows how different urban forms, levels and organization of job and people densities impact on resources used for transportation and those embedded in transportation infrastructure, and more generally in urban infrastructure networks. It also shows how different types of communities (typically car dependent, low density, single use versus mixed use, clustered at higher densities around transit nodes with co-location of people and jobs) affect travel demand and the resources needed for travel, and how urban design with more compact urban fabric (typically high-rise, low-density, towers-in-a-park, modernist developments versus dense and compact, traditional, continuous urban fabric with locally adapted bioclimatic features) reduces both embedded and operational energy of the built environment.

The first and primary resource used by cities is land. The amount of land used per person, the land-use pattern and its integration with transportation networks are, along with economic and industrial structure, significant drivers of urban resource use. Urban land expansion is a long-term trend that has characterized European cities for centuries. For example, while the population of Paris *intra muros* was 415,000 in 1637, at a density of 96,512 people per km$^2$, it had decreased to a density of 24,448 people per km2 for 2.24 million inhabitants in 2014, still among the highest global densities. A study that examined 30 world cities between 1800 and 2000 (Angel, 2012) found that 28 cities of this sample increased their areas more than 16-fold in the 70 years between 1930 and 2000, with the only exceptions being London and Paris—these were the two largest cities in the 1900 sample and had increased their areas 16-fold since 1874 and 1887 respectively (Angel, 2012). Between 1800 and 2000, urban area per person grew at an average annual rate of 1.5 percent in this representative sample of 30 global cities (Angel, 2012). The decline in densities generally started in the last two decades of the 19th Century (several decades before the advent of the automobile), when horse cars, trolleys and then trams and railways radiated to and from the compact urban core and enabled people to move further and faster, changing the shape of the city from roundish to spread out. On a sample of 25 world cities, densities declined fourfold from their peak, from an average of 39,700 people per km$^2$ to an average of 10,200 people per km2 circa 2000 (Angel, 2012). A global survey including data on 3,646 large cities (defined by a population of over 100,000 people) comprising some 2 billion people in 2000 found that a 10 percent increase in GDP per capita was associated on average with a 1.8 +/- 0.3 percent increase in urban land cover (Angel, 2012).

All data sets show that most cities, with exceptions in particular on the Indian subcontinent, are decentralizing and reducing densities as they grow and increase their GDP per capita. The recent reduction of overcrowding in Chinese cities, through land expansion and redevelopment, has vastly increased floor space per person in recent decades. In Tianjin, for example, it increased from 6.5 m$^2$ in 1988 to 19.1 m$^2$ in 2000 and to 25 m$^2$ in 2005.[30] The rapidly growing cities of the developing world can expect similar trajectories from very high densities to medium-high. Thus, this chapter does not advocate densification per se, but rather a more efficient, sustainable and inclusive distribution of densities across the urban space. In many cities of the developing world, land provision per inhabitant is hugely insufficient to cover basic population needs, transportation needs and economic growth needs. There is indeed a wide variation in average population densities. The span in 2015 between the two extremes is a 32-fold difference, exemplified by Chicago with a density of 1,740 people per km$^2$ on the built-up land and Dhaka with a density of 55,150 people per km2.[31] Urban densities (calculated based on the built-up land) in the USA, Canada and Australia averaged 2,300 people per km$^2$ in 2000. In contrast, they averaged 6,700 people per km$^2$ in Europe and Japan, an average reached in large Chinese cities such as Beijing and Shanghai in 2015. Densities in developing countries as a whole were significantly higher than those of Europe and Japan, averaging 13,600 people per km$^2$. In general, urban densities in Europe and Japan were found to be half those of developing countries, and urban densities in the USA, Canada and Australia were one third of those of Europe and Japan (Angel, 2012).

Thus, in developing countries where density on average is still at a sustainable level, they are at an important crossroads in their development. Some, like Mumbai and most Indian subcontinent cities, need sensible de-densification and reshaping of their urban form according to the levers of resource efficiency described in this chapter, with adaptation to local conditions, lifestyles and financial resources. Others need an efficient structuring of their present densities in order to remain at sustainable levels and avoid further decrease of density. The choices that these emerging cities (where 90 percent of the additional 3.5 million urban dwellers is expected between 2000 and 2050) make today about managing their urban growth and shaping their urban form and density will lock in economic benefits—or costs—for decades to come. The lifespan of capital-intensive, largely irreversible urban infrastructure investments, such as roads and buildings, typically ranges from 30–100 years, and the path dependencies created by urban form are sustained over centuries (Floater *et al.,* 2014b).[32] Poorly planned urban form is likely to have substantial economic costs and increase resource use. Urban sprawl, poor public transport infrastructure and a lack of basic services, such as energy, water and waste, can hinder accessibility and mobility, increase air pollution and exacerbate urban poverty, reducing the economic benefits of urban concentrations and increasing costs. This growth pathway also tends to lead to unnecessary resource consumption, GHG emissions and a range of other environmental and social costs (Floater *et al.,* 2014b).

Cities need to adopt a systemic[33] approach that is integrated rather than sectoral, and transformative rather than fragmentary, linking urbanization and human settlements to sustainable development by focusing on well-being for all, while reducing resource consumption. Sustainable cities should be fair, green and accessible (Simon *et al.,* 2017). The systemic nature of resource and energy use is a more significant driver of resource consumption than the individual efficiency of each component of the system. For instance, ecomobility can

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[30] Tianjin Municipal Statistical Bureau 2006.

[31] Data from Angel *et al.,* 2016.

[32] Over the coming decades, this will be particularly important for cities in emerging economies. For example, 70–80 percent of the urban infrastructure that will exist in India in 2050 has yet to be built (McKinsey Global Institute, 2010).

[33] City planning, finance and governance need to build more on system thinking because cities are complex systems. Urban agencies often work in silos, but urban reality never works as a silo. Ultimately, policies have a strong effect only when they are bundled.

reduce transport energy requirements far more effectively than making the urban vehicle fleet more fuel-efficient.

This chapter analyses the impacts of four levers of efficiency on the resources needed by the built environment, including buildings and urban infrastructures. Food and industry are excluded from this analysis. The chapter will demonstrate that improvements to human well-being depend on a more 'productive' and socially inclusive urban configuration. This can be achieved by using four main levers of change, namely:

1. **Compact urban growth,** that is, a highly accessible urban shape, spatially structured to achieve reasonably high densities, connected by well-articulated networks of efficient and affordable mass transit systems around strategically intensified nodes.
2. **Liveable, functionally and socially mixed neighbourhoods**, with a rich mix of housing types and social amenities for different income groups; a good jobs/residents balance in the neighbourhood providing job opportunities near homes; dense and connected grids of streets defining small perimeter blocks, which create conditions for soft mobility (e.g. walking, cycling) and passive heating, cooling and lighting at the building level thanks to a bioclimatic design.
3. **Resource-efficient buildings and urban systems,** such as energy-efficient buildings with innovative designs, new heating, cooling and lighting technology, and building control systems; public, soft and smart transportation systems, such as subways and BRT systems, cycle paths, vehicle sharing, walkability, smarter traffic information systems, electric vehicles and charging point networks; efficient energy, waste and water systems, street lighting technology and smart grids.
4. **The promotion of sustainable behaviours**, specifically the separation of waste at source for recycling, the use of public transport, walking or cycling, the use of public spaces, care for the young and the old, education on a lifelong basis and interaction within diverse communities.[34]

The actual improvements in energy and resource productivity from each of these interventions are not simply the sum of each intervention, but are multiplicative if they are implemented in mutually reinforcing ways. Implemented in combination with a range of other interventions, they can contribute to a decrease in urban resource use while increasing prosperity and well-being.

This chapter discusses in detail two of the four levers of change for achieving well-articulated urban forms, comprising a hierarchy of strategically intensified nodes of people and jobs interconnected with mass transit systems and liveable, functionally and socially mixed neighbourhoods. Although the chapter focuses on the form and level of density, it should be emphasized that density alone will not reduce resource use if the four levers are not implemented in an integrated manner, and if economic growth is based on an oversupply of urban infrastructure, as has happened in China over the last 20 years.

It should also be emphasized that increasing density is not an objective in itself; it should be balanced by the need, in some excessively dense cities in the developing world (e.g. Indian cities), to provide enough land per capita to achieve sustainable goals for living space per capita, connective streets and social

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[34] The fourth lever is seldom mentioned but it is extremely important. For example, by comparing the actual energy use of different block types of Paris building stock with their theoretical energy use resulting from modelling simulation, one can observe the influence of inhabitant behaviour that explains a 2.6-fold difference in heating consumption across Paris *intra muros* building stock of 96,000 buildings between buildings heated with electricity and buildings heated by district heating (Salat, 2009). When people's behaviour is taken into account, electric heating results in reduced consumption because of the price impact and the easiness to control consumption. Besides, in very efficient buildings, the behavioural impact is more limited because technology manages energy consumption and because one can observe rebound effects where efficiency is used not to decrease consumption, but to increase comfort.

infrastructure, such as education and health. The chapter should not be understood as a claim for densification per se, but as an assessment of the benefits of medium to high density (between 7,500 and 10,000 people per km$^2$ on built-up area at metropolitan region scale and around 15,000 people per km$^2$ on built-up area at central city scale) with an articulation and integration of density with transit accessibility, as opposed to low densities weakly integrated with transit. Reasonable benchmarks of density for both reducing resource use (environmental goal) and providing sufficient land for housing and social infrastructure per capita (economic and social goal) are documented in this chapter.

On the one hand, urban land-expansion rates across all regions are higher than or equal to urban population growth rates, suggesting that urban growth is becoming more expansive than compact. Land-expansion limitation approaches tend to foster urban growth based on a compact, dense model, where densities are articulated with higher densities of people and jobs around public transit nodes. Land-expansion limitation policies are a response to the increase in urban land area observed worldwide. On the other hand, the global affordable housing gap is currently estimated at 330 million urban households and is forecast to grow by more than 30 percent, to 440 million households or 1.6 billion people, by 2025 (King *et al.,* 2017). A policy concern in some highly dense cities is the shortage of ample and accessible land to provide adequate housing and the impact of this insufficient provision on affordability, especially for the poorest segments of the population. Mumbai, for example, is already highly dense, and is estimated to need 5 million housing units by 2036 (Mumbai Metropolitan Region Plan 2016–2036). The services and infrastructure gap is also huge. For example, more than 50 percent of the urban population in Southern Asia and 40 percent in sub-Saharan Africa lack access to sanitation services.[35] Lack of access to sanitation can reach extremes in slums, as exemplified in the slums of Nairobi, Kenya, where there is one toilet for every 500 people (Weru, 2004). We must acknowledge that in these cities, well-structured urban expansion is likely to be required to provide services at sufficient scale. City densities must remain within a sustainable range. If density is too low, it must be increased, and if it is too high, it must be allowed to decline, while being highly structured and articulated.

## 3.2. A four-lever framework to achieve Factor 10 resource productivity

Although context-specific urban planning is essential, the four main levers of change could be generalized for most cities facing urbanization in the developing world. Compact growth, functionally and socially mixed neighbourhoods, energy-efficient buildings and systems, and behavioural change will deliver benefits for resource efficiency and inclusiveness in a variety of contexts. Moreover, the New Urban Agenda also acknowledges the need for optimizing the spatial dimensions of urban form, calling for the reinvigoration of integrated urban and territorial planning and design.

### 3.2.1. Urban form contributes significantly to decoupling urban economic growth and carbon emissions

Compact urban form and reasonably dense and mixed land use, liveable communities, energy-efficient buildings and systems, and behavioural change deliver significant benefits by *decoupling* urban growth from urban infrastructure costs and environmental pressure. Compactness is an important geometric property of urban shapes that is different from density. The sustainability debate about the ‘compact city’ too often assimilates compactness to density of urban areas. The real meaning of compactness is a property of the shape of urban footprints. An urban shape can be compact and dense or compact and not dense. Density measures intensity of

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[35] 830 million urban dwellers lacked piped water on premises in 2015. If this included a criterion for defining slum populations, the number would be much higher. See Satterthwaite *et al.,* 2015.

land use; compactness measures key shape properties of the urban footprint. Dictionaries typically define a compact object as one closely and firmly packed, or having component parts closely fitted together. There are good reasons for making cities more compact. In purely geometric terms, for example, if two cities have the same area, residents in the more compact city will have to travel a shorter distance, on average, to the city centre or to any location within their city (for a discussion of geometrical compactness properties, see Angel *et al.,* 2010). In pedestrian-oriented historical cities, compactness led to roundish shapes in order to minimize walking distances and walking times from all points to the centre, and between any pair of points. With the introduction of commuter lines, travel times became more important than geometrical distance. The area that can be reached within 30-minutes commuting time by transit defines compactness in the transit city. In a transit city, public transportation networks shape the area that can be reached within 30 minutes in the form of radiating corridors (for a detailed discussion on the 'pulsating compactness of urban footprints' with the successive introduction of transit modes and transit lines, see Angel, 2012 [Chapter 14]). This explains why Copenhagen, Stockholm, Hong Kong and Tokyo, which are used as examples in this chapter, can be considered compact cities, because their radiating shapes are articulated by transit. Overall access in the more compact city will be greater than in the less compact one, and public infrastructure will be shorter on average (Angel, 2012). Thus, the geometrically compact city will require less embedded resources in infrastructure and less resources to operate. On the contrary, less compact forms decrease overall access in the urban area while increasing the length of and resources embedded in infrastructure lines extending out towards the periphery.

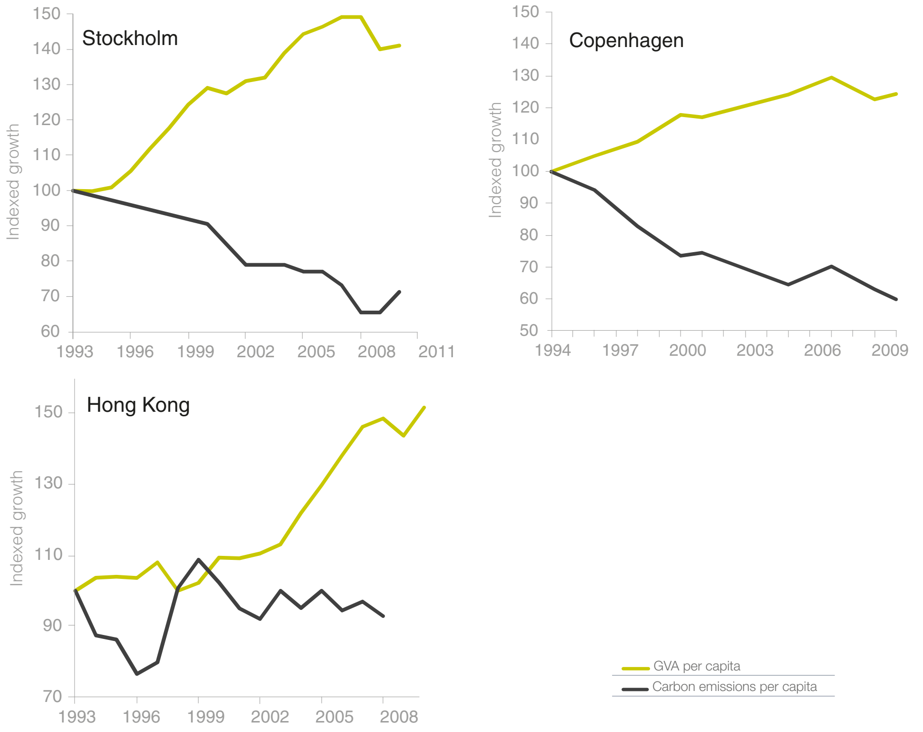
Credit: Ecuadorpostales/shutterstok.com

## Urban form matters for decoupling

From a wide body of international research, comparison of seven global cities (Bangkok, Chicago, London, Madrid, Mexico City, Milan and New York City) suggests that besides the significant role of climate conditions, urban density appears to be the main determinant in shaping residential emissions from direct fuel consumption, whereas for electricity, consumption patterns and technological features of power generation play a major role. For ground transport, urban form affecting mobility patterns and technological features of the vehicle stock stand out as the most significant determinants (Croci *et al.,* 2011).

Stockholm was able to reduce GHG emissions from transport, heating and electricity by 35 percent between 1993 and 2010 from a low starting point, while growing its economic output by 41 percent over the same period—one of the highest growth rates in Europe (Floater *et al.,* 2014b). By pursuing a planning vision for a desirable urban form consistently over a number of decades, the growth of Stockholm's built-up area has followed the city's main public transport corridors. During this time, the containment of urban development along these corridors has ensured a threshold level of density which, in turn, has facilitated a public transport-oriented mobility system. Even over the last 10 years, Stockholm's containment index—representing the growth of population within the core city compared with the outer belt—has remained positive. With an index of 0.38 percent, Stockholm displays a strong focus on new developments within the existing city.[35] Stockholm's long-term growth, current levels of wealth and rates of productivity are among the highest in the OECD (Floater *et al.,* 2013). The World Economic Forum ranked Stockholm fourth in the world for competitiveness, higher than any North American city.

**Figure 3.1**: Decoupling of economic growth and city carbon emissions in Stockholm, Copenhagen and Hong Kong. Carbon emissions are for the transport, heating and electricity sectors alone and do not include direct industrial emissions



(Source: Floater et al., 2014b - LSE Cities Urban Age)

Similarly, Hong Kong (an extremely compact city with high levels of transit accessibility) and Copenhagen have delivered strong and stable growth while reducing GHG emissions.

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36. Furthermore, compared to cities in other major OECD countries, Stockholm's urban containment is second only to London.

The following sections address in more detail the cascading effect of the four levers on built-environment energy and transportation energy use.

### 3.2.2. The cascading effect of the four levers on built-environment energy use

According to the International Energy Agency (IEA), existing buildings account for approximately 40 percent of the world's total primary energy consumption and 24 percent of the world's $CO_2$ emissions. However, a broader definition of the built environment should also include the energy for operating both buildings and the surrounding neighbourhoods. When combining these two scales, research has found that the built environment in an extended sense is responsible for a significant use of final energy (62 percent), and is a major source of GHG emissions (55 percent) (Anderson *et al.,* 2015). Achieving resource reduction goals in the built environment thus requires comprehensive methodologies to assess the impacts from both buildings and their surroundings, and the interaction between the two. Most research to date either focuses on individual buildings or on the urban level (e.g. metropolitan regions). Robust and accurate methodologies have been developed to quantify resource and energy impacts at both scales. While methodologies overlap between the building and urban levels, assessment remains largely confined within each scale. At the building level, research focuses on materials, architectural design, operational systems, structural systems, construction and analysis methods. At the urban level, urban form, density, transportation, infrastructure, consumption and analysis methods are the main research focuses. This section limits its scope to giving well-established results at both levels, but an expanded analysis framework to account for the interplay between the building level (lever 3) and the city level (levers 1 and 2) should be further elaborated to fully capture all induced impacts and to bundle together policies addressing both levels.[37]

There is a great opportunity to make significant reductions in built-environment energy demand, thereby reducing the need for supply, together with the energy costs. Energy-efficiency planning for the built environment should start with compact urban growth strategies and planning for liveable, functionally and socially mixed neighbourhoods. This provides the basis for implementing resource-efficient buildings and urban systems based on clean and renewable energy sources, and eventually incentives and price mechanisms to encourage people to consume less energy.

1. International research has demonstrated that more compact forms with higher densities can reduce infrastructures and GHG emissions by a factor of two or more (i.e. multiplied by 0.5 compared with sprawl) (Salat *et al.,* 2017).
2. Planning and designing liveable, functionally and socially mixed neighbourhoods, with a dense urban fabric made up of small-scale urban blocks and dense street patterns, facilitates a reduction in energy consumption by a factor of two or more (i.e. multiplied by 0.5 compared with BAU).
3. The energy-efficient buildings and urban systems lever includes retrofitting buildings to limit thermal losses, creating synergies between buildings, and enhancing the efficiency of energy systems, with renewable energies, demand-side management, etc. (Kolokotroni *et al.,* 2011). With energy-efficient buildings, reductions in energy demand by a factor of two or more could be achieved (i.e. multiplied by 0.5 compared with BAU), while efficiency of energy systems facilitates an additional 20 percent energy saving (i.e. multiplied by 0.8 compared with BAU).
4. Finally, the behavioural lever rests upon changes in individual behaviours by using awareness campaigns, implementing price signals or direct feedback on individual consumption. Empirical data have shown that people use less energy when energy price is higher and when they can control their consumption (Salat, 2009). This would also reduce energy demand by a factor of

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[37] For a review of methods at each scale and of the potential for integrating scales, see Anderson *et al.* (2015).

two (i.e. multiplied by 0.5 compared with BAU) (Salat, 2009).

These factor numbers are illustrated below, with examples that show that the factors listed above are conservative, and that higher levels of performance for the four levers can be observed.

First, compact urban growth has significant impacts. A 27-fold difference in average density between Atlanta and Barcelona results in more than a tenfold level of carbon emissions per capita in Atlanta than in Barcelona (Bertaud *et al.,* 2004).

Second, urban fabric at the neighbourhood scale impacts on urban heating energy by about a factor of two or more (Ratti *et al.,* 2005, Salat, 2009, Salat *et al.,* 2011). A recent study by LSE Cities and Eifer on the impact of urban texture (building density, surface-to-volume ratio, surface coverage options) on heating energy in four cities (London, Paris, Berlin, Istanbul) has identified, through modelling, a large variation up to a factor of six for the heating energy demand of different morphologies. A key result is that compact urban blocks consistently perform best and detached housing worst (LSE Cities & Eifer, 2014).[38] An important result in the Chinese context—established by a Massachusetts Institute of Technology (MIT), Tsinghua University and Energy Foundation study in 2009 and 2010 from data collected across 27 neighbourhoods in Jinan—is that superblocks[39] with towers-in-a-park urban forms use about two times more energy than other typical Chinese urban forms for building operations and embodied energy (Yang, 2010; MIT *et al.,* 2010).

Third, empirical data and modelling shows that increasing energy efficiency (essentially insulation of walls and efficient glazing) can reduce energy loads by a factor of two or more. For example, the Parisian compact and efficient urban block, in terms of shape factors, has a heat energy demand of 97 kWh with a wall U-value of 2, reducing to 37 kWh when the U-value is reduced to 0.5, thus a relative energy saving of 62 percent due to insulation alone. Berlin's detached housing shows a heat energy demand of 393 kWh at the high U-value of 2, reducing to 118 kWh at the low U-value of 0.5, thus a much greater relative energy saving of 70 percent (LSE Cities & Eifer, 2014).[40] Research has shown that a 5 percent change in U-values of structures results in about a 0.5–1 percent change both in modeled emissions and gross energy consumption (see Tab. 6 in Mattinen *et al.,* 2014). Energy systems' transition to electrification also has important potential. According to a recent report by the IEA (2014), increased electrification with a systemic approach is a driving force across the global energy system, with significant opportunities to reduce carbon intensity and global energy demand. The choice of technologies and their use along the steps of generation, transmission and distribution (T&D) and consumption of electricity will play a critical role in consumption reduction. Distributed energy systems,[41] for example, lead to a savings potential of 20 percent for energy use at the neighbourhood scale (GEA, 2012).

Fourth, people's behaviour matters. For example, in Paris, 1.3 times more energy than modeled is actually used by people with district heating as opposed to only one half with electrical systems, where people can control their energy use. Thus, in this example, human behaviour is a key

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[38] As early as 1996, Project ZED (Zero Emissions Urban Development) examined the heating energy efficiency of actual urban blocks in the centre of London. The findings vary from 166 kWh per m$^2$ to 282 kWh per m$^2$, a difference of 40 percent linked to a number of urban features, such as plan depth, level of obstruction and orientation (The Martin Centre for Architectural and Urban Studies *et al.,* 1997).

[39] In contrast to the grid and its public, high level of permeability, superblocks encompass large areas with no public streets. They are defined by large arterials (60 to 100 m wide with additional setbacks) every half kilometre in China. In Chinese cities, they are often gated and contain rows of identical, high-rise residential towers.

[40] The less efficient the form, the higher the impact of building insulation, however, it comes with a cost as there is a greater surface area to insulate.

[41] Distributed generation, also known as distributed energy, on-site generation (OSG) or district/decentralized energy is generated or stored by a variety of small, grid-connected devices referred to as distributed energy resources (DER) or distributed energy resource systems. Conventional power stations, such as coal-fired, gas and nuclear-powered plants, as well as hydroelectric dams and large-scale solar power stations are centralized and often require electricity to be transmitted over long distances. By contrast, DER systems are decentralized, modular and more flexible technologies, which are located close to the load they serve, albeit having capacities of only 10 megawatts (MW) or less.

factor in consumption reduction, with a factor of 2.6 (Salat, 2009).

The cascading impact of these four levers when applied to building energy is a multiplication of 0.5 x 0.5 x 0.8 x 0.5 = 0.1 compared to BAU. Using the multiplicative method, this would result in a tenfold reduction in energy use, which significantly exceeds the Factor 5 target that is usually referred to (von Weizsacker *et al.,* 2009).

### 3.2.3. The cascading effect of the four levers on transportation energy

The form and functionality of the city is crucial for sustainable mobility and the reduction of energy used for transportation fuel and embedded in transportation infrastructure. Transforming cities, wherein a mix of activities is closer together, in a more compact configuration, and interlaced by high-quality pedestrian and bicycle infrastructure is tantamount to the creation of a more *accessible* city. Accessibility lies at the core of achieving an urban form that is environmentally sustainable, socially equitable and inclusive (UN-Habitat, 2013a). The Intergovernmental Panel on Climate Change (IPCC) estimates that under poorly managed urban growth, carbon emissions from transport alone (of which a large proportion is conventional, motorized transport in cities) are projected to almost double by 2050 (IPCC, 2014a). To reduce transportation energy, the four key levers are as follows:

1. An efficient, compact growth at metropolitan scale with coordination of land use and transport planning, with a transit-oriented articulation of urban densities, including the following key characteristics: (i) diversity of land-use pattern and mix; (ii) articulation of transport network and densities to reduce distance to transit for people and jobs;[42] (iii) urban design features including co-location of places of employment and residence; and (iv) pedestrian design features. The metropolitan region should be articulated with a polycentric hierarchy, where the densest accessible clusters of jobs and population are agglomerated around the major public transportation interchanges. This reduces motorized travel demand and journey length.[43]
2. Walkable communities with pedestrian design features, such as well-designed public realms, streets as places for people, and dense and connected street patterns (at least 18 km of street length per km$^2$ and 80–100 street intersections per km$^2$, as recommended by UN-Habitat) to encourage walking and cycling.
3. Transport system efficiency (such as electric and hybrid cars, and electric transit systems connected to renewable energy grids) and upscaling of zero-carbon mobility systems (e.g. shared bike schemes, now in 20 European countries and roughly 1,000 cities worldwide).
4. A change in behaviour with a modal shift to walking, cycling and public transportation.

First, co-locating higher residential densities with higher employment densities, coupled with significant public transit improvements, reduces transportation energy consumption significantly. Highly accessible communities, designed according to the principles of TOD,[44] are typically characterized by lower travel demand, reduced journey length and shorter travel times (UN-Habitat, 2008), enabled by multiple modes of transportation (IPCC Fifth Assessment report, 2014). GHG emissions related to car use in London's peri-urban area, for example, are more than double those in the core urban area

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[42] As a benchmark, 75 percent of people and 84 percent of jobs are located less than 1 kilometre from a transit station in Hong Kong.

[43] A survey of 17 transit-oriented developments (TOD) in five US metropolitan areas showed that vehicle trips per dwelling unit were substantially below what the Institute of Transportation Engineers' Trip Generation Manual estimates. Over a typical weekday period, the surveyed TOD housing projects averaged 44 percent fewer vehicle trips than that estimated by the manual (3.754 versus 6.715). Vehicle trip rates of transit-oriented housing projects were particularly low in metropolitan Washington, D.C. and Portland, Oregon, both known for successful TOD planning at the regional and corridor levels. Trip rates also generally fell as neighbourhood densities increased (Cervero, 2008).

[44] See Section 3.3.4 for more on TOD.

(1.14 tonnes of $CO_2$ compared with 0.51 tonnes per capita of $CO_2$), whereas in New York they are four times higher in the peri-urban area compared with the core urban area (3.37 tonnes of $CO_2$ per capita compared with 0.84 tonnes of $CO_2$ per capita) (Focas, 2014).[45]

Second, walkable, mixed-use communities reduce transportation energy by a factor of two compared with urban superblock forms. In Jinan, for example, households in high-rise superblocks consume on average two to three times more transportation-related energy than those in any other urban fabric type. The single-use nature of towers-in-a-park projects requires that households use automobiles to accomplish all the activities of daily life; this is mitigated by the presence of shops, schools, services and employment made accessible by walkable environments (MIT *et al.,* 2010).

Third, transport system efficiency matters. Projections for 2050 from various sources compiled in the Global Energy Assessment (2012) envisage vehicle-efficiency improvements ranging from 28–45 percent for gasoline vehicles, to 40–55 percent for hybrid vehicles, compared with the base gasoline vehicle in 2012. Electricity produced from renewable sources can provide a significant stronghold for the global transformation of the transportation system.[46]

Fourth, human behaviour and modal share can be influenced by policies such as congestion pricing, for example. Urban road pricing schemes have been designed to reduce externalities generated by traffic, and can be used to generate public revenues. These schemes have reduced negative externalities generated by traffic, such as accidents, congestion and emissions, to varying degrees (Croci & Ravazzzi, 2015, Croci, 2016). The high modal share in the use of bicycles in cities such as Amsterdam and Copenhagen also demonstrates that integrated policies are key to shifting people's behaviour towards ecomobility. Copenhagen aims to be the first $CO_2$-neutral city by 2025 and encouraging cycling is an important policy for achieving this goal. Bicycles are used for 36 percent of all trips to work or educational institutions in Copenhagen (equating to 0 tonnes of $CO_2$ emissions), and the city targets a modal share of 50 percent of trips. There are two central principles in Copenhagen's bicycle strategy: prioritizing and innovation. Copenhagen will give more space to cyclists on the main arteries in order to increase their sense of security, make it possible for people to ride at their preferred speed and, not least, to make it more attractive for those who are currently too apprehensive to cycle. Travel times by bicycle will be improved compared with other transport forms by prioritizing ambitious shortcuts, such as tunnels and bridges over water, railways and large roads. Unique innovations, for example, making certain streets one way for cars in order to improve access for cyclists, introducing new types of bicycle parking (including cargo bike parking) and converting cobblestone streets into smooth cycle routes will encourage many new cyclists to start using their bicycles.

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45. A study of 11,000 households in Germany provides evidence that 50 percent of the total emissions from private transport and building operations can be attributed to urban and residential design choices, with density and physical concentration being key parameters contributing to greater carbon and fuel efficiency (Schubert *et al.,* 2013).
46. Plug-in hybrid electric vehicles (PHEVs) facilitate zero-tailpipe emissions for small vehicle driving ranges, e.g. in urban conditions. Hybrid electric vehicles (HEVs) can improve fuel economy by 7 to 50 percent compared with comparable conventional vehicles, depending on the precise technology used and on driving conditions. All-electric or battery-powered electric vehicles (BEVs) can achieve a very high efficiency (up to four times the efficiency of an internal combustion engine vehicle) (GEA, 2012).

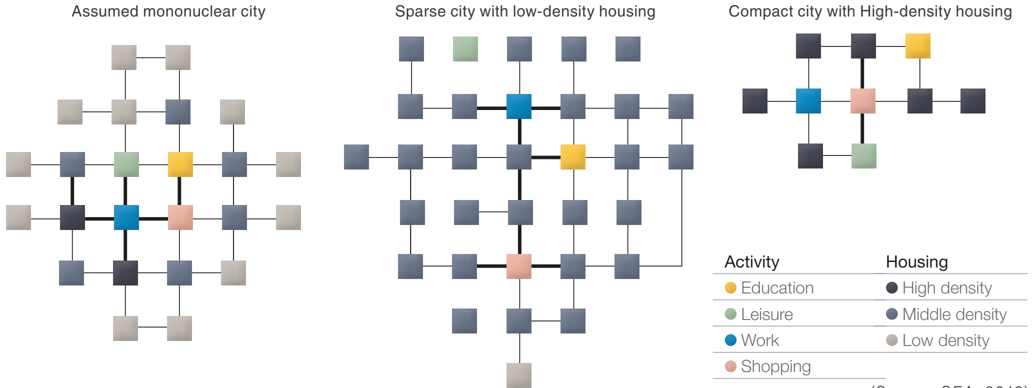
## The impact of urban layout scenarios on energy consumption

Introduced by Keirstead, Samsatli and Shah (2009), the SynCity Model has been used in the Global Energy Assessment (GEA, 2012 [Chapter 18]) to assess various scenarios for a town of 20,000 inhabitants. In these simulations, the city is an urban settlement for 20,000 people in a service-oriented, local economy, in a moderate climate and with natural gas (and oil) as the primary fuels.

Five scenarios were explored. At one extreme, a low-density city is fed from a power grid, with modest building-fabric energy performance. This city is considered as characteristic of one that has evolved in an economy in which resources are relatively inexpensive, such as the United States. The SynCity Modelling Toolkit, at the other extreme, optimizes a city for location of people, jobs and amenities, with a relatively high population density. It is comparable with an economy that is resource efficient, such as Japan.[47] Three intermediate cases are considered based on an intermediate density and imposed mononuclear layout (e.g. the United Kingdom). 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 with high-standard fabric implemented for all buildings, but at lower densities). Ultimately, 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, to avoid the risk that the efficiency improvements of building structures with better insulation are compensated by a shift towards less compact settlement patterns (GEA, 2012).

Conversely, the construction of large houses in a low-density, sparse layout results in increased heat loss (a 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 threefold increase in energy use compared to the optimized solution (GEA, 2012). As such, building a Passivhaus, standard, single-family home in a low-density (sub)urban area would not substantially lower energy use compared with 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 associated lower individual transport needs.

**Figure 3.2**: 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 coloured cells represent activity provision: green for leisure, blue for work, pink for shopping and yellow for education. The grey cells represent housing at different densities and the labels indicate the density in dwellings per hectare. The black lines that connect the cells indicate road connections and indicative traffic flows



(Source: GEA, 2012)

The results for each simulated city type are summarized in Table 3.1. Numerical values are indexed to the annual primary energy use of the sparse city design (144 GJ per 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, transport and upstream energy corresponds to the customary reporting of primary energy use.

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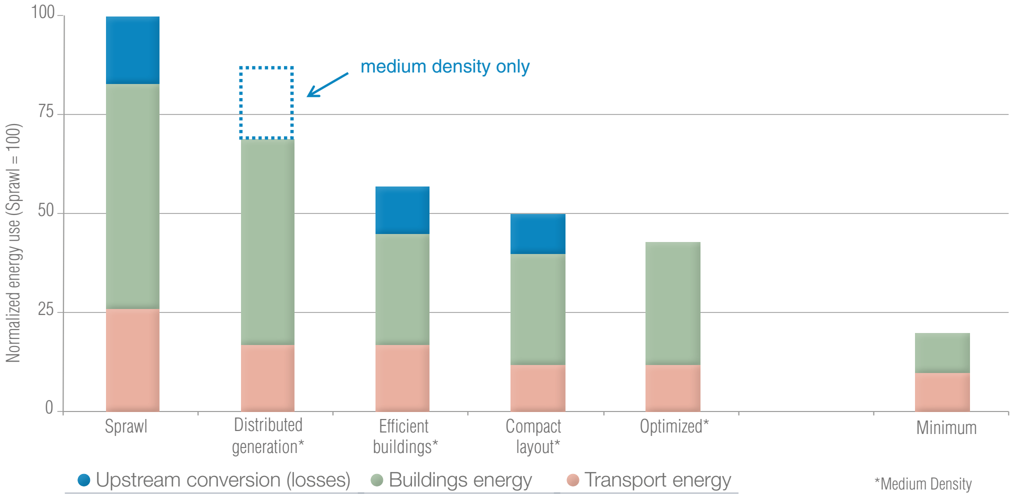
47. The location of housing and commerce, and the choice of distributed power generation sources are left to the optimizer.

**Table 3.1**: Primary energy use of five alternative urban designs for a town of 20,000 inhabitants. Results are indexed with sparse city =100 (144 GJ per capita in the simulation)

| 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 |

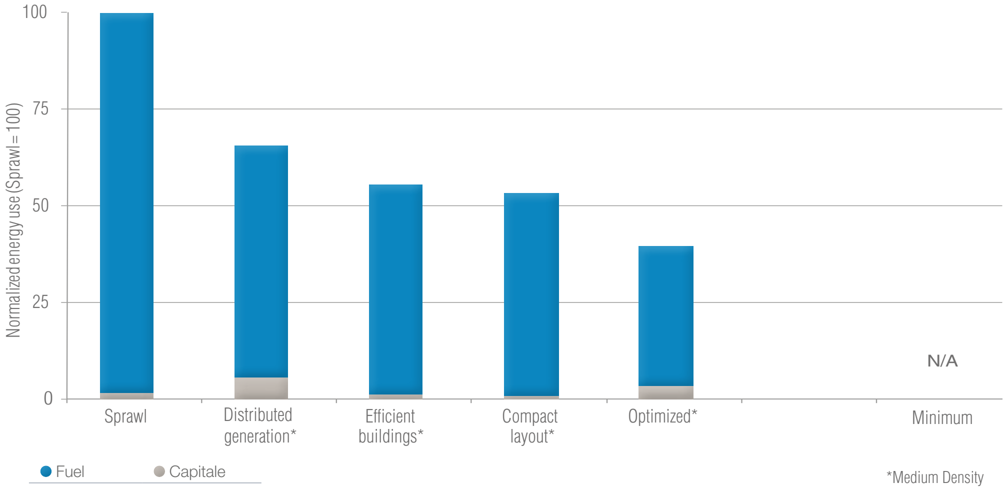
(Source: GEA, 2012)

**Figure 3.3**: Energy use for five alternative urban designs by major energy level and type. See above for definitions of the five simulations. The 'minimum' urban energy use estimate refers to implementation of the most efficient building designs and transport options available



(Source: GEA, 2012)

**Figure 3.4**: Total life-cycle costs (capital plus fuel) of the five city designs indexed to sprawl city = 100.



(Source: GEA, 2012)

The model results are as follows. First, where the grid is used, upstream energy loss in power generation represents 20 percent of primary energy (GEA, 2012). To ignore this contribution and focus only on delivered energy misses important upstream implications of energy choices for power. Second, a city with low resource efficiency is likely to consume about twice as much primary energy as one designed for high resource efficiency. The effects of urban planning and differences in fabric standards are comparable and should be considered together (GEA, 2012).

A detailed discussion of the first two levers of change will now follow: lever 1 (compact urban growth) is detailed in Section 3.3 and lever 2 (liveable, functionally and socially mixed neighbourhoods) is detailed in Section 3.4.

## 3.3. Lever 1: compact urban growth

Compact urban growth with a high concentration of production factors increases urban productivity. The theory of agglomeration economies argues that concentrating production factors leads to higher economic output, and that density and compactness reduce resource use. When these two processes are combined to improve social equity, inclusion of the urban poor and employment creation for the majority, the result can be significant enhancements in well-being.

Urban infrastructures use materials, including concrete and steel. These materials are heavily used in early phases of urbanization. If developing countries expand their infrastructure to current average global levels, the production of infrastructure materials alone would generate around 470 billion tonnes of $CO_2$ emissions by 2050 (IPCC, 2014b), much of this in sprawled cities. The continued expansion of infrastructure could produce cumulative emissions of 2,986–7,402 billion tonnes of $CO_2$ over the remainder of this century (Davis *et al.,* 2010). Poorly managed urban development could lock in higher operational emissions for decades and centuries to come. The IEA estimates that under BAU patterns of urbanization, carbon emissions from urban transport alone will almost double by 2050 (IEA, 2013).

Although this report uses density as a key metric for assessing compact urban growth, compactness should not be confused with density. The shape of urban footprints matters. Compactness is arguably the single most important aspect of urban shapes; it contrasts with fragmentation, which increases infrastructure and resource needs. High density of accessible jobs is also important, as is the overall 'order' of urban form, for which subsequent sections in this chapter will propose a definition.

The drivers of urban expansion and economic growth also matter, as demonstrated below by the case of Chinese cities.

Credit: Undrey/shutterstock.com

## Fragmented land conversion, massive investments in fixed assets and resource-intensive economic growth drive resource consumption in Chinese cities

Although their density is significantly decreasing, Chinese cities remain dense. Between 1997 and 2015, built-up area density has more or less halved in Chongqing—the largest city in the world, roughly the size of Austria, with a population of over 30 million—decreasing in density from 22,820 people per km$^2$ to 12,013 per km$^2$. From 2000 to 2014, Chongqing converted 1,031 km$^2$ of rural land for urban development to accommodate an additional 7.6 million new urban residents. This means that to accommodate each additional person, Chongqing had to convert and develop 136 m$^2$ of rural land.[48]

The excessive consumption of resources for infrastructure in Chinese cities is thus not driven by low density. It is, in fact, driven by fragmentation of the urban footprint. Analysing satellite images for 1990 and 2000 for a global sample of 120 cities, Angel *et al.* (2012) found that cities typically contain or disturb vast quantities of open space equal in area, on average, to their built-up areas. Chinese cities are characterized by a higher-than-average level of fragmentation. The mean value of the city footprint ratio (the ratio of the total area of the city, including urbanized open space, and its built-up area), which is hovering around 1.89 for world cities, was found to be 2.40 on average in 2000 for nine Chinese cities. This means that in 2000, the built-up area of Chinese cities fragmented and disturbed open space in and around the cities equivalent to 110–180 percent of their built-up areas.

Moreover, Chinese cities like Chongqing, Beijing or Shanghai, which have converted thousands of square kilometres of rural land, have also based a large part of their economic growth over the last two decades on investment in fixed assets and on infrastructure construction involving a huge consumption of raw material such as cement, steel and aluminium. Half of Chongqing's GDP is not concentrated, but fragmented and spread over an immense territory as large as Austria. Besides density, which is high in Chongqing by international standards, other characteristics of city form, such as compactness and fragmentation, which will be discussed further on in this chapter, impact on resource use, as do policies that encourage oversupply of infrastructure. While Chongqing's population doubled and its GDP was multiplied by 12 between 1996 and 2015, total investments in fixed assets have multiplied by 48, construction projects have multiplied by 45, real estate investment has multiplied by 68 and the length of expressways increased from 114 km in 1997 to 2,525 km in 2015, a multiplication of 22.[49] As a result, electricity production increased 5.3-fold, steel production increased 12-fold, aluminium production increased 22-fold and cement production increased 10.5-fold.[50] Energy economic productivity (energy per GDP), however, multiplied by 2.6 between 1997 and 2015, demonstrating significant efficiency increases in the industry. Chinese cities have a specific distribution of resource use. For most of them, GDP is derived from heavy industry[51] and from huge investments in infrastructure. In a typical Chinese city, half of the energy is used for industry, while another quarter is used for energy production, conversion and distribution.

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[48] Data from Chongqing Statistical Yearbook.
[49] Data from Chongqing Statistical Yearbook.
[50] Data from Chongqing Statistical Yearbook.
[51] For the last 20 years, secondary industry has contributed to two thirds of Chongqing's GDP growth, for example (data from Chongqing Statistical Yearbook 2016).

After discussing the trade-off between limiting land expansion and providing enough land for housing and infrastructure, and the negative impacts of present de-densification and sprawl patterns, this section will show how to shape urban densities efficiently through compact urban growth, based on integrated planning of transport and land use.

### 3.3.1. Present inefficient urban growth patterns with overly low or overly high densities: the trade-off between limiting land expansion and providing enough land for housing and infrastructure

In most developed countries, cities are growing more rapidly on the fringes than in the urban core, and in many developing countries, urban development is characterized by expansion on the periphery that is insufficiently served by public infrastructure. Land expansion in 292 city locations over three decades (1988–2008) shows that cities are expanding more rapidly than their populations are growing (Floater *et al.,* 2014a); urban areas have quadrupled over a period of 30 years, while urban populations at the national level have doubled (Seto *et al.,* 2011). Some estimates suggest that under BAU urban development, the area of urbanized land will triple between 2000 and 2030 (Seto *et al.,* 2012), compared with the observation in Chapter 1 that urban land area could increase from about 1 million km$^2$ to 2.5 million km$^2$. However, this general land expansion comprises markedly different situations.

First, density and land-expansion issues are distinct in developed and developing countries. Between 2010 and 2050, the urban population of the more developed countries will increase by a mere 170 million people, growing at a rate of 0.6 percent per year. During that same period, the urban population of the less developed countries will increase by 2.6 billion people, 15 times more than that of the more developed countries, and at a rate of 2.4 percent per year, which is four times faster than in the more developed countries (United Nations Population Division, 2013). Asian and African cities, where 90 percent of the next wave of urbanization will happen are, on average, around 35 percent denser than cities in Latin America, 2.5 times denser than European cities and nearly 10 times denser than cities in North America and Oceania (mostly in the USA, Australia and New Zealand). Overall, 39 of the world's 100 densest urban areas were situated in Asia in 2010 (UN-Habitat, 2008). Land provision per inhabitant in the more developed countries can be extremely high, especially in North America, while it can be extremely low in less developed countries, especially on the Indian subcontinent.

Second, there is an entire spectrum of cities, from those that are spread out at very low densities and contribute an unfairly large share of resource use and carbon emissions, and are thus unsustainable, to those that are so dense and overcrowded that they do not provide for basic urban habitation needs, services and infrastructure and even, as in Greater Mumbai, for example, enough land for economic activities. In excessively dense cities, density should be allowed to decrease on average, while compact urban form (a concept based on form and independent of density), articulated along efficient transit networks should be encouraged. Adhering to integrated planning principles has the potential to transform emerging cities, making them more affordable and unlocking land for affordable housing. For example, between 1970 and 2010, Hong Kong unlocked land for 600,000 affordable housing units close to transit routes by creating new towns along its subway lines (McKinsey Global Institute, 2014). In the middle of the spectrum, there are medium- to high-density cities—large, developed, Asian metropolitan regions tend to converge at a density between around 7,600 people per km$^2$ for Shanghai, Beijing or Tokyo and 11, 800 people per km$^2$ for Seoul. This is the result of land expansion starting from a point of low levels of land provision with substantial housing and infrastructure needs for affordability and social and economic development and, under the impact of increasing GDP per capita, stabilizing between 85 m$^2$ and 130 m$^2$ of built-up land per person.

### Density containment and land expansion require a dynamic perspective

Today, about one third of the urban population in the Global South lives in informal settlements. Land expansion will be a necessity in the Global South in the coming decades to provide well-located, affordable housing, transportation infrastructure, access to basic services such as electricity, running water and sanitation, and social infrastructure, such as health and education. In practice, a point of equilibrium will need to be found between limiting land expansion to ensure resource-efficient and accessible urban forms, and providing enough land for housing, infrastructure, public space and economic development.

**1. Increasing returns on infrastructure investment** characterize dense, mixed-use and compact urban patterns. The higher the density, the lower the cost per capita for infrastructure, such as transportation, water and wastewater, and the better the accessibility to social infrastructure, such as health or education. Higher density also increases the economic efficiency of land and enables cities to implement effective mechanisms of land value capture to finance infrastructure investments. It is essential to eliminate land-use segregation. Using land in mixed-use, accessible and denser configurations can provide multiple benefits when affordable housing is included. Mixed-use development can minimize the need to travel long distances if daily needs are catered for within walking distance. It also avoids the additional financial costs and time associated with travel and reduces congestion. Reforms to increase density include incentivizing better use of land, for example, by ensuring that under-utilized or vacant land is taxed to provide incentives for development, including mixed-use structures. Increasing overall floor-area ratios (FARs) will also bring down the price of land to make housing more affordable. Other such reforms include development charges that are density and location sensitive, not merely focused on plot or structure size, which require the cost of development to be fully priced and incorporated.

**2. Decreasing returns of density:** Beyond a certain threshold, high-density environmental and social externalities exceed density benefits. Excessive density can cause many problems, such as insufficient housing, infrastructure and public services, and traffic congestion. It can also result in insufficient living space, a lack of green space and social amenities, and congestion, including in public transit. For example, in Mumbai, an average of 10 people dies every day from trespassing on railway tracks or falling out of overcrowded trains.

**3. Dynamic perspective:** As cities expand, the land required for public streets, public infrastructure networks and public open spaces must be secured in advance of development. More land expansion in cities that lack living space and basic infrastructure for their inhabitants would lead to more efficient densities. Examples of excessive densities are Delhi or Dhaka, which from 1990 to 2015 provided only 25 m$^2$ and 18 m$^2$ of urban land per capita to their millions of new inhabitants respectively. In such cases, land expansion would bring more equity, inclusiveness and economic efficiency. Decreasing densities at a medium to high density of 15,000 people per km$^2$—as recommended by UN-Habitat and observed in Tokyo's 23 wards and Seoul Special City—is the right choice for Indian cities. On the contrary, when North American cities, for example, are expanding with excessive provision of land per inhabitant (generally over 500 m$^2$ per capita), densification and TOD policies would increase efficiency and reduce loss of farmland, impacts on local climate, fragmentation of habitats and threats to biodiversity.


Credit: Aleksandr Markin/shutterstock.com

## Indian subcontinent cities need land expansion and density restructuring

Dhaka, in Bangladesh, grew from 4 million to 13.6 million people from 1990 to 2015 with an excessive density increasing by 3 percent during that period to reach 55,150 people per km$^2$ in 2015, when calculated for the built-up area (Angel *et al.,* 2016), and a land provision per inhabitant of 18 m$^2$. In 2005, the average density in Dhaka slums, taken as a whole, was 222,000 people per km$^2$, resulting in only 4.5 m$^2$ of urban land per person on average, with peaks at 375,000 people per km$^2$, resulting in an even lower 2.6 m$^2$ of urban land per person.

Mumbai Metropolitan Region's population increased from 11.8 million to 19.6 million between 1991 and 2014, with a very high built-up area density at this scale of 36,890 people per km$^2$. Greater Mumbai comprised 12.4 million people in 2014, with a built-up area density of 45,900 people per km$^2$, providing 21.8 m$^2$ of land on average per inhabitant. In Greater Mumbai only, 5.44 million people live in slums on a cumulated land area of just 34 km$^2$, at an average density of 160,000 people per km$^2$, peaking at 500,000, with only 6.25 m$^2$ of land per inhabitant. As a result, the percentage of open space is very low overall in Greater Mumbai—3.7 percent with only 1.24 m$^2$ per person—when excluding the large park to the north. Land area for social infrastructure[52] (education, medical, social) is also very low in Greater Mumbai, totaling 15.2 km$^2$ (i.e. 1.22 m$^2$ per inhabitant). Additionally, there is much need for land for economic development; although Greater Mumbai is considered the country's economic and financial nerve centre, commercial and office space occupies just 3 percent (12.72 km$^2$) of the land. The Mumbai Metropolitan Regional Plan 2016–2036 estimates housing needs at 5 million units. As the average household size in urban Mumbai Metropolitan Region is 4.39 people,[53] this represents housing needs for more than 22 million people and necessitates building housing and physical and social infrastructure every year for the equivalent of a city of 1.1 million. Providing this amount of additional housing and infrastructure requires land expansion beyond the present 531 km$^2$. The region is forecast to comprise 32 million people by 2036. The only metropolitan region of a comparable size today is Tokyo (34.76 million people on 4,489 km$^2$ of land with a built-up area density of 7,740 people per km$^2$). A higher-density benchmark is Seoul Metropolitan Region, which presented a density of 25,320 people per km$^2$ in 1991 with 17.1 million people and of 11,880 people per km$^2$ in 2014 with 23.71 million people. Decreasing to the same density as Seoul in 1991 would imply multiplying the Mumbai region's land area by 2.4, while decreasing to the same density as Seoul today would imply multiplying it by five to reach a size of 2,693 km$^2$, which would still be 40 percent less than the Tokyo region. As this exceeds the amount of developable land in the region, the avenue of developing new towns outside the region's boundary should be explored.

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[52] The assessment conducted for Development Plan 2034 reveals that in 18 of the 24 wards of Greater Mumbai, the land demand for social infrastructure far exceeds the land available for reservation (Mumbai Metropolitan Regional Plan 2016–2036).

[53] Mumbai Metropolitan Regional Plan 2016–2036.

### Excessive de-densification impacts adversely on resource use and infrastructure costs

Dispersed settlement patterns combined with segregated zoning and land usage lead to an overconsumption of resources for infrastructures and increased capital, operations and maintenance costs for providing water, sewerage, power, heating and telecoms infrastructure. This was first experienced in North America and is now extending to developing countries, particularly in sub-Saharan Africa. The cost savings that can be achieved by containing sprawl in the United States are an estimated $12.6 billion for water and sewerage infrastructure and $110 billion for road infrastructure (Burchell *et al.*, 2002). The incremental external costs of sprawl in the USA alone are around $400 billion annually. Of this figure, an estimated $200 billion per annum could be saved by the USA if smarter, more compact growth policies were pursued, primarily through savings in the incremental costs of providing public services and capital investments, such as roads (Floater *et al.,* 2014b).

The construction sector accounts for over 30 percent of global resource consumption (UNEP, 2011b). Sprawling cities require an ever-increasing production of raw materials and construction materials. Overall, global resource consumption has increased more rapidly than the population, particularly the consumption of non-renewable construction materials (UN-Habitat, 2012). Between 1900 and 2005, material resource use in the world increased eightfold, which is almost double the rate of population growth (UNEP, 2011a). The World Business Council for Sustainable Development estimates that 30 gigatonnes of concrete alone were used in 2006, compared to 2 billion tonnes in 1950 (WBCSD, 2009).

The following subsections will investigate these inefficiencies in more detail.

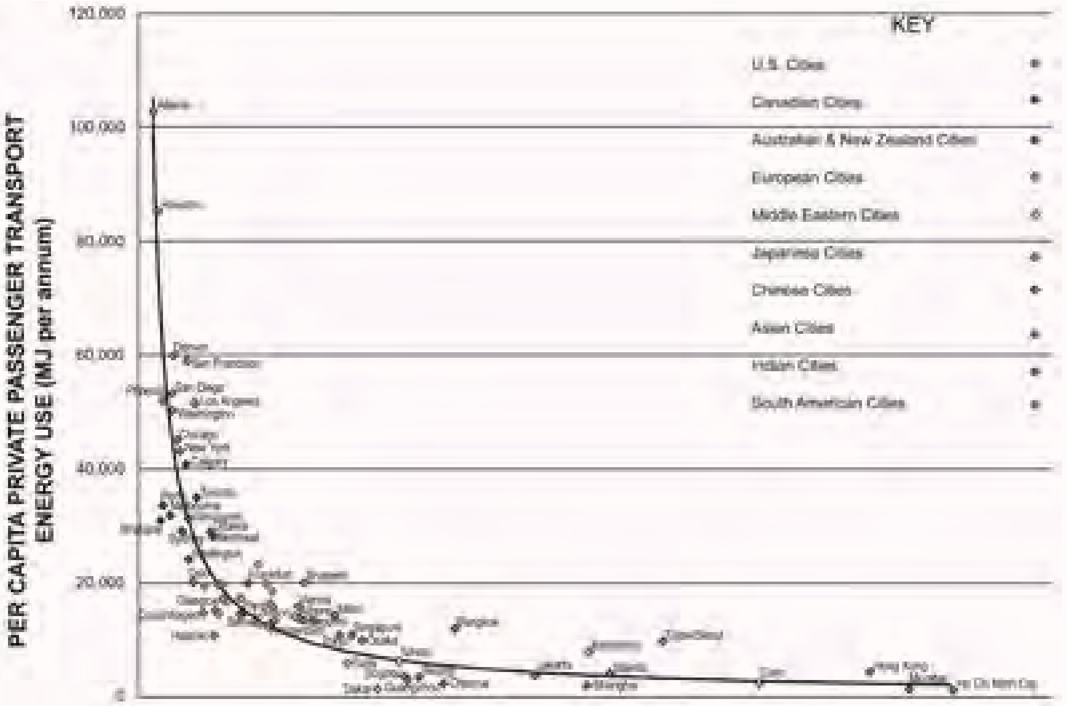
### De-densification has a strong impact on the increase in demand for transportation energy

Density is the very first feature of urban form that impacts on transportation energy.[54] The link between urban density and energy for private transport has first been analysed for a sample of 52 cities by Newman and Kenworthy (1989) and has subsequently been corroborated by dozens of papers. The correlation is shown in the following chart.

In a comparison of average emissions for transportation and average densities among 64 Chinese cities and 54 US cities, average population densities (calculated on the built-up area of these cities) were found to be seven times those of US cities on average, i.e. 16,200 people per km$^2$ compared with 2,300 people per km$^2$. Average annual $CO_2$ emissions from transport in the US cities studied were 56 times those in Chinese cities, i.e. 12.8 tonnes per household compared with 0.27 tonnes per household (Angel, 2012).

The correlation between density and carbon emissions for private transport is also verified at an intra-urban scale among various districts in the same city (Bourdic, 2011). Statistical analysis based on a sample of 51 cities, using a multi-variable regression analysis, has considered other variables and criteria (Bourdic, 2011),

Figure 3.5: Population density and transport energy use per capita for selected cities.



(Source: Newman and Kenworthy, 2015)

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[54] A study of 50 cities worldwide estimates that almost 60 percent of growth in expected energy consumption for transportation is directly related to urban de-densification—more than the consumption related to increases in GDP and demographic changes (Bourdic *et al.*, 2012).

notably econometric ones. Using the Cobb-Douglas function, it has shown that only two variables are significantly correlated with energy consumption for transport: demographic density and GDP per capita. It thus leads to the following equation, linking urban transport energy consumption per capita, demographic density and GDP per capita:

$$Energy_{cap}^{transport}=C_0\, d^{-0.65}\, GDP_{cap}^{0.23}$$

where $\text{Energy}_{cap}$ is urban transport energy per capita and $\text{GDP}_{cap}$ is GDP per capita.

The equation shows that the impact of de-densification on urban transportation energy is much stronger than the impact of GDP increase.

### De-densification has a strong impact on infrastructure costs per capita and urban productivity

Studies on road networks (Ingram & Liu, 1997) and urban water and wastewater networks (Müller *et al.,* 2013) suggest that per capita network length and material stocks tend to increase with declining urban density. Müller *et al.* (2013) have computed data on a representative sample of about 40 cities, which has been mathematically analysed by the Urban Morphology and Complex Systems Institute (Salat *et al.,* 2017). This statistical analysis facilitated the calculation of the elasticity of water, wastewater and street network lengths and costs per capita with regard to average residential density. Network costs are assumed to be proportional to network length, which leads to the following equations:

$$Wastewater\ network\ costs/cap=C_{ww}\, D_{res}^{-0.278}$$

$$Water\ network\ costs/cap=C_w\, D_{res}^{-0.792}$$

$$Street\ network\ costs/cap=C_s\, D_{res}^{-1.119}$$

where $C_{ww}$, $C_w$, $C_s$ are constants and where $D_{res}$ is the residential density.

These negative elasticities mean that network costs per capita systematically decrease as densities increase, which is logical given that more people per area means more users per length of infrastructure. Network costs per capita are not proportional to the number of people using them, but there are economies of scale offered by higher densities. For example, doubling density reduces water network costs per capita by 42 percent and street network costs per capita by 54 percent (Salat *et al.,* 2017). As infrastructure networks have a high material footprint in raw materials, these elasticities show that delivering basic services with urban infrastructure is more resource efficient when densities are increased.

Network costs per capita can be replaced by network costs per km$^2$ using residential density:

$$Wastewater\ network\ costs/km^2=C_{ww}\, D_{res}^{-0.722}$$

$$Water\ network\ costs/m^2=C_w\, D_{res}^{-0.21}$$

$$Street\ network\ costs/m^2=C_s\, D_{res}^{-0.119}$$

where $C_{ww}$, $C_w$, $C_s$ are constants and where $D_{res}$ is the residential density.

From these equations, we derive the respective elasticity for the wastewater, water and street network costs per km$^2$ with regard to residential density: 0.722, 0.21 and –0.119 respectively. These elasticities address the issue of the cost of networks for servicing urbanized land. Network costs per km$^2$ decrease infra-linearly with increased density. For example, doubling density increases the cost of water networks per unit of land by 64 percent. The cost per unit of land for street networks even decrease with increasing densities due to economies of scale.

These relationships are illustrated below by the comparative examples of Atlanta and Barcelona.[55] Differences between a compact, planned extension, such as the *Eixample* district

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[55] Barcelona, the capital of Catalonia, is the first city in which the principles of scientific urban planning were applied in the 1850s by Ildefons Cerdà. The efficiencies of this forward-looking plan are visible today in the efficiency and resilience of the city.

(Expansion district) in Barcelona, and unplanned growth, like Atlanta's sprawl, are striking when Barcelona's efficiency is compared with that of Atlanta. The two cities have similar populations and wealth levels but very different energy, carbon, resources and economic productivities. Atlanta's spread-out urban form leads to waste, inefficiency and high costs. Its sprawling scale necessitates roads, utilities and public services that cover 26.5 times as great an area as Barcelona's public infrastructure and services.

**Figure 3.6**: Comparison of Atlanta and Barcelona at the same scale.

| **ATLANTA** | **BARCELONA** |
|---|---|
| Population: 5.25 million | Population: 5.33 million |
| Built-up area: 4,280 km$^2$ | Built-up area: 162 km$^2$ |
| Carbon emissions (tonnes $CO_2$ per person for public and private transport): 7.5 | Carbon emissions (tonnes $CO_2$ per person for public and private transport): 0.7 |

(Source: Bertaud and Richardson, 2004)

## Atlanta versus Barcelona

Atlanta is 27 times less dense than Barcelona and emits 10.7 times more $CO_2$ per person per year. The average density, calculated on the built footprint, is 32,900 people per $km^2$ in Barcelona and 1,220 people per $km^2$ in Atlanta.

Low density in Atlanta severely limits the choice of transport mode. A 2011 Brookings Institution study placed Atlanta 91st out of 100 among US metro areas for transit accessibility (Tomer *et al.,* 2011). Urban rail is within 600 m of 60 percent of the population in Barcelona, whereas only 4 percent of Atlanta's population enjoy this level of accessibility. The low density of Atlanta renders this city unsuitable for rail transit.[56] The length of metro lines that would be required to achieve the same level of rail transit accessibility in Atlanta as in Barcelona would be 3,400 km and the number of stations required would be 2,800 (Bertaud, 2003).

In Atlanta, the impact of low density on transportation energy consumption is about 10 times higher than the impact of GDP; while a higher GDP per capita in Atlanta leads to an increase of only 9 percent in transport energy consumption, the comparatively lower density results in transport energy consumption that is 8.5 times greater in Atlanta than in Barcelona.

Road length per capita is 40 times higher and water network cost per capita is 13.5 times higher in Atlanta than in Barcelona. Water networks cost more per $km^2$ in denser cities; their cost per $km^2$ in Barcelona is double the cost in Atlanta, however, they cost much less per capita—13.5 times less in Barcelona than in Atlanta.

Although Atlanta is more productive per capita,[57] Barcelona's higher density significantly increases its resource productivity. The tonnes of $CO_2$ emitted for transportation to produce one unit of GDP are, for example, 7.7 times higher in Atlanta than in Barcelona. The average GDP per $km^2$ of built-up area is 15 times higher in Barcelona than in Atlanta ($68.7 million in Atlanta and $1,050 million in Barcelona). Urban productivity can be decomposed into three components (Salat *et al.,* 2017), on which the impact of each urban planning characteristic can be assessed. The decomposition of urban productivity is as follows, with GDP being gross domestic product, CapEx being Capital Expenditure and OpEx being Operational Expenditures:

$$\text{Urban productivity/km}^2 = GDP/km^2 - CapEx/km^2 - OpEx/km^2$$

This equation shows that urban productivity is much lower in Atlanta than in Barcelona: GDP per $km^2$ is 15 times lower; components of capital expenditure, such as road networks costs per $km^2$ are 50 percent higher; operational cost components, such as transportation energy consumption, are 10 times higher.

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[56] 4.5 percent of trips make use of urban rail in Atlanta compared with 30 percent in Barcelona.

[57] According to the Brookings Institution estimated PPP adjusted GDP in 2014: Atlanta has a GDP of $294 billion for a population of 5.6 million, with employment of 2.5 million, while Barcelona has a GDP of $171 billion for a population of 4.73 million, with employment of 1.98 million. The differences in productivity per job ($117,000 per job in Atlanta compared with $59,000 per job in Barcelona) are related to the differences in shares of output by industry in the two cities.

The relationships between density, networks and GHG emissions lead to contrasting scenarios when applied to various density trajectories for China's future urbanization.

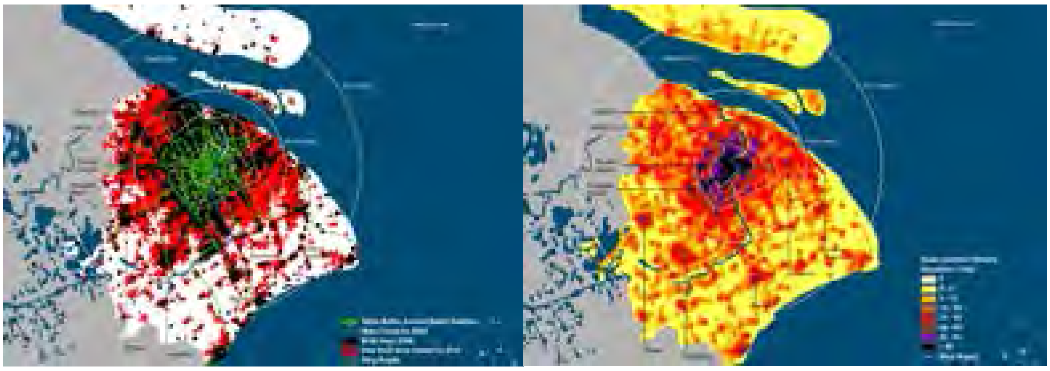
## The impact of density scenarios on urban infrastructures and transportation energy in Chinese cities

From 1980 to 2008, during the period of rapid urbanization, China's DMC per capita increased at a rate much higher than the world average, and considerably higher than that of the region as a whole (West *et al.,* 2013). Today, China alone consumes a large proportion of the world's materials used in infrastructure; it consumes 54 percent of aluminium, 48 percent of copper, 50 percent of nickel, 45 percent of all steel and 60 percent of the world's concrete (World Economic Forum, 2015). China consumed more cement between 2011 and 2013 than the United States did in all of the 20th Century (Smil, 2013). Notably, China uses 49 percent of global coal for power generation as well as metallurgical processes in making steel.

BAU urbanization in China will require 5 billion m$^2$ of roads to be paved by 2025 (Floater *et al.,* 2014b). According to the World Bank, China could save up to $1.4 trillion in infrastructure spending—equivalent to 15 percent of China's GDP in 2013—if it pursued a more compact, transit-oriented urban model, and this could reduce China's estimated investment gap of $160 billion (World Bank, 2014). If China shifted to a more compact and less infrastructure-intensive mode of urbanization, it would relieve pressure on limited global resources in raw materials.

In China, according to Deng and Huang (2004) and Wu (2007), urban sprawl is a result of the government's land reform, which led to large and discontinuous urban areas, and to urban population growth resulting from migration inflows of those seeking employment and study opportunities. China's overconsumption of raw materials is partly due to this inefficient pattern of urbanization, which is illustrated in the below example of Shanghai.

**Figure 3.7**: (Left) Map of built-up land in 2000 and 2010 and metro network by 2020.
**Figure 3.8**: (Right) Map of road junction density in Shanghai in 2010.

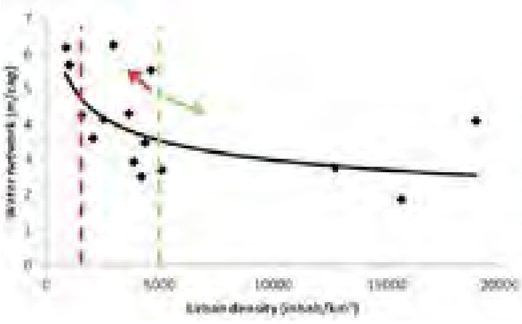


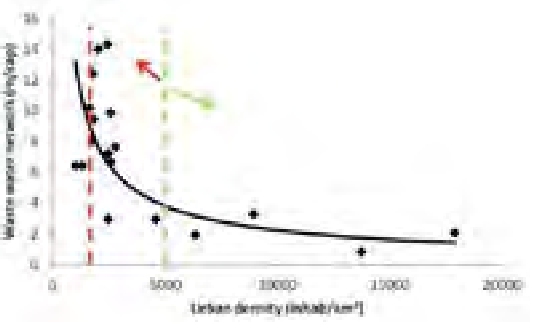
(Source: World Bank and Chreod Ltd., 2015)

In Shanghai, spatial expansion and subway network development have been poorly coordinated, creating issues of increased transportation energy over the last 10 years. Furthermore, Shanghai has built up an additional land area equivalent to 125 percent the area of New York City and to two-thirds the area of Greater London over the last 10 years, with an urban pattern of superblocks (of around half a kilometre per side) (Work Bank & Chreod Ltd., 2015). The density of road junctions of 12 intersections per km$^2$ in the 1,049 km$^2$ added to Shanghai's built-up land area between 2000 and 2010 is typical of the highly energy-intensive superblocks that will be analysed further on in this chapter. As a comparison, UN-Habitat recommends dense patterns of streets with at least 80–100 intersections per km$^2$ and 18 km of streets per km$^2$.

Using data from 40 international cities, which model the relationship between urban networks and density, the following graphs display various density scenarios for Chinese cities. The green line corresponds to the current average urban density levels in Chinese cities. The red line corresponds to what could become average density in China in 2030 if average densities continue decreasing at the same rate. The green arrow corresponds to a green scenario in which densities increase. The red arrow corresponds to the BAU scenario, in which average densities decrease and infrastructure needs (in terms of lengths in metres) per capita increase (World Bank, 2014).

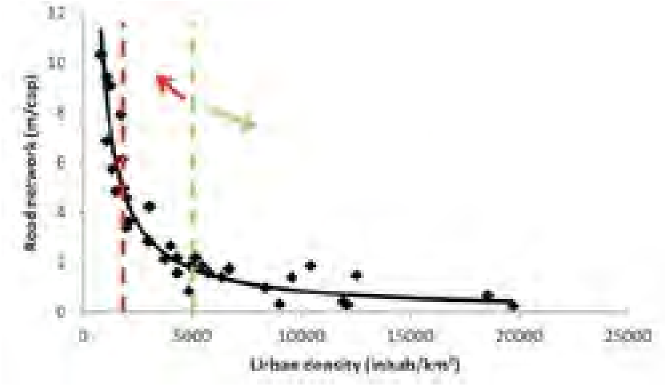
**Figure 3.9**: (Left) Water network length (metres per capita) and urban density (people per km²)
**Figure 3.10**: (Right) Wastewater length (metres per capita) and urban density (people per km²)





(Source: World Bank, 2014)

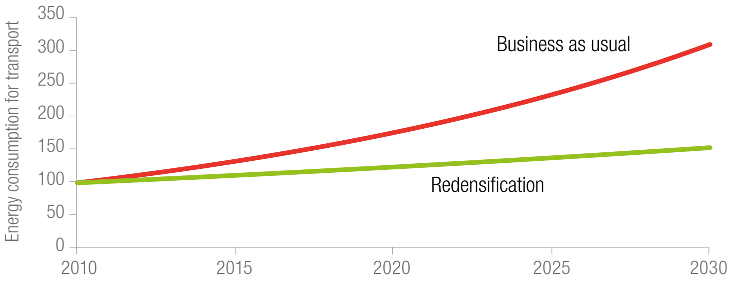
**Figure 3.11**: Road network length (metres per capita) and urban density (people per km²)



(Source: World Bank, 2014)

By 2030, urban China's GDP is expected to multiply by 2.5 from base year 2010, urban population by 1.5 and urban area by 3 at the current rhythm of land expansion, where the urbanized land doubles every 10 years (World Bank, 2014). As a result, according to the model presented above, energy consumption for transportation would triple.[58] Two scenarios can be forecasted for urban China's population increasing by 50 percent: (1) a BAU scenario, leading to a decrease in density, a tripling of urban area and a tripling of transportation energy; and (2) a densification scenario, with a doubling of density within the current urban area and transportation energy multiplied by 1.5, resulting in an increase of 66 percent of transportation energy productivity relative to GDP.

**Figure 3.12**: Two urban density scenarios for China's emission levels for transport (basis 100 in 2010)



(Source: Salat, 2013)

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[58] Within the tripling of transportation energy, demography would be responsible for 12 percent, GDP growth for 29 percent and de-densification for 59 percent.

### 3.3.2. Disordered urban growth versus efficient clustering of densities

This section examines the impacts of disordered urban growth on transportation energy compared with hierarchically organized urban growth, where there is clustering and concentration of densities. Disordered urban growth can be measured by the spatial *entropy* of density (a concept explained below); clustering and concentration can be measured by *hierarchy* in the organization of densities (also explained below). These metrics will be applied to a set of 34 European cities to model the impact of density distribution across urban space on transportation energy.

#### Articulated density and hierarchy in urban space

A first approach of the hierarchy in urban form and densities is looking at patterns of centrality and dispersal. Historical city boundaries were defined by the maximum radius of walkability and for accessibility and resource-efficiency reasons, adopted a roundish shape (Angel *et al.,* 2010). However, at the end of 19th Century cities started to spread, thanks to the advent of the omnibus and horsecar. They became monocentric with a highly dense core. In the historic walking city, workplaces and residences were interspersed at uniformly high densities while in the monocentric city, spatial segregation of residences and workplaces began to occur, with rapidly decreasing densities as distance from the centre increased, and with radial mass transit corridors leading into the city core.

A classic measurement of this transformation is looking at the gradient of residential density, that is, the coefficient of an exponential curve fitting the decrease of densities from the city centre. Research has shown a general flattening of this gradient over time in both Latin American and US cities. For example, while densities in the centre of Buenos Aires remained high at 24,500 people per km$^2$ in 2001 (more than the density of 22,500 people per km$^2$ observed in 1810, 1869 and 1895), the gradient of the density curve for greater Buenos Aires declined sixfold, from 0.36 in 1869 to 0.06 in 2001 (Angel, 2012). This indicates that in 1869, density declined by 36 percent, on average, when distance from the centre of Buenos Aires increased by one kilometre, thus a sharp decline. In 2001, this decline was much smoother at only 6 percent and the gradient was flatter.

A parallel phenomenon happened in the USA but with a significant difference. In a sample of 20 US cities, the average value of the gradient declined fourfold, from 0.22 in 1910 to 0.04 in 2000, and at a rate similar to that of greater Buenos Aires. However, while residential densities remained high in the central city of Buenos Aires at 24,500 people per km$^2$, they declined in the United States to a fifth of that value as central cities lost a large share of their population to the suburbs, and because less than 25 percent of workplaces remained in the centre (Angel, 2012), except in global cities such as New York City (Salat, 2017). As a result, commuting patterns were transformed, with most trip origins and destinations being outside the core city. For example, in the case of Chicago, the entire city can be encircled with a radius of 73.5 km and only 15.8 percent of commuter trips are within 6 percent of this radius (i.e. within a circle of 4.4 km), still a high value for the USA. The corresponding value for Los Angeles is only 6.2 percent (Angel, 2012). Thus, the dispersal of the city spatial pattern has been accompanied in the USA by a dispersal of commuting trips, which became more random and less structured, while being dispersed within a circular area 280 times larger than the urban core, with important impacts on energy for transportation and resources embedded in transportation infrastructure.

Despite its strong descriptive attributes, the approach using urban density gradients does not fully capture the complexity of the contemporary polycentric city, in which high densities can be dispersed in clusters. Recent research (Salat, 2016) has shown that efficient and productive cities are spatially organized according to similar patterns, with highly dense and productive areas, peaks of economic concentration and resource productivity, and long tails of low-density/low-productivity areas, organized in space by mathematical regularities that reflect a form of organizational hierarchy.

**Figure 3.13**: Pareto distributions or inverse power laws model the hierarchy of urban densities

People, jobs and economic densities (GDP per km$^2$), office space density, accessibility to jobs, rents, subway network centralities and energy densities across the urban space (Salat, 2016; Salat & Ollivier, 2017) can be modeled by inverse power laws referred to in economics as Pareto distributions. Contrary to density gradients, which are based on a monocentric city model, modelling the hierarchy of densities with inverse power laws does not postulate a unique city centre, and thus can be applied to any city configuration, including polycentric cities. Urban areas with a fine-grain resolution are ranked from the densest to the less dense. This reveals universal patterns across many cities that comprise a few large and very large density values (in green on the left of the above figure) and a 'long tail' of small density values on the right.

More generally, a Pareto distribution or inverse power law, relates high values (of density, accessibility or connectedness), intermediary values and small values with an identifiable and measurable mathematical regularity. The frequency of an urban area of intensity (meaning density, accessibility, centrality) x is proportional to the inverse of its intensity (density, accessibility, centrality) at an exponent *m* characteristic of the system hierarchy, . In other terms, there are few dense, accessible, connected urban areas, a medium number of intermediate values and a very large number (a long tail) of small values, and the relative frequency of each value is determined by the rank-size distribution.[59] The higher the exponent *m,* the steeper the organizational hierarchy between high-density and low-density areas. The example below shows how Pareto distributions organize the hierarchy of densities in Greater London.

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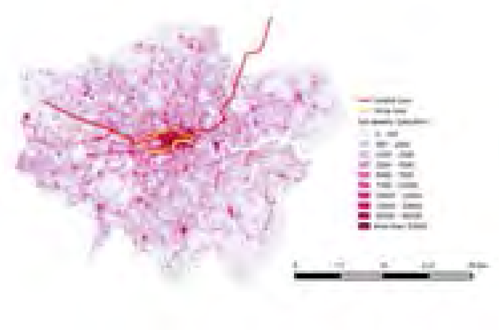
[59] The size (density, accessibility, connectivity) of any urban component is related to its rank within the distribution.

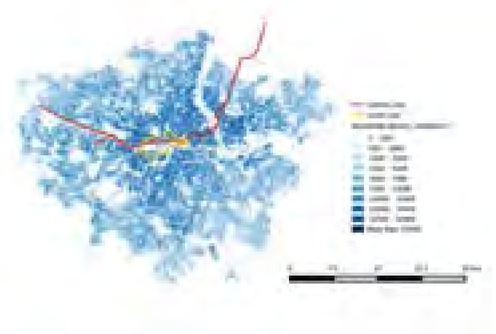
Credit: Ruslan Kudrin/shutterstock.com

## Density distributions in Greater London follow Pareto distributions

**Figure 3.14**: (Left) Map of job density in Greater London. It shows concentration of jobs in the core of central London corresponding to the most connected and most accessible part of the subway network, and job density around transit stations along branches radiating from the core, ensuring a good jobs-to-housing ratio around transit stations outside the core. Contrary to what might have been expected, communication technology has not reduced the need for face-to-face contact and the benefits of agglomeration in a global service provider city like London.

**Figure 3.15**: (Right) Map of people density in Greater London. It shows a more even distribution of residential densities.





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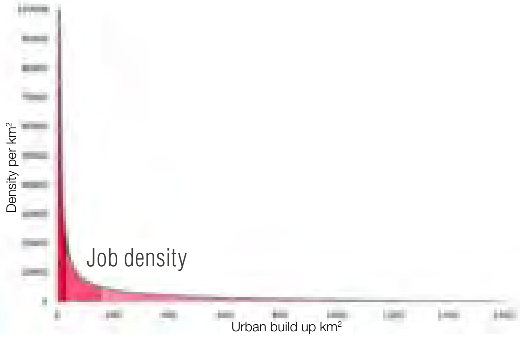
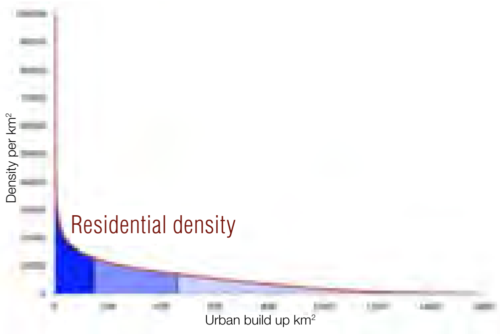
Central London is very dense in terms of jobs, with one third of Greater London jobs in 1 percent of its land area—1.5 million jobs in 15 km² in Central London—creating intense agglomeration economies and knowledge spillovers in advanced services industries, while making these jobs accessible by transit lines that radiate from the Circle Line and concentrate population densities along transit corridors. Two thirds of jobs and half the people are less than 1 km from a mass transit station, ensuring high transit ridership for commutes.

**Figure 3.16**: (Left) Greater London urban land is ranked in the chart below from the land with the highest job density to the land with the lowest job density. The area under the curve corresponds to the total number of jobs. The density distribution follows a Pareto distribution, with a steep exponent (–1) that also characterizes New York City. As a result, jobs are extremely concentrated in London and peak at a density of 150,000 jobs per km² in the City of London, which produces 14 percent of London GDP (and 3 percent of UK GDP) within one square mile. New York City presents the same pattern of extreme job concentration with 1.5 million jobs within 9 km².

**Figure 3.17**: (Right) Residential density distribution in Greater London also follows an inverse power law distribution with a coefficient of –0.48. The area under the curve corresponds to the total number of people. The distribution is much less steep than job distribution, and results in the densest third of people (2.72 million) being distributed across 145 km² with an average density of 18,790 people per km². The hierarchy of residential density in New York City presents a higher exponent of –0.74. Residential density is more articulated and hierarchically organized in New York City than in Greater London.





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### Fragmentation, sprawl and spatial entropy

In the middle decades of the 20th Century, another significant transformation occurred with the rapid increase in the use of cars, buses and trucks. Trucks in particular enabled dispersal of industrial workplaces, but commercial and service workplaces in most cities remained concentrated in central areas. When carefully planned with a hierarchy of sub-centres, this dispersal would lead to new concentration of jobs in secondary nodes at the periphery in order to benefit from agglomeration economies and transit accessibility, transforming the monocentric city into a truly polycentric city, as in Seoul, Singapore or Hong Kong. When unplanned, the dispersal of activities transforms the city shape into a highly fragmented and scattered form.

Sprawl can be defined as lack of continuity in expansion. Today, most cities and metropolitan areas exhibit this lack of continuity, typically consisting of disconnected patches of urban fabric broken up by swathes of open space, including a variety of green, barren, unbuilt and unpaved areas (Angel, 2012). Both city and countryside now interpenetrate and fragment each other on a vast scale. Analysing satellite images from 1990 and 2000 for a global sample of 120 cities, a recent study found that cities typically contain or disturb vast quantities of open space equal in area, on average, to their built-up areas (Angel *et al.,* 2012). The fragmentation of urban footprints is an important concern in terms of inefficiency of land use and loss of economic productivity of urbanized land (considered as a production factor), with an overwhelming increase in resources embedded in infrastructure per capita (as demonstrated in the previous case study of Atlanta), with adverse effects on climate change and local ecology.

Two complementary metrics have been developed to measure the fragmentation of urban footprints:

1. The openness index is a local metric measuring the average share of open pixels within the walking distance circle (a circle of 1 km$^2$ in area) around every built-up pixel in the city (Burchfield *et al.,* 2006).
2. The saturation is a city-wide measure of fragmentation and measures the ratio of the built-up area to the total urban extent of the city (including built-up area and urbanized open space).

The results of a study on a global sample of 120 cities show that fragmentation measured by these two metrics is not correlated to density. For example, as at 2015, Kolkata, a city of 15 million people, is highly dense like most Indian cities, with a built-up area density of 25,000 people per km$^2$, and is highly fragmented (saturation of 0.62; openness index of 0.32), whereas Los Angeles, also a city of 15 million, is 7.5 times less dense than Kolkata at 3,300 people per km$^2$, on average, and much less fragmented (saturation of 0.78; openness index of 0.17). This means that Los Angeles' urban extent was only 128 percent of its built-up area in 2015, while Kolkata contains much more disordered and fragmented open space, with an urban extent of 161 percent of the built-up area.[60] The non-correlation of fragmentation and density shows that they are independent characteristics (density describes the intensity of land use, fragmentation describes its shape), which impact independently on resource and energy needs. A subsequent section of this chapter will determine their respective impacts on transportation energy.

Among the key findings for contemporary cities are the following: in the 1990s, the average value of the openness index on a sample of 120 cities was about one half and saturation was also one half, meaning that, on average, urbanized open space added an area to the city equivalent to its built-up area, and at a minimum, added 36 percent to the built-up areas. Cities in developing countries were found to be more fragmented, on average, than cities in developed ones (Angel *et al.,* 2016).

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[60] Data from Angel *et al.,* 2016.

As land-use fragmentation is such an important feature of contemporary cities (Alberti, 2005) and as this fragmentation contributes to significant economic costs for infrastructural development (Burchell & Mukherji, 2003), a key question is to measure not only its amount but also its structure. The structure of fragmentation—its level of spatial order or disorder—can be approached by measures of entropy, as in thermodynamics and information theory (Journel & Deutsch, 1993). Shannon first devised entropy theory and Batty developed this into spatial entropy (Batty, 1974). Entropy has been widely used in measures of urban systems (for a literature review see Cabral *et al.,* 2013). Entropy is an important concept in thermodynamics and enables the measurement of the irreversibility between concentrated and dispersed states of energy. Entropy is a measurement of the disorder or randomness of a system. 'Disorder' may be very clearly defined as the Shannon entropy of the probability distribution of microstates given a particular macrostate. A more recent formulation associated with Frank L. Lambert describes entropy as energy dispersal.[61] Entropy can be measured by the following Shannon formula:

$$Entropy = -\frac{\sum_{1}^{N} \frac{Pi}{P_N} \log\left(\frac{Pi}{P_N}\right)}{\log N}$$

Spatial entropy[62] is highly sensitive to deviations from the most spatially ordered reference configurations (Piasecki, 2000).[63]

### Impacts of entropy and hierarchy of densities on transportation energy

Articulated density is associated with high levels of density hierarchy. Sprawl is associated with high levels of fragmentation and spatial entropy. Stuttgart is an example of disordered spatial structure, where density is scattered randomly over the entire urban area. Barcelona is an example of an urban area with a density distribution clearly articulated by a hierarchy.

Intuitively, a disordered distribution of densities with high entropy resulting in random trips across urban space should lead to a higher consumption of transportation energy than a hierarchical organization of densities with networks articulated by important hubs and

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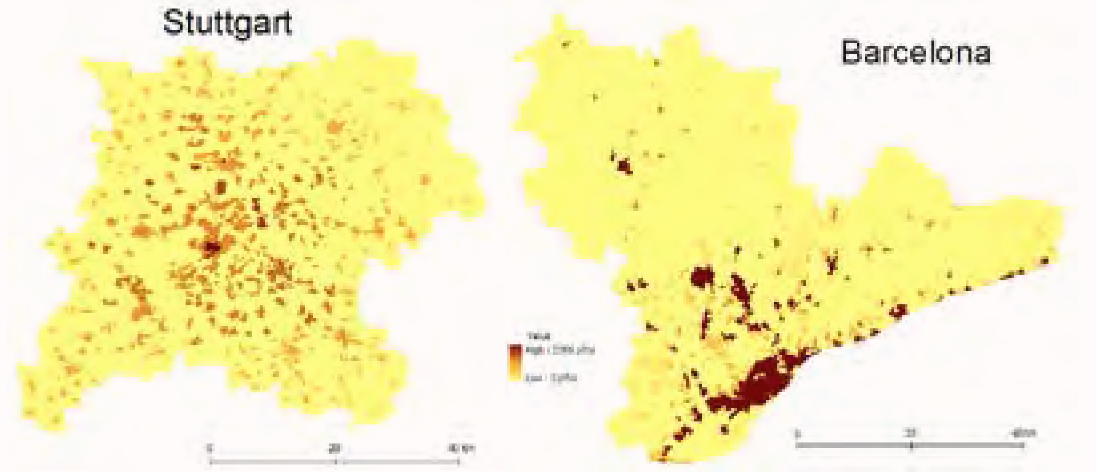
[61] 61. Entropy Sites — A Guide Content selected by Frank L. Lambert.

[62] 62. The relative entropy, also called Shannon equitability index, because of its simplicity, has been most important as a measure of diversity and evenness for spatial-related issues in fields such as biology, landscape ecology and urban studies (Yeh and Li, 2001). The concept of entropy in urban analyses was further refined and enriched by Batty (1974), with the definition of spatial entropy.

[63] 63. R. Piasecki's work (Piasecki, 2000) has shown that the relative configurational entropy can be considered as an alternative, qualitatively correct and highly sensitive measure of spatial disorder at every length scale for systems of finite-sized objects. For a review of the concept of entropy in urban systems and its application to sprawl, see Cabral *et al*., 2013.

**Figure 3.18**: Population density spatial distribution in Stuttgart and Barcelona



(Source: Le Nechet, 2012)

a strong hierarchy of commuting flows.[64] A multivariate analysis carried out on 34 European cities by the Urban Morphology and Complex Systems Institute using a database created by Le Nechet (2012) shows that this is the case; only four factors out of more than a dozen analysed were shown to significantly impact on energy consumption for transportation per capita:

$$Energy = C_0\, GDP^{0.35}\, dens^{-0.14}\, hier^{-0.52}\, entrop^{0.86}$$

where *Energy* is transportation energy per capita; *GDP* is GDP per capita (elasticity 0.35); *dens* is average density (elasticity –0.14); *hier* is the hierarchy of the density spatial distribution (elasticity 0.86); and *entrop* is the hierarchy of the density spatial distribution (elasticity –0.52).

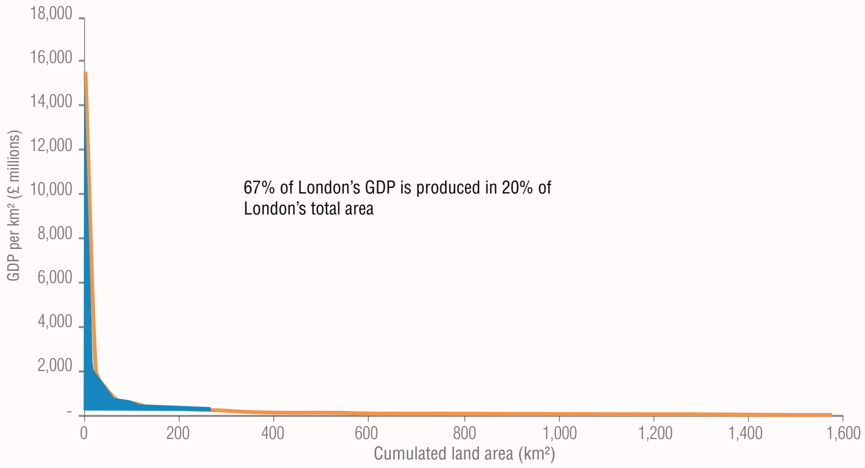
Compared with the previous analyses on the impacts of densities, which only examined average densities and not the uneven distribution of density across urban space, this analysis provides a new perspective on density. It is the organization of density that matters, not the average density across a given space:

1. The more hierarchically organized density is (i.e. with high levels of spatial concentration and steep gradients), the less transportation energy is needed because there is an efficient order and hierarchy in the flows of commutes and in the transit network that supports them—density is articulated.
2. The more disordered (scattered, fragmented) density is, the more transportation energy is needed because commutes are random, and in most cases, car dependent and supported by the weak hierarchy of highway patterns instead of the strong, converging hierarchy of mass transit patterns—hierarchy is non-articulated.
3. It is essential to increase the articulation of density, with peaks of density corresponding to peaks of transit accessibility.

### 3.3.3. Beyond a certain limit, urban expansion costs are higher than additional marginal GDP

Analyses of the distribution of GDP across urban space show the same patterns as jobs densities. GDP is not evenly distributed (Salat, 2016; Salat & Ollivier, 2017). When urban space is ranked from the highest GDP density (GDP per km²) to the lowest GDP density in London, the pattern of a Pareto distribution appears with an exponent of –0.9.

**Figure 3.19**: GDP per km² in Greater London by cumulated land area. Urban land in Greater London is ranked from the most productive (highest GDP per km2) to the less productive. The area under the curve is the total GDP of Greater London. Its spatial distribution follows an inverse power law of exponent –0.9. Inner London, with 20 percent of Greater London's area, produces 67 percent of its GDP[65] and concentrates 56 percent of all Greater London's private sector jobs.



(Source: Urban Morphology and Complex Systems Institute)

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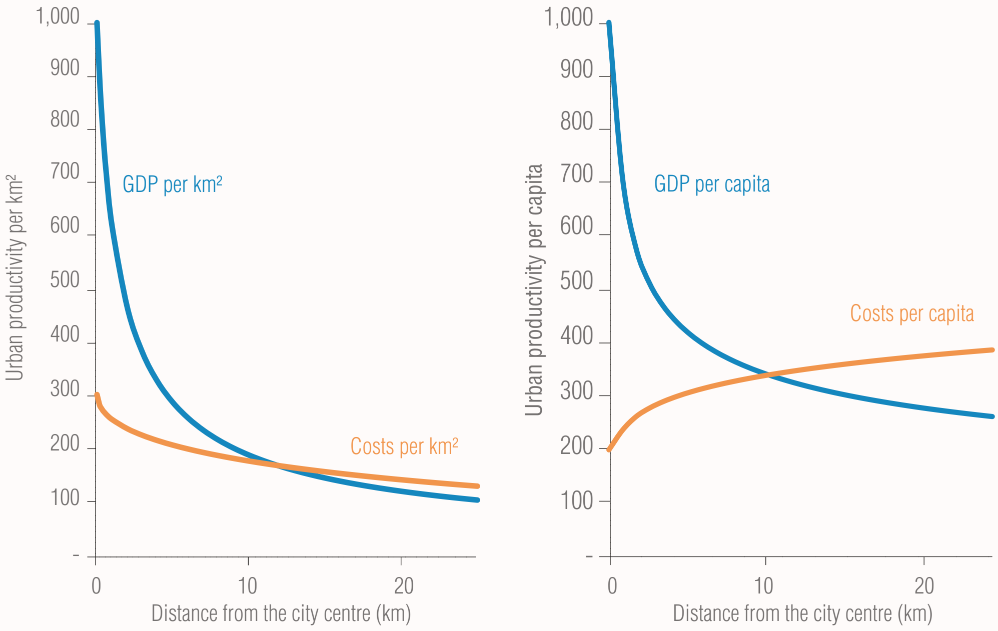
[64] It has also been shown in the example of Paris that commuting flows follow hierarchical patterns. See Salat and Ollivier, 2017.

[65] In 2009, Outer London generated £83 billion GDP and Inner London generated £186 billion. Source: Regional and sub-regional GVA estimates for London, UK Office for National Statistics Briefing Note, 2009

Urban productivity decreases continuously with urban expansion. GDP per km$^2$ declines as densities decline far from the city core. Beyond a certain radius, infrastructure lengths and costs per km$^2$ (and thus, capital and operational expenditure per km$^2$) become higher than additional economic output. As a result, urban marginal productivity as defined above becomes negative. This pattern is captured in the following figures (Salat, 2016; Salat *et al.,* 2017).

**Figure 3.20**: (Left) GDP per km$^2$ versus infrastructure costs per km$^2$
**Figure 3.21**: (Right) GDP and costs per capita across urban land



(Source: Urban Morphology and Complex Systems Institute based on international benchmarks of infrastructure costs per km$^2$ linking urban density and pavement costs, water network costs and wastewater network costs. Data have been normalized on base 1,000 for GDP per km$^2$ and on base 100 for GDP per capita (Salat 2016; Salat et al., 2017)

Urban expansion at low density is thus a highly inefficient urban growth pattern, where capital expenditure and operational expenditure per km$^2$ become higher than economic benefits after a break-even point. This makes the case for policies of urban containment, which have ensured the prosperity of cities such as Stockholm and London.

### 3.3.4. Shaping urban densities efficiently through integrated planning of transport and land use

How accessible the city is for people, the movers of goods, service providers and information providers determine the extent and nature of economic development in that particular city. The better and more efficient this access, the greater the economic benefits through economies of scale, agglomeration effects and networking advantages. Cities with higher levels of agglomeration tend to have higher GDP per capita, higher levels of productivity and also tend to be more integrated and equitable. The way in which cities facilitate accessibility through their urban forms and transport systems has direct and indirect positive impacts on other measures of human development and well-being (Floater *et al.,* 2014c). Accessibility in cities is created through the co-dependence of urban form and transport systems (Ewing & Cervero, 2010) and this relates to resource and energy use. In any city, patterns of urban development are inseparable from the evolution of urban transport and mobility. Likewise, urban transport cannot be considered independently from urban form. The impact of transport infrastructure on urban form is increasingly well understood. For US metropolitan regions, empirical estimates show that each new highway constructed through an urban core led to an 18 percent decline in central city residents (Baum-Snow, 2007). Recent research on the expansion of Chinese cities found that the combined effect of radial highways and ring roads was a relocation of around 25 percent of central city residents to surrounding regions, while regional railways were found to have no such effect (Henderson, 2010; Baum-Snow *et al.,* 2012).

The first principle of achieving accessibility in cities is based on the physical concentration of people, services, economic activities and exchange. In that regard, the most defining characteristics include residential and workplace densities, the distribution of functions and degree of mixed use, the level of centralization and local-level urban design. More compact and dense cities are a typical example of facilitating agglomeration economies through greater proximity.

### Planning for articulated density: integrated land-use and transportation planning

Cities should be built around their public transit systems. Many of the greatest cities are known for their public transit systems—New York, Paris, London, Hong Kong, Curitiba, Bogotá and Singapore are excellent examples. Many cities in developing countries are now investing in mass transit, including Lagos, Addis Ababa, Dar es Salaam, Johannesburg and Bangkok. Higher densities around mass transit stations and along transit-served corridors ensure a critical mass of trip origins and destinations to fill up trains and buses, increasing cost-effectiveness.

TOD is a powerful, crosscutting urban planning approach that can advance environmental sustainability, economic development and socially inclusive development. TOD's emphasis on density, a variety of land uses around high-capacity transit and local accessibility achieved through dense and connected street patterns can be harnessed to create more resource-efficient urban communities. TOD approaches are distinct in their involvement of public-private partnerships, which make it possible for the public sector to capture a portion of the improved land values (known as the 'value capture' approach). In this way, the substantial costs of the transit infrastructure are fully or partly recovered from subsequent property developments. The result is greater public control of the urban developments that emerge and therefore, much improved environmental and social outcomes. Articulated density should be planned across three interacting levels—metropolitan, network and local. Articulated density at the metropolitan level requires spatial coordination of economic, land-use and transport plans. At the network level, it involves planning transit lines with strong hubs connecting many lines where clusters of jobs can foster strong agglomeration economies. At the local level, it requires the creation of liveable, dense, mixed-use and well-connected communities. The following subsections detail the metropolitan and network levels, while Section 3.4 will cover the community level.

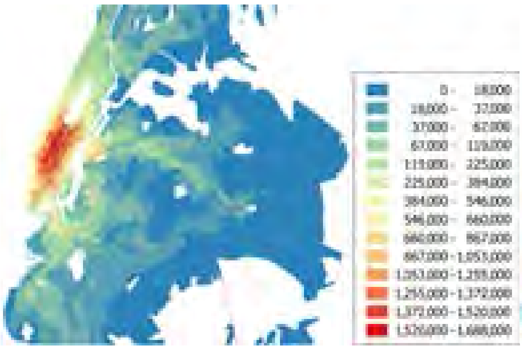
### Integrated land-use and transportation planning matches levels of density with levels of transit accessibility

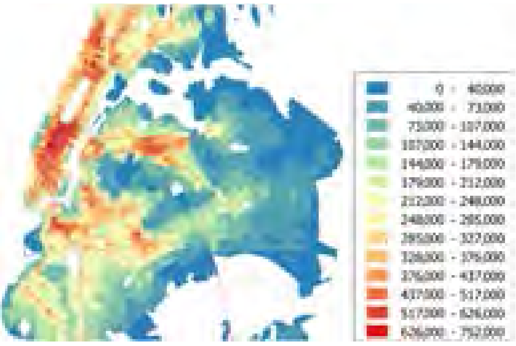
Networks define levels of accessibility. Businesses and people tend to make locational choices according to these levels of accessibility, thus creating positive feedback loops that reinforce some areas of the city as being more desirable than others. Regulatory planning should guide and encourage the optimal locational choices that people and businesses make, based on the broader interests of society. Transit networks offer better accessibility for people and businesses in the network core, where multiple intersecting lines offer many route alternatives, and where there is a high and constant station density. The core is the natural place for concentrating advanced service economy jobs at high density, while secondary centres can organize a polycentric urban form around the core, as observed in Singapore or Seoul. Scattered growth at the periphery is inefficient as networks cost more per capita, and economic output (per capita and per serviced land area) decreases when development occurs far away from the urban core. As urban land tends to be more expensive in the highly accessible cores, there is a push to locate activities further afield. The right balance is to channel outward development in transit corridors along transit lines and around transit nodes, as has been successfully done in Hong Kong, Bogotá and Curitiba, and as is starting to happen in Addis Ababa and Johannesburg.

## Densities in New York City match levels of transit accessibility

International experience suggests that intensity of land use should not be evenly distributed across urban space. On the contrary, it should present strong variations and peak where accessibility to jobs is at a maximum. Businesses locate preferentially where they can increase their productivity through agglomeration and localization effects. In efficient cities, there is a strong connection between how accessible places are and how densely populated, utilized and built-up they are. The strong spatial match between density and transit accessibility creates an efficient urban form. In New York City (8.5 million people and 780 km$^2$ of land area), 4 million jobs are located less than half a mile from a mass transit station. The high concentration of jobs in Manhattan and the dense provision of subway infrastructure in New York City have created a highly efficient urban form with an integrated labour market: 1.35 million jobs are accessible within a 30-minute transit commute, on average, for households; 0.7 million workers are accessible to an employer within a 30-minute transit commute, on average.

**Figure 3.22**: (Left) Number of jobs accessible from any location in New York City in less than 30 minutes (door to door) by transit.
**Figure 3.23**: (Right) Number of people that can access a given location by transit within 30 minutes (door to door) from any location in New York City in 2015.





© Urban Morphology and Complex Systems Institute. Data from NYC Open Data

These accessibility levels peak in Manhattan where, on average, 2.6 million jobs are accessible within a 30-minute trip via transit, and on average, more than 1 million workers are accessible to an employer within a 30-minute transit commute. The highest concentration of accessibility is in Midtown, which is undergoing rezoning at higher density to benefit from this accessibility premium.

By comparison, in the Chicago municipality, with a less compact and accessible urban form, only 535,000 jobs are accessible within a 30-minute transit trip and 28 percent of commuters use transit, while in the Los Angeles municipality, 567,000 jobs are accessible within a 30-minute transit trip and 11.6 percent of commuters use transit.

(Source: Center for Neighborhood Technology)

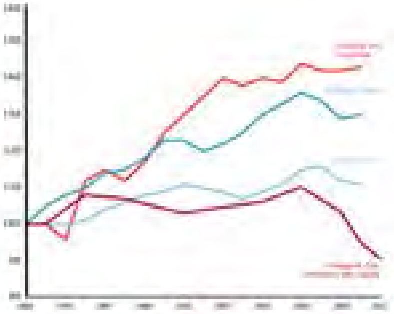
### Articulating metropolitan densities enables decoupling of urban economic growth and pressure on resources

An efficient urban form at the metropolitan level is a well-articulated network of strategically intensified urban nodes, interconnected with efficient and affordable mass transit systems. This enables a decoupling of urban economic growth from resource use, as shown below with the examples of Copenhagen and Hong Kong.

## Decoupling with integration of land use and transit in Copenhagen

Copenhagen's 'Finger Plan' promotes urban growth along rail corridors radiating from the city centre, while protecting 'green wedges' from development. First proposed in 1947, it remains a powerful spatial concept and has been given renewed regulatory support at the national level through the 2007 Danish Planning Act.[65] Copenhagen has also seamlessly linked transit, biking and walking facilities. One third of Copenhagen's suburban rail users use bicycles to access stations. Urban development investments cut across urban regeneration and city centre densification, alongside significant investments in public realm improvements. The Municipality of Copenhagen is aiming for 75 percent of all trips to be by foot, bicycle or public transport by 2025. The share of those commuting by bicycle is extraordinarily high, accounting for 36 percent of work trips (compared with 2 percent in London and 7 percent in Stockholm) (Floater *et al.,* 2014a).

**Figure 3.24**: (Left) Population density along major transit routes in Copenhagen.
**Figure 3.25**: (Right) The Copenhagen metropolitan regional economy, measured by Gross Value Added (GVA) per capita, grew by 30 percent from 1993 to 2010. Over the same period, transport-related carbon emissions in the Municipality of Copenhagen decreased by 9 percent to 0.76 $tCO_2$ per capita. All variables are indexed 1993 = 100.



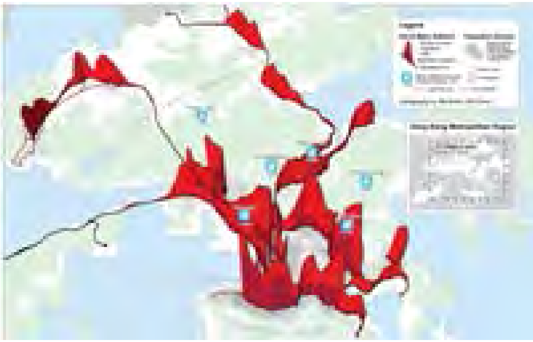
(Source: Floater et al., 2014a - LSE Cities Urban Age)

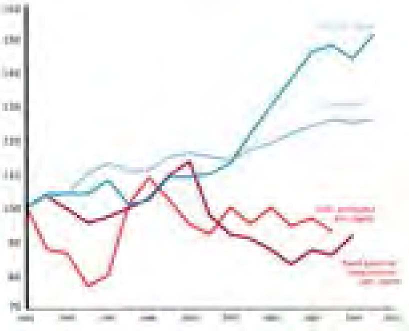
## Hong Kong: Decoupling economic growth and resource use by shaping urban form at high density with transit

Key concepts of Hong Kong's spatial planning include a rail-based pattern of development and a commitment to 'doing more with less'—prioritizing regeneration of existing urbanized territory rather than expansion into greenfield areas. Related regulations and guidelines specify where development can occur and at what density levels, while limiting car-parking provision. Urban expansion occurs in strictly defined areas, since 46 percent of Hong Kong's territory has been legally protected by 'Country Park' status since the 1970s. A further 30 percent of land remains undeveloped and subject to various degrees of protection under a 'hierarchy of no-go areas'. Land is zoned according to maximum FARs, with extremely dense building permitted directly above and adjacent to rail stations.

**Figure 3.26**: (Left) Successful integration of land-use and transit planning in Hong Kong. This integration has put 75 percent of people and 84 percent of jobs at less than 1 km from a mass transit station, achieving one of the highest rates of public transit use (90 percent of motorized journeys) and one of the lowest rates of car ownership (56 cars per 1,000 people compared with an average of 404 per 1,000 in OECD countries).

**Figure 3.27**: (Right) TOD policies in Hong Kong have succeeded in decoupling economic growth and energy intensity with an increase in GVA per capita of 50 percent between 1993 and 2011, while $CO_2$ emissions per capita and road gasoline consumption per capita declined by about 10 percent.





(Source: Rode et al., 2013 - LSE Cities Urban Age)

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66. This includes the 'Station Proximity Principle', which generally requires new large offices of more than 1,500 m² to be located within 600 m of a railway station. Regulation of retail developments promotes the location of shops in town centres by restricting the size of shops and specifying the location of town centres where retail development is permitted. In addition, city-level land-use planning stimulates mixed-use, high-density development around stations and limits parking provisions (Floater *et al.,* 2014a).

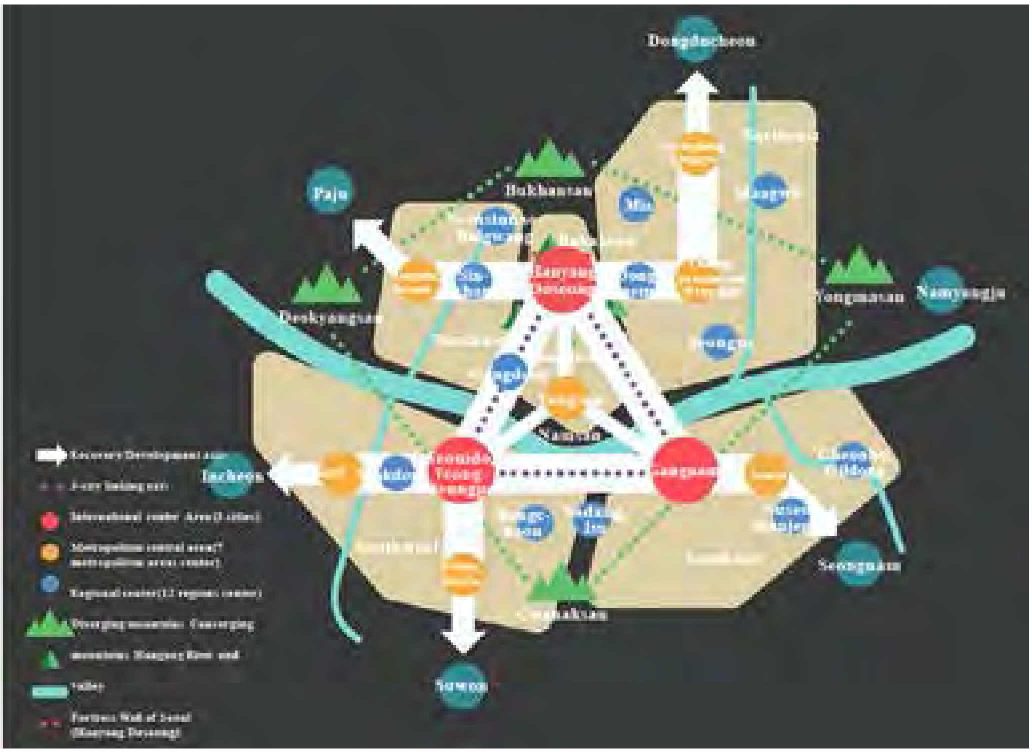
### Polycentric urban systems

Most cities shaped by subway systems are polycentric, with a ring of strong economic sub-centres along the loop line (e.g. the *Yamanote* line in Tokyo or the Circle line in London). Seoul's subway network, inaugurated 90 years after London's Circle line, is less concentrated and more grid-like, encouraging the emergence of sub-centres such as *Gangnam-gu*. Similarly, Singapore has actively pursued a polycentric structure with sub-centres linked by mass transit. Agglomeration benefits in a polycentric spatial configuration lead to stronger support for public transit and other, more sustainable modes of transportation, such as walking and cycling, along with lower $CO_2$ emissions from transportation and less pressure on undeveloped land (Anas *et al.*, 1998; McMillen, 2001).

Policies to develop polycentric spatial formations are as follows: (1) support new, more efficient public transportation networks between centres to enable them to better exploit their aggregate urban size, leading to a greater development of agglomeration economies; (2) enhance the complementarity among centres on the metropolitan scale in terms of economic sectors, occupations and urban functions through promoting TOD and compact city development; (3) support new, more efficient public transportation networks between centres and their neighbouring areas to stimulate activity in centres and increase nearby residents' access to the agglomeration benefits.

## Seoul's polycentric spatial restructuring

**Figure 3.28**: Seoul's polycentric spatial restructuring.



(Source: Seoul Plan 2030)

Seoul's spatial restructuring plan aims to develop a polycentric megalopolis with one centre, five sub-centres, 11 local centres and 53 district centres. The polycentric vision fosters the enhancement of centrality in each region, the systematic development of urban centres considering the topography and the urban scenery, and construction of a green network by linking four inner and four outer mountains, rivers and streams, creating a water-friendly landscape. A key policy is to align land use and transportation structure by intensifying spatial centrality at the nodal points of transportation and enhancing functionality of mass transportation by developing urban centres at the transportation nodes.

## Policy instruments for containing land expansion and articulating densities

Urban containment instruments, such as greenbelts or urban growth boundaries, have been employed in many cities including London, Berlin, Portland, Beijing and Singapore. In the UK and South Korea, greenbelts delineate the edges of many built-up and rural areas. In many European cities, after the break-up of the city walls in the 18th and 19th Centuries, greenbelts were used to delineate cities. Some US states have passed growth management laws that hem in urban sprawl through such initiatives as creating urban growth boundaries, geographically restricting utility service districts, enacting concurrency rules to pace the rate of land development and infrastructure improvements, and tying state aid to the success of local governments in controlling sprawl (Seto *et al.,* 2014). However, the mixed evidence on the impacts of urban containment instruments on density and compactness (decreases in some cases and increases in others) indicates the importance of instrument choice and particularities of setting, and the need for a finer grain approach to managing urban forms, such as setting FARs with a fine granularity, as in Seoul or Singapore.

The regulatory instrument to articulate densities is FAR. FAR[67] is the ratio of a building's total floor area (gross floor area) to the size of the piece of land upon which it is built. Zoning policies can be fine-tuned to accessibilities within public transportation networks. First, it is encouraged that FAR be set at different levels depending on use and accessibility, as in the example of Seoul below. Second, it is recommended that FARs include a margin of flexibility both for transferring FAR between uses according to market changes and for allowing the private sector to adjust intensity of development to market needs. This increases the marketability of real estate operations in developments that take years to complete. This margin of flexibility can also be used to capture part of the value created by real estate development to finance public transportation infrastructure provision, public space and affordable housing.[68] Seoul has successfully shaped its urban form by setting FARs to encourage high-density development around public transportation nodes, as explained in the box below.

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[67] Also floor space ratio (FSR), floor space index (FSI), site ratio and plot ratio.

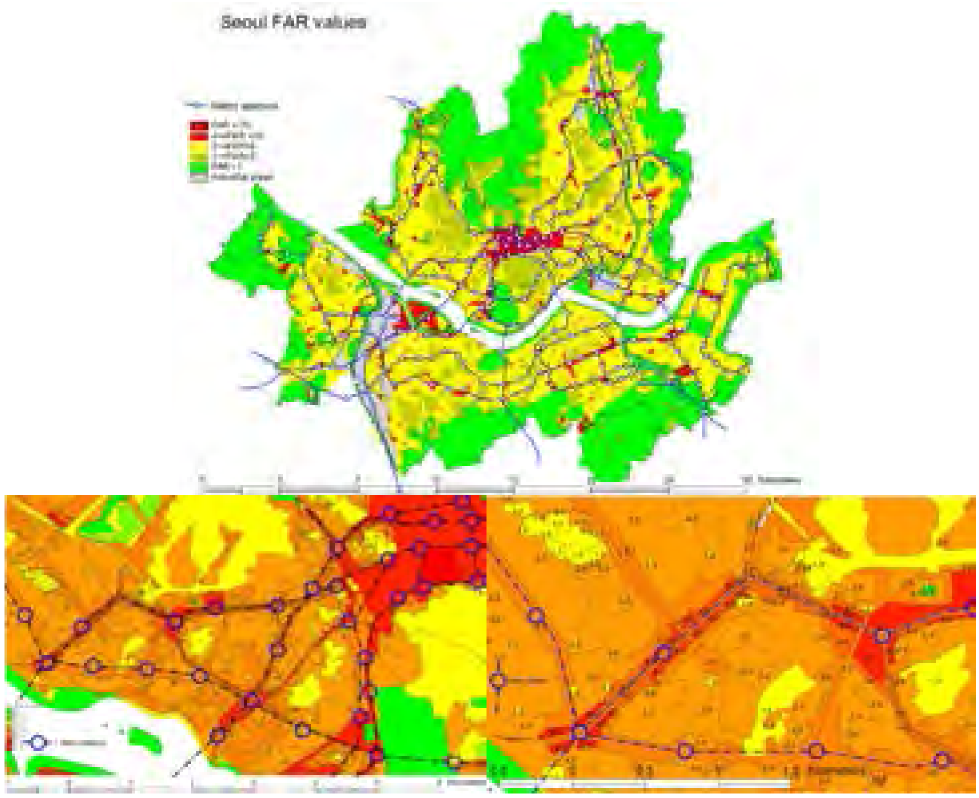
[68] For example, adapted zoning in Hudson Yards, New York sets varied FAR for predominantly commercial (FAR 10 to 33), mixed-use (FAR 6.5 to 12), and predominantly residential (6 to 15) development, with a range between base and maximum FAR, in order to introduce flexibility and capture value. Developers who want to build over base FAR and up to maximum FAR (for example, between base FAR 10 and maximum FAR 33 for commercial use in the densest blocks) can do so by making bonus payments into the zoning-based District Improvement Fund (DIF). This creates an additional real estate opportunity and facilitates demand-driven development. DIF can be used to finance subway line extensions, public space and inclusionary housing, creating a positive feedback loop of development from the initial rezoning at higher density, and a social mix within a grade A, mixed-use business district.


Credit: KoreaKHW/shutterstok.com

## Seoul zoning regulations encourage high-density development around transportation nodes

Seoul zoning regulations set FARs as high as 10 for commercial use around the most connected and central public transportation stations, at between 2 and 4 for mixed residential and business areas, and at between 1 and 2 for residential use. Uses are defined with a fine granularity depending on proximity to and importance of public transportation stations. This creates a varied city with small residential neighbourhoods in close proximity to thriving business districts.

**Figure 3.29**: Seoul variations in floor space index (FSI) are linked to the location of metro stations and to the network of main streets.



(Source: Alain Bertaud – Used with his permission)

### Articulated density at the network level

Cities are networks from which locations emerge. Transportation networks can have a strong lock-in effect as they reinforce density patterns with positive feedback loops.

International experience suggests that efficient subway patterns in global cities tend to converge towards a similar layout characterized by a core and branches structure (Roth *et al.,* 2012). The core of a radius of about 5 km is densely connected with a constant density of stations, highly interconnected by crisscrossing lines, and ensures high levels of accessibility for people and companies. The structure then changes for branches, with a density of stations decreasing sharply[69] when moving away from the city core. Thus, levels of accessibility decrease sharply when crossing the core limit. The core and branches layout has a strong impact on local development potential. Once established, this core and branches structure determines the long-term trajectory of densities.

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[69] The sharp decrease in density of stations with distance to city centre follows an inverse power law of the form $R^{-1.6}$. See: Salat and Bourdic, 2015.

To reap the benefits created by investments in public transportation networks, it is necessary to coordinate intensification of land-use and economic policies by: (1) encouraging development in the major interchanges, in the most accessible stations of the network and in the stations that are major articulations of the network; (2) moderating development in the areas that are less accessible within the network; (3) discouraging development in areas that are more than 1 km from a subway station.

## Achieving energy productivity by articulating densities along transit networks in Tokyo

**Figure 3.30**: A map of Tokyo's urban rail structure, consisting of branches radiating from the Yamanote line and the polycentric concentration of economic activity in the hubs (in red) along the Yamanote line. Map of Tweets and Flickr activity in Tokyo.

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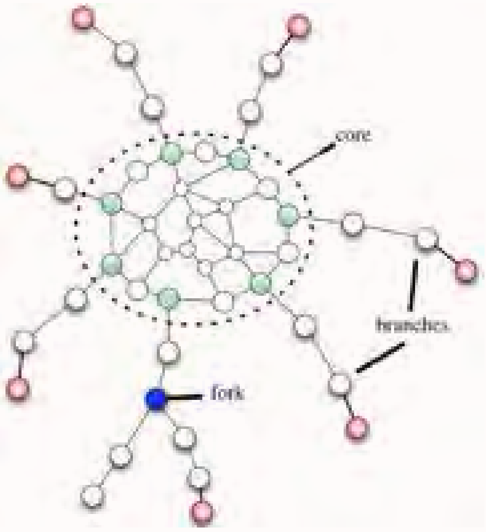
Japan is a country with dense cities. For example, the density in Tokyo's 23 wards (9 million inhabitants) is above 15,000 inhabitants per km$^2$ on 600 km$^2$. Japanese cities have the densest and most connected street patterns—the average distance between intersections is 50 m, the shortest in the world. The density of intersections is around 300 intersections per km$^2$, the highest of any global city. Japan has the world's highest level of transit connectivity and intensity of use. With 2,200 stations and more than 4,000 km of lines, Tokyo's urban rail network is by far the longest in the world—six times longer than the second longest in Seoul. While the passenger traffic is 8 million people per day across the entire Shanghai subway network, it is 3.6 million people per day in Tokyo's Shinjuku station alone, making it the most active hub in the world.

Japanese cities have experienced one century of TOD under the joint action of governmental planning and market forces, and they have compact and connected urban forms. Due in part to this exceptionally dense and well-connected urban form, Japan has the highest world energy productivity (ratio of energy consumption to added value), close to three times the global average.

**Figure 3.31**: Schematic of subway networks. A 'ring' encircles a core of stations. Branches radiate from the core and reach further areas of the city. The core is densely connected with a constant density of stations, highly interconnected by crisscrossing lines, and ensures high levels of accessibility for people and companies at less than 500 m.

(Source: Roth et al., 2012)



## The shape of the urban energy landscape matters for energy transitions

In parallel to spatial planning, energy planning can play a key role in facilitating an urban energy transition towards sustainability. Like urban densities, energy uses vary in relation to the structures of the built environment and show similar patterns of order and disorder, continuity and fragmentation, concentration and dispersal. However, urban energy landscapes follow their own spatial logic and may not be entirely congruent with spatial density patterns. Urban energy landscapes relate to the spatial organization of multiple energy services, depending on how people use energy (for lighting, thermal comfort, communications, cooking, transportation) and how energy services are provided—whether this is for the generation of electricity, gas provision or for the direct use of fuels for heat or mechanical power. Urban energy landscapes are experienced as a continuous arrangement of artefacts that mediate the transformation of energy resources to provide different but simultaneous services (Castán Broto, 2017). Recent international research suggests that spatial regularities in the way systems of energy provision and use are organized are manifest in these urban energy landscapes (Castán Broto, 2017).

From cases studies in Hong Kong, Bangalore and Maputo, Castán Broto (2017) suggests a general typology of energy landscapes with four types: (1) uniform, as in Hong Kong; (2) zoned, as in Maputo; (3 and 4) and a scattered landscape characterized by hotspots (scattered A) or cold-spots (scattered B), which we can find in Bangalore at different times during the year. This preliminary typology, similar to the typology of densities but not necessarily congruent to it, shows the heterogeneity of urban development patterns and energy landscapes patterns and how they may coevolve in different contexts. Coevolution is a concept that explains the uniqueness of the landscape perspective. It refers to processes of interaction between evolving human and biophysical systems, which account for the changes in both systems (Norgaard & Kallis, 2011). Coevolution occurs when changes over time in seemingly separated systems (human and biophysical) lead to a mutual response (Weisz, 2011). Such patterns of urban energy landscapes shape the possibilities for change in determined urban trajectories. Castán Broto's (2017) analysis suggests that there is a mutually reinforcing relationship between the way energy systems are spatially organized in different urban areas and the potential for innovation in sustainable energy, which in turn, shapes any possible trajectories towards energy sustainability.

This section has determined the main relationships between resource use, urban form and spatial distribution of urban functions, and has given policy insights into how to shift city trajectories towards more sustainable, systemic organization at the metropolitan scale. The following section focuses on the community scale. Creating compact urban patterns with low-resource and low-energy urban fabric at the local level requires paying particular attention to urban design of mixed-use, accessible communities at the human scale. This is the second lever of the cascading strategy presented in this chapter and is detailed in the following section.

## 3.4. Lever 2: Liveable, functionally and socially mixed neighbourhoods

There has been a steady body of scholarship on sustainable urbanism studying how urban morphology (the granular structure of urban areas in blocks or groups of buildings) and urban form (its distribution in zones) impact the embodied and operational energy of the built environment, from influencing heat demands to shaping users' behaviour (recent examples include: Howard *et al.,* 2012; Rode *et al.,* 2013; Salat, 2009; Wong *et al.,* 2011; Zanon and Verones, 2013; Zhou *et al.,* 2013). This body of research shows that sustainable urban forms can be achieved in multiple ways and with attention to city-specific contexts (Williams *et al.,* 2000).

Based on this research, this lever describes the benefits of well-designed urban fabric and functionally and socially mixed neighbourhoods, with a rich mix of housing types and social amenities for different income groups; of dense and connected grids of streets defining small perimeter blocks, which create conditions for zero-carbon mobility (walking, cycling); and of passive heating, cooling and lighting at the building level thanks to a bioclimatic design (DeKay, 2012).

Grids are a traditional 19th Century urban pattern of rectilinear public streets and private blocks (Marshall, 2004). A wide variety of low- and high-density housing types may be built within the blocks, with shops and services along principal routes of movement, all unified by the system of streets. This enables high accessibility and walkability within a mixed-use, liveable environment. Small perimeter blocks are defined by small-scale, connected buildings of three to five storeys, arranged around a central shared space or a series of courtyards. The courtyards allow sun to penetrate into all units, retain heat in the winter and can mitigate the effects of wind in cold climates. They also allow for individual front doors on the perimeter and semiprivate spaces inside—a highly liveable arrangement. Such schemes can accommodate great diversity within their morphology. In a bioclimatic design, the same integrated approach is taken in the design of buildings and associated outdoor areas; natural ventilation and passive solar principles guide the building form.

After discussing the negative impacts of present neighbourhood design patterns, this section will show how to develop compact neighbourhoods according to smart growth principles.

### 3.4.1. Negative impacts of urban fabric design in sprawl patterns on resources and energy use

Sprawled urban fabric patterns are characterized by two main types: detached single houses (the dominant urban fabric of suburbia in the USA and Europe) and towers-in-a-park superblocks in many emerging cities, and notably in China.

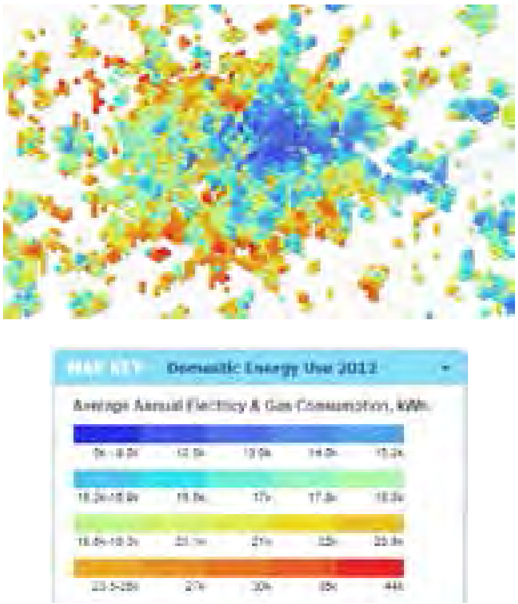
#### Detached, single, suburban houses

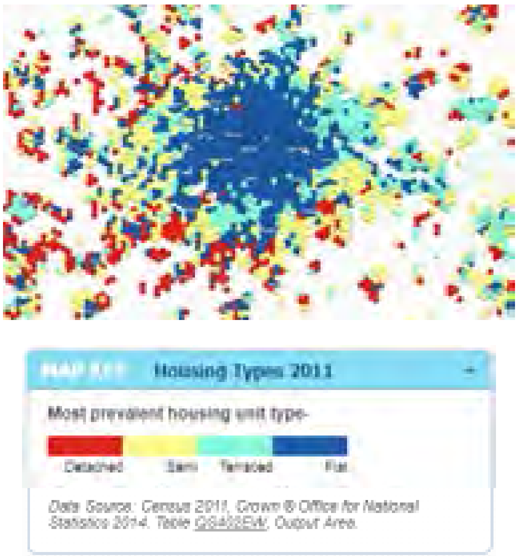
Many studies have found a correlation between urban fabric shape and energy consumption for buildings (Martin Centre, 1997; Traisnel, 2001; Ratti *et al.,* 2003 and 2005; Salat, 2009; Salat *et al.,* 2011; Salat, 2013; APUR, 2007 and 2009; LSE Cities & Eifer, 2014). All these studies have found urban fabric to have significant impacts on energy consumption, with more than twofold variations between most efficient and less efficient fabrics. The study presented below maps these differences geographically and associates them with different housing types. In the London example, it shows that average domestic energy use per household is much lower in dense urban centres than in the suburbs—it can be five to nine times lower. This result is confirmed by other studies, for example, LSE Cities and Eifer (2014), which found differences up to sixfold when studying dozens of urban fabric types in four cities—Paris, London, Berlin and Istanbul.

## Housing types impact on urban energy in Greater London

The following maps show, in the example of Greater London, that the dense urban centre's average domestic energy use per household is much lower than that of the suburbs, and can be five to nine times lower. Similar results have been confirmed in other cities. City centre households have considerably lower energy use, with a strong bias towards inner East London where incomes are lower.

**Figure 3.32**: (Left) Domestic energy use in Greater London—average annual electricity and gas consumption, kWh. The map shows average household domestic electricity and gas consumption estimates, at the scale of 1 km$^2$ grid cells. Gas data have been weather corrected; cell heights show residential population density
**Figure 3.33**: (Right) The most prevalent housing types in Greater London, at the scale of 1 km$^2$ grid cells. Note that all areas contain a mix of housing types and the mix is not shown here. The height of the grid cells shows residential population density





Note: Grid cell = 1 square kilometre

(Source: Duncan A. Smith, CASA, Bartlett UCL, Luminocity, Urban density and dynamics explorer).

### Modernist superblocks with towers in a park

Modernist, high-rise, towers-in-a-park superblocks consume almost twice as much energy as more conventional mixed-use neighbourhoods developed with small perimeter blocks. These inefficiencies come from the non-efficient shape factors of isolated, large buildings compared with a continuous, fine-grain urban fabric. A continuous, small-block urban fabric has less radiative losses through building envelopes, more solar gains and better availability of natural lighting, and can use passive cooling techniques, such as natural ventilation. For transportation, superblocks have created an energy-wasteful urban context with single-use, widely spaced, residential high-rise buildings and above- or below-grade parking, where people must use elevators and cars for all their daily needs.[70]

Despite its tall and massive buildings, this urban form is generally less dense than medium-scale, traditional urban fabric with its multiplicity of human-scale green spaces and courtyards. In most parts of Paris, the built density (FAR) is between four and five, while in Shanghai, for example, it is around one at the neighbourhood scale (Salat *et al.,* 2011) and much lower at global city scale because of all the space lost in giant arterials and setbacks. This is a legacy of modernist planning, which reversed the relationship between built forms and empty spaces. The plot coverage (i.e. the ground surface occupied by buildings in a block) is about 0.65 in continuous historical fabrics—houses with courtyards, row houses, terraces or small perimeter blocks with courtyards. Since built density is calculated by multiplying the plot coverage ratio by the number of floors, towers in a park need to compensate for their low coverage ratio with height. This simplified, oversized urban fabric type is particularly wasteful, as illustrated below with empirical evidence from Chinese cities.

Credit: Renata Sedmakova/shutterstok.com

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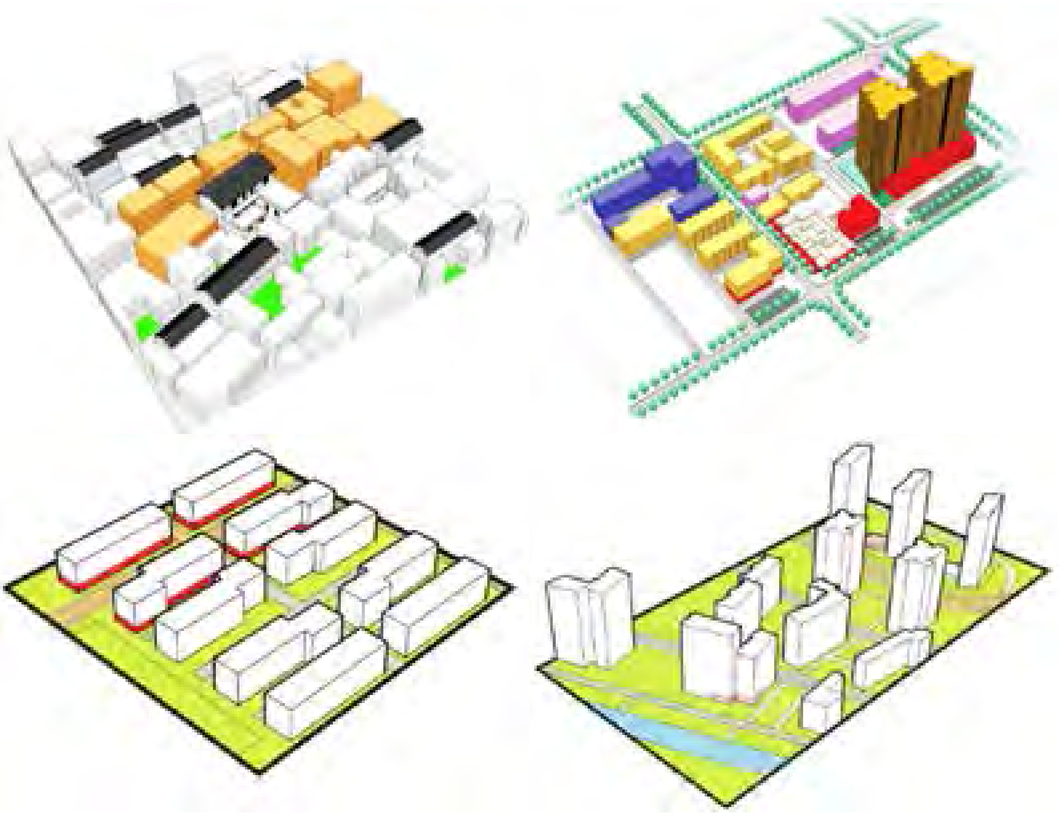
[70] Such projects are versions of the 'modernist city', developed in Europe a century ago in the 1920s to reflect the 'machine age' of industrialization and of the automobile. Based on standardization and segregation of functions, modernist cities were planned with separated housing superblocks consisting of identical buildings, shopping centres, recreation parks, offices and industrial districts organized within a vast, undifferentiated space, where machines (cars and elevators) are needed to link together the various aspects of daily living.

## Energy efficiency of different urban fabrics in China

Current regulatory planning in China requires a main arterial road every 500 m and an eight-lane road every kilometre. The width of these roads is 60–100 m, to which should be added setbacks of up to 40 m each side. This creates impassable barriers for pedestrians. Development happens within the superblocks defined by these roads, most of the time in the form of gated communities. As seen in the discussion about lever 1 in the example of Shanghai, in recent decades this has been the major mode of urban growth in China. These superblocks are two times more energy intensive than any other urban fabric found in China, as demonstrated by a MIT study in Jinan comparing operational, transportation and embodied energy per household for four urban fabric types in 27 neighbourhoods across the city (Yang, 2010; MIT *et al.,* 2010).

The following four patterns constitute the urban fabric of most Chinese cities:

**Figure 3.34**: (From left to right, top to bottom) Traditional settlement, urban grid, enclave and towers in a park.



(Source: Energy Foundation, MIT, Tsinghua University)

1. Pre-1910: Traditional settlement—low-rise, high-density courtyard housing organized along hutongs with a central commercial street.

2. 1920: Urban grid—conventional streets and blocks with mixed uses and building types.

3. 1980: Enclaves of low-rise slabs—rows of repetitive, six- to seven-storey, walk-up apartments. The government or *danwei* (work units) developed them to house working-class families during China's first wave of urbanization, beginning in the 1970s.

4. 2000: Towers in a park—mainly single-use, residential districts consisting of widely spaced, 20- to 30-storey towers with surface or underground parking.[71]

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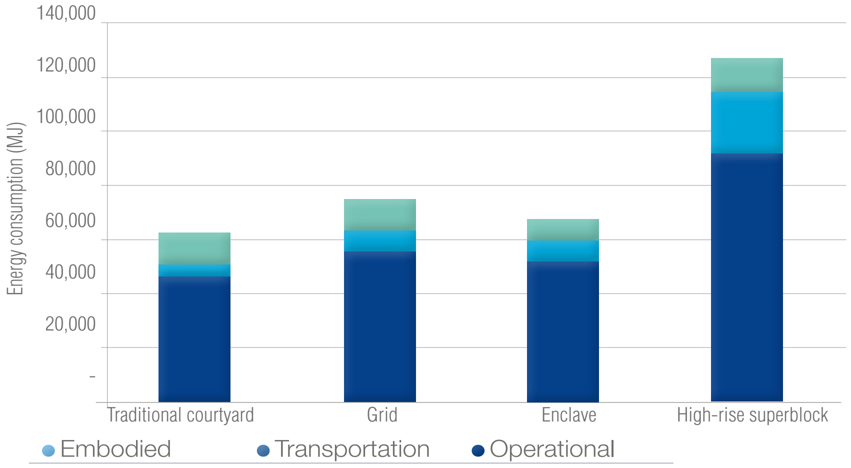
[71] This form emerged in the 1990s when land reform benefited private developers who generally sought to fit the maximum amount of housing on large sites in the least expensive way; however, in practice, these projects are not significantly denser (and, in many cases, are less dense) than the grids or the enclaves.

Superblocks use twice the energy of other patterns.[72] Operational consumption (in home and common area) accounts for the largest estimated share, approximately 71–79 percent of estimated total household energy consumption in each case. The high level of operational energy in the superblocks is mainly due to the need for vertical transport of people, water and goods, but also to the operation of parking facilities (lighting, ventilation) and to vast open space. The results also reveal a significant relationship between urban fabric types and transportation energy use. Households in the high-rise superblock projects consume, on average, two to three times more transportation-related energy than those in other neighbourhood types. The single-use nature of the towers in a park requires that households use automobiles to accomplish all day-to-day activities.

**Figure 3.35: Energy consumption per household by prototypes.**



(Source: Energy Foundation, MIT, Tsinghua University)

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[72] Data have been collected across 27 neighbourhoods in Jinan. Based on the embedded, operational and transportation energy estimates, the energy consumption and GHG emission patterns across neighbourhoods were compared with form types, and income and behaviour factors have been neutralized, revealing the 'pure' impact of urban fabric form.

### 3.4.2. Planning and designing sustainable neighbourhoods with the four levers

In contrast to modernist urban planning, the morphological textures of historical cities combine a high degree of complexity with granular patterns at various scales. A smaller, more complex and denser fabric of small blocks and small buildings accommodates mixed uses and creates an airy, accessible city. This urban fabric reduces the amount of resources and energy currently required to support excessively sized buildings and infrastructures. After presenting a case study on a sustainable neighbourhood where the four levers of change have been successfully implemented, this section will successively detail the perimeter block energy efficiency, sustainable street patterns, green spaces, key planning parameters, the importance of good urban design and bioclimatic design.

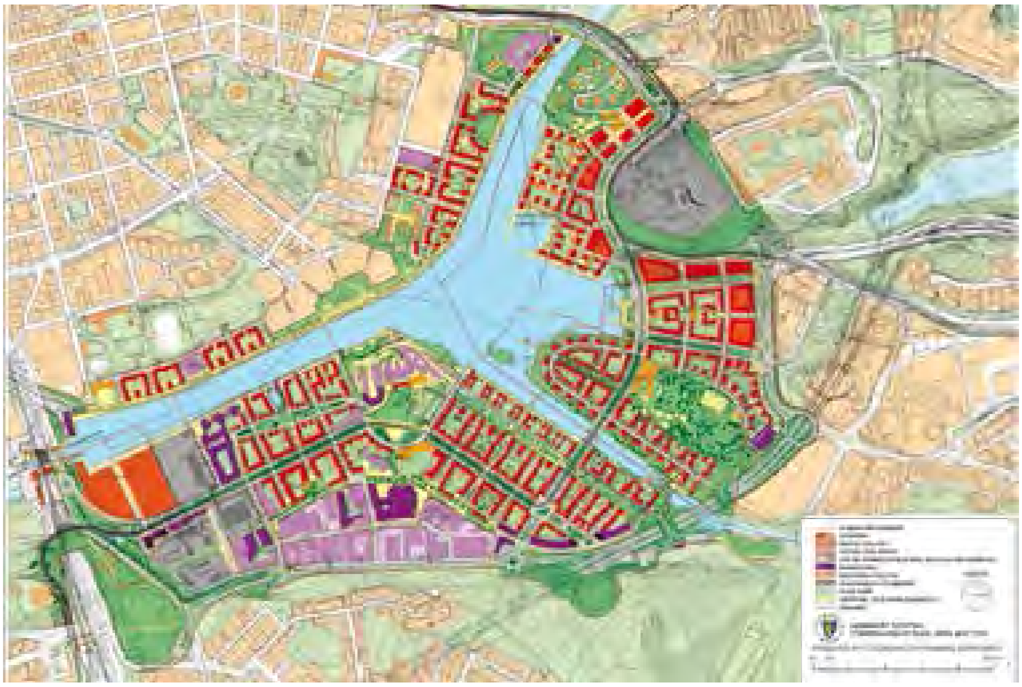
Credit: jamesteohart/shutterstok.com

## Applying the four levers in Hammarby Sjöstad

Hammarby Sjöstad in Stockholm, Sweden, is widely recognized for having implemented an integrated approach to district planning incorporating the four levers with high density and a TOD[73] approach of sustainable transportation, a human-scale urban design, innovative, eco-friendly infrastructure and behavioural change. The 160-hectare district was built on a former industrial and harbour brownfield area located on the south side of Hammarby Lake, 3 km south of Stockholm city centre.

### First lever — Compact urban growth: Articulated densities with a TOD approach of sustainable transportation

**Figure 3.36**: Layout of Hammarby Sjöstad. It was designed to integrate transportation, amenities and public spaces in a high-density district, based on a flexible grid of small blocks with large provision of public green space and streets designed as places for people.



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Hammarby Sjöstad is a high human density district with a projected density of 15,000 people and 7,500 jobs per km². The integration of transportation and land-use planning was recognized as a key component affecting the sustainability of the project. The spine of the district is a 37.5-metre wide boulevard and transit corridor, which connects key transport nodes and public focal points, and creates a natural focus for activity and commerce. These policy and design measures have proven effective—it is estimated that overall transport-related emissions for residents of Hammarby Sjöstad are less than half that of an average Stockholm resident, and less than a third that of an average resident of Sweden.

### Second lever — Functionally and socially mixed neighbourhoods with human-scale urban design

Dense and compact urban form is achieved through medium-height, small perimeter blocks with a network of parks, green spaces, quays and walkways running through the development.

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[73] Transit-oriented development (TOD) is a planning and design strategy to ensure compact, mixed-use, pedestrian and two-wheeler friendly, and suitably dense urban development organized around transit stations. It embraces the idea that locating amenities, employment, retail shops and housing around transit hubs promotes transit usage and non-motorized travel. Well-planned TOD is inclusive in nature and integrates considerations of resilience to natural hazards.

**Figure 3.37**: Hammarby Sjöstad's urban block pattern and sizing is based on the block typology of inner Stockholm.

(Source: van Assche et al., 2000)

**Figure 3.38**: Hammarby Sjöstad water landscaping.

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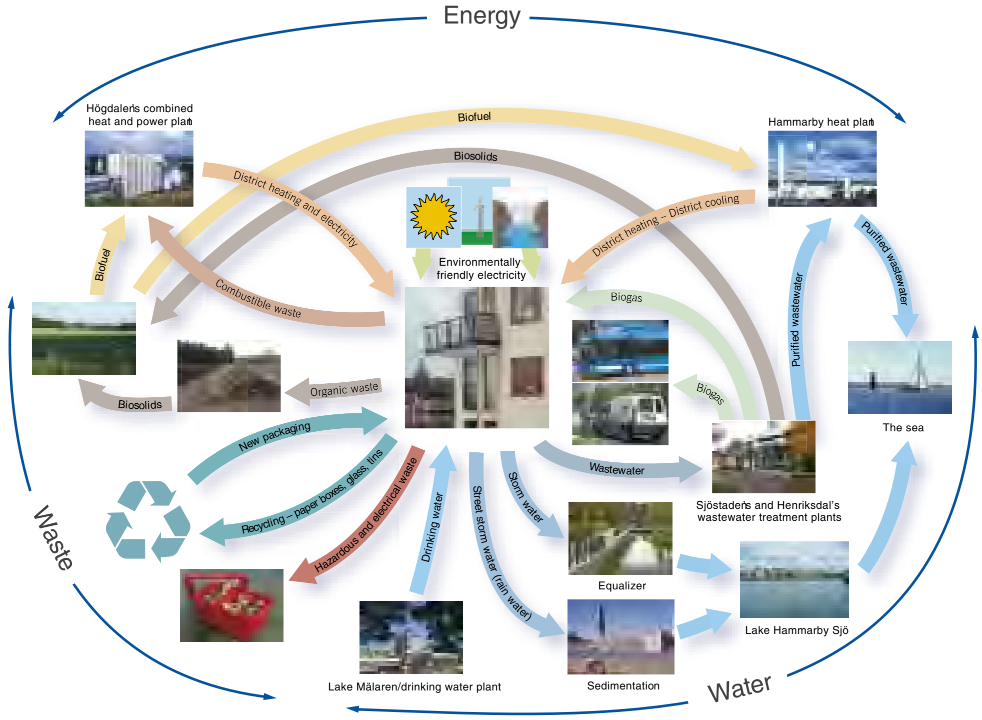
Urban planning and design have transformed an industrial brownfield into a desirable place to live by providing the site and urban fabric with aesthetic qualities based on the traditional block typology of the inner city. The district has been planned as a dense settlement structure, typically with four- to five-storey buildings in a compact neighbourhood outline, but with reasonably spacious green courtyards. The design follows standards for Stockholm's inner city in terms of street width (18 m), block sizes (70 x 100 m), density and land use. The traditional city structure of Stockholm has been combined with a new architectural style that responds to its specific waterside context, promotes the best of contemporary sustainability technology and follows modern architectural principles of maximizing light and views of the water and green spaces.

### Third lever — Resource-efficient buildings and urban systems: innovative eco-friendly systems

The Hammarby model is a unique eco-cycle system that integrates energy, solid waste, water and wastewater from homes, offices and other activities in the area. It is a balanced, 'closed-loop' or 'circular' urban metabolism in contrast with traditional models of linear flows. The total energy supply is based solely on renewable sources.[73]

**Figure 3.39**: The Hammarby model is a unique eco-cycle system.



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### Fourth lever — The promotion of sustainable behaviours

In order to meet the targets set out for the project, there has also been a need for individual residents to change their behaviour. The project includes an education centre, known as *Glashus Ett* (Glasshouse One), which is a showcase for environmental technologies and hosts regular exhibitions to explain and encourage pro-environmental behaviour by residents.

In conclusion, Hammarby Sjöstad is well on its way to becoming a low-carbon, resource-efficient community. Relative to conventional development, the project reduced air, soil and water emissions and pollution by 40–46 percent, non-renewable energy use by 30–47 percent and water consumption by 41–46 percent.

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74. The adjacent Hammarby thermal plant extracts heat from the treated wastewater and contributes by-product energy to the district-cooling network. The Högdalen cogeneration plant separates combustible waste as an energy source in electricity and district-heating production. Hammarby Sjöstad also has solar panel installations on its walls and rooftops, which use photovoltaic cells to convert sunlight into energy for heating water.

### Energy-efficient urban forms are based on small perimeter blocks and courtyard forms

Small perimeter blocks are typically between 50 m (Japan), 70 m (Mediterranean Europe) and 100–120 m per side (19th Century Europe). They can be square or rectangular. Their edges are incrementally developed and defined by small-scale adjacent buildings of two storeys in Japan, three to five storeys in Mediterranean Europe and seven storeys in 19th Century Europe, arranged around a central shared space—a series of courtyards (like in Paris or Berlin) and/or green spaces (like in Amsterdam). Studies have shown that these perimeter blocks are more energy-efficient than other forms of urban fabric (Salat, 2009; LSE Cities & Eifer, 2014). In Paris *intra muros*, for example, some types of urban block (namely modernist slabs and towers developed in the 1960s and 1970s) emit nine times more $CO_2$ per $m^2$ for heating than more recent urban blocks. This is the result of a number of factors, of which urban form is the most significant (APUR, 2007; Salat, 2009). These results are confirmed in a different context by empirical studies in China (Yoshino *et al.,* 2008). In the African context, examples of higher urban density formations include Stone Town on Zanzibar, the island of Gorée off the coast of Senegal, Timbuktu (before it was recently destroyed), parts of old Cairo and Alexandria, the Kasbah of Algiers and Bo-Kaap in Cape Town.

### Sustainable street patterns

The street system provides the connectivity matrix for the city, which is fundamental not only for urban mobility but also for inclusiveness, economic vibrancy and human interactions. As underlined by UN-Habitat Executive Director Dr. Joan Clos:

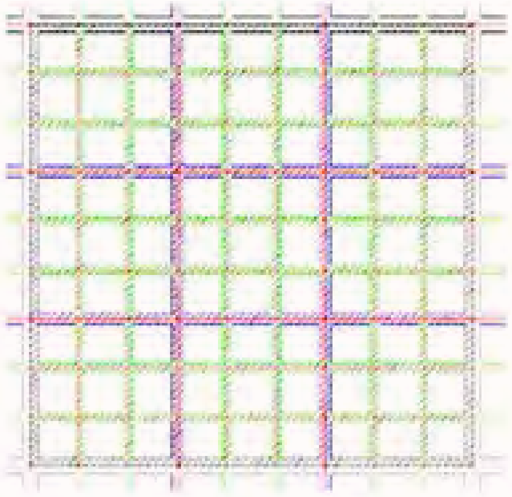
> *The efficiency of this mobility is a determinant for urban economic productivity. Secondly, the street pattern also provides the matrix for the layout of urban basic services, mainly energy, water supply and sanitation, drainage, transportation, parking slots and other services. The affordability of these urban services is also related to the quality of street patterns. Thirdly, the street pattern, including plazas and public gardens, is the key element of personal interaction and communication between the citizens. In that sense, it defines the cultural and political quality of city life. Fourthly, the walkability of the spaces, the safety of the pavements and the form and location of shops along the street determines the quality and quantity of street life. When safety and security issues arise, public space is abandoned and gated communities emerge as a form of protection against the rest of the city. This results in the failure in the function of cultural life of the street. (UN-Habitat, 2015a)*

### Green spaces

An interconnected system of natural spaces, ranging from a regional greenbelt to a pocket play park, should, from a landscape ecology perspective, provide the main structuring elements of urban settlements. This principle reflects the importance of identifying natural systems and strategic landscape patterns, which protect valuable ecosystem services and biodiversity hotspots, and designing the city around these (i.e. linking these systems if fragmented). Green spaces and the use of nature-based systems play an important role in building a city's resilience to climate change and natural disasters, and should be valued as important urban assets (Francis & Chadwick, 2013). Green spaces in particular cool and provide shade in the city and decrease energy use. In addition to the direct benefits


Credit: Oscity/Shutterstock.com

**Figure 3.40**: Street network model



### Street network model design

Dense street patterns promote efficient traffic, sustainable accessibility, social interaction, public safety and access to amenities. The figure shows a simple street network model. In an area of 1 km$^2$, nine vertical and nine horizontal streets are designed to form a street grid. The distance between two adjacent streets is 111 m, and the total street length is 18 km. In this street network model, both street hierarchy and block size are considered. This simple model demonstrates the balance between street and other land uses. City management and urban planners could adjust the design pattern of the street network to the topography of the site or create rectangular patterns, but a street density level similar to the one recommended in the model should be maintained (UN-Habitat, 2014a).

of shading, green spaces help reduce the UHI effect (Rosenzweig *et al.,* 2006; Salat, 2015). They save costs by controlling rainwater run-off, thus reducing the need for more expensive engineering approaches to guard against flood risk (Zhang *et al.,* 2012 and 2015). Green spaces can also provide opportunities for local food production, thus improving the availability of fresh produce and reducing the need for food to be transported from rural hinterlands. Green spaces are also beneficial for human health and social interaction.

### Key planning parameters

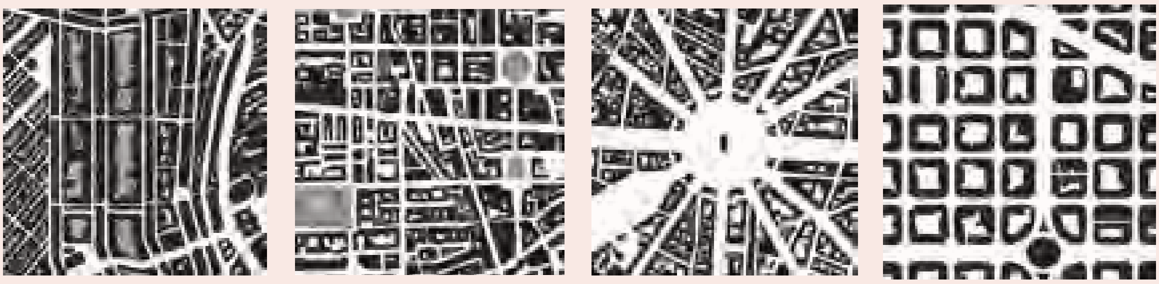
Key recommendations for planning resource-efficient communities are summarized below (UN-Habitat, 2014a):

- High density: Densities of at least 15,000 people per km$^2$ or 150 people per hectare should be pursued (according to UN-Habitat 2014a recommendation).
- Adequate space for streets and an efficient street network: The street network should occupy at least 30 percent of the developed land area and comprise at least 18 km of street length per km$^2$. Efficient and well-connected street networks comprise a variety of moderate street widths and between 80 and 100 street intersections per km$^2$ in order to manage variable flows, thus avoiding congestion.
- Mixed land use: At least 40 percent of floor area should be allocated for economic use in any neighbourhood.
- Social mix: Houses should be available in different price ranges and tenures in any given neighbourhood to accommodate different incomes; 20–50 percent of the residential floor area should be for low-cost housing, and each tenure type should be no more than 50 percent of the total.
- Limited land-use specialization: To limit single-function blocks or neighbourhoods, single-function blocks should cover less than 10 percent of any neighbourhood.

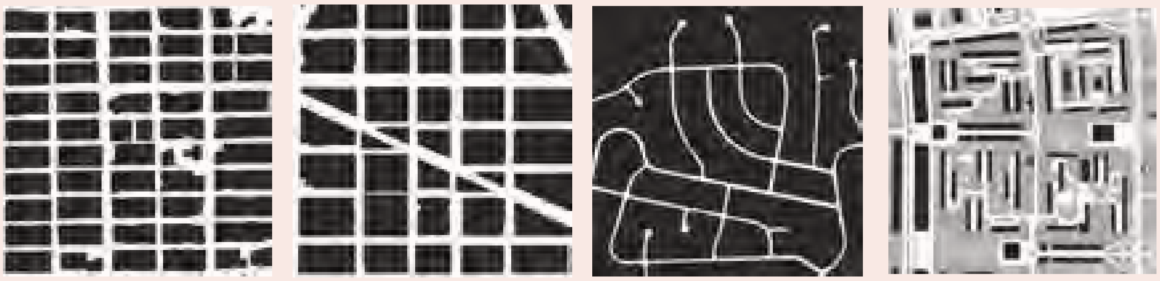
These UN-Habitat recommendations correspond to the types of urban fabric of the cities that rank highest in the UN-Habitat City Prosperity Index (UN-Habitat and International City Leaders, 2015). The figure below shows international benchmarks of street patterns and compares traditional urban fabric with modernist planning. Each square is 800 x 800 metre. European historical cities had very high numbers of street intersections while recent Chinese developments have among the lowest and follow the model of Le Corbusier's Radiant City.

**Figure 3.41**: Density of street intersections per $km^2$ in traditional and modernist urban fabrics in 16 cities

Venice: 688 Toledo: 420 Florence: 255 Turin: 191



Amsterdam 17th Century: 195 London Mayfair 1735: 165 Paris Etoile: 133 Barcelona Cerdà plan: 103



Manhattan: 120 Washington L'Enfant plan: 48 Washington suburbia: 36 Brasilia Quadra: 41

Beijing South: 16 Beijing South: 13 Shanghai Lianyang towers: 27 Shanghai Lujiazui (Pudong): 17

(Source: Salat et al., 2011)

## The importance of good urban design and public places

Public space gives vibrancy to urban life and is intimately linked to the sizing, scaling and rhythm of the urban fabric. Urban designers cannot design good public places independently of fine-grain urban fabric. Numerous perceptual qualities affect the individual reactions to a place, the walking experience, the sense of safety, the sense of comfort and the level of people's interest. To achieve overall walkability, urban designers should create urban qualities, such as spirit of place, enclosure, human scale, layering of space, complexity, coherence, legibility and linkage (Salat & Ollivier, 2017).

## Bioclimatic design

The sun moves by day and by season. It is an ever-changing source of heat and light, a source that we can tap only to the degree to which we consider its dynamic character. Designing with nature derives energy and provides thermal comfort, ventilation and lighting from the natural forces of sun, wind and light (Olgyay, 1963; Brown & DeKay, 2014). Technologically sophisticated systems tend to be less robust, subject to cascading failures when highly networked and require more maintenance.

Urban designers can look for ways to reveal natural energy processes in the city and to give them meaning in the lives and experiences of its inhabitants. Through light and shade, through coolness and warmth, along delicate webs of narrow streets that transformed their light pattern like sundials responsive to seasons and the hours of the day, the traditional city was a rhythmic pattern of forms and light, making visible the flows of sun energy through the city. At a time when most of our cities conceal their environmental control systems and segregate occupants from the rhythm of life, integrated bioclimatic design strategies can be used to heal the relationship between people and the living systems of which we are all a part.

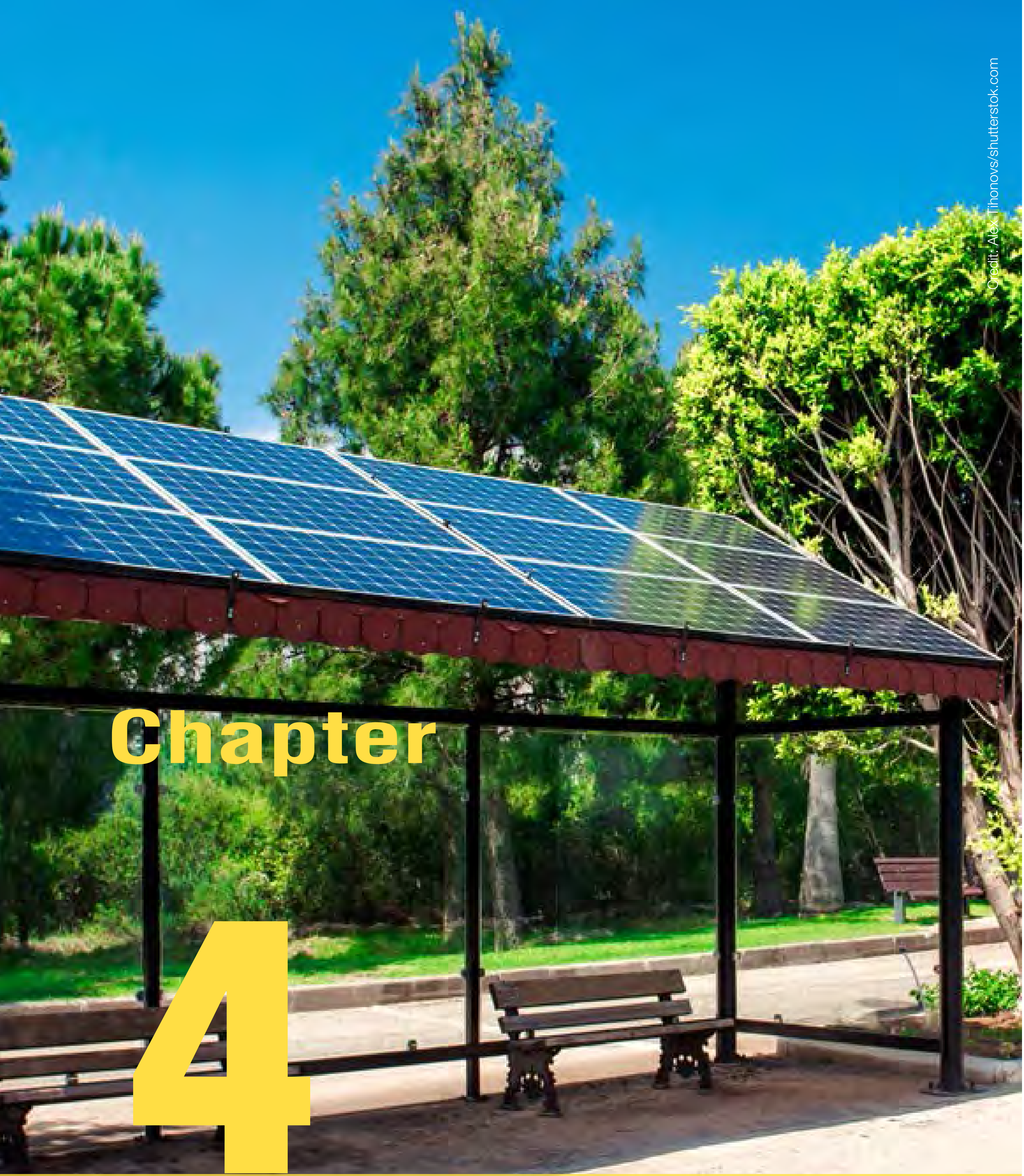
Complex structures found in nature optimize energy and material exchanges across


Credit: Olga Kashubin/Shutterstock.com

membranes. In urban forms, courtyard textures respond to the need for bioclimatic optimization (Steemers *et al.,* 1997). This is why they almost universally characterize historical cities from China to India and from the Islamic world to Greece and Italy. They did not disappear until the emergence of artificial means of controlling interior environments, which are very costly in terms of fossil fuels. Well-oriented, well-designed cities can make the best use of passive solar gains and of natural lighting, cooling and ventilation. Optimizing urban fabric and building shapes greatly increases the efficiency of technologies and systems while diminishing their costs. Well-designed density makes it possible to attain good shape factors for buildings (S/V: envelope area divided by interior volume), thereby simultaneously reducing heating and cooling needs. With a good street aspect ratio coefficient (height/width) and a good street orientation as a function of cardinal points and dominant winds, urban fabric can be efficient in terms of natural lighting and passive ventilation. Optimizing urban fabric and building layouts according to different climates can halve heating and air-conditioning needs (Salat *et al.,* 2011). This optimization should be adaptive. In a living city, built-environment structures are constantly changing, so bioclimatic designs should be adaptable and change with changing human needs (see for example: Castán Broto and Bulkeley, 2013).

## 3.5. Conclusion

The spatial framework proposed in this chapter would result in the kind of inclusive, resource-efficient urban configuration that could contribute significantly to the achievement of the urban DMC target of 6–8 tonnes. However, as there are many drivers of rising DMC per capita, it would be dangerous to focus solely on strategic intensification around a hierarchy of key nodes. The two levers of change that were discussed—compact urban growth and liveable, functionally and socially mixed neighbourhoods—result in reductions that are multiplicative, which is why they need to be implemented in an integrated way. The third and fourth levers of change—connecting cities with innovative resource-efficient systems and changes in urban living behaviour—are just as important as the other two. Urban systems are discussed in further detail in Chapters 4 and 5. Behavioural change is the outcome of social and cultural processes that activate citizens as part of a wider dynamic of institutional and governance transformation, which results in much greater social inclusion and reduced spatial-economic inequalities; this is addressed in Chapter 6. Finally, the spatial guidelines developed in this chapter need to be integrated into a coherent governance framework that is context specific (see Section 6.7 of Chapter 6).


Credit: Alex Tihonovs/shutterstok.com

# Chapter 4

# Life-cycle assessment of resource-efficient urban systems

## 4.1. Introduction

As one element of a wider process of urban restructuring aimed at fostering more equitable and resilient cities, aggressive deployment of resource-efficient technologies is a strategy that can potentially help cities reduce their resource consumption and contribute to mitigating global environmental challenges. This chapter builds on the urbanization scenarios developed in Chapter 2 to assess how the deployment of resource-efficient technologies in key infrastructure systems (understood as integrated sociotechnical systems) can enable resource efficiency and environmental impact reductions in cities worldwide by 2050. To accomplish this, we use an integrated hybrid LCA model to estimate the life-cycle energy, GHG emissions, water use, metal consumption and land use for providing services using both resource-efficient and conventional technologies. Four key sociotechnical systems are studied: (1) passenger transportation, (2) commercial buildings, (3) provision of heating and cooling and (4) waste management. The benefits of resource-efficient technologies that satisfy those services from 2010 to 2050 are assessed, namely: (1) BRT, (2) green buildings, (3) district energy and (4) zero-waste systems. It is important to note that these technologies were selected for the purpose of gauging the potential of resource-efficient sociotechnical systems, and are not recommended as the best options for all circumstances.

The scenarios in our model incorporate a transition to low-carbon electricity generation and changes in demand for the services provided by sociotechnical systems over time at the city level. This enables us to calculate the total life-cycle impact of the provision of the sociotechnical services in 84 cities around the world, including cities in both developing and developed nations. The results show the range of potential environmental and resource benefits that can be achieved under our scenarios in a wide variety of cities over the coming decades.

Chapter 2 presented scenarios based on the assumptions that infrastructure remains resource intensive and that average densities decline as BAU urban metabolic transitions continue. Chapter 3 argued that well-articulated intensification using a networked hierarchy of transit-linked urban nodes would deliver more resource-efficient and socially inclusive urban metabolic configurations. By addressing four specific sociotechnical systems from an LCA perspective, this chapter demonstrates that if resource-efficient sociotechnical systems are implemented within increasingly densified urban systems, resource consumption within each of the sectors analysed can be halved. This does not mean a resulting decline of average DMC per capita across the whole urban system because, as already stated, there are a multitude of drivers for rising DMC per capita that are also context specific. Even without densification, it is evident that significant resource efficiencies can be achieved by shifting from resource-intensive to resource-efficient sociotechnical systems.

## 4.2. Scope: sociotechnical systems considered

The four key sociotechnical systems chosen for analysis render key services that individuals and societies demand at all levels of development, namely, mobility, shelter and thermal comfort, jobs (via commercial buildings) and waste management. These systems have been selected as examples of resource-efficient alternatives to conventional infrastructure approaches (as detailed in Table 4.1), based on the LCA data available at the time of writing the report. Although the technologies are widely applicable, they are not proposed as a package of solutions that will be applicable to all cities. Each technology can be implemented in different ways depending on the context (e.g. different fuels can be used to propel buses, district energy systems can be used for cooling in hot countries), so the assumptions used in the LCA are not intended to be prescriptive. Nature-based solutions (NBS) that optimize ecosystem services in a sustainable manner, or behavioural changes that shift resource demand should be considered over the construction of technological artefacts wherever possible, however, calculating LCAs for these NBS alternatives was not possible within the scope of this study. In this section, the four examples of resource-efficient sociotechnical systems are described and a review of existing LCA literature on the resource-efficiency potential of particular technologies is provided.

### 4.2.1. Bus Rapid Transit

BRT systems, combined with high ridership, fuel efficiency and alternative drivetrains (e.g. engines powered by renewable fuels, electricity or fuel cells) represent an opportunity to reduce the GHG emissions from passenger transportation. A BRT system is defined as "a flexible, rubber-tired rapid-transit mode that combines stations, vehicles, services, running ways" (Levinson *et al.,* 2003a). In practice, BRT systems can implement one or more of the following, typically including: dedicated running ways, attractive stations, distinctive, easy-to-board vehicles, off-vehicle fare collection, use of information technologies (IT) and frequent, all-day service (Levinson *et al.,* 2003b). Over 80 percent of BRT systems feature exclusive running ways, such as bus lanes that enable rapid transit (Levinson *et al.,* 2003a). BRT systems can potentially be implemented with any fuel type or drivetrain (e.g. biodiesel, compressed natural gas or electric fuel cell) and have varying capacities, travelling distances and stop frequencies. Regarding performance, newly introduced BRTs have witnessed a 25–75 percent increase in passengers compared with non-BRT bus transit systems (Levinson *et al.,* 2003b). These increases include modal shifts from passenger cars as well as new riders who previously used other modes of transit. As with any sociotechnical transition, it should be noted that implementation of BRT systems is not always perfectly successful. For instance, some BRT systems implemented in the Indian cities of Delhi, Pune and Ahmedabad were criticized by the media and motorists due to poor coordination among stakeholders and for the larger lane requirements of buses (Deng and Nelson, 2011).

The environmental benefits of BRT systems and public transit are studied frequently in LCA literature. An example of this is Taptich *et al.* (2015), who analysed the potential air emissions savings in passenger transportation from increased fuel efficiency in buses and increased ridership over long-term energy scenarios to 2050. Chester *et al.* (2013) analysed the life-cycle implications, specifically the energy and GHG emission reductions made possible by the introduction of the BRT and light rail systems that displaced private passenger transport in Los Angeles, California. This study found that including the impacts of infrastructure associated with these systems increased the life-cycle energy and GHG emissions of public transport modes by up to 100 percent. However, unsurprisingly, the authors found that the resource impacts of infrastructure were less significant in bus systems compared with light rail. This means that BRT systems generally have faster payback times in terms of energy and emissions (Eckelman, 2013). Chester *et al.* also found that future renewable energy developments, namely increasing the amount of renewables in the local electricity mix, would reduce GHG emissions because electric buses could recharge their batteries from grids powered by low-carbon energy.

Others investigated the environmental impacts of alternate fuel forms for BRT, including Cooney *et al.* (2013), Sandén and Karlström (2007) and Bi *et al.* (2015), who consider the life-cycle impacts of electric buses, fuel cells and various charging stations, find that future technological changes in electricity generation and bus drivetrain technology would be critical in ensuring the sustainability of these alternate transportation modes. Recent benchmark assessments by the US-based National Renewable Energy Laboratory (NREL) demonstrated that a great deal of progress has been made in battery technology for electric buses (Eudy *et al.,* 2016), suggesting that electric buses may be poised to provide major GHG emission benefits in the near future. This chapter builds on this previous literature by projecting how high ridership and improvements in battery technologies, combined with low-carbon electricity sources, can make a significant contribution to overall decarbonization targets.

### 4.2.2. Green buildings

Both commercial and residential buildings offer a significant opportunity for energy savings in most climate mitigation scenarios (IEA, 2013), combining many different efficiency measures to reduce energy consumption and GHG emissions. According to the United States Environmental Protection Agency (US EPA), the term 'green building' refers to "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction" (US EPA, 2015). In practice, compliance with one of the green building standards, codes or certificates, such as the Leadership in Energy and Environmental Design (LEED), the International Green Construction Code (IgCC) and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers' (ASHRAE) Standard 189.1 is considered an important characteristic of a green building (Retzlaff, 2008; ASHRAE, 2009; ICC, 2012). While these certifications vary in terms of their emphasis on energy, water or indoor air quality, most definitions include some standard for energy and water efficiency (Retzlaff, 2008; ASHRAE, 2009; ICC, 2012). Green buildings can implement various combinations of different technologies, including:

- Thermal mass
- Thermal insulation
- Efficient lighting (e.g. light-emitting diodes (LEDs))
- Environmentally friendly building materials (rapidly renewable materials, recycled materials, materials with low life-cycle impacts)
- Renewable energy technologies (e.g. roof-mounted solar photovoltaic panels)
- Building Information Management (BIM) systems and Building Energy Management Systems (BEMS)
- White/green roofs
- Use of native species/drought-tolerant species in landscape

Naturally, the environmental and resource implications of green buildings vary significantly depending on the choice of such technologies, and the location and design of the building. Suh *et al.* (2014 a) ) analysed the environmental performance of green building certifications using a comprehensive set of indicators. Furthermore, a great deal of literature quantifies the impacts of efficient lighting technologies (Bergesen *et al.,* 2016; Scholand and Dillon, 2012), smart, energy-saving building controls (Beucker *et al.,* 2016), green roofs (Saiz *et al.,* 2006), heat pumps (Ecoinvent, 2010) and photovoltaics (Bergesen *et al.,* 2014; Lu and Yang, 2010). The majority of the technologies cited here show the potential for environmental benefits when installed and used properly.

### 4.2.3. District energy

District energy systems are viewed favourably due to their potential to cost-effectively and efficiently provide heating and cooling to concentrated areas of population. According to UNEP, a district energy system "represents a diversity of technologies that seek to develop synergies between the production and supply of heat, cooling, domestic hot water and electricity" (UNEP, 2015). Various technologies and fuels can be incorporated into district energy systems, including:

- Waste-to-energy
- High-efficiency boilers
- Waste heat recovery
- Combined heat and power (CHP)
- Heat pumps
- Solar thermal
- Absorption chillers

In addition, district energy systems can benefit from local characteristics, such as sea-water cooling (UNEP, 2015). Variables that affect the environmental performance of district energy systems in terms of their natural resource and environmental impacts include climate, population density and infrastructure requirements.

Due to the diversity of configurations made possible by combining these technologies, generalizing the environmental and resource benefits of district energy systems is challenging. Furthermore, district energy systems may use a variety of fuel types, such as natural gas, coal and biomass, with differing environmental and resource implications. However, case studies generally report substantial improvement of energy efficiency and significant GHG emission reductions. For example, it is reported that Denmark has reduced its GHG emissions by 20 percent by using district energy systems (UNEP, 2015). Several LCA studies investigated the impacts of district energy using traditional and alternative fuels, sometimes including infrastructure (Cherubini *et al.,* 2009b; Eriksson *et al.,* 2007; Oliver-Solà *et al.,* 2009; Knutsson *et al.,* 2006).

Previous LCA studies generally focused on assessing the impacts and benefits of district heating in colder, developed countries, where district heating is already prevalent. Much of the economic and population growth expected over the coming decades will occur in developing countries, which tend to be further south and therefore warmer. As these countries develop, district cooling may become an especially efficient and economical way of cooling homes and businesses, according to recent reports by UNEP (UNEP, 2015). While there are few available life-cycle studies of district cooling systems in developing countries, it is likely that the infrastructure requirements are similar to district heating systems. This means that literature on the energy and material requirements for district energy infrastructure (Oliver-Solà *et al.,* 2009) and the energy performance of district cooling systems (Fahlén *et al.,* 2012; Chow *et al.,* 2004) can also be used to estimate the impacts of both district cooling systems and district heating systems.

### 4.2.4. Zero waste

According to the Zero Waste International Alliance, zero waste means "designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them" (http://zwia.org/standards/zw-definition/). Zero waste is a concept rather than a specific set of technologies. Zero-waste programmes can be implemented through various strategies, including:

- Source reduction
- Waste minimization
- Design for disassembly/recycling/re-use
- Reduction of packaging materials
- Composting
- Reusing, recycling, remanufacturing and refurbishing
- Reduced consumption
- Education

Some of these strategies are technological and some rely more on incentivizing sustainable behaviour. For example, waste minimization may be implemented through waste stream segregation or a product take-back system, both of which require new techno-infrastructures. On the other hand, policy-based strategies such as volumetric waste charges require little technology, but have been shown to achieve measurable reductions in waste diversion (Abrashkin, 2015; Skumatz, 2008; Skumatz and Freeman, 2006). Such programmes, most famously implemented in South Korea and Belgium, have been shown to reduce waste generation by as much as 17 percent (Lee and Paik, 2011; Abrashkin, 2015).

LCA case studies have evaluated specific strategies or technologies in detail, such as waste stream segregation, volumetric waste charges, paper waste management and heat recovery technologies. (Cherubini *et al.,* 2009a; Arena *et al.,* 2003; Clift *et al.,* 2000; Ekvall and Finnveden, 2000; Kondo and Nakamura, 2004; Lundie and Peters, 2005; Buttol *et al.,* 2007). Fruergaard and Astrup (2011) analysed the optimal use of waste-to-energy for cities; Blengini (2008) used LCA to evaluate the resource conservation potential and impacts of composting. In most cases, transportation (i.e. collection) is not the major contributor to the impacts of waste management, but reducing transportation and its impacts could lead to substantial reductions at scale. For example, Iriarte *et al.* (2009) found that increased urban density can help lower the transportation-related impacts of waste management, which are generally underestimated for inner-city urban areas. This means that the strategic densification advocated in Chapter 3 could reduce some of the impacts associated with waste management.

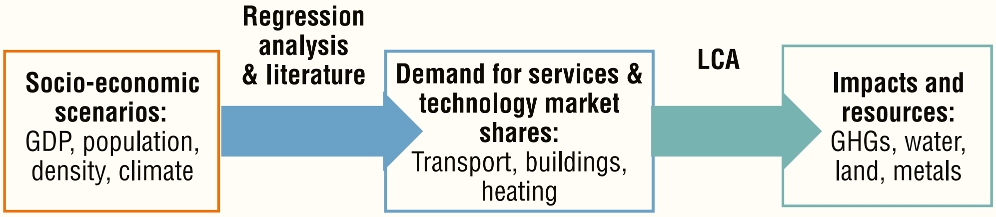
A comprehensive evaluation of the resource-efficiency potential of reducing waste would be difficult to accomplish using only available LCA data and case studies. While the impacts that arise from the transportation, processing and disposal of waste are not insignificant, the burdens that could potentially be avoided by recycling, re-use and source reduction would likely result in the greatest reductions in environmental impacts. To quantify such benefits, however, would require an understanding of the embodied energy, materials and environmental impacts inherent in all the major consumer products consumed within a city. Such an analysis would not be feasible within the scope of this report. Thus, the authors discuss zero-waste concepts on a more qualitative basis in this report, and LCA case study results for waste are not presented here.

## 4.3. Methods

We used an integrated hybrid LCA model to assess the environmental and natural resource implications of efficient sociotechnical systems by 2050. The model has been built to calculate the life-cycle GHG emissions, water consumption, land use (i.e. occupation) and metal consumption associated with the services rendered by resource-efficient and baseline technologies (Suh, 2004; Suh *et al.,* 2004b; Gibon *et al.,* 2015). The model relies on the Baseline Scenario presented in Chapter 2, following its projections of population, GDP and density for urban areas by 2050. In contrast with the scenarios presented in Chapter 2, which directly relate material consumption to those socio-economic indicators, this chapter projects the demand for key sociotechnical services as a function of GDP, density and population, and LCA is used to quantify the impacts of providing those services with different technologies. Further, this model specifies the sources of global electricity generation, comparing BAU trajectories with a 2°C scenario, where electricity is increasingly provided by low-carbon sources following the IEA Energy Technology Perspectives scenarios (IEA, 2012), and using data on low-carbon electricity generation from Hertwich *et al.* (2014) developed for previous UNEP reports (Hertwich *et al.,* 2015).

Figure 4.1 provides an overview of the assessment methods used in this chapter. Baseline population, income and density scenarios from Chapter 2 are the basis for the analysis. Regression analysis and estimates from literature are then used to relate those socio-economic scenarios to the demand for services by cities from present day to 2050, and to estimate the baseline market shares of technologies that deliver those services. Finally, LCA is used to understand the overall trajectory of cities' resource impacts.

**Figure 4.1**: Methodological overview



## 4.3.1. Life-cycle assessment

LCA is a method that quantifies the environmental impacts of a product or service across the value chain—from extraction of raw resources to manufacturing, use and end of life. In LCA, these environmental and natural resource impacts are scaled based on the functional service provided by a product, known as the 'functional unit'. For example, the functional unit of transportation could be one passenger transported for one kilometre (i.e. one passenger kilometre (pkm)). This functional unit could then be provided by either a car or a bus, and each would provide that functional service while using different kinds of fuel and emitting different amounts of GHGs. Table 4.1 outlines the functional units used to assess the technologies considered in this chapter.

**Table 4.1**: Sociotechnical systems, technologies and functional units

| Sociotechnical system | Resource-efficient technology | Baseline technology | Functional unit |
|---|---|---|---|
| Transportation | Diesel-powered and electric BRT | Passenger cars | Passenger kilometres |
| Commercial buildings | Green-certified building (ASHRAE and LEED) | Typical office building | $m^2$ floor space |
| Heating and cooling | District energy (heating and cooling) | Natural gas boilers and air-conditioning | kWh heating or cooling load |
| Zero waste | Composting, recycling, reduced packaging, waste-to-energy and waste reduction policies | Landfill, incineration | Tonne of waste processed or avoided |

To understand the resource and environmental impacts of deploying efficient technologies in cities as they develop, and to understand how rates of resource use and negative environmental impacts can be decoupled from economic growth rates, an LCA based on a traditional functional comparison is not sufficient. Instead, what is needed is an analysis of how demand for sociotechnical services will change as cities evolve. In particular, we relate the demand for services (e.g. transportation measured in passenger kilometres) to macroeconomic indicators for cities from 2010 to 2050, specifically, GDP per capita, population, population density and climate. The challenge for this chapter is how to derive relationships among those variables using available data for (1) the projected level of demand for sociotechnical services from 2010 to 2050 and (2) the baseline penetration of resource-efficient technologies (e.g. BRT as a percentage of total passenger transportation). Thus, a variety of data sources, assumptions and regressions were used in this study to build city-level scenarios for the demand for key sociotechnical services. The methods and data used to develop these scenarios will be elaborated on in Section 4 of this chapter.

## 4.3.2. Methodological framework

This section outlines the framework by which resource-efficient technologies are assessed. First, we define the following parameters for the model:

**Scenario**:
$s$ = {baseline (BL), resource-efficient (RE)}

**Time**:
$t$ = {2010, 2030, 2050}

**Service**:
$i$ = {transport (passenger km), heat (kWh), commercial building space (square metres per year), waste management (tonne waste)}

**Technology**:
$j$ = {gasoline car, diesel bus, battery electric bus, natural gas boiler, etc.}

**City/region**:
$k$ = {Cape Town, Beijing, San Francisco, etc.}

**Impact category**:
$l$ = {greenhouse gas emissions, water, land, metal consumption}

Estimating the resource intensity of providing key urban services over the course of a BAU (hereafter referred to as baseline, or BL) and resource-efficient (RE) scenario requires estimates of the total aggregate annual demand for those services. We define $y_{i,k}^{s,t}$ as the yearly demand for service $i$, in scenario $s$, in time $t$, for region $k$, and $f_{i,j,k}^{s,t}$ as the fraction of service $i$ provided by each technology $j$. We also define $m_{i,j,k,l}^{s,t}$ as the resource or environmental impact intensity on impact $l$ of using technology $j$ in region $k$ for providing one unit of service $i$. Then, the total yearly resource or environmental impact ($M_{i,k,l}^{s,t}$) on impact $l$ of providing a service $i$, in city $k$, under scenario $s$ at time $t$ is calculated by:

$$M_{i,k,l}^{s,t} = \sum_{j} m_{i,j,k,l}^{s,t} f_{i,j,k}^{s,t} y_{i,k}^{s,t}$$

Therefore, the total global resource or environmental impact ($M_l^{s,t}$) on impact $l$ across the cities considered under scenario $s$ at time $t$ is calculated as:

$$M_l^{s,t} = \sum_{i} \sum_{k} M_{i,k,l}^{s,t}$$

Under this framework, it is apparent that the resulting impacts of providing the four sociotechnical services considered in this chapter can be changed by altering the following parameters: (1) the emission or resource intensity of technology ($m$), (2) the market shares of the technologies that provide equivalent services ($f$), and (3) the level of demand for services ($y$). These three parameters may be affected by socio-economic variables such as population density and income, which in turn may be affected by regional and local policies, urban planning and macroeconomic growth models.

### 4.3.3. Integrated hybrid life-cycle assessment model

Assessing the environmental and resource impacts of resource-efficient technologies deployed in cities from 2010 to 2050 requires, in the first instance, detailed life-cycle information for each specific technology. However, for this information to be used for assessment, information will also be needed on the energy and material production systems in the global economy, and how these systems will most likely change in BAU and climate change mitigation scenarios. These two information sources can then be used to establish a comparison. For this purpose, a hybrid LCA model constructed to assess the changing impacts of low-carbon electricity generation technologies and energy/resource-efficient demand-side technologies over the coming decades was used (Hertwich *et al.*, 2014; Gibon *et al.*, 2015; Suh *et al.*, 2004).

This model employs a regionalized version of the ecoinvent 2.2 database (Ecoinvent, 2010), along with the EXIOBASE multi-regional input-output database, accounting for local differences in the production of materials and energy. The mix of electricity generation (renewables and fossil fuels with and without carbon capture and sequestration) and its impacts under both the baseline and resource-efficient scenarios are based on the IEA 6°C scenario (6DS) and 2°C scenario (2DS) respectively (IEA, 2012). The 2DS reflects the goal of limiting global warming to just 2°C by 2050. This model divides the globe into nine regions as defined by the IEA: China, India, OECD Europe, OECD North America, OECD Pacific, Economies in Transition, Latin America, Other Developing Asia, and Africa and the Middle East, thereby accounting for regional differences in the technology mixes used to generate electricity and produce materials. The model also accounts for changes in the energy efficiency, materials efficiency and environmental performance of key industrial sectors, namely pulp and paper, iron and steel, aluminium and copper, as explained in detail by Gibon *et al.* (2015).

### 4.3.4. Technology data

Data on the life-cycle energy and material requirements of resource-efficient and baseline technologies were taken from a variety of sources and required several assumptions. Table 4.2 summarizes the many data sources used to build life-cycle models for each of the technologies considered in this chapter.

**Table 4.2**: Data sources for life-cycle inventories of efficient and baseline technologies

| Sociotechnical system | Technology | Comment | References |
|---|---|---|---|
| Transport | Passenger cars (gasoline) | Estimated present and future vehicle production, fuel efficiency and passenger occupancy of private vehicles in nine global regions. | Taptich *et al.*, 2015 |
| | BRT (diesel) | Estimated present and future vehicle production, fuel efficiency and passenger occupancy of buses in nine global regions. | Taptich *et al.*, 2015 |
| | BRT (battery electric) | Estimated impacts of lithium-ion battery production from Hawkins' data. Estimated battery requirements from Cooney *et al.* and current drivetrain efficiency (kWh per km) from Eudy *et al.* | Cooney *et al.*, 2013;<br>Eudy *et al.*, 2016;<br>Hawkins *et al.*, 2013 |
| Commercial buildings | Green office building | Suh *et al.* estimated the reduced energy and water consumption and increased amount of insulation and construction materials for green-certified office buildings. | Suh *et al.*, 2014a |
| | Baseline office building | Energy and water consumption and construction materials for typical office buildings were based on NREL commercial building reference data for small office buildings. | Deru *et al.*, 2011 |
| Heating and cooling | District energy infrastructure | Estimated infrastructure requirements for district energy system. | Oliver-Solà *et al.*, 2009 |
| | District heating and cooling | Data on the energy requirements and GHG emissions of heating and cooling from natural gas cogeneration. | ecoinvent v2.2 |
| | Natural gas boilers | Estimated life-cycle GHG emissions from burning natural gas. | ecoinvent v2.2 |
| | Air-conditioning | The IEA 'Transition to Sustainable Buildings' (2013) was used to estimate the efficiency of typical building air-conditioning systems. | IEA, 2013 |

## 4.4. Development of scenarios

The purpose of this chapter is to understand the potential reductions in the resource impacts of cities through high penetration of efficient technologies and strategic urban densification. While it is acknowledged that this would most likely require a fundamental change in the macroeconomic structure of the economy, the transition to this model is not addressed in this chapter. Instead, it is assumed that the necessary macroeconomic conditions are in place for alternative resource-efficient sociotechnical systems to be a viable, implementable option. This section discusses the development of the scenarios used to evaluate the impacts of and the potential reductions resulting from these alternatives. This analysis is based on three scenarios: (1) baseline, (2) resource-efficient and (3) resource-efficient with strategic densification. For all of these scenarios, projections of urban population, GDP and density are based on the Baseline Scenarios presented in Chapters 1 and 2, and climate data for cities were acquired from BizEE Degree Days data (degreedays.net). The baseline scenario assumes that there is no concerted effort to reduce resource impacts through deployment of resource-efficient technologies or decarbonization of electricity, consistent with the IEA 6DS. The resource-efficient scenario, however, includes high penetration of resource-efficient technologies and decarbonization of electricity, consistent with the IEA 2DS. Under the baseline and standard resource-efficient scenarios, observed trends continue in cities and they become less dense at a rate of 2 percent per year. Under the strategic densification scenario, we assume a reversal of this trend, with cities becoming denser at 2 percent per year.

To estimate the resource impacts of these scenarios, it is first necessary to relate the demand for services provided by sociotechnical systems to the many socio-economic variables that characterize cities: per capita GDP, population, population density and climate. This section outlines how regression analysis and estimates from scientific literature were used to infer these relationships. It is important to clarify that while Chapter 2 directly related these variables to DMC, LCA quantifies the resource requirements and environmental impacts of providing sociotechnical services based on functional units. As such, regression analysis is needed to bridge the gap between socio-economic variables (e.g. GDP and population) and the demand for services required to scale up LCA results to the city level.

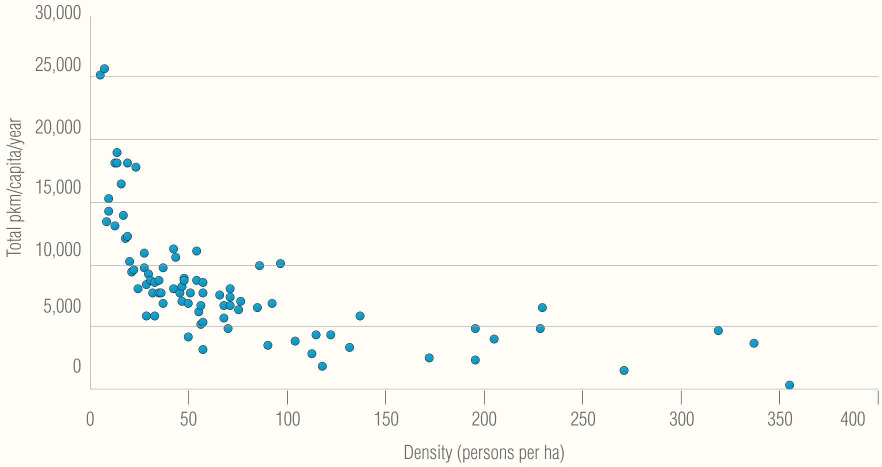
For sociotechnical systems with available data, the projected level of demand for a sociotechnical service (irrespective of technology) and the baseline penetration of resource-efficient technologies are estimated for the 2010–2050 period. These two estimates are then used to compile an assessment of the future trajectories of 84 cities/urban settlements, clustered according to GDP per capita, population, population density and climate.

The data available did not always allow for a statistically significant inference of the relationship between demand for services and a socio-economic indicator, and in those cases, the best possible estimates from literature were used. Sometimes these relationships can be obscured by social, cultural or political differences across cities in different countries or regions. Scenarios must be developed nonetheless, and literature-based, cross-sectional data were used to better understand how these socio-economic indicators might be related to the demand for services and the market share of efficient technologies. In a seminal article, Bettencourt and colleagues (Bettencourt *et al.,* 2007) and Batty (2008) show remarkable power law scaling relationships for the properties of cities as their population size grows. Given these relationships, we follow the approach also articulated in Chapter 3, which makes it possible to hypothesize a similar power law relationship among our socio-economic variables and the demand for services in cities. A key caveat of this analysis is that statistical regressions are used to create reasonable scenarios, rather than make predictions about the demand for sociotechnical services over time.

### 4.4.1. Bus Rapid Transit scenarios

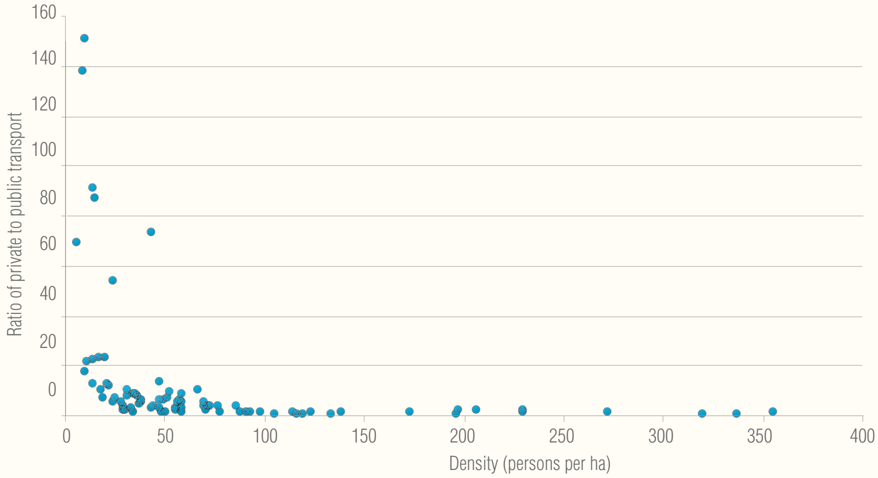
Cross-sectional data on 84 cities from the International Association of Public Transport (*Union Internationale des Transports Publics*, UITP) Millennium Cities Database show strong relationships between urban population density (persons per hectare), the total demand for passengers travelled (in passenger kilometres per year) and the proportion of private to public transportation (i.e. private pkm divided by pkm), as shown in Figures 4.2 and 4.3.

**Figure 4.2**: Urban demand for total transportation (passenger kilometres per year) predicted by population density (persons per hectare) for 84 cities around the world in 1995



(based on UITP data)

**Figure 4.3**: The ratio of private to public passenger transportation by population density for 84 cities around the world in 1995



(based on UITP data)

These graphs suggest that there is a likely relationship between total passenger kilometres travelled and urban density, namely that the amount of passenger kilometres travelled by vehicle declines as urban density increases (see Chapter 3). Similarly, this relationship also implies that people must use vehicles for transportation more often in lower density environments. Total passenger transportation and the ratio of private to public transit also tend to increase as income increases. These relationships are unsurprising given that people living in a more complex, dense urban area, characterized by a mix of residential and non-residential spaces, are less likely to need to travel far to go to work, visit friends or run errands compared with people living in low-density environments, which are often urban residential monocultures. Similarly, people in denser environments may be more likely to walk or cycle, modes that are not included in the passenger transportation data. Additionally, as a person becomes wealthier, they are more likely to be able to afford a private vehicle (which they will depend on for mobility if they also choose to move outwards into more affluent, less dense environments) and less likely to take the bus, especially if the bus service is of a poor quality. The implication of these relationships is that as cities and urban settlements become denser, less private vehicle transportation would be needed overall, and more of that transport would be provided by public transportation modes, such as BRT, light rail systems and underground rail systems. This is not just a hypothetical trend—the growth of the so-called 'new urbanism' movement has resulted in the 're-urbanization' of inner cities and the related challenge of gentrification (Smith, 2002).

Given these hypotheses, we use multiple regression analysis to relate the total demand for passenger transportation (pkm per capita per year) and the ratio of public to private transportation (pkm public divided by pkm private) to income (GDP per capita) and population density (persons per hectare) for the 84 cities. The best relationship was observed for a power law regression that incorporated both density and income. Tables 4.3 and 4.4 present the results of the multiple regression analysis relating total passenger transportation per year ($v$) and the ratio of public to private transportation ($r$) to density ($d$) and income ($i$).

**Table 4.3**: Regression results for total passenger kilometres as a function of density and GDP. 'ln' is the natural logarithm

| $ln(v) = \beta_0 + \beta_1 ln(d) + \beta_2 ln(i)$ | | | |
|---|---|---|---|
| | *Coefficients* | *Standard error* | *R Square* |
| Intercept | $\beta_0 = 8.48$ | 0.51 | 0.73 |
| $d$ (density) | $\beta_1 = -0.46$ | 0.05 | |
| $i$ (income) | $\beta_2 = 0.23$ | 0.04 | |

**Table 4.4**: Regression results for the ratio of public to private passenger kilometres as a function of density and GDP. 'ln' is the natural logarithm

| $ln(r) = \alpha_0 + \alpha_1 ln(d) + \alpha_2 ln(i)$ | | | |
|---|---|---|---|
| | *Coefficients* | *Standard error* | *R Square* |
| Intercept | $\alpha_0 = -1.63$ | 1.28 | 0.70 |
| $d$ (density) | $\alpha_1 = 1.15$ | 0.13 | |
| $i$ (income) | $\alpha_2 = -0.43$ | 0.10 | |

The results of the multiple regression analyses support the hypothesis that demand for vehicle transportation increases as income increases, but declines as urban density increases. They also support the hypothesis that public transportation is more prevalent in higher-density and lower-income cities and urban settlements. As shown in Table 4.3, the estimated coefficient $\beta_1$ indicates that the demand for passenger transportation decreases as cities become denser, and coefficient $\beta_2$ shows that the demand for passenger kilometres increases as income increases. As shown in Table 4.4, the estimated coefficient $\alpha_1$ indicates that public transportation satisfies a greater percentage of transportation demand in higher-density cities, and the estimated coefficient $\alpha_2$ indicates that public transportation satisfies a smaller percentage of transportation demand in higher-income cities. For comparison, Chapter 5 of this report employs slightly different methods to estimate the relationships between vehicle miles travelled, density, income and several other socio-economic factors. Chapter 5 also employs more detailed data than the available cross-sectional data on 84 cities used here (Transportation Research Board, 2009). Thus, it is possible that estimates of the reductions in passenger transportation demand from increased urban density might diminish if we can account for additional variables across this large set of cities. For example, Chapter 5 shows that a 25 percent decrease in vehicle miles can be seen from a doubling of urban density, which is a smaller effect compared with what is found in this analysis.

We use these regression results to project baseline scenarios for transportation demand as cities and urban settlements develop. Under these scenarios, private transportation is provided mainly by passenger cars fuelled by petroleum (gasoline), using regional fuel economy estimates from Taptich *et al.* (2015). Public transport is considered to be 100 percent diesel-fuelled BRT in 2010 and transitioning to 50 percent battery electric buses by 2030 and 90 percent battery electric buses by 2050.

### 4.4.2. Green building scenarios

In this section, we build scenario projections of the growth in commercial building space for cities as they develop economically and grow in population size. The cross-sectional data on 84 cities discussed above also include data on the urban density and job density. We hypothesize that the amount of commercial building space required in a city is related to the number of jobs and job density. We therefore expect a correlation between income (GDP per capita) and the number of jobs per capita. Labour economics generally relates jobs to the proportion of the population at working age, rather than just GDP and population, however, scenarios for this statistic were not available for this report. Figure 4.4 shows the observed relationship between the number of jobs per capita ($y$) and income ($x$). The relationship observed with this data is weak, having an R Square of just 0.28. Naturally, we expect many other factors besides GDP to influence the number of jobs.

This relationship between income and jobs, along with estimates of building occupancy, is used to approximate the growing demand for commercial building space as cities develop under the macroeconomic scenarios analysed in this chapter (Suh *et al.,* 2014b). We used a default value of 25.5 m$^2$ of commercial floor space per employee for a small office building, following Deru *et al.* (2011).

The energy demand from buildings is highly dependent on climate, as well as the design of the building. The amount of energy needed to heat or cool a building can be quantified in terms of heating degree days (HDD) and cooling degree days (CDD). HDD, for instance, represent the amount of time that the temperature in each city remains below room temperature. HDD and CDD were obtained for the 84 cities considered in this report to estimate the heating and cooling demand of standard and energy-efficient buildings (i.e. green buildings) given the climate of those cities (degreedays.net).

The materials and energy required to construct and operate standard and green-certified buildings was estimated by Suh *et al.* (2014b). The buildings considered in this article are small-sized office buildings, as defined by the US Department of Energy commercial reference building models (Deru *et al.,* 2011). Baseline energy performance was estimated for several climate regions using the EnergyPlus software, and various building energy-efficiency standards were considered to compute the potential energy savings from that baseline. Table 4.5 shows the assumed energy consumption of commercial buildings per m$^2$ of floor space and per HDD and CDD.

**Figure 4.4**: Jobs per capita as a function of GDP. The orange line represents the regression model predicting jobs as a function of GDP for the 84 cities

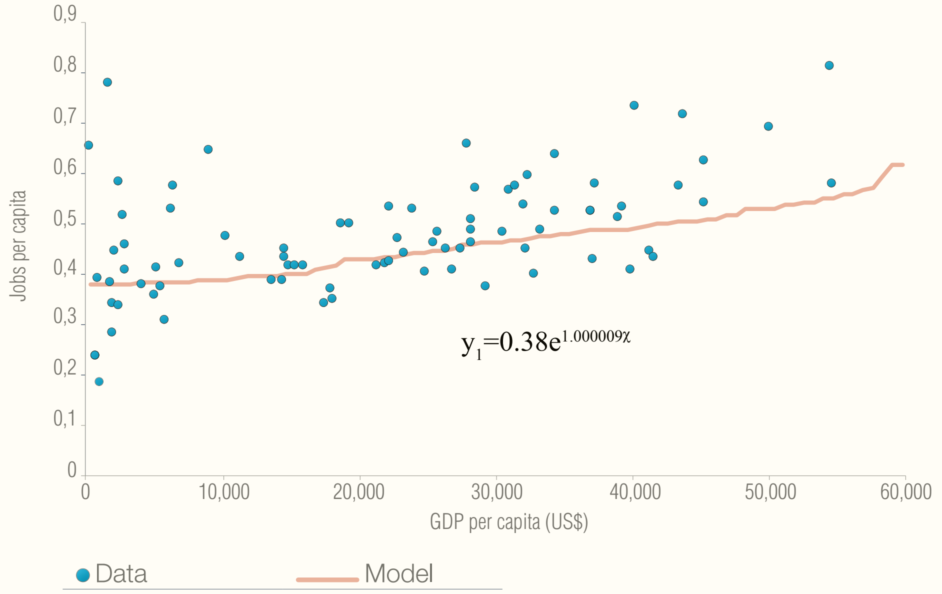


**Table 4.5**: Baseline commercial energy consumption

| | Quantity | Unit |
|---|---|---|
| Electricity for cooling | 0.013 | kWh/m²/CDD/year |
| Natural gas for heating | 0.091 | kWh/m²/HDD/year |
| Electricity not used for heating or cooling (e.g. lighting) | 117.95 | kWh/m²/year |

For this analysis, we consider the best-case energy savings prescribed by the U.S. Green Building Council (USGBC) LEED certification system, translating to a 48 percent reduction, on average, in building electricity use and natural gas consumption, and a 40 percent reduction in water consumption. The green building also incorporates on-site renewable energy generation from solar and requires additional insulation relative to the baseline building, resulting in higher impacts from the construction phase. Since not all of these buildings are likely to incorporate the highest level of energy savings assumed in this analysis, a lower percentage of green buildings in 2030 and 2050 is assumed.

### 4.4.3. District energy scenarios

The deployment of district heating and cooling systems in cities worldwide depends on a number of factors, most importantly climate. Population density can also affect the infrastructure required for district energy systems. Most current district heating systems are deployed in colder than average countries in the developed world, typically in Russia and Northern Europe, while stand-alone district cooling systems have been deployed in warmer climates, including Hong Kong and several cities in India and the Middle East (UNEP, 2015). Limited information is available on the percentage of heating and cooling demand that is met by district energy systems worldwide, so it was necessary to make assumptions to construct the scenarios. Assumptions about the market share of district energy systems in each region are included in the appendix to this chapter.

In this analysis, the energy demand for space heating and cooling (kWh per capita) is estimated using benchmark data and projections from the IEA ‘Transition to Sustainable Buildings’ (IEA, 2013), which is based on the Energy Technology Perspectives scenarios (IEA, 2012). These data include the average heating and cooling energy consumption per person for the regions considered in this report. They also include estimates of the residential floor space per person for these regions. For specific cities, the demand for space heating and cooling also depends on climate. The district energy analysis uses the same information as the green building section on how heating and cooling loads increase with HDD and CDD (see Table 4.5). District heating systems typically have efficiencies of 90 percent and district cooling systems of around 65 percent, as stated in the first comprehensive global assessment of district energy systems (UNEP, 2015).

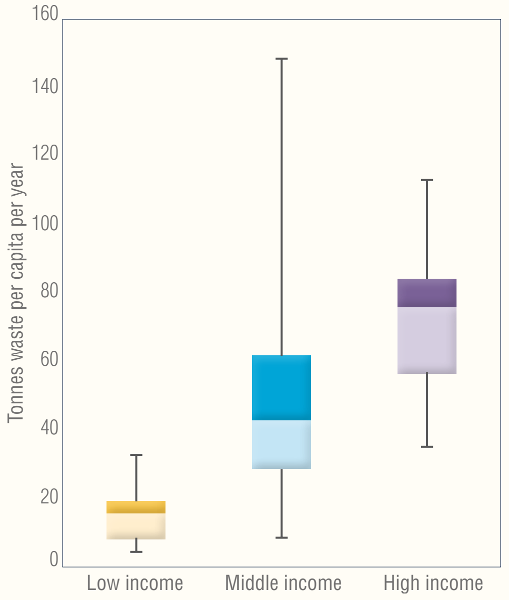
The penetration rate of district heating and cooling assumed in our scenarios are shown in the appendix (Table A5). We acknowledge that the penetration rates in the resource-efficient scenario are rather high. We are not attempting to project the future penetration rate; we are interested in the potential under ‘what-if’ scenarios.

### 4.4.4. Zero-waste scenarios

Literature has generally shown that as population and GDP increase, so does the generation of waste. The World Bank study on global waste generation (Hoornweg and Bhada-Tata, 2012) benchmarks the generation, composition and collection of municipal solid waste (MSW) per capita in countries around the world. In doing so, the World Bank study groups together countries of similar GDP to classify the average waste generation per capita of those income groups.

Figure 4.5 shows the range of total waste generation per capita per year for low-, middle- and high-income countries. There is high variability in waste per capita even among countries with similar incomes. Many of the outliers, particularly in middle-income countries, are island nations. Our scenarios follow the observed relationship between income and

**Figure 4.5**: Summary of waste generation by income group based on Hoornweg and Bhada-Tata (2012). Boxes represent the interquartile range and whiskers represent the 95 percent confidence interval



MSW generation as seen in Figure 4.4 and outlined by Hoornweg and Bhada-Tata in their 2012 report. As cities transition from low to high income, waste generation per capita will increase under the baseline scenarios in this chapter. The same report contains additional data on the composition of generated waste (e.g. organic, metals, paper, plastic and other), which is used to estimate the demand for different waste management services, including landfill, waste-to-energy, recycling, composting and others.

## 4.5. Results and discussion

This section shows the life-cycle impacts of efficient sociotechnical systems for GHG emissions, water consumption, metal consumption and land occupation under the (1) baseline, (2) resource-efficient and (3) resource-efficient plus strategic densification scenarios. For each sociotechnical system, we look at the overall trends seen for all 84 cities, using this cross-section of cities to investigate the general potential for decoupling resource impacts from GDP growth and population growth. Additionally, each section presents selected case study cities to illustrate more specifically how the introduction of efficient technologies can influence energy and resource impacts. While the main text of this report presents results from only selected cities, Appendix B includes additional figures covering at least one city in each of the IEA regions. Further, Appendix C includes figures that present the potential of each technology to reduce resource impacts in all 84 cities under each scenario. In these figures, cities are classified by their income (i.e. total urban GDP per capita) in 2010, 2030 and 2050, and the per capita life-cycle GHG emissions, water consumption, land use and metal consumption are shown for each year in each scenario. These graphs provide insight into the potential for decoupling resource impacts from economic growth in cities from the present to 2050, and show the wide variability among all cities considered.

### 4.5.1. Bus Rapid Transit

Enabling BRT systems to form a greater portion of public transit has the potential to reduce the environmental and resource impacts associated with passenger transportation. This section quantifies the potential environmental and resource benefits of a high penetration of BRT systems in various cities worldwide. Cross-sectional data shows that as cities develop economically, increasing in GDP and becoming less dense, there is an observed trend away from public transportation towards more private vehicles, namely passenger cars. This baseline scenario follows a 2 percent decrease in urban density per year worldwide, consistent with observed trends reported in the IPCC Fifth Assessment report (Seto *et al.,* 2014). As an alternative, the impacts of two different resource-efficient scenarios are analysed in comparison to the baseline. The first resource-efficient scenario assumes that the ratio of public to private transport can be increased by a factor of 12 by 2050, which would increase the median percentage of transport provided by BRT in the 84 cities from 4 percent under the baseline scenario to 37 percent under the resource-efficient scenario. The rationale for assuming a factor improvement in BRT penetration rather than specifying a particular percentage of BRT was that many cities naturally have higher percentages of public transit, and assuming a factor improvement would show the potential for improvement in all cities analysed in this chapter. Under this resource-efficient scenario, total demand for passenger transportation follows baseline projections, with demand increasing as urban GDP increases and population decreases. The second resource-efficient scenario—strategic densification—also considers a reversal of the baseline trend of declining densities. Under the strategic densification scenario, urban population density increases by 2 percent per year, resulting in a lower overall demand for private vehicle transportation and a naturally larger portion of that demand fulfilled by public transport. Under both resource-efficient scenarios, BRT is increasingly electrified, with 90 percent of all buses electrified by 2050. Furthermore, renewable and low-carbon energy sources provide a greater portion of electricity by 2030 and 2050, as discussed in the methods section. These two resource-efficient scenarios are intended to reflect the policy choices of investing in and promoting affordable public transit and/or utilizing urban planning to make cities more amenable to public and non-motorized modes of transportation.

## Analysis of overall scenarios

In this section, the resource impacts of providing vehicular passenger transportation in 84 cities are analysed under three scenarios: baseline, resource-efficient (i.e. high penetration of BRT) and strategic densification (i.e. high penetration plus increased population density). By comparing these three scenarios in 2030 and 2050 for this cross-section of cities, we can see the extent to which the impacts of providing passenger transportation can be mitigated through high penetration of BRT, electric BRT and strategic densification (i.e. reducing the need for vehicular transportation by increasing urban population density).

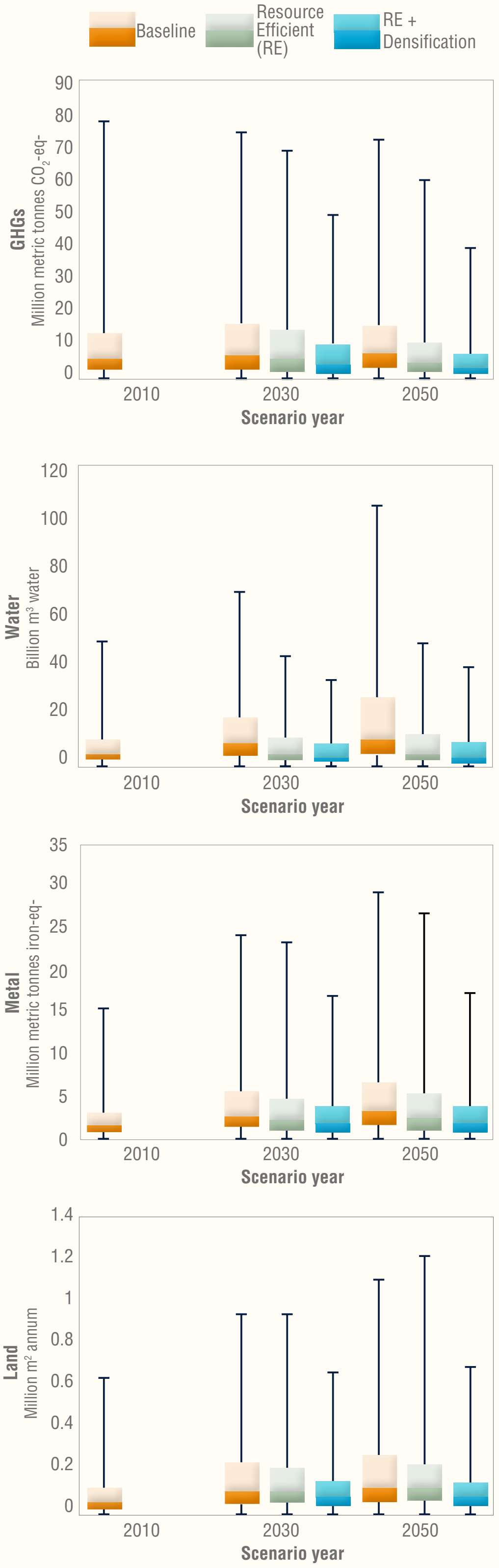


**Figure 4.6**: Impacts of baseline, resource-efficient (RE) and strategic densification (RE + densification) scenarios for transportation in 84 cities. Boxes represent the interquartile range of impacts; the border between the light and dark shaded area is the median; whiskers show the maximum and minimum values among all cities

**Figure 4.7**: Potential impact reductions of BRT by 2050 under the (1) resource-efficient and (2) resource-efficient + densification (RE dense) scenarios compared to the baseline scenario in 2050

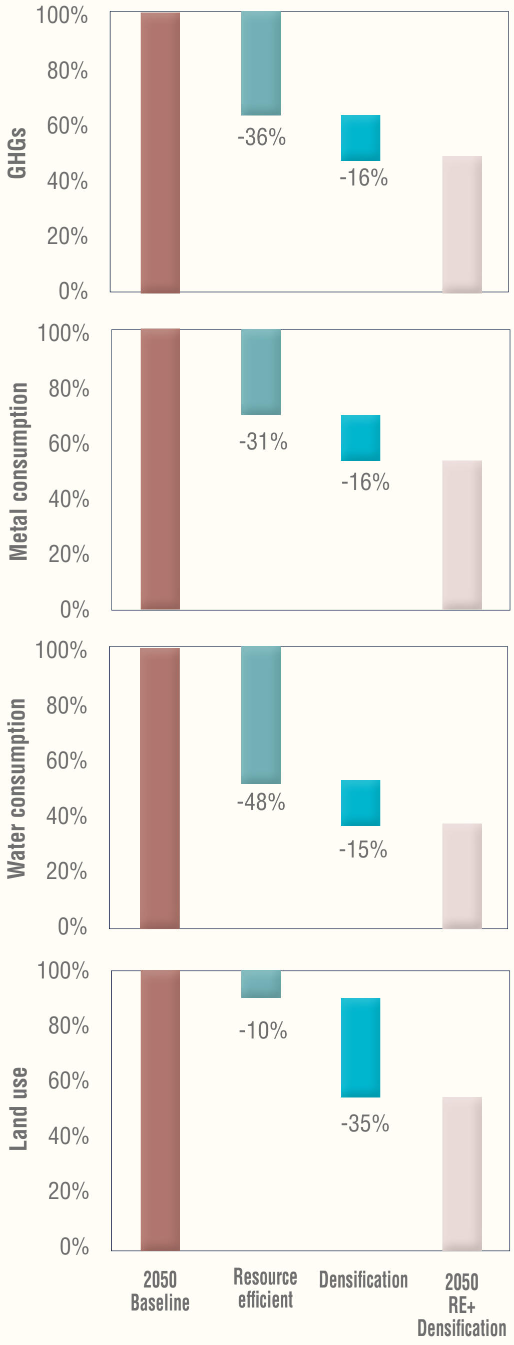


Figure 4.6 presents the resource impacts of meeting transportation demand projections in all 84 cities under each scenario. This figure uses box and whisker plots to summarize the results of each scenario in each year by presenting the middle 50 percent of cities (represented by the two-toned box), the median (the line dividing the box) and the minimum and maximum cities (the whiskers). By comparing the boxes representing the resource-efficient scenarios in 2030 and 2050 to the baseline scenario in 2010, the absolute change in potential resource impacts can be seen. Similarly, by comparing the resource-efficient scenarios in 2030 and 2050 to the baseline scenario in the same years, the relative change in potential resource impacts can be observed.

Compared with the baseline in 2030 and 2050, Figure 4.6 shows that both the standard resource-efficient and strategic densification scenarios reflect a high potential for substantial reductions in resource consumption. Figure 4.7 summarizes the results for all 84 cities together.

Although the scenario assumes that the total demand for passenger transportation grows as GDP and population increase, high penetration of BRT could mitigate GHG emissions and water consumption and help achieve lower levels of GHG emissions and water consumption compared with the present day. For life-cycle metal consumption and land use, impacts are likely to increase compared with the present day, but show relative reductions compared with the baseline scenario in 2030 and 2050. In conclusion, this analysis suggests that high penetration of efficient BRT coupled with low-carbon electricity and strategic improvements in urban density can contribute to the decoupling of growth rates of resource use from urban economic growth, while providing greater amounts of transportation services, and thus improving well-being in urban environments across the globe.

### Case studies

Here, the scenario projections in two specific cities of the developing and developed world are analysed. This comparison illustrates how cities at different stages of economic development in different regions might respond differently to high penetration of BRT and increased urban density.

Figure 4.8 compares the projected growth in GDP and population with the potential change in resource impacts due to changing transportation

**Figure 4.8**: Resource efficiency and growth projected for transportation in Cape Town, South Africa. Impacts in each year are compared with the estimated impact in 2010

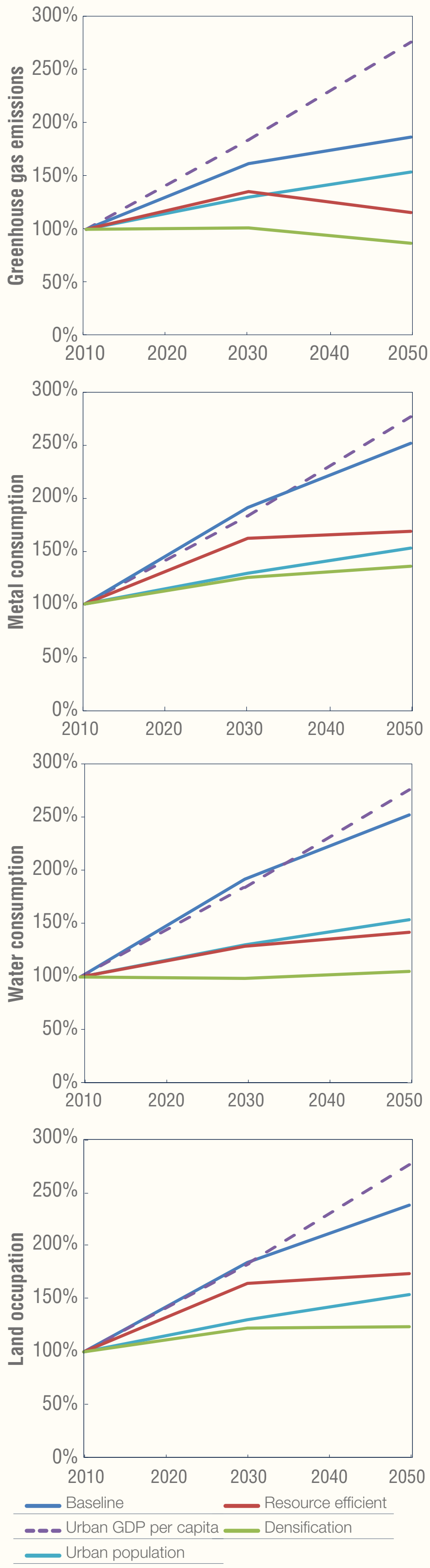
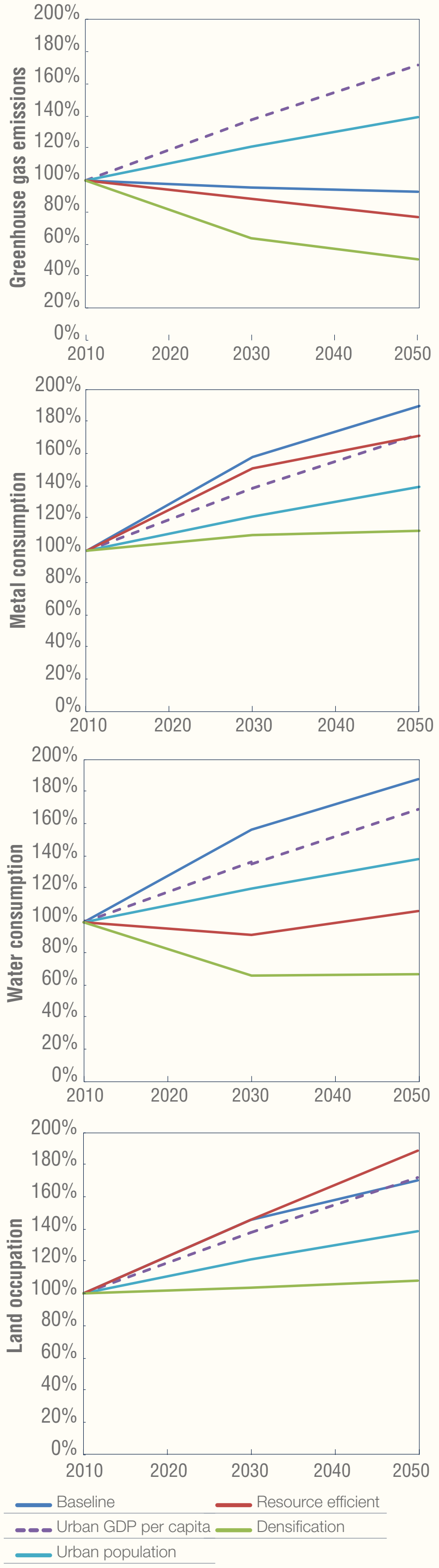


**Figure 4.9**: Resource efficiency and growth projected for transportation in Los Angeles, California, United States. Impacts in each year are compared with the estimated impact in 2010



demand in Cape Town, South Africa. Significant growth is expected in population and GDP for cities in South Africa, leading to a similar magnitude of growth in the GHG emissions and resource impacts of transportation under the baseline scenario. Increasing the penetration of BRT or urban densification would mitigate the growth of these resource impacts, resulting in the relative decoupling of urban growth from transportation impacts with respect to GHGs, water, metals and land use. Absolute reductions in impacts compared with 2010, however, would require actions beyond those considered in these scenarios.

In contrast, Figure 4.9 shows the same metrics projected for the city of Los Angeles, California. Less growth of GDP and population is projected for cities in Northern America than in developing countries. Higher penetration of electric BRT and/or urban densification combined with low-carbon electricity could contribute to overall reductions in GHGs by 2050, while keeping other resource impacts relatively stable. Under the 2°C scenario used for electricity in this analysis, electricity generation in OECD countries becomes less GHG intensive than in other regions, resulting in more rapid impact reductions from high penetration of electric BRT (as seen in Figure 4.9 for Los Angeles). What is significant, however, is that without strategic densification, a high penetration of BRT systems will result in greater land occupation.

## 4.5.2. Green buildings

### Analysis of overall scenarios

In this section, the resource impacts generated by commercial buildings in 84 cities under baseline and resource-efficient (i.e. high penetration of green buildings) scenarios are analysed. The penetration of green commercial buildings varies in each scenario. According to the USGBC, around 40–48 percent of new non-residential buildings in the USA had incorporated some kind of green building certification by the end of 2015 (USGBC, 2016). This statistic implies that the percentage of green-certified buildings will still be substantial under the baseline scenario, so we assume 45 percent green buildings by 2050. For the resource-efficient scenario, we consider 100 percent green building penetration by 2050. It is important to note that different urban forms, for instance, a tendency towards high-rise tower blocks versus medium- and low-rise commercial buildings, would affect the energy performance of green buildings, but this analysis considers typical low-rise commercial buildings. A comparison of these three scenarios in 2030 and 2050 for this cross-section of cities shows how the impacts of commercial building space can be mitigated through high penetration of efficient green buildings.

Figure 4.10 presents the resource impacts of meeting commercial building demand projections in all 84 cities under each scenario. These figures use box and whisker plots to summarize the results of each scenario in each year by presenting the middle 50 percent of cities (represented by the two-toned box), the median (the line dividing the box) and the minimum and maximum cities (the whiskers). By comparing the boxes representing the resource-efficient scenario in 2030 and 2050 with the baseline scenario in 2010, we can see the absolute change in potential resource impacts. Similarly, by comparing the resource-efficient scenario in 2030 and 2050 with the baseline scenario in the same years, we can see the relative change in potential resource impacts.

Compared with the baseline in 2030 and 2050, Figure 4.10 shows that high penetration of green buildings under the resource-efficient scenario has the potential to substantially reduce impacts in all impact categories considered. Summing the results of all 84 cities together, the resource-efficient scenario provides:

- 50 percent reduction in GHGs
- 16 percent reduction in water consumption
- 9 percent reduction in metal consumption
- 38 percent reduction in land use

This scenario analysis reveals that while commercial building space grows as GDP and

**Figure 4.10**: Impacts of baseline and resource-efficient scenarios for district energy in 84 cities. Boxes represent the interquartile range of impacts; the border between the light and dark shaded area is the median; whiskers show the maximum and minimum values among all cities

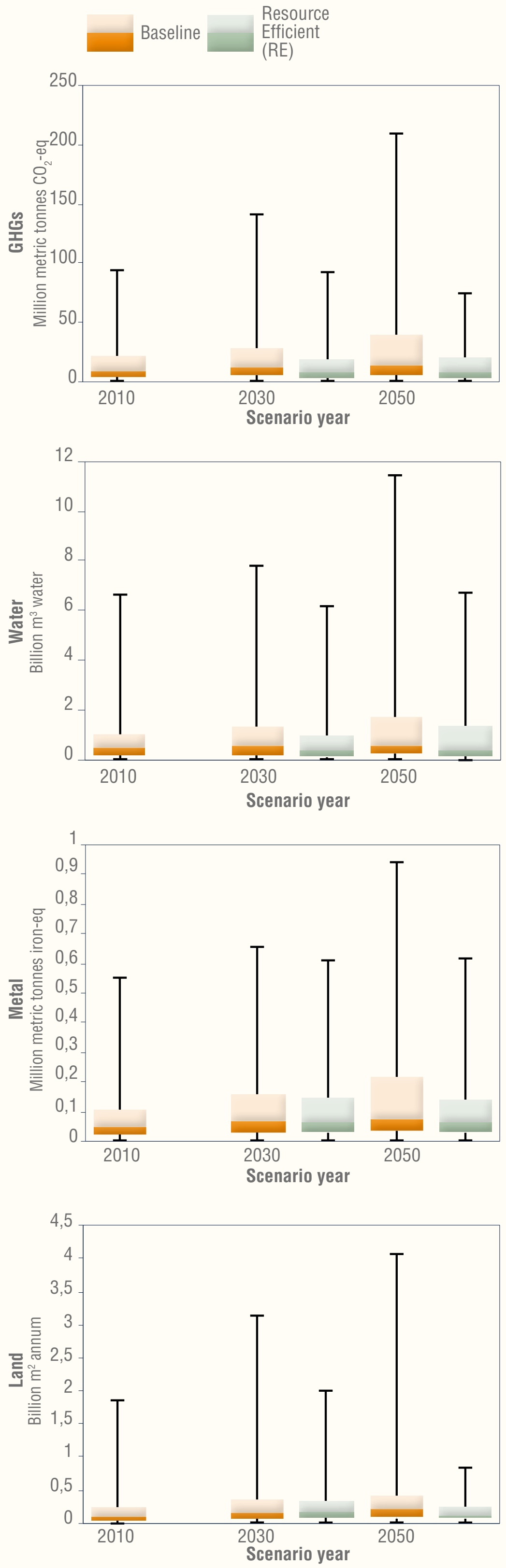
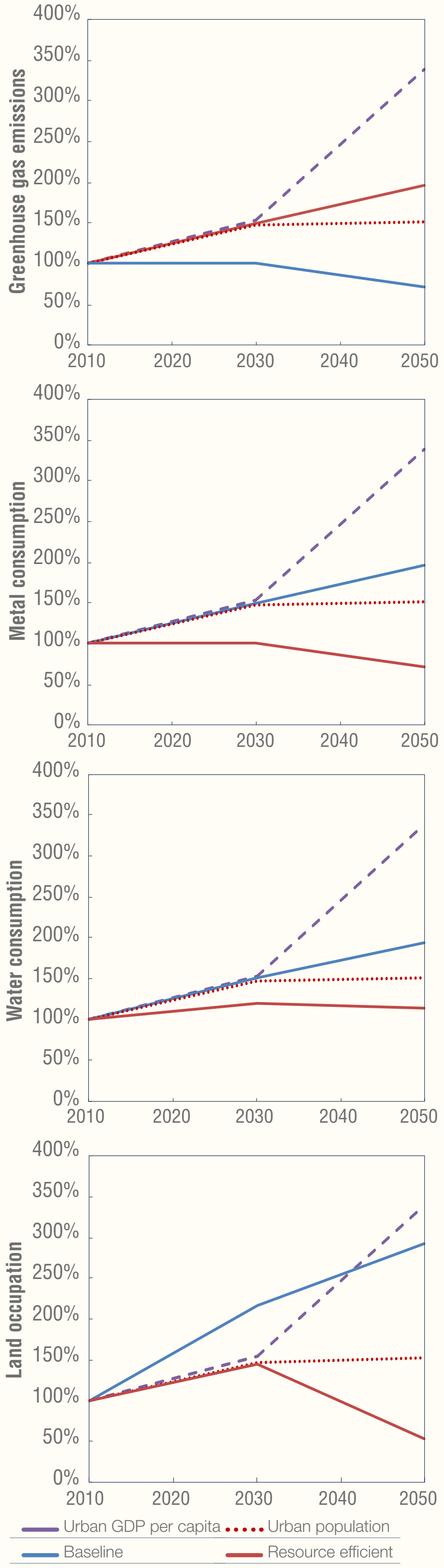


**Figure 4.11**: Resource efficiency and growth projected for commercial buildings in Bangkok, Thailand. Impacts in each year are compared with the estimated impact in 2010



population increase, a high penetration of green buildings combined with low-carbon electricity supply could provide absolute reductions in GHG emissions by 2050 in the cities considered. Relative reductions are observed for life-cycle metal consumption, water consumption and land use compared with the baseline scenario in 2030 and 2050. In sum, this analysis suggests that a high penetration of green buildings, which incorporate on-site, distributed renewable energy and consume centralized, low-carbon electricity has the ability to decouple resource impacts from economic growth while providing greater amounts of commercial space, and thus the potential for more jobs, in cities worldwide. This therefore has the potential to contribute significantly to a more inclusive, resource-efficient urban metabolic configuration.

### Case studies

Scenario results for specific cities illustrate how cities at different stages of economic development in different climate regions might respond differently to high penetration of green buildings.

Figure 4.11 compares the projected growth in GDP and population with the potential change in resource impacts due to green buildings in Bangkok, Thailand. Significant growth is expected in population and GDP for cities in Asia, but the moderate penetration of efficient buildings expected in the baseline scenario would provide some relative decoupling of climate change and water consumption from GDP. A 100 percent penetration of green buildings by 2050, as assumed in the resource-efficient scenario, could aid absolute reductions in climate and land impacts.

Figure 4.12 shows the same metrics for new commercial buildings in Stockholm, Sweden. GDP and population growth are projected to be lower in developed Europe than in Asia, for instance, but greater heating demands in cold countries could place a larger strain on GHG emissions. The resource-efficient scenario shows absolute decoupling for GHG emissions and relative decoupling for water consumption in Figure 4.12.

## 4.5.3. District energy

District energy systems can efficiently provide both space heating and space cooling to urban populations. Over the coming decades, economic growth in developing nations will lead to increased demand for cooling in particular (UNEP, 2015).

This section investigates the potential savings resulting from a high penetration of district energy systems for both heating and cooling in cities worldwide. District energy systems require substantial upfront investment in infrastructure, including power plants (e.g. cogeneration), pipes, pumps and building systems. The inputs required to produce district energy infrastructure were taken from Oliver-Solà *et al.* (2009), who quantified the environmental impact of providing district heating infrastructure to residential neighbourhoods in Spain. Despite these upfront requirements, the impacts of providing heat or cooling using district energy are dominated by the combustion of fuels. For this analysis, we assume that district heating and cooling systems have the same infrastructure requirements, with the exception of the absorption chiller used to convert waste heat into chilled water. While district energy systems can utilize heat from a number of fuel types and sources, the district energy systems in this analysis use by-product heat from natural gas cogeneration. Further analysis could quantify the potential benefits of using waste-to-energy or biofuels to provide district energy, however, those fuels are not covered in this analysis. We assume distribution losses of 10 percent for both district heating and cooling (UNEP, 2015), and that absorption chillers have a coefficient of performance of 0.6 (Ecoinvent, 2010). In actuality, losses and efficiency vary seasonally, and further energy efficiency can be gained by utilizing sea-water cooling in coastal cities (Chow *et al.,* 2004).

### Analysis of overall scenarios

In this section, the resource impacts of providing heating and cooling services in 84 cities are analysed under baseline and resource-efficient (i.e. high penetration of district energy) scenarios.

**Figure 4.12**: Resource efficiency and growth projected for commercial buildings in Stockholm, Sweden. Impacts in each year are compared with the estimated impact in 2010

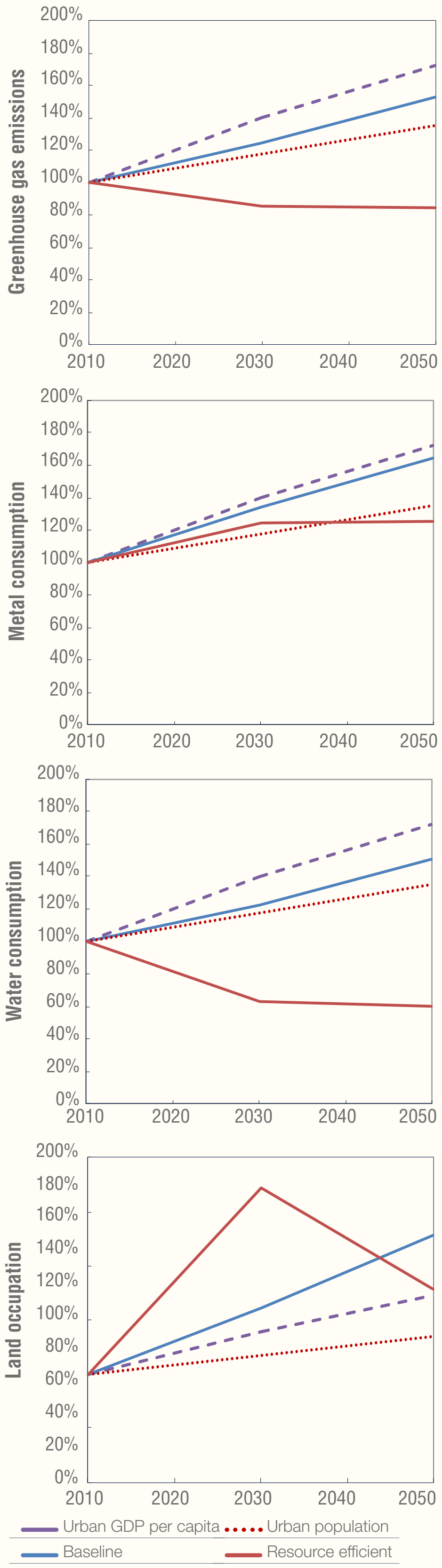
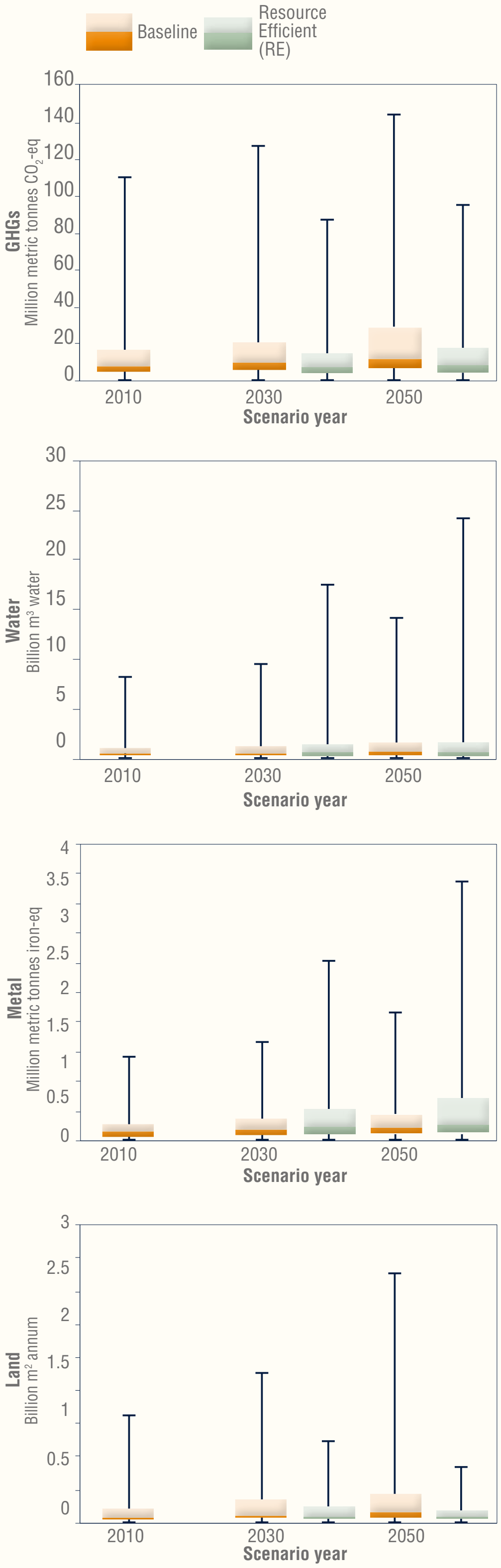


**Figure 4.13**: Impacts of baseline and resource-efficient scenarios for district energy in 84 cities. Boxes represent the interquartile range of impacts; the border between the light and dark shaded area is the median; whiskers show the maximum and minimum values among all cities



By comparing these three scenarios in 2030 and 2050 for this cross-section of cities, we can observe the extent to which the impacts of providing thermal comfort in residential buildings can be mitigated through high penetration of district heating and district cooling systems utilizing waste heat.

Figure 4.13 presents the resource impacts of meeting residential heating demand projections in all 84 cities under each scenario. These figures use box and whisker plots to summarize the results of each scenario in each year by presenting the middle 50 percent of cities (represented by the two-toned box), the median (the line dividing the box) and the minimum and maximum cities (the whiskers). By comparing the boxes representing the resource-efficient scenarios in 2030 and 2050 with the baseline scenario in 2010, we can see the absolute change in potential resource impacts. Similarly, by comparing the resource-efficient scenario in 2030 and 2050 with the baseline scenario in the same years, we can see the relative change in potential resource impacts.

Compared with the baseline in 2030 and 2050, Figure 4.13 shows that high penetration of district energy under the resource-efficient scenario shows potential for substantial reductions in impacts in GHGs and land use, but larger impacts in metal and water consumption due to higher infrastructure requirements and direct water use, compared with heating from natural gas and cooling provided by electricity. Summing all 84 cities together, the resource-efficient scenario provides:

- 38 percent reduction in GHGs
- 39 percent increase in water consumption
- 44 percent increase in metal consumption
- 68 percent reduction in land use

This scenario analysis reveals that while the total demand for heating and cooling grows as GDP and population increase, expansion of district energy systems by 2050 could decrease GHG emissions and life-cycle land use to below present-day estimates. For life-cycle metal and water consumption, impacts are likely to increase somewhat compared with the baseline scenario in 2030 and 2050. In conclusion, this analysis suggests that high penetration of district energy coupled with low-carbon electricity can help decouple resource impacts from economic growth while providing greater well-being from improved thermal comfort in urban environments worldwide. If this was part of a global transition to low-carbon energy, including the energy used for mining and processing virgin and recycled metals over the life cycle, this could contribute significantly to a resource-efficient urban metabolic configuration.

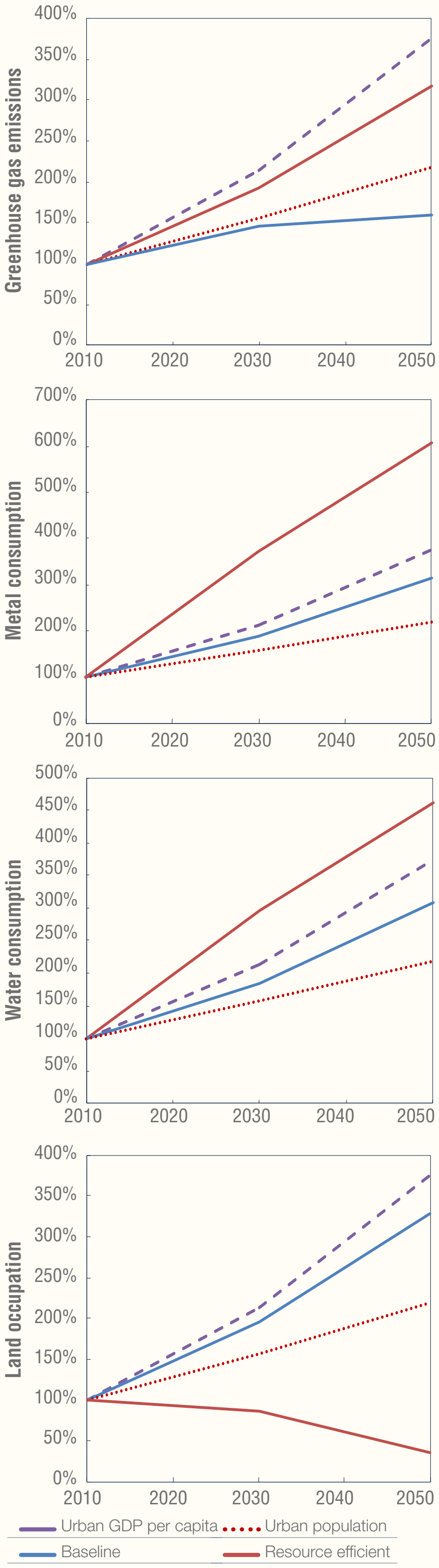
### Case studies

Figure 4.14 shows the resource-efficiency potential of district energy systems in Chennai, India, which is one of the 84 cities analysed, as an example. The climate in the city of Chennai is very warm, with a high number of CDD. The scenarios shown here consider a 20 percent market share of district cooling by 2050 in the baseline scenario, and a penetration of 50 percent of district cooling by 2050 in the resource-efficient scenario. The remainder is considered to be traditional air-conditioning. From these figures, it is apparent that the increased GHG emission and land-use impacts associated with providing space cooling to a growing population can possibly be avoided via high penetration of district cooling, but these technologies generally require more infrastructure (leading to increased metal consumption) and more water over their life cycles.

## 4.6. Discussion

We analysed the potential environmental and natural resource impacts of deploying a few resource-efficient sociotechnical systems and of urban metabolic configuration by 2050. To understand the resource-efficiency potential of three key sociotechnical systems across the globe, we analysed a sample set of 84 cities and used empirical estimates and available

**Figure 4.14**: Resource efficiency of district energy systems in Chennai, India. Impacts in each year are compared with the estimated impact in 2010, and assume 50 percent of space cooling is provided by district cooling in 2050 in the resource-efficient scenario compared with 20 percent in the baseline

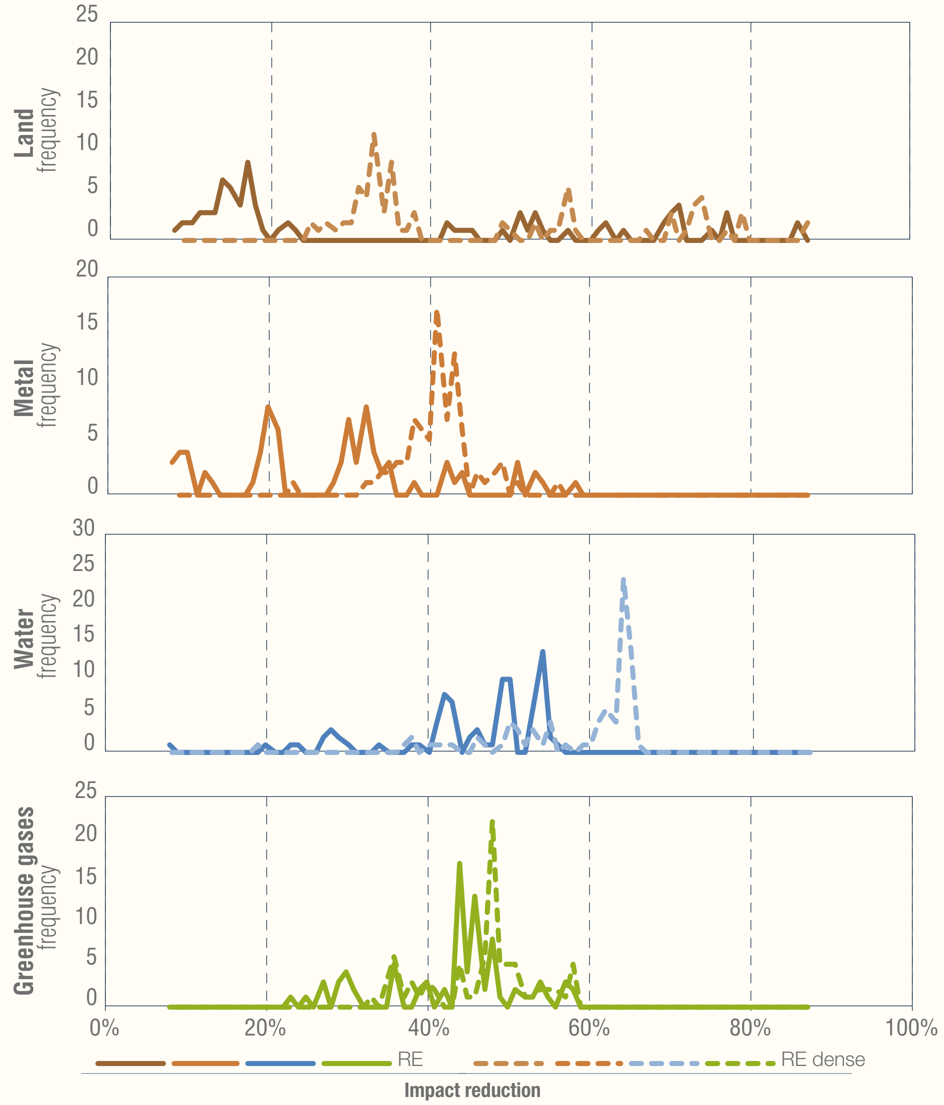


literature to project the demand for vehicular passenger transportation, commercial buildings and heating/cooling energy from the present to 2050.

The baseline scenario assumes an urban metabolic configuration characterized by growth in population and income, decreasing urban density and marginal technological changes in the production of energy and materials. The long-term implications of this baseline scenario are captured in Chapter 2. The standard resource-efficient scenario assumes an urban metabolic configuration where the same population, income and density scenarios apply as in the baseline, but incorporates high penetration of resource-efficient technologies (i.e. buses, district energy and green buildings) coupled with a transition to a low-carbon electricity supply consistent with 2°C climate mitigation scenarios. In addition to the improvements assumed by the standard resource-efficient scenario, the strategic densification scenario considers increasing urban population density from the present to 2050, in reverse of observed trends. This provides the basis for aggregating the results for the 84 cities, in order to generalize how resource-efficient technologies like the ones considered here can contribute to achieving inclusive and resource-efficient urban metabolic configurations.

When combined, the resource-efficient technologies considered in this chapter show considerable potential to reduce resource consumption and environmental impacts in all of the impact categories presented. Figure 4.15 shows the spread, or distribution of percentage reductions in resource impacts for the 84 cities when combining the effects of all the resource-efficient technologies as if they were implemented in an integrated way. The vertical axis represents the frequency, or number of cities that achieve the impact reduction shown on the horizontal axis. This figure shows that for the resource-efficient scenario, most cities can expect a 5–20 percent decrease in land use, a 5–30 percent improvement in metal consumption, a 35–50 percent improvement in water consumption

**Figure 4.15**: Histograms showing the relative reduction in life-cycle resource impacts under the resource-efficient (RE) and strategic densification (RE dense) scenarios for 84 cities in 2050 compared with the baseline scenario in 2050



and a 30–50 percent improvement in GHG emissions. For the strategic densification scenario, these improvements could be even greater, mainly due to the improvements in the impacts of transportation. For the strategic densification scenario, the majority of cities considered show a 20–40 percent improvement in land use, a 30–50 percent improvement in metal, a 36–60 percent improvement in water consumption and a 40–60 percent improvement in GHG emissions. These further improvements under the strategic densification scenario come primarily from the reduced need for vehicle transportation when urban densities are higher. This highlights the absolute necessity to focus on both infrastructure alternatives *and* strategic densification (as outlined in Chapter 3). Understanding these distributions as shown in Figure 4.15, and how they can be improved if there has been strategic densification, is important for understanding how different urban environments will respond to the introduction of more resource-efficient technologies.

## 4.6.1. Limitations

### Coverage of cities

The analyses presented in this chapter are not without uncertainties and biases. The 84 sample cities analysed represent a combined population of 515 million people, growing to around 753 million people by 2050 under the scenario projections. While this total is sizeable, and the sample covers a wide variety of cities throughout the world, the sample population includes a greater number of cities in Northern America, Europe and Asia than other regions due to data availability (see Appendix B). However, the framework used in this chapter can be readily applied to a wider range of cities and infrastructure services when data become available.

### All cities are different

Additionally, many of the socio-economic variables used to predict the demand for services have differential effects for different urban cultures and nations, which means that these scenarios of demand may not hold for every single country. Thus, the results for individual cities should be interpreted with care. Further, the resource-efficient scenarios considered also assume a global transition to low-carbon energy supply during the four decades to 2050. In the absence of such a transition, the magnitudes of reductions in resource use would actually be smaller than those presented in the chapter.

Chapter 5 will present case studies on individual city types and highlight how the best strategies to reduce resource consumption will vary, because all cities are unique. For example, BRT systems may be better suited to some regions or cultures than others. For systems as complex as cities, one size does not fit all.

### Simplification of scenarios

In addition, the potential future trajectories of cities were simplified in order to gauge the impact of resource-efficient sociotechnical systems applied to a large number of cities. In doing so, regression models were used to estimate some of the key parameters used in our model. For example, private and public passenger vehicle miles for the 84 cities in 2030 and 2050 were estimated as a function of population density and GDP using a multiple regression model. The relationships observed do not necessarily prove a causal relationship between the variables of these scenarios (i.e. population density and income) and private and public passenger miles. Instead, these observations are used to develop scenarios that are feasible and based on real-world conditions as closely as possible.

### Coverage of technologies

The resource-efficient technologies analysed are merely the important examples among the many relevant technologies that can be used to reduce the energy and resource consumption of cities. The inclusion of more technologies in this type of analysis would be desirable, but will remain a task for future work. Additionally, the estimates of impact reductions presented are based on our current state of knowledge, and do not include any potential breakthrough technologies that are yet to be developed or currently under development. The technologies presented are well known, and a conservative view has been taken as to the rate at which these technologies will improve. As innovation continues, resource efficiencies may evolve faster than anticipated, or new and much more efficient technologies may emerge, resulting in more significant resource savings than those estimated here.

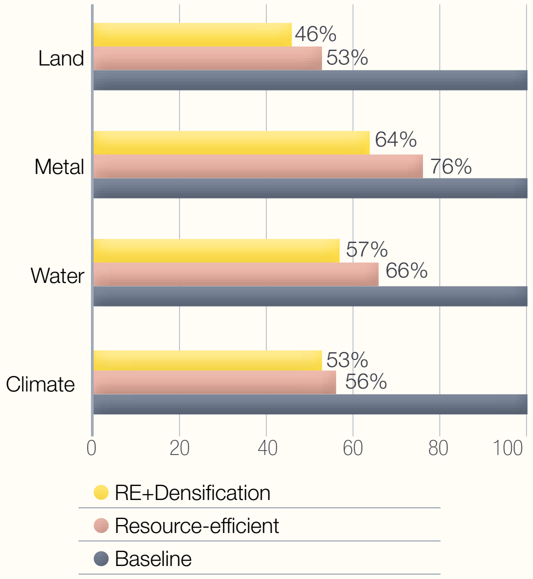
## 4.7. Conclusion

Our analysis shows that a substantial reduction in environmental and resource impacts can be achieved under the resource-efficient and strategic densification scenarios across the globe by 2050. Most sociotechnical systems show relative or absolute reductions in all impact categories considered over the course of these scenarios. The one exception is that district energy systems potentially use more water to provide heating and cooling and more metal for their infrastructure than traditional natural gas or electric heating and cooling systems.

Summing up the impacts of the sociotechnical infrastructure systems under different scenarios across the 84 example cities can facilitate an understanding of how efficient technologies might reduce resource impacts in general, as existing cities continue to develop and as new cities emerge across the globe. While the sociotechnical infrastructure systems considered in this chapter satisfy only a subset of the vital services required by cities, they can serve as a proxy to estimate the potential for resource improvement in cities in general, especially when this analysis is supplemented by the analyses in the other chapters.

Figure 4.16 summarizes the aggregate reduction in resource use by three sociotechnical systems—BRT in transportation, green buildings in commercial buildings and district energy in heating and cooling—that can be achieved by more aggressively introducing resource-efficient technologies to 84 global cities by 2050. Improvements due to more efficient waste management technologies are not included in this summary result. The results show that a 24–47 percent reduction in resource impacts can be achieved by 2050 through high penetration

**Figure 4.16**: Aggregate change in resource consumption for each sociotechnical system (transport, district energy and green commercial buildings) for 84 cities combined under resource-efficient scenarios in 2050 (compared with baseline in 2050). RE + Densification considers high penetration of resource-efficient technologies in addition to increased urban density, which lowers the demand for passenger transportation

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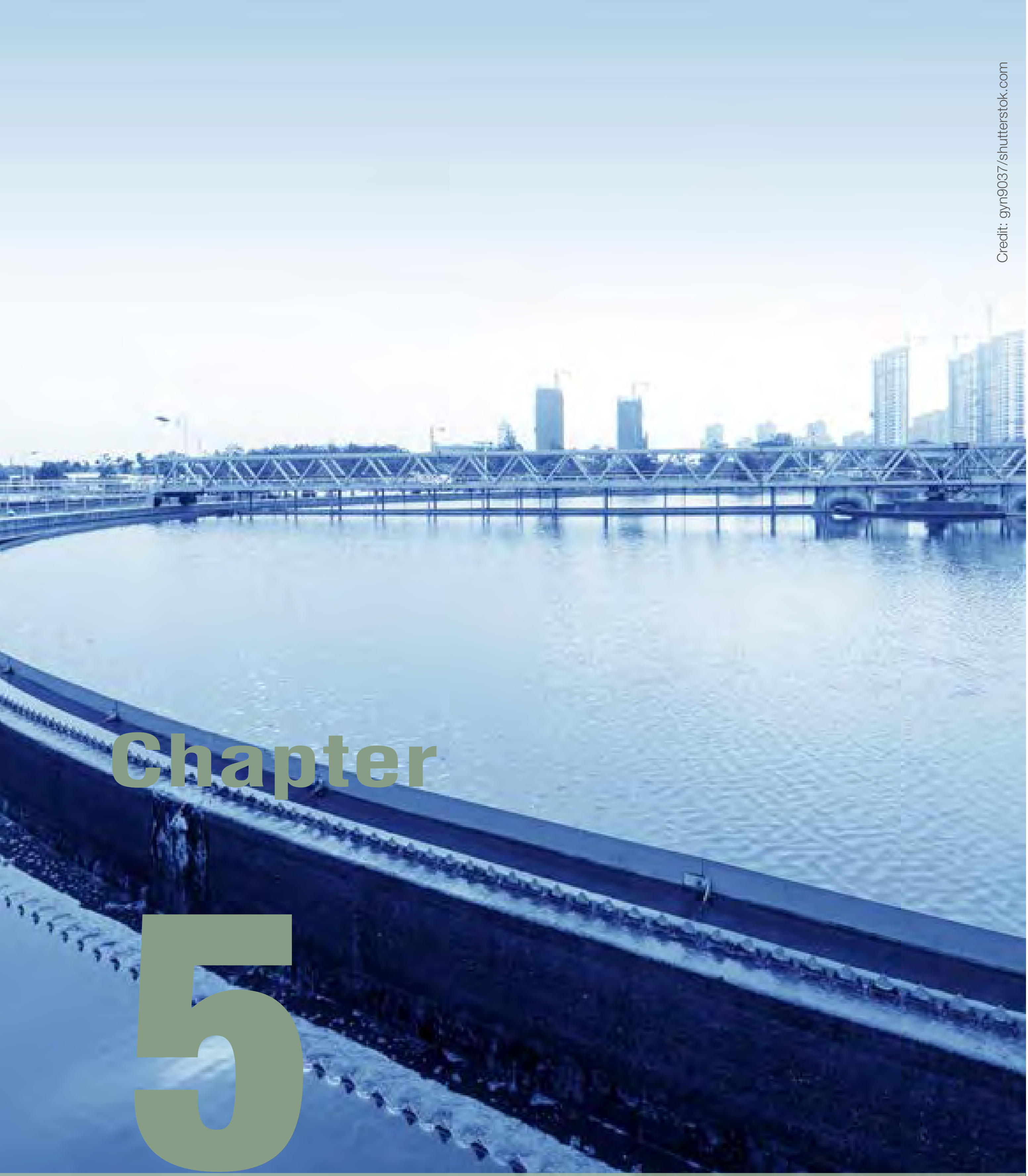
of the efficient technologies considered. When a strategic densification scenario is overlaid on the resource-efficient scenario, the results show a 3–12 percent additional reduction in resource impacts. In other words, the combination of resource-efficient infrastructures and strategic densification generates resource efficiencies of 36–54 percent compared with the baseline. While the LCA results presented here are not strictly comparable to DMC, these results seem to indicate that the consumption target of 6–8 tonnes per capita per year set by the IRP would be achievable. An important disclaimer, however, is that LCA results and resource consumption measured by DMC are fundamentally different. LCA considers the materials consumed over the full life cycle of individual products, whereas DMC considers the direct material consumption by entire cities, countries or regions. While choosing resource-efficient technologies that reduce environmental and resource impacts as measured by LCA may coincide with reductions in DMC, there is currently no quantitative scientific understanding of the relationship between these different kinds of indicators.

The LCA in this chapter examined the examples of specific sociotechnical systems and their likely impact on urban resources, when combined with densification and a transition towards decarbonized electricity in the supply chain of all materials and technologies. The systems are analysed individually for better understanding, but there may be additional resource efficiencies to be gained when considering the interactions between infrastructure systems within a given city. Chapter 5 examines the resource implications of multiple infrastructure interactions using empirical case studies from cities around the world, building the argument for an integrated approach to infrastructure planning that optimizes resource transfers between systems.



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# Chapter

# 5

# Resource efficiency via multiple infrastructure interactions

## Case studies from China, India and the USA

## 5.1. Introduction

This chapter analyses how multiple and cross-sectoral urban infrastructure interactions can leverage the sharing of locations, land, activities and material energy flows in ways that can foster more resource-efficient urban metabolic configurations. The exchange and reutilization of 'waste energy' (in the form of heat in particular, to generate heat and cooling) and waste materials across infrastructures within cities opens up significant opportunities for resource efficiency. Whereas Chapter 3 focused on the inclusionary and resource-efficient potential of a well-articulated, transit-connected hierarchy of strategically intensified urban nodes, and Chapter 4 demonstrated the potential from an LCA perspective of a particular set of resource-efficient infrastructures within higher-density environments, this Chapter uses empirical case studies to demonstrate the potential of an integrated approach to infrastructure planning that makes it possible to share resource flows between infrastructure systems to generate impressive resource efficiencies over time. Significantly, the infrastructure interventions analysed in this chapter are all realizable if the existing policy and regulatory frameworks of their host countries are fully implemented. The policy and regulatory environment for each case is derived from real-world cities, thus significantly reinforcing the argument that the resource-efficient metabolic configurations that can result in reductions of 30–50 percent compared with the BAU scenario are more realizable in practice than many tend to assume.

This chapter presents three case studies of such interactions, which exemplify the resource-efficiency gains that can be achieved by leveraging connections and interactions across one or more of the following infrastructure sectors:

- the building and construction sector;
- the energy supply sector, focusing on electricity supply;
- energy supply, including heat supply, incorporating reutilization of waste heat from industrial resources;
- travel behaviours and transportation;
- water and wastewater treatment;
- waste management.

It is important to note that this analysis assumes that infrastructure sectors are situated within an urban fabric where proximity enables the interactions to be implemented, for example, through eco-industrial parks and district energy systems drawing from combined heat, power plants and industrial waste heat.

Consistent with the urban metabolism framework, this chapter focuses on cross-sector interactions, where there is an explicit sharing or transfer of materials and energy across various infrastructure sectors. There is wide recognition, however, that urban infrastructure systems demonstrate other important linkages. These can be broadly grouped as functional interdependencies and multiple functionalities. Researchers have argued that distributed infrastructure (i.e. smaller-scale localized provision of energy, water, food systems, etc.) can provide sustainability benefits, as well as benefits for resilience. This can occur when leveraging interactions between infrastructures at a smaller scale (Derrible, 2016). For example, solar panels can be positioned on public shade structures, in turn providing shading for urban farming practices, with the water retention capacity of urban farms yielding reductions in the urban heat island (UHI) effect and so on. Similarly, a 'one-water approach', which seeks to integrate various water supply, treatment and management infrastructures into a single infrastructure system perspective that considers the full life cycle of water provisioning in urban areas, can simultaneously deliver liveability, resilience and sustainability benefits (Brown *et al.,* 2016). In such cases, these infrastructures can provide multiple services, and their interactions with each other are important.

Critical interdependencies occur when failure in one infrastructure sector cascades into failures in multiple infrastructure sectors, for example, when an electricity outage also causes transportation failures and water supply outages (Department of Energy, 2007; Department of Homeland Security, 2015). In general, there is a consideration that distributed infrastructure may provide benefits for the environment as well as for resilience through these multifunctional benefits. Quantitative assessment of these benefits is a topic of emerging research (Sustainable Healthy Cities, 2017).

Thus, given the focus on materials, this chapter focuses on the quantification of energy and material benefits through cross-sector interaction, exploring the potential in three diverse city types. Within each city, the specific mix of economic (industrial-commercial) activities, household activities, travel patterns, climate conditions, population growth rates that provide the impetus for change and other regional factors, such as the availability of sustainable timber or waste industrial heat, shape the degree of resource-use reductions possible from these multiple infrastructure interventions and interactions. The three case studies represent the following different groupings of conditions:

- Developed cities with stable population growth and infrastructure lock-in: Minneapolis is a US city that represents a pathway for resource efficiency that is similar for many other developed, resource-intensive cities in cold climates, which have high heating energy demand and have historically developed through sprawl surrounding an efficient urban core. Such cities are already established and ongoing opportunities for change are relatively small or slow, driven by modest population growth that requires new infrastructure, as well as refurbishment or replacement of existing, aging infrastructure. Many of these cities are located in resource-rich regions and can take advantage of new technologies, such as new timber technologies suited to high-rise construction, next-generation district energy systems and multi-sector strategies linking buildings, energy and water systems, as well as renewable energy policies.
- Symbiotic design in rapidly growing, industrial cities in China: Beijing and Kaifeng are examples of rapidly growing cities in China, where the predominant use for fuel is to generate industrial energy nationwide, contributing more than 70 percent of GHG emissions. We explore the reutilization of waste heat from industries for the heating and cooling of buildings, modeled to different efficiency standards, and supported by waste-to-energy projects and CHP for electricity generation. This represents a fast-growing city scenario and models opportunities for interactions across infrastructure sectors that focus on symbiotic exchange and reutilization of material and energy, which can be embedded into city designs. We illustrate results using model data for Beijing, which has a primarily commerce-based economy and for Kaifeng, which is a highly industrial northern city. Such examples are relevant given that future urbanization is likely to be accompanied by industrial growth in many, albeit by no means all, expanding cities of Asia and Africa.
- Resource implications of infrastructure rehabilitation in inequitable cities: The Delhi and Ahmedabad case studies explore the challenge of inequity in cities that have a large portion of slum populations. The cases explore how slums can be rehabilitated in situ within the urban core, in a multi-storey format that preserves compact urban form, with innovations in building materials as well as innovative policies to enable the financing of these multi-storey constructions in a manner that ensures low demand for motorized travel. This study focuses on infrastructure innovations and policy experiments around slum rehabilitation in Indian cities, drawing on effective policy experimentation documented in Ahmedabad and Delhi. A future policy scenario of a more equitable city is modeled to illustrate the hypothetical case where all slum housing is upgraded and there is sufficient electricity access for current median electricity consumption levels.

The choice of cities was made based on the availability of data for all the infrastructure sectors. In addition, having a range of different types (as explained above) was a key consideration, in order to represent a global diversity of cities with real-world policies that can be discussed.

Bottom-up, city-level data on demographics, socio-economic parameters and energy and material use by multiple infrastructure sectors (electricity, water, cooking fuels, etc), disaggregated by homes, businesses and industry are very sparse. Such data are needed to carry out a detailed analysis, as undertaken in Chapter 5. Among the at-scale data sets available worldwide, Ramaswami's team collected detailed data for Delhi, to represent a megacity in the developing world (low income), and for Beijing, a megacity in a middle-income country that has experienced dramatic transformation. We also selected a US city to represent a high- income country, a city that has recently developed a plan to reduce its GHG emissions by 80 percent—a remarkable goal.

Through these city case studies, we represent a diversity of economic development, while also representing at-scale data on people, economy and infrastructure, as well as policies. Case studies were not selected to describe cities of particular national interest.

## 5.2. Overview of methods

The interventions that were modeled in the case study cities are listed in Table 5.1. This also describes the effectiveness or elasticities per relevant unit of activity that were derived from the literature cited for modelling purposes. Based on the extent of each activity in the city, the final impact on city resource use can vary, as shown in the far-right column. The resource impacts were evaluated using a 'what-if analysis', assuming the future growth in the city results in a distribution of energy use in the various sectors similar to the baseline case.

**Table 5.1**: Interventions modeled in the case studies presented in this chapter

| Intervention | Known elasticity or sensitivity to change | Resources or activity impacted [reference] | Estimated reduction in case study cities |
|---|---|---|---|
| Strategic densification | • 25% vehicle miles of travel (VMT) reduction for population experiencing a doubling of density with favourable diversity, design and distance to transit.<br>• Elasticities with respect to a doubling of individual variables are noted to be lower. | VMT<br>[Transportation Research Board, 2009; Ramaswami *et al.,* 2012] | Minneapolis, USA: ~1% reduction in community-wide VMT is estimated, assuming all new population growth occurs in the urban core, impacting ~3.7% of Minneapolis' 2050 population. |
| Transit | • 10% VMT reduction due to transit effect (2%) and associated land-use effect (8%) based on US average. | VMT<br>[Gallivan *et al.,* 2015] | Minneapolis, USA: Projected reduction of 9.6% of VMT impacting 96% of population. |
| Fourth-generation district energy linked with combined heat and power (CHP) and utilization of sewer system as heat sink/ source: US application in cold climate | • Fourth-generation district energy estimated to reduce GHG emissions from buildings and industry by 19% in initial phases and by 38% to 42% when utilizing the sewer as a heat source/ sink, according to the design in Prospect Park, Minneapolis. | Reduction in use of natural gas for heating.<br>[Ahern *et al.,* n.d.] | Minneapolis, USA: District energy contributes to a 4% reduction in overall building sector energy use (2.3% of community-wide $CO_2$). Building and industrial efficiency contribute a 12.4% reduction. |
| Fourth-generation district energy systems in China | • Improvement in efficiency up to a factor of 10. About 30–50% heat loss in current steam-based district energy system versus only 5% heat loss in advanced fourth-generation system. | 80–90% reduction in energy use to heat residential and commercial buildings compared with current system.<br>[Zhang *et al.,* 2015b] | See next. |

| Intervention | Known elasticity or sensitivity to change | Resources or activity impacted [reference] | Estimated reduction in case study cities |
|---|---|---|---|
| CHP and reutilization of waste heat from industry in more efficient buildings (per codes in China) and more efficient industries (based on twelfth Five-Year Plan (FYP)) | • Energy intensity (kWh/m$^2$) reduced by 15% in new buildings and 5% in current buildings.<br>• Co-location of industry and residential-commercial buildings enables reutilization of low-grade industrial waste heat, fully avoiding fossil fuel use.<br>• Industrial energy efficiency improved to meet international best practices and targets set by twelfth FYP. | Reduction in residential and commercial building energy intensity per m$^2$.<br>Reduction in industrial energy use.<br>Reduction in coal/gas used to heat residential and commercial buildings based on availability of waste heat.<br>[Ramaswami *et al.*, 2017] | Kaifeng city, China: $CO_2$ reductions of up to 37% seen in Kaifeng city, an industrial city in northern China.<br>Reductions vary based on city type and availability of industrial waste heat versus residential and commercial applications for that heat. |
| Waste-to-energy | • ~280 kWh electricity per tonne of MSW—conversion of MSW via incineration to produce electricity. | Reduction in fossil fuels used to produce electricity.<br>[Zheng *et al.*, 2014] | Kaifeng city, China: 0.5% impact on city-wide infrastructure-related GHGs. |
| Material substitution for Portland cement | • Using dry slag granulation process, assuming a 1:1 substitution ratio of steel slag to cement up to 25% based on strength requirements.<br>• 1.4 GJ high-grade heat/tonne steel slag, which could be converted to electricity using the Organic Rankine Cycle at 15% efficiency. | Reduction of virgin materials and GHG emissions from cement use in concrete (1:1 substitution by mass of cement).<br>[Federal Highway Administration, 2016; Slag Cement Association, 2006; Jahanshahi & Xie, 2012] | Demonstrated for Beijing based on 25% reduction of cement use by material substitution. Overall impact of 2.4% on Beijing's community-wide $CO_2$ emissions. |
| Material implication of slum versus single-family home construction (India case study) | • 3,140 kg of material mass compared with the baseline of 656 kg per m$^2$ for existing slums (470% increase). | Bulk material use per m$^2$.<br>[Nagpure *et al.*, 2018] | All rehabilitation was assumed to be in multi-storey format (see next). |
| Material implications of single-family versus multi-family multi-storey concrete construction (India) | • 2,015 kg for multi-storey (36% reduction) compared with a single-storey unit that would require 3,140 kg of material. | Bulk material use per m$^2$.<br>[Nagpure *et al.*, 2018] | Delhi, India: Upgrading housing for 46% of Delhi's population by 2021, assumed in multi-storey format, increased per capita mass cement use by 25%. |
| Alternatives to high-rise concrete building construction in USA, including new timber technology[1] | • 64% reduction in bulk materials in multi-storey new timber versus concrete construction, and 29% reduction in bulk materials in multi-storey steel versus new timber construction.<br>• 40% reduction in construction-related GHGs from new timber versus conventional.<br>• Additional 39% potential for carbon sequestration for new timber technology buildings based on sustainable timber production and end of life. | Reduction in construction material use and embodied GHG emissions per m$^2$.<br>[John *et al.*, 2008] | |
| Using manufactured sand in areas of extreme sand scarcity where riverbed mining of sand has negative consequences | • Manufactured sand, also known as 'crushed' aggregate, uses five times more energy (81 versus 17 kJ/kg; NIST, 2007) compared with alluvial aggregate, but avoids riparian damage. | | No analysis was performed. Information provided on response to scarcity. |

A sociotechnical scenario-modelling approach was taken, describing what may reasonably be achieved through the real-world policies already adopted in these cities, incorporating potential behavioural and physical constraints. For example, district energy is assumed to apply only in denser downtown neighbourhoods with multi-storey buildings; densification is only estimated to impact 3.7 percent of the population in the urban core where new population can be accommodated; the number of people taking transit is modeled based on real-world behaviours in response to land-use change and access to transit.

Indeed, we recommend that all cities track the penetration of interventions through voluntary versus regulatory approaches. For example, the voluntary adoption of green building standards by new building construction in US cities is of the order of 5 percent, while mandatory policies requiring such standards for large commercial buildings will raise the penetration of said technology/strategy. Several researchers have identified the voluntary rates of adoption of several strategies in US cities, and also identified the behaviours that shape adoption of strategies to be an important component of the GHG mitigation wedge (Dietz *et al.,* 2009; Ramaswami *et al.,* 2012). Theories around social norming and planned behaviour are often used in community behavioural change campaigns; tracking actual adoption of strategies in these campaigns is important for understanding where voluntary behaviour change can be successful and where mandatory regulations may help, recognizing that investments are needed to monitor any regulations and impose suitable sanctions. For example, Berkeley, CA and San Francisco, CA have shown the success of mandatory, time-of-sale building energy-efficiency programmes. Ramaswami *et al.* (2012) have shown that a far greater adoption of energy-efficiency retrofits can be anticipated in US cities through a well-designed regulatory programme than through typical voluntary energy-efficiency campaigns with incentive models (Ramaswami *et al.,* 2012).

## 5.3. Case study 1: Established city, stable growth, strong path dependency and infrastructure lock-in

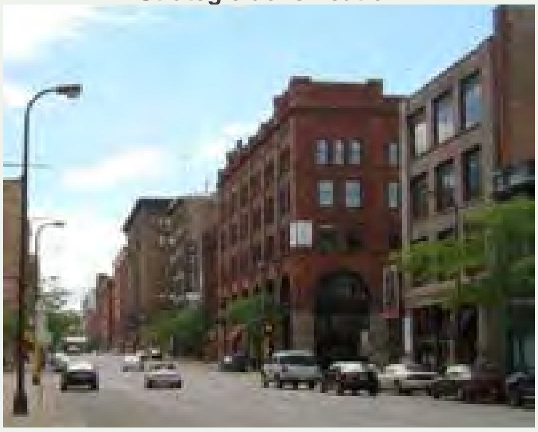
### 5.3.1. Context

The city of Minneapolis has a population of 411,273 (Metropolitan Council, n.d.) and a projected growth rate of 0.4 percent. Its overall land area is 149 km$^2$ (14,868 hectares) with an average gross population density of 2,760 persons per km$^2$ (Metropolitan Council, n.d.). There is significant density variation ranging from the core to the city periphery. More than 90 percent of new residential construction is in the form of mid- to high-rise buildings, indicating the city's commitment to more compact growth (Minneapolis Community Planning & Economic Development, 2015). In the larger metropolitan region, of which Minneapolis is one city, the median household income (including benefits) was $67,532 in 2013 (Metropolitan Council, 2015) and the GDP per capita was $62,054 in 2014 (U.S. Bureau of Economic Analysis, n.d.).

Minneapolis has a relatively dense downtown area resulting from the residual urban design from the streetcar operations of the first half of the 20th Century, and the leaf-like urban pattern of traditional compact cities (Salat *et al.,* 2014). Minneapolis is also well known for repurposing old warehouses in its downtown area into apartment buildings, especially in the Theatre District and Warehouse District, representing a model for urban revitalization. It is a recognized national and international leader in innovative sustainability solutions. In transportation, Minneapolis has invested in bicycle paths, a bike-sharing system and mass transit. In the Prospect Park neighbourhood, a multi-sector stakeholder group consisting of developers, architects, utility providers and community leaders engaged in active plans to implement district energy, connecting commercial and residential buildings with waste heat from an industrial source (pulp and paper mill), and utilizing the sewer system for thermal storage/exchange.

The city of Minneapolis has a strong local government that has adopted the goal to achieve an 80 percent reduction in in-boundary energy use and GHG emissions by 2050. The larger metropolitan planning region, of which Minneapolis is a member city that represents the regional commuter shed, is governed by the Metropolitan Council. The Metropolitan Council has adopted the Thrive MSP 2040 Plan, a 30-year comprehensive development plan. The state of Minnesota has adopted strong renewable energy standards requiring utilities to provide 25 percent renewable energy by 2025 (Minnesota Statute 216B.1691) (New York Times, 2014; Revisor of Statutes, State of Minnesota, 2015a). Therefore, Minneapolis presents an excellent case study for integrated, multi-sector infrastructure innovation and multi-scale governance from the city, to the planning region, to the state.

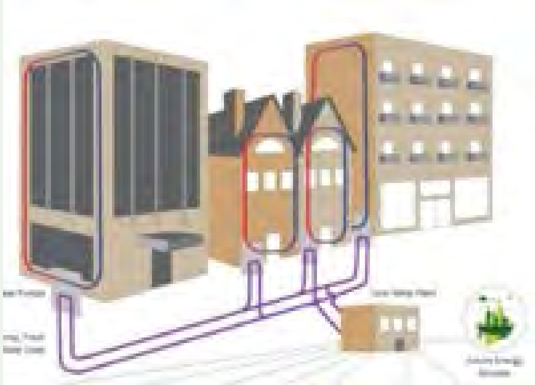
**Strategic densification**



**Alternate building materials**

**Increased public transit**

**District energy and CHP**



## 5.3.2. A sociotechnical approach

Six sociotechnical initiatives have been modeled to illustrate the multisectoral infrastructure solutions being considered or implemented today in Minneapolis:

- strategic densification with respect to the five Ds—density, diversity, design, destination accessibility and distance to transit (Transportation Research Board, 2009)—implemented in the metropolitan region;
- increased public transit across the metropolitan area with significant increases planned within the city of Minneapolis;
- enhanced building efficiency on a city-wide basis;

- in strategic locations, enhanced building energy efficiency and highly efficient fourth-generation district energy systems that utilize waste heat from a local industry and utilize the water infrastructure as a thermal sink/source in summer and winter, respectively;
- advanced timber construction materials as alternative to current energy-intensive construction materials;
- renewable energy policy, committed to by the local electric utility, with the aim of achieving >40 percent wind energy by 2050.

The major aims of these interventions are diverse and range from GHG mitigation commitments by the city of Minneapolis (city scale), the liveability goals of the Metropolitan Council, as articulated by the Thrive MSP 2040 Plan (Metropolitan Region scale) and the state of Minnesota's Renewable Energy Policy and Bioincentive Program (state or province scale). This coordination across multiple levels of government and other stakeholders is consistent with the SEIS framework (Ramaswami *et al.,* 2012) introduced in Chapter 1.

We combine the impact of the above six diverse strategies on Minneapolis's 2010 Infrastructure Supply Chain GHG footprint (Hillman & Ramaswami, 2010) to illustrate the impact of city-wide infrastructure provision, incorporating direct energy use, as well as embodied energy of buildings and transport fuels.

### 5.3.3. Quantifying resource impact

Strategic densification in the Minneapolis context means integrating land use and transportation in order to bring new populations into existing infill areas. The majority of new construction in Minneapolis is multi-family buildings (Minneapolis Community Planning & Economic Development, 2015), and policies to promote compact and sustainable land use are modeled to channel new populations into more compact areas of the city, which exemplify the five Ds: density, diversity of land uses, design, destination accessibility and distance to transit (as discussed in Chapter 3). A doubling of density in these areas is assumed, modeled to impact approximately 75 percent of the new population growth and an equivalent population already living in these areas, based on methods developed for wedge analysis (Ramaswami *et al.,* 2012)[75]. In Minneapolis, areas such as the Warehouse District already have moderate density, with four- to six-storey buildings on a grid-type street pattern, with transit and mixed-use, walkable streets. A synthesis report by the US National Research Council (Transportation Research Board, 2009) suggests that in the most favourable case of doubling density in a favourable urban form, a 25 percent reduction in VMT can be achieved for the impacted population. Although the reduction on a percentage basis (25 percent) is significant, the population impacted is small since existing housing cannot be significantly altered. Only the equivalent of the new population in the area is modelled to be impacted by density changes. The population growth rate is small in stable cities such as Minneapolis, and hence, only 3.8 percent of the population is impacted by 5D densification by 2025 (assumed to travel 23 VMT per person per day based on 2010 data).

Increasing public transit is modeled in Minneapolis to provide benefits for the remaining population of the city. Recently reported elasticities for US cities are applied, which include *land-use effects*—compact development around public transit—and *ridership effects*—switching of modes from private vehicles to public transit (Gallivan *et al.,* 2015). In the USA, land-use effects have been found to translate to a VMT reduction of 8 percent and ridership effects of 2 percent, on average (Transportation Research Board, 2009). In general, higher densities with a reported threshold of >10 dwelling units per hectare (corresponding to 5,485 people per km$^2$ at an average household size of 2.22 persons per household, and corresponding to four to six storeys) are needed for several sustainable transport options to be effective (Louis Berger

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[75] Wedge analysis looks at GHG stabilization scenarios compared with a baseline or BAU case, by identifying different strategies for emissions reduction that each form a wedge of the full GHG reduction scenario.

Group Inc., 2004). Transit reductions are applied to the remaining 96.2 percent of the population, also assumed to travel 23 VMT per person per day based on 2010 data.

Building efficiency regulations and technologies improve both the existing buildings and the new housing required to accommodate new populations' growth. As part of Minneapolis' 2025 Climate Action Plan, 75 percent of existing residences will be retrofitted with energy-efficiency upgrades to reduce overall residential energy use by 15 percent and 'challenge' commercial and industrial buildings to reduce their energy use by 20 percent by 2025 from the 2006 baseline (Minneapolis City Coordinator, 2013). The model assumes that the new buildings are built to the Sustainable Building 2030 (SB 2030) Energy Standard or the Department of Energy (DOE) Zero Energy Ready Standard, meaning they will be so efficient that their energy consumption can be offset by an on-site renewable system, such as rooftop solar (Minnesota Buildings, Benchmarks & Beyond, n.d.; U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2016; Minneapolis City Coordinator, 2013). The building energy intensity data used for Minneapolis show residential buildings emitting 1.6 million tonnes of $CO_2e$ annually, and commercial and industrial buildings emitting 3.9 million tonnes of $CO_2e$ annually (Hillman and Ramaswami, 2010). The 15 percent energy reduction in residential buildings accounts for 2.9 percent of the city's GHG footprint, and the 20 percent energy reduction in commercial and industrial buildings accounts for 9.5 percent.

Mass timber is a recent technological innovation that is being used in mid-rise and high-rise buildings in Vienna, London and Portland (Watts and Helm, 2015). Mass timber includes a new technology called Cross-Laminated Timber (CLT), which laminates or nails lumber boards together, alternating the direction in layers to form very strong structural support. This represents a new innovation, with timber being used for the first time in high-rise construction, and can serve as an alternative to concrete construction in bioresource-rich areas. LCAs indicate an approximate 40 percent reduction in the construction energy plus embodied energy of CLT-based, mid-rise buildings compared with conventional steel buildings and concrete buildings (John *et al.,* 2010; Dixit *et al.,* 2012; Siemens AG, 2016). The timber must be locally produced to achieve these benefits. Prefabricated mass timber can be used in all above-ground construction; it is not used in foundations due to rot and termite issues. Further, such timber has high structural strength that enables long architectural spans and also (contrary to common knowledge) greater fire resistance. Studies in Minnesota show wooden buildings to be long-lived compared with concrete and steel, since most buildings are demolished for reasons other than deterioration or fire (O'Connor *et al.,* 2004). The reductions in embodied emissions of construction materials, shown in Figure 5.1 below, do not include the carbon that can be sequestered in timber, assuming it is produced sustainably. Under the right circumstances, timber can create even greater potential for carbon sequestration in bioresource-rich regions.

Advanced fourth-generation district energy systems utilize energy from diverse sources—CHP plants, industrial waste heat, biogas and from renewable energy—to circulate warm water (60–80°C) to heat buildings that are designed to high energy-efficiency standards (<15 kWh per $m^2$-year for new buildings and 50–150 kWh per $m^2$ for existing buildings (Lund *et al.,* 2014). In summer, absorption chillers and/or heat pumps are utilized for cooling. Such advanced district energy systems are being proposed in the Prospect Park neighbourhood of Minneapolis, where waste heat from a pulp and paper mill is being integrated with CHP plants that can operate using flexible fuels, including wood chips and wood waste. Furthermore, the systems are profitable when wastewater in the sewer is used for heat exchange in the system, providing heat in winter and a heat sink in summer. This innovative design will be implemented at Prospect Park in Saint Paul by Ever-Green Energy, a pioneer in district energy. This private firm has done analyses of their planned project for Prospect Park, which show 19–38 percent energy savings compared with each building having its own heating and cooling systems (Ahern, n.d.). For the scale-up scenario, it was assumed that similar district energy systems will be developed to achieve a 38 percent thermal energy reduction in 42 percent of existing buildings, which represents the share of multi-family housing estimated in Minneapolis (Metropolitan Council, n.d.). This estimate is based on current multi-family housing penetration and multi-family buildings accounting for 92 percent of new residential construction in Minneapolis, based on 2015 data (Minneapolis Community Planning & Economic Development, 2015).

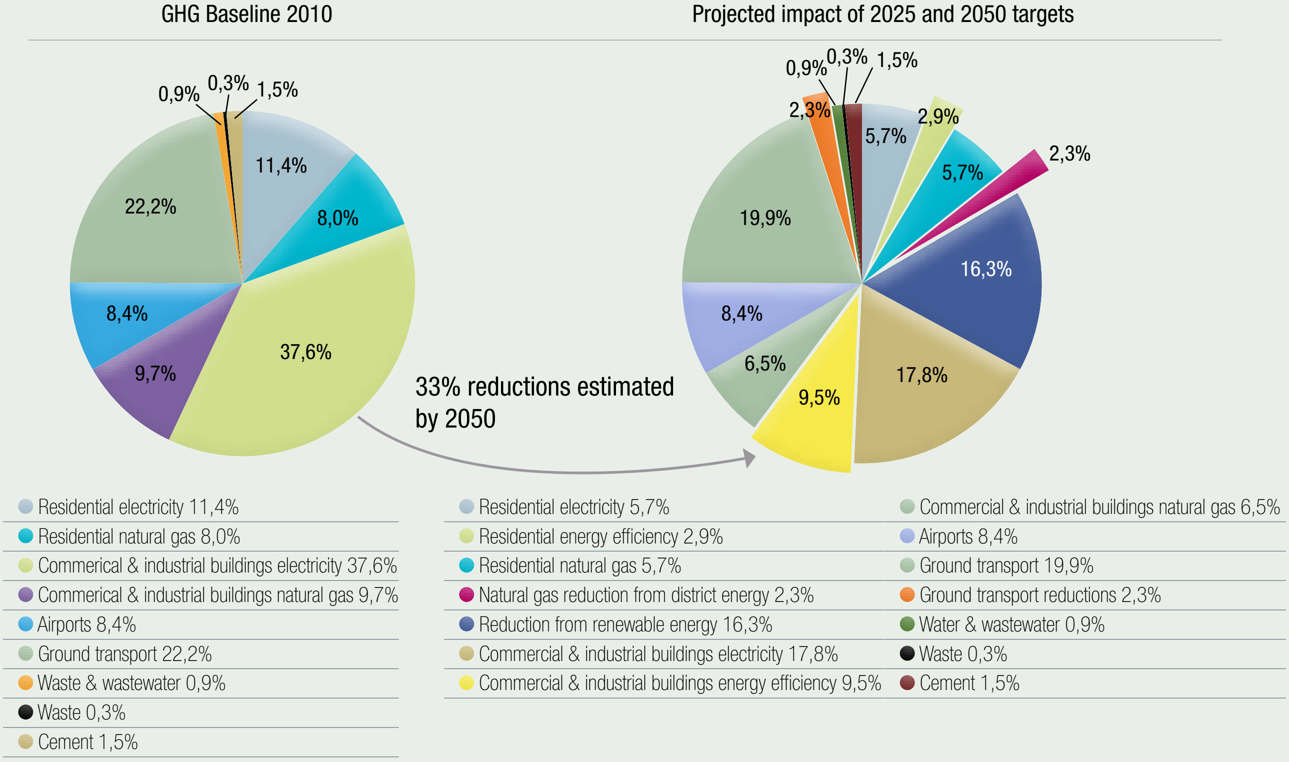
Renewable energy policy in Minnesota requires utilities to provide 25 percent renewable energy by 2025 (Minnesota Statute 216B.1691 (Revisor of Statutes, State of Minnesota, 2015a)). The local utility, Xcel Energy, has accordingly planned to increase its use of wind energy from 13 percent to 25 percent, and solar power from <1 percent to 8 percent between 2015 and 2025, decreasing its emissions factor from 459 to 269 kg per MWh (Siemens AG, 2016). Xcel Energy has a 2050 target that includes 50 percent renewables accompanied by a legacy nuclear power system, which is expected to continue into the future. Although nuclear power may not be an option in other parts of the United States, these reductions will provide 65 percent of electricity from renewable sources by 2050, which will result in a 41 percent reduction in GHG emissions from today's mix of electricity generation (Siemens AG, 2016).

### 5.3.4. What-if analysis of city-wide infrastructure provision

The overall impacts of all the above interventions on Minneapolis's GHG footprint of infrastructure provisions (based on annual 2010 data) are shown below.

The implementation of all these interventions results in a 33 percent (approximately one

**Figure 5.1**: GHG emissions baseline and reductions associated with multiple infrastructure provisions in Minneapolis, USA. Year 2010 baseline emissions from Hillman and Ramaswami (2010); efficiency estimates of multiple infrastructure interventions are based on year 2025 and 2050 targets proposed by the city and other policy actors



third) reduction in GHG emissions overall by 2050. This shows that significant reductions are possible, even in an existing city with significant path dependency.

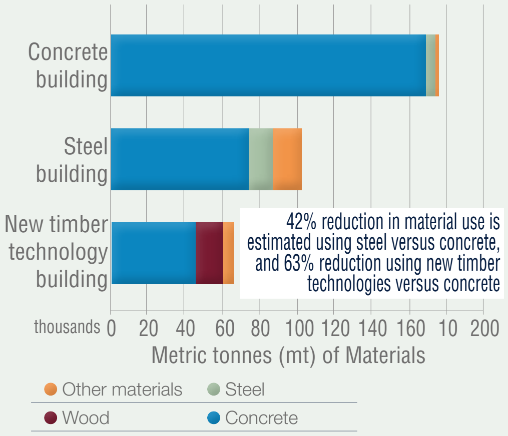
As far as building materials are concerned, a 48 percent reduction in material use is estimated using steel rather than concrete, and a 64 percent reduction if new timber technologies, such as cross-laminated timber (CLT), replace concrete-based construction (John *et al.,* 2008). CLT shows promise in areas with reliable and significant wood availability. It is important to note that recent studies show that concrete has significant potential to sequester $CO_2$ over the construction-use-demolition cycle (Xi *et al.,* 2016), as does timber. These sequestration benefits are not shown in Figure 5.2. to enable a better comparison because the end-of-life pathways can differ greatly.

### 5.3.5. Policy context, stakeholders and activities

The above infrastructure interventions are enabled by several policies adopted by governments at different levels, and involving several actors and stakeholders, as noted below:

- The city of Minneapolis conducted a comprehensive GHG inventory in 2010 (City of Minneapolis, 2012) and adopted a Climate Action Plan with a target of 30 percent GHG emissions reduction by 2025 (Minneapolis City Coordinator, 2013). The city of Minneapolis also participated in a US study conducted by the University of Colorado, which compares energy use in eight US cities and enables the city's energy use in multiple infrastructure sectors to be computed and compared with benchmarks in a standardized manner (Hillman & Ramaswami, 2010). In 2015, the city of Minneapolis collaborated with Siemens in a public-private partnership to perform an analysis of 80 percent GHG reduction by 2050 (Siemens AG, 2016).

**Figure 5.2**: Potential for carbon sequestration in urban high-rise, new timber technology buildings. Greenhouse gas (GHG) emissions per $m^2$ of building in life-cycle phases: initial embodied energy, end of life and $CO_2$ storage in materials. The sequestration potential for timber and concrete is not shown because varying reductions can be achieved based on end-of-life pathways



(Source: John et al., 2008; Xi et al., 2016)

- The city of Minneapolis works with the Metropolitan Council, the regional governmental organization and metropolitan planning organization for the Twin Cities area that coordinates land-use and transportation planning for seven counties in 16 districts in the area, encompassing a population of almost 3 million. The Metropolitan Council is required by state law (Revisor of Statutes, State of Minnesota, 2015b) to create regional plans and policies and review local comprehensive plans.

- Minneapolis is located in a bioresource-rich region and many state policies seek to stimulate the use of these resources. For example, the state of Minnesota's Bioincentive Program, established by the Minnesota Legislature in 2015, provides production payments to encourage commercial-scale production of advanced biofuels, renewable chemicals and thermal energy production from biomass (Minnesota Department of Agriculture, 2016). If favourable, similar programmes could apply to new timber technologies which could serve as a large employment draw in the region. The state of Minnesota requires electric utilities to produce 25 percent of their electricity from renewable sources by 2025, as well as stimulate efficiency and reduce their sales by 1.5 percent of their revenues (2015 Minnesota Statute 216B.1691 (Revisor of Statutes, State of Minnesota, 2015a)).

Xcel Energy is the local utility for Minneapolis, which operates in eight states and is a regulated, investor-owned monopoly that provides electricity in the region and serves as a carrier for natural gas. Its 2015–2030 long-term resource plan for power generation includes an increase from 15 percent to 25 percent wind power in the Midwest and 65 percent non-fossil energy sources, which include 28 percent nuclear power from an earlier, legacy system (Xcel Energy, n.d.). The city of Minneapolis, Xcel Energy and natural gas utility CenterPoint Energy are front runners in city-utility cooperation, having established in 2014 a Clean Energy Partnership in which they collaborate on strategic planning; this includes significant demand-side reduction as well as aggressive penetration of renewable energy, including wind and community solar (Clean Energy Partnership, 2016). The agreements for this partnership were negotiated by a non-profit organization, the Center for Energy and Environment, and demonstrate the momentum created by multi-sector engagement that counters the impact of legacy systems (Center for Energy and Environment, 2016).

District Energy St. Paul was formed as a non-profit entity in the late 1970s, emerging from a public-private partnership among the city of Saint Paul, the state of Minnesota, the U.S. Department of Energy and downtown businesses. The system was built in three phases through various financing sources (Seidman and Pierson, 2013). Ever-Green Energy is a private firm founded by District Energy St. Paul to advance the national model established for Saint Paul's community energy system. Ever-Green Energy is now a key player in the diffusion of district energy systems in the USA.

Prospect Park stakeholders are Prospect Park 2020, University of Minnesota, Metropolitan Council, city of Minneapolis (Community Planning and Economic Development and Public Works), Hennepin County, The Wall Companies, Greater MSP, Minneapolis Public Housing Authority, Metro Clean Energy Resources Team (CERTS), Mississippi Watershed Management Organization, Cunningham Architects, The Cornerstone Group, local gas and electric utilities, United Properties and Blue Cross Blue Shield (Ever-Green Energy Inc., 2016).

## 5.4. Case study 2: Urban industrial symbiosis in the context of rapid urbanization with industrialization

### 5.4.1. Context

The pairing of rapid urbanization with large-scale industrialization is taking place in China (Bai *et al.,* 2014; Ohshita *et al.,* 2015) and is a likely pathway in many parts of the developing world. This will create large infrastructure demands for buildings, roads, energy supply and water for urban residents in cities, as well as substantial water and energy requirements for industries. Unsurprisingly, this has created extraordinary demand for finite resources. Industrial energy use is responsible for more than 70 percent of China's coal use and the air pollution ramifications of these industrial emissions have been well documented.

A unique opportunity exists in China, arising from the fact that industrial location strategies and spatial urbanization patterns have resulted in many industries being co-located in special economic zones (SEZs) that include highly dense urban areas. The co-location of residential and commercial buildings in China's SEZs makes large-scale resource sharing possible. A recent analysis conducted by Ramaswami *et al.* (2017) used diverse data sources to model the co-location of industries with homes and commercial establishments in cities, to explore the potential for urban industrial symbiosis, i.e. the exchange of materials and reutilization of waste heat in more than 630 Chinese cities. These exchanges connect multiple infrastructure sectors, including electricity supply using CHP, fourth-generation district energy with urban industrial symbiosis involving waste heat exchange, MSW-to-energy and production of construction materials. From this larger study, the case studies of Beijing and Kaifeng cities are drawn upon. The city examples model a future scenario that integrates efficiency policies established in multiple individual sectors, upon which cross-sector symbiosis, i.e. energy and material exchange is added. These are brought together to illustrate multi-sector synergies. These multi-sector interventions across residential/commercial/industrial sectors incorporating energy and material exchange can yield significant resource-efficiency gains.

Beijing, which produces 6.3 million tonnes of MSW and uses 20.6 million tonnes of cement per year on new construction, is the case study site for waste-to-energy and material exchange interventions through the re-use of steel slag in cement. The reutilization of industrial waste heat from co-located industries in commercial and residential buildings is also modeled, assuming energy and modest building efficiency improvements consistent with China's twelfth five year plan and fourth-generation district energy systems.

Kaifeng, located in the Henan Province, has historically been a centre for major chemical industries. The city of nearly 5 million has seen a 12.3 percent population growth in the past 10 years (UN-DESA, 2014). The CHP, industrial efficiency, industrial waste heat exchange and building efficiency interventions are demonstrated here. Both Beijing and Kaifeng are in northern China, which has a cold climate, such that the district heating system is a readily available reutilization opportunity for waste heat.

### 5.4.2. A sociotechnical approach

There is an opportunity for Chinese cities to utilize industrial waste heat and material exchange to improve resource efficiency, and reduce air pollution and GHG emissions. Centralized heating is already prevalent in Chinese urban areas located within the designated climate zones for indoor heating with about 70–80 percent (Zhang *et al.,* 2015b) of the urban population in these areas covered. However, inefficient residential coal-fired boilers and stoves are still being used to supplement centralized heating and may significantly contribute to local air pollution issues. Given the highly industrial nature of many of these cities and the heating policy reforms occurring over the past 20 years, there is an opportunity to rethink the resource efficiency of current methods of heat supply to Chinese cities.

Further, there is also great potential to significantly enhance the energy efficiency of material use in the construction sector by impacting the production-side of steel and cement through industrial symbiosis. Industrial symbiosis is the beneficial exchange of materials and energy between co-located industries (Chertow, 2007). There is also demonstrated potential for other material exchanges between the residential/commercial sector and industries, which is referred to as urban industrial symbiosis (Van Berkel *et al.,* 2009).

The proposed infrastructure transition (urban industrial efficiency and symbiosis) takes place in multiple sectors:

1. Industrial efficiency: Efficiency improvements are based upon the Top 10,000 Program and international industrial energy-efficiency benchmarks of 16 major industries. In the twelfth FYP, the Top 10,000 Program targets the 10,000 largest-polluting enterprises through energy-efficiency improvements with the goal of reducing 250 million tonnes of carbon equivalent (tce) by 2015 (IEPD, n.d.). The 'circular economy' development model has been espoused in China over the past 10 years to encourage resource reutilization and recycling to conserve resources, reduce environmental impact and improve industrial competitiveness (Su *et al.,* 2013). Adopted in 2002 by the central government, the implementation of the circular economy strategy has accelerated under the twelfth FYP.

2. Fourth-generation district energy system: Centralized heating already serves about 70 percent of urban residents (Zhang *et al.,* 2015b), but could be more efficient and use

cleaner burning fuels if upgraded to a fourth-generation district heating system. In the twelfth FYP, about 800 million m$^2$ of district heating floor area from CHP and renewable sources was to be added by 2015. Fourth-generation district energy systems use low-temperature hot water rather than steam, and there is only 5 percent heat loss in the network compared with 30–50 percent in current high-temperature district heating systems. This can yield an 80–90 percent saving of fuel used for residential and commercial heating purposes.

3. Industrial waste heat reutilization in district energy: A few infrastructure experiments are under way in China exploring the reutilization of waste heat from co-located industries to displace fossil fuel use in urban district energy systems (Fang *et al.,* 2013). Such strategies have also been explored in the European Union (Brueckner *et al.,* 2014).

4. Building energy efficiency: In the twelfth FYP, China set targets of retrofitting 400 million m$^2$ of residential buildings in northern China and 800 million m$^2$ of new green buildings by 2015 (Yu *et al.,* 2014). The Green Building Action Plan launched in 2013 set a target of 10–15 percent reduction in energy use per m$^2$ for commercial buildings. Based on building code improvements and projected increases in household energy intensity (kWh per m$^2$), a 5 percent energy intensity reduction is assumed for existing buildings, and a 15 percent energy intensity reduction for new construction (Zhou *et al.,* 2014).

5. CHP: Assume a 30 percent CHP penetration for low- and medium-grade waste heat applications. China has recently ramped up efforts to expand CHP with the goal of 30 percent of thermal power plants by 2030 (IEA, 2009).

6. Waste-to-energy: China has set a goal of diverting 30 percent of MSW to waste-to-energy plants designed to produce refuse-derived fuels or electricity by 2030. Additionally, there are subsidies in place for power generated from waste-to-energy plants. Beijing eliminated household recycling to move towards centralized sorting of recyclables and landfilled/incinerated waste, which enables a consistent stream of MSW for the new waste-to-energy plant in Lujiashan (Themelis and Mussche, 2013; Zhang *et al.,* 2015a).

7. Material exchange/substitution: Cement and power plants are key industries supporting urban infrastructure. Symbiotic exchange of materials among these large industries can significantly contribute to resource efficiency. Recent studies show that by using the dry slag granulation process, steel slag that is normally wasted can be reutilized in a 1:1 ratio, replacing up to 25 percent of cement production (Slag Cement Association, 2006). Fly ash reutilization from power plants in cement and brick production is already occurring in many provinces in China. The Beijing MCC Equipment Research & Design Corporation (MCCE) has recently signed an agreement with CSIRO Australia to pilot and commercialize a new dry slag granulation technology. China produces about 60 percent of the world's slag and more than 50 percent of the world's supply of cement.

### 5.4.3. Quantifying resource impact from urban industrial efficiency and symbiosis

The analysis assumes that all the industrial waste heat generated is reutilized in district energy for residential and commercial centres based on the demand. High-grade industrial energy is assumed to be converted to electricity using a Rankine cycle turbine, and this does not require co-location. The supply and demand of waste heat in different city types effectively shapes the city-wide impact of these interventions, as shown in the simulations for Beijing and Kaifeng.

#### Beijing

It is estimated that a $CO_2$ reduction of up to approximately 11 percent over a four-year period is achievable in a commercial city like Beijing.

Of Beijing's total Scope 1 and 2[76] $CO_2$ emissions of 129 million tonnes, about 11 million could be reduced from material exchange, heat exchange and waste-to-energy strategies. This assumes that 25 percent of Beijing's cement use could be replaced by reutilized steel slag through the dry slag granulation process, and 30 percent of Beijing's MSW could be incinerated—which has air pollution implications, making it an example of problem displacement. The $CO_2$ savings are calculated as the displaced electricity generation by waste-to-energy based on the average electricity emission factor of China's northern grid. Cement and MSW amounts were determined based on previously gathered infrastructure activity data (Tong *et al.,* 2016).

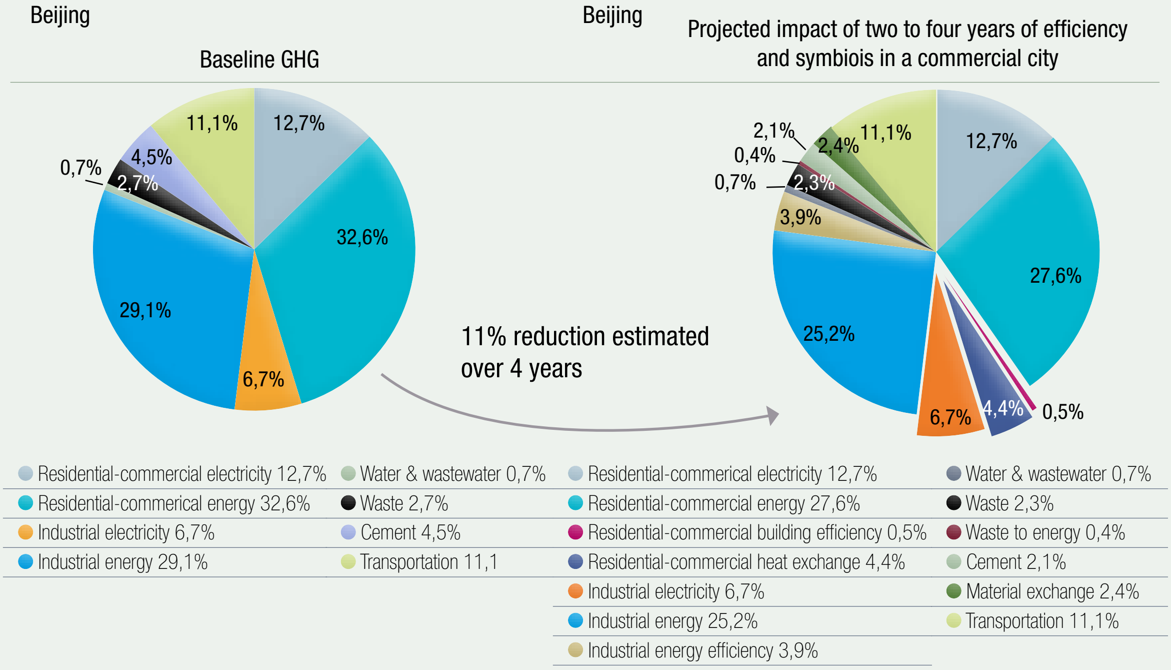
### Kaifeng

A $CO_2$ reduction of up to 36 percent over a four-year period can be achieved in industrial cities like Kaifeng. Of Kaifeng's total Scope 1 and 2 $CO_2$ emissions of 9 million tonnes, about 22 percent could be reduced from industrial efficiency, building efficiency and heat exchange strategies (Ramaswami *et al.,* 2017).

## 5.4.4. Barriers and enablers

Barriers to adoption of these proposed infrastructure transitions include cost and penetration of CHP for thermal power generation. While CHP has accelerated in recent years, it accounted for only 13 percent of total thermal power generation in China as of 2008, but is projected to reach 28 percent by 2030 (IEA, 2009). CHP costs vary based on fuel type: $3,250 per kWe (fluidized bed—coal) to $1,150 per kWe (natural gas turbine), which could be 10–40 percent higher than typical systems (IEA, 2010). However, although the capital investment may be higher, case studies such as Pudong International Airport's new CHP system have shown a payback period of less than six years (IEA, 2008). In looking at the cost of potentially retrofitting an existing heating network, a case study in Anshan identified the costs and payback period of retrofitting a centralized city heating network with capital cost recovery occurring in less than three years (UNEP, 2015). While the existing centralized

**Figure 5.3**: Anticipated Scope 1 and 2 GHG benefits in a period of two to four years based on modest policies already included in China's FYP, complemented by urban industrial symbiosis



(Data from Ramaswami et al., 2017 and Tong et al., 2017)

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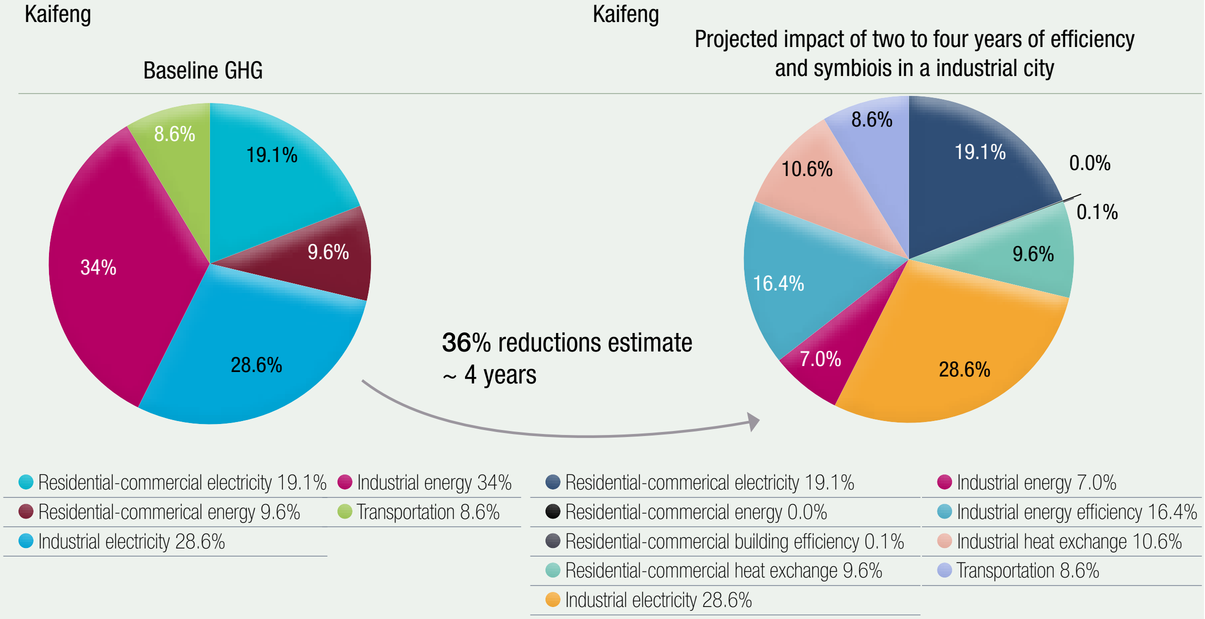
[76] According to the Greenhouse Gas Protocol, emissions under Scope 1 and 2 account for all direct GHG emissions and indirect GHG emissions from consumption of purchased electricity, heat or steam. Other indirect emissions fall under Scope 3.

**Figure 5.4**: Anticipated Scope 1 and 2 GHG benefits in a period of two to four years based on modest policies already included in China's FYP, complemented by urban industrial symbiosis



(Data from Ramaswami et al., 2017)

heating networks in northern Chinese cities may be inefficient, the infrastructure already in place can be used to create more advanced district heating systems that can utilize waste heat.

As mentioned previously, current Chinese policies in the twelfth FYP have encouraged energy efficiency through industrial efficiency, building efficiency, district energy and CHP. These policies, as well as the material exchange already occurring (He *et al.,* 2012) show a political commitment towards a circular economy in China. This commitment, in addition to rapid urbanization, may facilitate the transition towards urban industrial efficiency and symbiosis if the infrastructure investments in new and growing Chinese cities are directed at improving energy and material efficiency (Tong et al., 2017).

### 5.4.5. Cautions and uncertainties

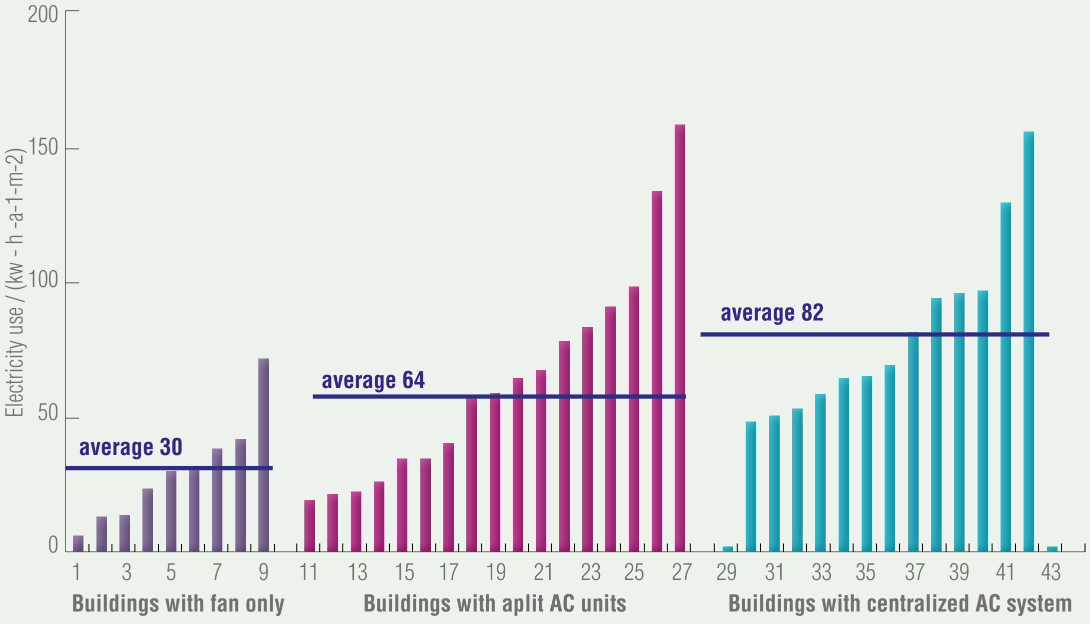
Are centralized district energy systems more efficient than vernacular buildings in China? This is an important question as buildings in China are already efficient in their use of spot heating/cooling. However, there is a healthy debate as to whether district buildings with centralized air-conditioning are less energy intensive than vernacular buildings (see Figure 5.5). As China urbanizes and becomes wealthier, residents will seek more thermal comfort from new buildings. This, along with increased appliance usage, may increase energy intensity (kWh per m$^2$) unless significant building efficiency improvements are undertaken through building codes.

## 5.5. Case study 3: Resource requirements to address infrastructure inequities in fast-developing cities

### 5.5.1. Context and background

In India, approximately 95 percent of the required new housing is to meet the needs of the urban poor. Rehabilitation of existing housing cannot be seen in isolation from planning for new housing, nor can housing projects be considered for the urban poor without consideration of access to jobs and the densification of urban centres. These multi-sector considerations essentially drive the economics of selecting appropriate construction types: single family (SF) and multi-family (MF). The choice of construction type has tremendous impacts on the demand for construction

**Figure 5.5**: Annual unit area electricity use of campus office buildings based on cooling technology in Beijing. Studied buildings are numbered



(Source: Zhang et al., 2010)

materials and associated environmental impacts. We address these issues and compare outcomes against in situ rehabilitation of existing slums (informal communities) as a baseline for comparison of housing construction options in the national capital territory (NCT) of Delhi.

### 5.5.2. A sociotechnical approach

At the national level, the current estimates for the Government of India's Housing for All by 2022 programme will require over 100 million new units, with Delhi alone requiring more than 2 million new households by 2025 (McKinsey Global Institute, 2014). However, when considering this new housing in addition to ongoing maintenance, repairs, alterations and improvements for existing housing, this creates a demand on construction materials for a total housing demand of over 4 million housing units (Nagpure *et al.,* 2018).

The issue of housing affordability and proximity to work are key drivers for determining the type of housing construction, i.e. SF or multi-storey MF. However, these two drivers are often conflicting—the cost per unit area of land increases towards the urban centre, but the daily cost of commuting to work declines. On average, over 30 percent of commuters in India use non-motorized (or 'free') transport (Government of India, 2011). Therefore, rehabilitation in the urban core in multi-storey MF buildings is needed to reduce the cost of urban living for the urban poor. Since India has well-established building codes to ensure safety in multi-storey constructions, such rehabilitation in multi-storey MF units is possible and has been demonstrated in several successful case studies in Ahmedabad. This in situ rehabilitation has been found to be more effective than earlier policies that would provide housing for the urban poor on the urban peripheries, which mostly resulted in the residents returning to informal settlements within the city in search of employment. Effective and novel financial instruments are used in Ahmedabad, whereby builders are encouraged to finance in situ slum rehabilitation on the condition that they secure the consent of more than 80 percent of the slum residents in a given area. In return, they are offered an opportunity to build using a higher floor-area index in highly desirable areas of the city. Interviews with builders revealed that it was not the development opportunity that attracted them to this scheme, but rather their desire to work more closely with the municipal government.

Given the relative unavailability of wood in India, housing construction is primarily dependent on concrete, aggregates and steel as the primary bulk materials for construction of multi-storey buildings. The National Building Code of India (NBCI), developed in 1970 with two more editions in 1983 and 2005, prescribes performance-based structural requirements. The NBCI is also intended to ensure relative uniformity of construction, and therefore material requirements. The capacity to enforce these codes is the responsibility of each municipality.

As there have been very few case studies comparing material requirements for housing construction for the urban poor with the material requirements of in situ rehabilitation, primary data on material requirements in three residential housing case studies was obtained: a baseline estimate of materials for existing slum dwellings in Delhi, and new SF and MF constructions representing in situ examples of successful slum rehabilitation in Ahmedabad. The case studies, drawn from Nagpure *et al.* (2018), are scaled up to provide for discussion as to the expected environmental and embodied energy impact of housing if all urban poor housing in the NCT of Delhi were to be upgraded.

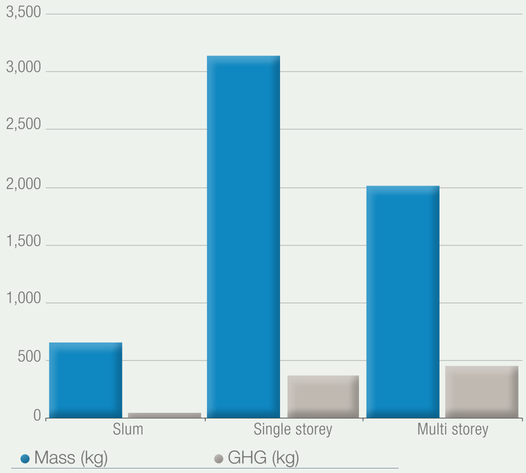
## 5.5.3. Quantifying resource impact

### Baseline slum single-family housing, India

To establish the baseline of bulk materials required per housing unit, we conducted a case study of existing slum housing in Kathpulti Colony in Delhi. There were no basic services in Kathpulti and only a shared toilet located a five-minute walk away from the colony. The shelters were constructed from available materials that could be acquired, for example, tarps, thatch, brick and mud. Material data were collected by a research team from the University of Minnesota in 2015 from nine individual house surveys to produce an 'average' house. Normalizing on a square metre basis, the average Kathpulti house requires 656 kg of material mass and produces 45 kg of $CO_2e$. The low embodied GHG emissions are primarily attributable to the use of unprocessed clay, wood and thatch. The liveable floor area for the average house was only 16 $m^2$ in the slum areas, about half of the 32 $m^2$ government requirement for rehabilitated homes (Delhi Development Authority, 2010); family size is about 4.8 people per home.

Credit: Tatiana Dyuvbanova/shutterstock.com

**Figure 5.6**: Housing material by mass and by embodied GHG emissions for MF homes. Single-storey and multi-storey designs are derived from real-world, structurally code-compliant buildings in India



(Source: Nagpure et al., 2018)

### Single-family housing rehabilitation

The Centre for Emerging Markets Solutions (CEMS) and the Indian School of Business (ISB) participated as knowledge partners in a pilot affordable housing project in an industrial area called Ashray, approximately 15 km from Rajkot, in the western state of Gujarat, India. Launched in August 2010 and completed in January 2012, the affordable housing project comprises 218 units and offers two different floor plans: one with two rooms, a kitchen and a bathroom covering an area of 40 m$^2$; and the other with one room, a kitchen and a bathroom covering an area of 25 m$^2$ (CEMS/ISB, 2012). The unique selling point of this project was that the floor space index (FSI) ceiling was at 1.25, giving the option of adding a second floor at a later date. As such, all homes at Ashray are built similar to high-rise MF housing with concrete floors, walls and roofs, with appropriate steel reinforcements (RAND ISB, 2014). Both types used similar construction materials and techniques effectively yielding the final 40 m$^2$ house. When normalized per m$^2$ of final construction, the house required 3,140 kg of material mass and 359 kg of CO$_2$e (embodied).

### Multi-family, multi-storey, high-rise housing

The typical construction material for MF, multi-storey, high-rise buildings is reinforced concrete (whether block and mortar, precast or formed on site). The more upscale middle-income and high-income groups (MIG and HIG, respectively) will also include additional materials for aesthetic reasons, such as aluminium, glass panels, ceramic fixtures and finishes that add more to the cost and the associated embodied GHG emissions than would be included in economically weaker section and low-income group (LIG) buildings, however, the main construction materials will be similar. Two such MIG high-rise MF buildings were constructed in Ahmedabad, in the state of Gujarat, India: the Swareet and Swara apartment buildings. The typical MIG housing units are 32 m$^2$ and, when normalized to per m$^2$ of final construction, the Swara housing unit requires 2,420 kg of material mass and produces 450 kg of CO$_2$e, while the Swareet housing unit requires 1,607 kg of material mass and produces 458 kg of CO$_2$e. The higher CO$_2$e, despite less-intensive material consumption by mass, was primarily attributable to the higher use of aluminium. On average the total construction material use in the multi-storey construction was 2000 kg per m$^2$.

Resource impact of different rehabilitation options: The materials increase from slum to SF construction (470 percent increase) and the reductions when transitioning from SF to multi-storey construction (36 percent decrease) are shown in the figure below (on a per m$^2$ basis). The case studies are built on bottom-up construction-level data from India, and the material use for SF homes is fairly similar to other countries on a per m$^2$ basis. The less populated developing countries with bioresources are considering CLT, which may be a sustainable option, but at the same time, new studies are showing that significant CO$_2$ (around 43 percent) is absorbed by concrete over its lifetime (Xi *et al.,* 2016). Low-cost, alternative construction materials, such as fly ash bricks and reinforced concrete filler slab have been explored in India to replace traditional kiln-fired bricks and reinforced concrete roofing. These technologies show promise in reducing the embodied energy of materials in excess of 20 percent, though they need cultural acceptance for widespread adoption by engineers and contractors (World Bank, 2011).

The total material mass and embodied energy of a typical housing unit are included in the figure below.

### 5.5.4. State-wide materials estimate for Delhi

The case study data were then applied to estimate the material requirement for upgrading all the urban poor housing in Delhi. Furthermore, an advanced equity scenario was generated, in which electricity access enabled the bottom 50 percent of Delhi's population to consume the current median per capita electricity consumption of 40 kWh per month.

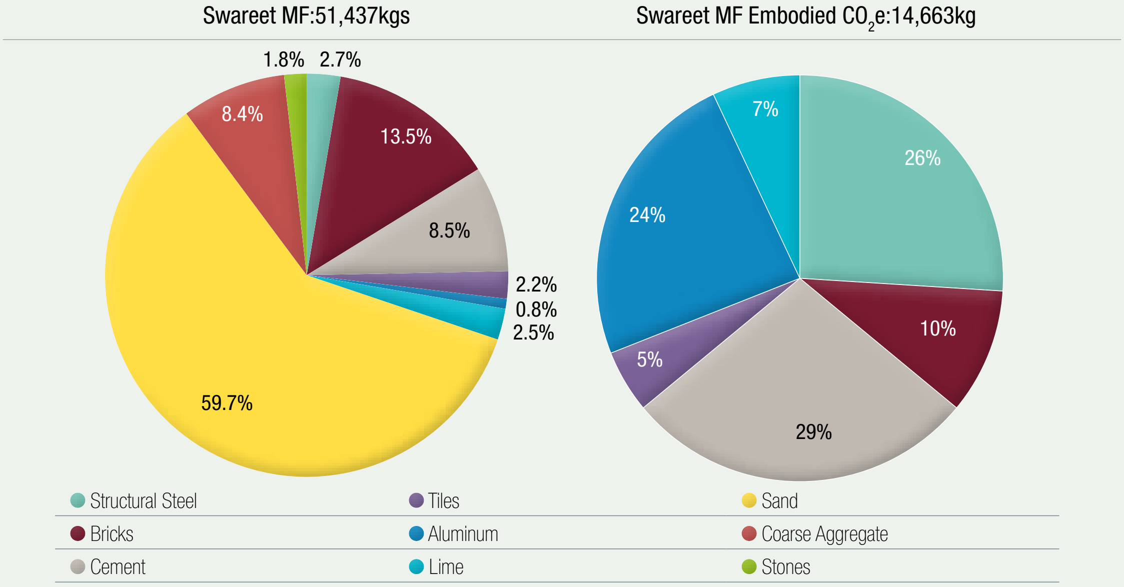
The total bulk material requirements for rehabilitating all of Delhi's underserved population (living in temporary and semi-permanent housing in 2011) is estimated from Figure 5.6 and 5.7 and assumed to occur over a construction period of ten years (2012 to 2022). This will provide 134,000 rehabilitated housing units (35 m$^2$ in size) for a population of 0.65 million people (4 percent of Delhi's homes) by 2021. The added material requirements for such rehabilitation averaged over Delhi's total population yields an added annual per capita requirement of steel, cement and lime of 1.8 kg, 5.8 kg and 1.7 kg , respectively if construction proceeds over ten years (Nagpure, et al., 2018; Census of India, 2011). For comparison, the total annual community wide (residential, commercial, and industrial) per capita consumption of cement in Delhi is 240 kg (Cement Manufacturers Association, 2010). Thus rehabilitation for 4 percent of Delhi's population that is presently living in poor housing conditions —achieved over ten years would increase community wide cement use by only 2.4 percent, indicating more inclusive development can be achieved with relatively little added material requirements in this case study city.

The impact of addressing energy poverty is even lower: if the lower 50 percentile of the population had electricity access equivalent at least to the median per capita electricity consumption of 40 kWh per month, the overall increase in electricity use would only be an additional 13 percent compared with BAU—this is well within the bounds of practical possibility. Figure 5.8 shows the negligible impact on total consumption if energy poverty was ended for the bottom 50 percent of the population.

### 5.5.5. Material substitutions and scarcity impacts

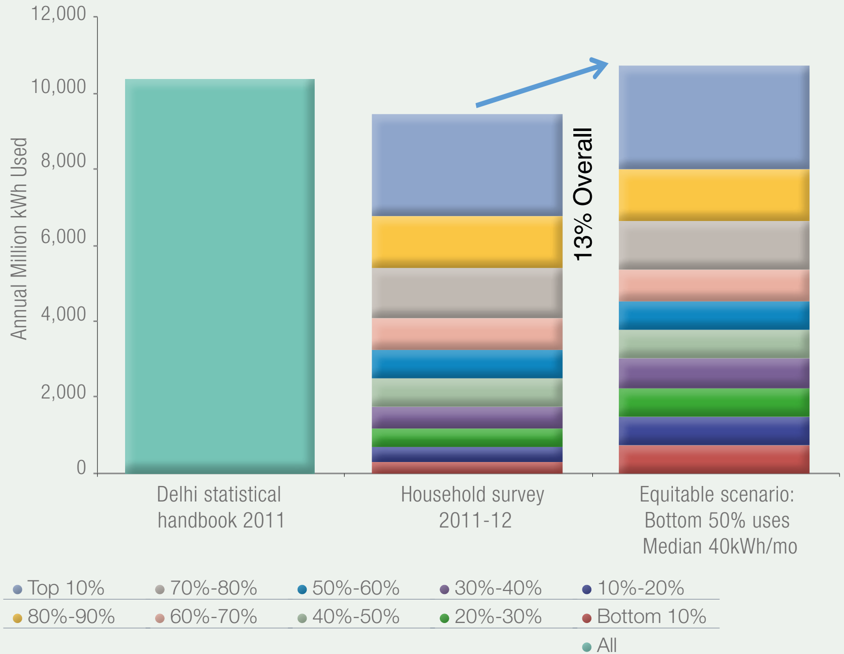
The widespread use of manufactured sand (also known as m-sand) in India has provided an alternative to natural sand at equal or lesser costs per tonne—m-sand costs around $6.72–$9 per

**Figure 5.7**: Mass of materials (left) and embodied GHG emissions (right) for a multi-storey, multi-family home (40m$^2$), Swareet



(Source: Nagpure et al., 2018)

**Figure 5.8**: Annual electricity consumption in Delhi, India, according to the Delhi Statistical Handbook, household survey and advanced equity scenario, where the bottom 50 percent of Delhi's population consumes the current median per capita electricity consumption of 40 kWh per month



(Source: Nagpureet al., 2018)

tonne, while natural sand costs $11.20–$17.90 per tonne.[77] Structurally, according to Jadhav and Kulkarni (2013), concrete mixes consisting of a 50 percent replacement of natural sand by manufactured sand showed a higher compressive strength when compared with the base mix of 0 percent replacement—primarily attributable to the angular nature of m-sand. Additionally, m-sand is compliant with United States ASTM C33 and European standard EN13139.

Embodied energy and GHG emissions are not the only significant environmental impacts. While natural sand—a geological term based on grain sizes between 0.06 and 2.0 mm in diameter—can be directly excavated and sorted without additional crushing, manufactured sand is produced by excavating larger rocks (typically granite) and putting them through primary and secondary crushers (jaw crusher and cone crusher) before the final stage of running through a vertical shaft impact crusher to reduce the particle size to that of sand. While this process certainly adds to the energy consumption and GHG emissions of m-sand (81 kJ per kg versus 17 kJ per kg), a case could be made for an overall reduced environmental impact. Where source rocks for m-sand can be obtained from non-environmentally sensitive areas and areas closer to the project, natural sand is typically extracted from riparian corridors and riverbeds. The depletion of natural sand sources has led to the implementation of new environmental/land-use legislation, which has made the procurement of natural sand difficult and expensive in India. In nations with such high demand for concrete, m-sand is fast becoming a necessity. Scarcity of sand has caused organized crime groups to seize armed control of many natural sand supply areas, causing serious conflict (Ward, 2015).

There are, of course, alternatives to Portland cement, including 'blended cement', which is a mixture of Portland cement and blast furnace slag or pozzolan (fly ash). While this alternative is regarded as an improvement from an environmental and economic performance perspective, it is primarily the engineer and contractor that resist using this alternative. Despite the fact that standards exist for blended cement (ASTM C595) and performance-based cement (ASTM C1157), such substitutions are not as widespread as they are beginning to be in China,

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[77] Exchange rate of 66.92 Indian Rupees to US dollars used.

where green economy policy helps stimulate the use of alternatives to Portland cement.

## 5.6. Conclusion

To recap, the key results of the three case studies were as follows:

**Minneapolis: an established US city with stable population growth**

- Up to a 33 percent reduction in GHG emissions associated with infrastructure provision can be achieved, although over a long period of time (2010–2050), through multiple infrastructure interventions and by using existing policy commitments across different levels of government.
- A strong commitment to renewable energy in the grid is a critical factor, enabled by unique multi-sector partnerships.
- New timber technologies have the potential to save 62 percent of mineral construction materials and also have the potential for carbon sequestration under the right conditions.
- District energy, in conjunction with use of the sewer system as a heat/cold sink, offers innovation and achieves about a 40 percent reduction in energy use for the heating and cooling of buildings.

**Beijing and Kaifeng: Urban industrial efficiency and symbiosis in fast-growing Chinese cities**

- An 11 per cent and 40 percent reduction in city GHG emissions can be achieved, in Beijing and Kaifeng respectively, over a short period of time (about four years) by implementing existing building and industrial efficiency targets established in FYPs, plus the consideration of urban industrial symbiosis as a novel cross-sectoral intervention.
- Reutilization of waste heat from industries and material exchange strategies have a particularly large impact in highly industrial cities, e.g. Kaifeng, compared with more commercial cities, driven by the balance between industries and co-located commercial and residential homes.
- Design strategies that enable exchange of materials and energy in co-located networks in cities can be a viable resource-efficiency strategy, particularly in conjunction with fourth-generation (hot water-based) district energy systems.

**Resource implications of infrastructure rehabilitation in inequitable cities**

- Rehabilitation from slums to multi-storey construction within the city core offers benefits in the form of reduced material use (36 percent less than single-storey construction), reduced motorized travel demand and improved access to employment.
- Innovative financing through incentives offered to developers has seen success in Ahmedabad, where in situ slum rehabilitation has been done effectively with the consent of 80 percent of the residents.
- Providing more equitable access to better shelter and electricity has little overall resource impact. For example, if the lower 50 percentile of Delhi’s households had access and consumed the median 40 kWh per month of electricity, the resulting increase would only be 13 percent.
- These examples indicate that improvements in human well-being are possible with reduced resource requirements.

The three case studies confirm that significant resource savings of between 30 percent and 60 percent are possible if infrastructure operations can be configured to ensure resource sharing, and if new technologies that are less resource intensive than BAU technologies are adopted. By using bottom-up data sources across the three case studies, the results of this analysis triangulate the top-down data used in the preceding chapters on densification and LCA of infrastructure alternatives. This chapter also brings to the fore the efficiencies that can be achieved through integrated infrastructure planning, which enables waste and by-products of urban systems to be reused within the city, reducing resource demand and GHG emissions.

Credit: monicaodo/shutterstok.com

# Chapter 6

# Governance and planning for urban transitions

## 6.1. Introduction

Chapters 2 to 5 have established that there are more inclusive and resource-efficient approaches to urban metabolic configurations than the existing, resource-intensive ones. These alternatives allow for a break with the pattern of long-term urban de-densification. Chapter 2 showed that if we fail to re-invent urbanism to achieve more resource-efficient urban metabolic configurations, urban DMC could more than double from 40 bt/y to 89 bt/y, and urban land cover could increase by 150 percent: from under 1 million km$^2$ to 2.5 million km$^2$ by 2050, with much of this expansion encroaching onto some of the world's most productive food-producing land (Hajer *et al.,* 2015b). Chapter 3 demonstrated that if polycentric space economies were strategically intensified by forming a hierarchy of high-density urban nodes interconnected by efficient and affordable mass transit in each city, this could increase urban resource productivity by a factor of 10. Chapter 4 confirmed the analysis in Chapter 3 by showing that if resource-efficient BRT, district energy systems and green buildings became the norm in strategically intensified urban metabolic configurations, resource efficiencies of 44–66 percent compared to the baseline could be achieved within these respective sectors.

This is not to argue that sector-level resource efficiencies will automatically translate into city-wide efficiencies, because there are wider determinants of city-wide resource use (e.g. rising incomes). Using case studies drawn from India, China and the USA, Chapter 5 confirmed the overall analysis in Chapters 3 and 4 by showing how resource sharing across a range of interconnected infrastructure sectors can result in significant resource efficiencies with—in some cases—inclusionary implications. It is clear, therefore, that all cities need to promote context-specific transitions to inclusive resource-efficient urban metabolic configurations.

Cities and urban settlements are, and will remain, relevant and strategically important spatial loci of political, policy and social action. Crucial urban qualities such as proximity, density and diversity will also remain important in future economic constellations. Cities have never been static: their cultural characteristics, layouts, dynamics, built forms and routines of everyday life are constantly developing and continuously in transition. Cities can be seen as both the product and the object of endless discussion and contestations about who belongs, who benefits, who loses and how urban life should be lived and reproduced.[78] These contestations have given rise to ongoing layers of social, spatial and technical innovations that have resulted in the urban metabolic configurations embedded in the way our cities and urban settlements are currently structured, inhabited and governed. This metabolic dimension of urban development now needs to take centre stage as humanity faces the combined challenge of a majority urban world and life in the Anthropocene. The focus must urgently shift to the burst of innovations that is emerging across all world regions. Viable strategic options must be extracted from the multiplicity of increasingly complex context-specific contestations between policymakers, investors, households, designers, communities, movements, social enterprises, cultural workers, knowledge networks and property developers to address what many regard as the challenge of the era.

The argument will proceed as follows:

- **To face the challenge of the urban transition, there must be a balance between informational development, human development and sustainable development:** Recognizing that the information age and ICT development provide the keys to building urban futures consistent with the SDGs, the concept of development must go beyond economic growth in order

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[78] This 'everyday urbanism' approach is, of course, very different to the 'planetary urbanization' approach to urban studies. The latter questions whether the notion of 'the city' (and its implication that a 'non-city' reality exists) remains an appropriate reference point for understanding a world where everything is dominated by the global capitalist urban system and therefore everything is fully urbanized, including the most remote wildernesses.

to adequately frame the challenge of urban transition within more resource-efficient and inclusive urban metabolic configurations.

- **To this end, urban experimentation will require goal-oriented, mission-driven entrepreneurial governance:** Based on a historical overview of the changing nature of urbanism and associated modes of urban governance since the end of the 19th Century, it will be proposed that urban experimentation as a mode of entrepreneurial governance is already emerging in cities and urban settlements around the world. A new strategy for urban transition must focus on improving connections between the diverse experiments taking place so that entrepreneurial governance becomes a systemic way to deliver sustainable and just urban development.

- **For cities and urban settlements to be economically inclusive and resource efficient, the 'competitive cities' approach to urban economies will need to be replaced by the 'well-grounded cities' approach:** It is necessary to recognize that cities and urban settlements are embedded within a hinterland of intersecting regional, national and global economic dynamics and financial flows that they can do very little about. The focus, therefore, must be on the dynamics of the real foundational economy where the majority of people live, work and play, rather than on the financial circuits facilitated by property developments aimed at attracting high-end investments that tend to benefit the richer sections of society.

- **Integrated urban planning holds the key to the strategic intensification of urban space economies:** This chapter will show how planning can help foster well-articulated hierarchies of high-density urban nodes interconnected with efficient and affordable transit, without which well-grounded cities would be impossible to achieve.

- **The diversity of urban regulatory regimes must be recognized, ranging from the structurally formal to the highly informal:** As patterns of urbanization and urban development differ vastly across different world regions, regulatory hegemony must be counter-posed to regulatory hybridity. Although neither exists in its pure form, the former refers to modes of urban governance in cities and urban settlements where very little happens outside the prevailing regulatory regime, whereas the latter characterizes cities and urban settlements where anywhere between 20 percent and 90 percent of urban activity occurs outside the routines of formal regulatory regimes. This results in the hybridized co-existence of formal and informal modes of urban regulation that, in turn, has serious implications for future urban planning.

- Many state-led, market-led, technology-led and citizen-led urban experiments are already under way around the world. These suggest that the notion of urban experimentation is, indeed, emerging as a new mode of urban governance, with trends drawn from case studies to illustrate this argument.

In line with accepted assessment logics and social science procedures, core arguments are drawn from established authorities within particular literature sets, and then connected to help frame the challenge of urban transition. This discussion takes the empirical realities discussed in Chapters 2–5 as the point of departure, and case studies have been included to illustrate the argument.

## 6.2. Informational, human and sustainable development in the Urban Anthropocene

Before proceeding with a discussion of urban governance, it is necessary to briefly summarize a conception of development in general that is consistent with the SDGs and recognizes the significance of the 'information age'. This provides the framework for understanding urban development and urban governance.

In a recent volume, Manuel Castells and Pekka Himanen synthesize the great intellectual traditions of the past century (especially the advances made by the United Nations Development Programme's (UNDP) annual Human Development Reports that derive from the thinking of Nobel laureate Amartya Sen) to provide an appropriate definition of development for a world that has committed itself to the SDGs and is taking the first steps to go beyond GDP as the only measure of development (see Fioramonti, 2015):

> *Development...is the self-defined social process by which humans enhance their well-being and assert their dignity while creating the structural conditions for the sustainability of the process of development itself (Castells & Himanen, 2014:7).*

Development conceived in this way, however, is not simply the rational outcome of good public policies implemented by formal rule-based bureaucracies. The world has become more complex than that. Nowadays, various 'agents of change' hold the capacity and willingness to steer events in a different direction, and can include a far wider range of actors, including those from the business community, the world of non-governmental organizations (NGOs) and indeed the world of academia (Hajer *et al.,* 2015a). Within each country there is instead a specific set of social forces that contest the meaning, directionality and implementation of development priorities and actions, and particular 'coalitions' of actors that try and influence the course of events.

Economic development (to increase material wealth), human development (to improve human well-being), institutional development (to facilitate the governance of social organization to achieve various purposes) and sustainable resource use (to ensure the efficient use and restoration of natural resources) all occur within particular spatial formations with distinct characteristics (e.g. low-density sprawl versus high-density compaction, formalized versus informal settlements, high-rise versus low-rise buildings, transit-connected nodes versus car-based systems). Economic development is, in turn, determined by the way production and consumption is organized, and by technologies that improve productivity. In capitalist societies, production and consumption is organized on the terms of those who own/control capital. Although this may be changing (Mason, 2015), on the whole the global economy remains a capitalist economy.

Technologies, however, have changed fundamentally: since the ICT revolution, there has been a technological shift from industrialism towards informationalism as the primary driver of productivity (Castells & Himanen, 2014), and the rapid deployment of ICT has played an important role in transforming the lives of those in cities (UN-Habitat, 2016). This technological shift also led to the rise of the networking form of social and economic organization that displaced the more hierarchically organized public and private bureaucracies that emerged during late 19th Century industrialism, peaking by the 1970s. Castells has referred to this transition as the 'rise of the global network society' (Castells, 1997).

Human development covers welfare, education, mobility, security and health, and affordable access to these services, especially in urban settlements, where access can range from 100 percent to 10 percent of the population, depending on the region.

Sustainable development, in turn, is primarily about decoupling economic growth and human well-being from rising levels of resource use and environmental degradation over time (Fischer-Kowalski *et al.,* 2011). Although all four components (economic productivity, technology, human development and sustainable resource use) need to be in balance, governance arrangements have tended to reinforce the prioritization of material wealth via economic development at the expense of human and sustainable development. This has resulted in a world that needs—in the words of the preamble to the SDGs—to be "transformed". Indeed, instead of harnessing the enormous wealth generated by increases in productivity caused by informationalism and networking since the 1970s for re-investment in human and sustainable development, interconnected governance arrangements at all levels (global, national, local) have, in most countries, tended to facilitate the massive flows of this surplus wealth into financial instruments and property speculation to drive short-term growth (Krugman, 2012; Mason, 2015).

From the late 1970s onward, cities were restructured to enable financial flows into elite enclaves, urban regeneration for gentrification, urban sprawl and infrastructure development, all of which were resource intensive (Graham and Marvin, 2001). What is more, the Habitat II Summit that took place in Istanbul in 1996 took a normative leap by defining cities as coherent entities that must now *compete* with each other for investments (Simone and Pieterse, 2017). More equitable new wealth creation via innovation and skills development in the manufacturing and agricultural sectors became less important than returns to elites from financialization and urban property development (Harvey, 2012; Stiglitz, 2013). The commodity boom, while it lasted, underpinned financialization and reinforced elite accumulation in resource-exporting countries, due to the way extractive industries tend to be financed and owned (Mohamed, 2016). The end result was unprecedented wealth accumulation: by 2010, 0.6 percent of the world's adult population possessed 39.3 percent of global wealth, compared to the 69.3 percent of the adult population who possessed only 3.3 percent (Calderon, 2014). This shocking level of inequality resulted in divided cities (Graham and Marvin, 2001).

Nowadays, investment in human development is seen as the single best way to address the gross inequities facilitated by the unequally distributed wealth generated from informationalism and networking (Castells & Himanen, 2014). As more equitable development is dependent upon such investment, action needs to be substantially reoriented. Contrary to mainstream economic approaches, this is no longer expected to happen via 'trickle-down' mechanisms. Instead, the focus is on investing directly in people to make them more entrepreneurial and to allow them to take control over their own lives (e.g. via support for small businesses, land-use decisions that favour diversity, creation of innovation districts, non-exploitative microcredit systems and subsidized integration of poor communities into the core circuits of the city) (Castells & Himanen, 2014; Mazzucato, 2011).

The new focus on smart cities will not be sufficient: its algorithmic governance approach is focused too narrowly on productivity, competitiveness and technology (Luque *et al.,* 2013) and concentrates more on selling systems to existing urban governments than on creating enabling structures for more diverse, equitable and integrated urban environments. Where state interventions have aimed to promote "synergistic effects leading to both higher productivity growth and greater human well-being" (Castells & Himanen, 2014), the results have been more inclusive and redistributive at country and city levels (e.g. Costa Rica at the national level, and Curitiba and Seoul at the city level). This is particularly evident in the most innovative urban experiments that have mushroomed around the world (especially where the focus has been on city-wide infrastructure reconfigurations associated, in particular, with mass transit or renewable energy). Interventions in urban spaces need to explicitly aim to achieve these 'synergistic effects'. This could involve, for instance, urban planning interventions that combine working and living in mixed-use districts, thus avoiding unnecessary mobility and enhancing urban security; or institutions for higher education supporting urban experiments in resource-efficient urban metabolisms; or creating the preconditions under which people or neighbourhoods can themselves become agents of change, as this report will discuss later on.

A liveable, well-grounded urbanism is one in which informational and human development are in balance. However, in a world of rising carbon and resource costs, unless this balance is achieved on the basis of resource-efficient urban metabolisms, the gains made could be undermined by the negative impacts of climate change, resource depletion and ecosystem breakdown. A liveable, well-grounded, *sustainable* urbanism must, therefore, also be resource efficient. All this has major implications for how we understand urban governance. The case of New Hope Ecotech shows how ICT can help connect the formal and informal sectors to reduce urban waste streams while creating livelihood opportunities for the poor.

### Harnessing information technology to promote informal recycling in Brazil

New Hope Ecotech is a technology company in Brazil that provides a digital platform to connect manufacturers with waste pickers via an innovative environmental currency, similar to a carbon credit (Waste Not, 2016; The Guardian, 2016). Founded in December 2014 by Luciana Oliveira and SBAC Lawyers, New Hope Ecotech uses waste recyclables rather than the traditional carbon credit as an environmental currency. By issuing 'recycling certificates' to private enterprise, the group helps them to meet their corporate social responsibility commitments or regulatory based obligations, while aggregating recyclables as an output that directly creates work opportunities for informal waste workers.

New Hope Ecotech recognized that while legislative and policy measures in Brazil were pressing private enterprises to invest in environmental initiatives, there were few opportunities to engage the informal sector (e.g. waste pickers) or participate in small-scale waste recycling services. By connecting the informal sector with private enterprises and creating a socio-environmental currency (e.g. recycling certificates), New Hope Ecotech has been able to provide private enterprises with a legislative/CSR solution, while enhancing the existing operations of informal waste workers.

In 2015, New Hope Ecotech tracked over 3,600 tonnes of recycled material among 1,120 waste workers across 53 waste management and recycling facilities. The company issued approximately $ 500,000 in recycling certificates to private enterprises. Current clients of the group include AB Inbev, NeoEnergia and Giral Viveiro de Projetos (Waste Not, 2016).

## 6.3. Metabolic perspective on changing urbanisms

It is necessary to recognize that the configuration of urban form and infrastructure, functions and metabolisms have changed several times and quite radically over the past 150 years. Appreciating this historical track record makes it easier to understand what may be emerging during the post-financial crisis era (that started in 2007), as cities come to terms with the challenges of social inclusion and ecological sustainability.

Swilling and Annecke (2012) refer to five urban metabolic configurations that reflect different interactions between economic productivity, well-being and resource use as inclusive urbanism, splintered urbanism, slum urbanism, green urbanism and liveable urbanism. Each corresponds to a specific configuration of infrastructures, flows, economic dynamics and ways of life, as follows:

- Inclusive urbanism reached maturity during the 1930s–1970s era of Keynesian welfarism and was characterized by the vision of universal access to publicly delivered, cross-subsidized urban services for all, and based on the assumption that resources are unlimited.
- Splintered urbanism was the spatial expression of neo-liberalism from the late 1970s onward and entailed a preference for commoditized privately delivered urban services on a cost-recovery basis, and again ignored resource constraints.
- Slum urbanism emerged from the quiet encroachment of millions of urbanizing households on the rapidly growing cities of the Global South with the onset of the second urbanization wave in the 1950s, accelerating each decade into the current conjuncture.
- Smart urbanism reflects the aspirations of the global technology companies that have built on and extended the strategic vision of the 'green buildings' movement. 'Smart' and 'green'

urbanism have established the principle of 'minimizing environmental damage' through the way that urban developments are designed. The problem, of course, is that the positive goal of sustainable planetary systems cannot be achieved by minimizing damage, which may better be described as retarded collapse.

- Finally, liveable urbanism refers to the aspiration to go beyond 'minimizing damage' to 'restoring nature' by designing urban developments and inserting them into sustainable bioeconomic regions in ways that enhance both productivity and well-being.

These five urban metabolic configurations are effectively all alternative visions of urbanism, some historical, some anticipatory. However, they never exist in their pure form. They are in effect five different ways of assembling the societal actors and related techno-infrastructures described by the SEIS framework (see Chapters 1 and 5).

In order to restructure urban metabolisms, we need a theory of how such a reordering may be brought about. This will now be outlined using the historical examples of the 'sanitation movement' of the 19th Century and the subsequent restructuring of the city according to the 20th Century paradigm of the car-oriented city. Both were highly expensive and dramatic urban transitions. We will argue that the current need to address dysfunctional and unsustainable urban metabolisms comes at a time when massive infrastructural works may be just what the (capitalist) economic system needs in order to control its complex contradictions (especially deflationary and recessionary conditions). We see an opportunity to bring about a more entrepreneurial mode of governance in which governments, businesses and NGOs join hands to produce cities that meet the requirements of the SDGs. This, in turn, can provide the physical basis for a regenerated productive urban economy that is far more inclusive, equitable and sustainable than the splintered urbanism produced by the neo-liberal economic and urban policies pursued since the 1980s.

It should be noted that previous long-waves of economic change always manifested in urban transitions. At each juncture, a major technological innovation or upgrade in urban infrastructure played a key role in shifting the balance between economic productivity and well-being (Hajer and Dassen, 2014; Swilling and Annecke, 2012). By way of example, the introduction of sanitation systems in the late 19th Century across many cities was part of the 'public works' approach of that era as the limits to a privatized solution for the upper classes (living upwind, organized living in exclusive neighbourhoods) became clear. Instead, what followed was a wave of public infrastructure investments to provide water and sewage that clearly improved urban well-being for most. This focus on fighting 'urban blight' (Hall, 1988) and improving the health conditions of the urban working class continued until well into the 1930s.

Indeed, one of the hallmarks of the modern movement in architecture and urban design was to create the houses, factories and urban layouts that would put an end to the 19th Century slums of Northern America and Europe (Kunstler, 1993). Similarly, planners in both Northern America and Europe invented 'garden cities' close to the big cities to provide a better quality of life. However, this idealism paved the way for vast industrially produced urban agglomerations later on. In many cities that developed during the 20th Century (with the exception of some cities in Asia), the careful distributed layout and relations between living and labour made way for a generic 'suburbanization' in which living and work became more distant from one another. This coincided with the massive rise of the automobile, seen as the vehicle for mastering space (Kunstler, 1993). Moreover, it was interlinked with the move to mass production of consumer goods that brought new lifestyles within reach of an increasingly educated industrial working class, and new forms of pollution to cities. The construction of highway systems during the middle decades of the 20th Century effectively 'compressed' space and, together with the diffusion of the private car, allowed workers to live further away from their work (Hall, 1988).

Although these urban development patterns emerged mainly in the Western developed countries, they generated a body of urban theory and a powerful set of popular images that shaped the aspirations of at least two generations of urban planners and policymakers in developing countries in the Global South. Despite very different conditions in these countries compared with the Western developed countries, the aspiration to replicate urban models derived from the first urbanization wave was almost irresistible. Although the desire to break from this generic template only entered academic debate in the last two decades, it is now represented in a substantial body of literature (Allen *et al.,* 2016; Edensor and Jayne, 2012; Parnell and Oldfield, 2014; Pieterse, 2008; Simone & Pieterse, 2017; Simone, 2006; Simone & Abouhani, 2005; Swilling *et al.,* 2003). This report emphasizes the importance of making this break if the search for more resource-efficient urbanisms in the rapidly urbanizing Global South is to be successful.

Statistical evidence massively supports the thesis that modern urban patterns resulted in drastic increases in resource requirements (see Chapter 2). Undoubtedly, the combustion engine and the car-oriented techno-infrastructure related to it was a key catalyst of the resource-intensive 'great acceleration' that occurred after the Second World War. In cities with modern aspirations, this resulted in increasingly sprawled-out urban forms interconnected by cheap car-based intra-urban mobility (Kunstler, 1993). It was this 'great acceleration' that drove the transition from a dependence on biomass to a dependence on non-renewables from the 1950s onward (Krausmann *et al.,* 2009). Justified by an industrial variation of the 19th Century 'garden city' design mode, property developers drove suburbia into the countryside by converting cheap land into desired low-density spaces. The widespread adoption of mortgages helped the middle and upper classes to access the money needed to escape the polluted industrial environments of the old cities. In the process, this led to a demise of the 'urbanism' of sharing public spaces and amenities with people from other backgrounds in many 20th Century cities, a phenomenon lamented by sociologists such as Richard Sennett and Jane Jacobs.

The next phase started from the 1980s onward, as globalization and neo-liberalism resulted in 'splintering urbanisms' across both the Global North and South (Graham and Marvin, 2001). Urban regions were fragmented into premium infrastructure enclaves for the increasingly wealthy Internet-linked elites, including gentrification of inner-city areas previously abandoned by the middle and upper classes. Depending on the location, poorer residents ended up in 1960s high-rise 'projects', degenerating sprawling ghettos, ramshackle suburbs and—especially in the Global South—mushrooming slums on cheap outer-city land or inner-city zones of occupation. Rising inequalities reflected the imbalance between the rise of informational development and the deteriorating well-being of the majority located outside the middle- and upper-income enclaves (Tonkiss, 2013).

Sociotechnical interventions played a key role in all three waves of urban development. Waterborne sanitation was the iconic innovation of the late Victorian era and publicly constructed highways the exemplar of the great acceleration. The commercialization and commodification of public space as well as the rise of privatized enclaves and services (railways, water, electricity, telephony, refuse collection) were the iconic infrastructure innovations of the neo-liberal era, which manifested in splintered urbanisms from the late-1970s onward.

Many researchers are now looking at the post-2007 urban landscape and identifying a wide range of urban experiments that are sustainability-oriented in one way or another (Evans *et al.,* 2016; Castán Broto, 2017). However, sociotechnical interventions alone will not facilitate a transition towards global sustainability, as these interventions are always embedded within specific socio-economic dynamics. Up until the 1980s, the dominant economic paradigm was (relatively) inclusionary welfarist Keynesianism. From the 1930s onward, this paradigm had created the urban context for a mass-production approach with a strong focus on national economic development. Inclusionary urbanism with a relatively healthy balance between productivity and well-being via redistributive tax regimes gave way to the exclusionary neo-liberalism expressed in splintering urbanism. This provided the context for the debt-driven consumerism that became the driver of financialized globalization from the early 1980s onward (Graham and Marvin, 2001).

The decline of human development imperatives in favour of productivity and growth would not have been possible without computerization (Castells, 1997). As China became the world's manufacturer (using cheap, disciplined labour), its financial surpluses were transformed into the credit that drove the consumer boom and massive escalations in urban property values across most economies during the decade leading up to the crash in 2007/2008 (Stiglitz, 2010). The negative side effects of this financialized, short-term oriented form of global capitalism continue to haunt society and the natural environment. As the UNEP 'Green Economy report' put it:

> *Although the causes of these crises vary, at a fundamental level they all share a common feature: the gross misallocation of capital. During the last two decades, much capital was poured into property, fossil fuels and structured financial assets with embedded derivatives, but relatively little in comparison was invested in renewable energy, energy efficiency, public transportation, sustainable agriculture, ecosystem and biodiversity protection, and land and water conservation (UNEP, 2011:8).*

As this report will discuss in more detail, the urban transformations instigated by the economic transition from welfarist/Keynesian/mass production to neo-liberalism/debt-funded consumerism resulted in far-reaching changes in urban governance. These changes occurred during the 1980s and 1990s with respect to city-level state structures, modes of governance and types of political leadership. Significantly, since 2009 a new wave of changes has been under way as a new ecology of actors emerge who share, in one way or another, the notion that urban futures will depend on the reconfiguration of urban infrastructures to ensure that urban systems are in some way more sustainable (in social and ecological terms) than they were before. SDG 11 best expresses this aspiration to rebalance economic productivity, human well-being and sustainable resource use. Once again, state structures, modes of governance and political leadership can be expected to transform in what can now be referred to as the information-based 'SDG era'.

## 6.4. Urban governance and infrastructure

Urban metabolic configurations both shape and are shaped by the changing *modes of urban governance* over time. Since the term 'governance' is so loosely and widely used it has now almost lost its meaning, it is worth using Claus Offe's rather disciplined definition that comes from his highly critical review of the history and meaning of the term. He argues that "*governance* aims to capture the range of phenomena that extends *between* the poles of competitive markets and the hierarchical expressions of state authority (and thirdly, the private sphere of citizens protected by basic rights)...Governance refers to institutionalized, if often 'informal' modes of interaction, in which the participants cooperate in a conscious and goal-oriented manner, while not exclusively pursuing their own interests, but also the common concerns of the members of a political community…" (Offe, 2009:553). In short, it is not a substitute for government, the market or private individuals. A particular mode of urban governance, therefore, is what specific coalitions of city-level forces assemble within a multilevel governance context in pursuit of a particular urban vision, and specifically the way urban infrastructures are designed to achieve well-being and access natural resource flows.

A history of changing modes of urban governance can help in developing new configurations of governance that are fit-for-purpose. Following and adapting DiGaetano and Strom (2003), there are five modes of urban governance, plus a sixth that they do not refer to. None of them exist in their pure form.

- *Clientelist* modes form around powerful political personalities who dispense patronage for the material gain of special interests.
- *Corporatist* modes form around formal ruling coalitions of powerful local political elites who work closely with business and/or community interests to steer urban development in accordance with clearly defined negotiated programmes.
- *Managerial* modes are based on formal bureaucratic systems and rules controlled by powerful officials who make authoritative decisions that set the rules for all other players so that public goals can be achieved.
- *Pluralist* modes emerge in cities where rivalries exist between powerful competing interests, with the government brokering conflicts to manage competing blocs seeking to direct the policy agenda in their own material interests.
- *Popular democratic* modes tend to form around politicians who form alliances with popular grass-roots movements—democratic participation, inclusion and accountability are the key symbolic practices that legitimize a populist governing coalition.

The sixth mode, which DiGaetano and Strom do not refer to, and following Mazzucato (2011), is what we refer to as the 'entrepreneurial mode of urban governance'. In this mode, politicians and officials work closely with innovation-oriented entrepreneurs and knowledge networks to mount niche-level 'urban experiments' at various levels of ambition (Evans *et al.,* 2016), often with 'intermediaries' playing a key role (Davies and Swilling, 2015). Table 6.1 summarizes the differences between the six urban governance modes with respect to governing relations, governing logic, key decision makers, political objectives and correlations with different types of urbanisms.

**Table 6.1**: Modes of governance

| | Clientelist | Corporatist | Managerial | Pluralist | Popular democratic | Entrepreneurial |
|---|---|---|---|---|---|---|
| Governing relations | Particularistic, personalized, exchange | Exclusionary, negotiation | Formal, bureaucratic/ contractual | Brokering or mediating among competing interests | Inclusionary, negotiation | State-led partnerships |
| Governing logic | Reciprocity | Consensus building | Authoritative decision-making | Conflict management | Mobilization of popular support | Urban experimentation |
| Key decision makers | Politicians & clients | Politicians & powerful civic leaders | Politicians & civil servants | Politicians & organized interests | Politicians & community movement leaders | Politicians, entrepreneurs, researchers, innovators |
| Political objectives | Material | Purposive | Material | Purposive | Symbolic | Change |
| Correlations with type of urbanisms | Splintered/ slum | Splintered/ inclusive | Inclusive | Inclusive/ splintered | Inclusive | Smart-green or liveable |

(Source: DiGaetano & Strom, 2003)

It is worth recalling that the history of urban infrastructure governance has been marked by crises. The 1929 crash brought an end to the great *laisser-faire* boom period of the Victorian era, and marked the start of a Keynesian era of welfare economics, starting with the New Deal in the USA (Krugman, 2012). It was expanded on a grand scale during the reconstruction of Europe following the Second World War (the Marshal Plan), further extended into the building of the Japanese industrial miracle, and then (incompletely) implanted (legitimated by modernization ideology) into the post-colonial environments in Asia and Africa during the 1950s and 1960s (Chang, 2007). The mode of urban governance that emerged during this era was primarily managerial, with corporatist orientations in most locales, and in many developing countries the managerial mode also had either clientelist (especially in Africa) or populist orientations (as in Latin America) (DiGaetano and Strom, 2003). Government had a strong role to play in Keynesian economics as a stimulator or provider of investment that would translate into improved economic welfare. At its centre was the desire to boost economic productivity via improvements in human well-being. This imperative was reflected in the way urban forms and infrastructures were configured (e.g. mass housing, extensions of infrastructure services, welfare systems, etc.) (Graham and Marvin, 2001).

The 1973 oil crisis triggered a recession that exposed the fiscal weakness of Keynesian economics. By the end of the 1970s, the neo-liberal alternative had gained ascendancy via the Reagan-Thatcher alliance against welfarism. By massively reducing state subsidies, privatizing whatever could be privatized, lowering inflation and interest rates, massively subsidizing the innovations that drove the information revolution and deregulating the financial sector and global trading regimes, the neo-liberal governments across the developed and developing world prepared the way for accelerated, business-led globalization that was driven primarily by the financialization of the global economy (Gowan, 2009). Accelerated improvements in economic productivity were made possible by this shift from industrialism to informational development (Castells, 1997). De-industrialization of many Western economies followed, coupled to the rise of new developed nations in Asia (eventually including China), and the emergence of ICT-based flexible specialization and just-in-time production and distribution systems.

As cities competed for a share of the emerging post-Fordism economy and now highly mobile deregulated capital flows, new urban coalitions emerged around urban redevelopments aimed at creating premier urban infrastructures of electronically connected enclaves, from free trade zones to efficient aerotropolises, stylish cultural centres, premium resorts, and a network of enterprise zones spread out across the global space economy (Graham and Marvin, 2001). As Keller Easterling narrates, this was made possible by a tremendous global effort in standard-setting that enabled the flourishing of a system of global trade and the creation of hi-tech niche enclaves often structured as Export Processing Zones or tax-free zones (Easterling, 2014). The inclusive urbanism of the 1930s–1970s era literally splintered into increasingly divided urban environments presided over by new modes of decentralized, unaccountable, urban 'special purpose' authorities on the one hand, and corporatist business-led public-private partnerships on the other. They filled gaps in investment and economic activity, while opening up the urban system for massive flows of credit that drove up property prices and securitized the consumption boom (Harvey, 2012). The rise of information and communication technologies made all this possible at incredible speeds.

Policy commitments to devolve state powers and functions to the city level was a general trend across all regions during the post-1970s period of globalization and neo-liberalism. This, however, was not accompanied by a corresponding increase in funding for these new responsibilities when, and if, they were actually devolved (Pieterse, 2015). This explains the rise of corporatist public-private partnerships to secure the investment resources needed for managing urban developments that neglected well-being (DiGaetano and Strom, 2003). This included the unique form that public-private partnerships took in China, where managerial local governance regimes were empowered to mount their own land-development initiatives to attract foreign investors—a process that effectively drove the remarkable rise of China as the world's manufacturer (Lee, 2007). The opposite emerged in the USA: business-led coalitions took control of urban regimes to drive the credit-fuelled property boom. In many African countries where clientelist modes of governance have always dominated, particularly pernicious fusions of clientelist and corporatist modes reinforced slum urbanism.

However, in Latin America a tradition of popular democratic urban governance emerged in many cities when social movements formed alliances with political elites who resisted business strategies with an exclusionary urban agenda. It is therefore no coincidence that many of the most inspiring examples for an inclusive resource-efficient urbanism, such as Bogotá, Medellín or Curitiba (although the latter is much less inclusive than the other two), are Latin American. We may see it as the evolutionary potential for a new 'green' or even 'liveable' urban metabolic configuration (Campbell, 2003).

The emergence of green urbanism in the 1990s reflected a realization that both the welfarist/Keynesian era and the post-1970s era of neo-liberalism/globalization—the two eras that made up the post-Second World War long-term development cycle (Swilling, 2013)—suffered from a failure to recognize that conventional infrastructures facilitated unsustainable urban metabolisms (Beatley, 2000). While for some this has reinforced the case for further deregulation, based on the assumption that markets can respond more efficiently to unsustainable urbanism, new progressive political coalitions provide a more common response. These coalitions initiate creative interventions by state institutions to harness and mix public investments, market responses and civil society involvements.

In response to the 2007 crisis, the search is now on for an interventionist state that promotes innovative responses to both the economic and ecological crises (Scoones *et al.,* 2015). This is expressed most clearly in the emergence of a vast number of global coalitions emphasizing the role of city governments as leading innovative sustainability-oriented change (e.g. C40, ICLEI, UCLG, Metropolis). At the same time, the post-2007 'smart city' agenda promoted by the giant technology companies represents a neo-corporatist bid to capture this dynamic (Hajer, 2014; Luque *et al.,* 2013). This latter option is reflected most dramatically in the cities of Songdo and Masdar, where the new algorithmic modes of urban governance have been most explicitly promoted in order to lure city leaders from around the world into thinking that these corporates could run their cities (Kuecker, 2013). This is a return to corporatist modes of urban governance, rather than the recommended entrepreneurial mode.

The clearest indicator of an entrepreneurial mode of urban governance is when city policymakers (at political or managerial level, or both) form coalitions/partnerships with a range of knowledge institutions, public agencies, social enterprises, civil society formations, creative industries and entrepreneurial businesses (usually locally rooted) to address a particular challenge which, in turn, tends to create the basis for a more durable alliance that goes on to tackle wider issues. So, for example, what might start out as an initiative to create a new youth development centre in a run-down part of town might turn into a much wider urban regeneration initiative. Or an initiative to address the need for toilets in an informal settlement might turn into a large-scale upgrading programme. And so on. If this kind of entrepreneurial urban governance is to become systemic, over time regulatory and institutional capabilities will need to be built to further integrated urban planning (Section 6.7) and to promote 'well-grounded' cities (Section 6.6). Although city administrations can attempt to promote this business model within their existing constraints, it may also be necessary in some countries to introduce national-level reforms that empower city governments to provide this kind of leadership. With this precise goal in mind, UCLG (2016) has developed a detailed programme of reforms, reinforced by the recommendations of the German Advisory Council on Climate Change (2016).

Modes of governance have always corresponded to particular planning paradigms. For instance, managerial modes have tended to correspond to a rational technocratic approach that laid down clear, bureaucratically determined rules of the game. Corporatist modes of governance often resulted in market-oriented planning systems that were less about determining desired futures and more about responding to market signals and the requirements of property developers. Popular democratic modes of governance emphasized participatory planning approaches. An entrepreneurial governance mode that validates urban experimentation would entail a planning approach that combines ‘learning from what is already emerging’ (evolutionary potential of the present) and ‘visioning’ (or ‘futuring’) inspired by engagements between planners, knowledge networks, the creative arts, entrepreneurs and citizens. What characterizes this planning approach is the ability to inspire and mobilize a new consensus (often using visualization techniques) about liveable, people-centred, sustainable environments rather than environments that work for profit-seeking property developers or pre-determined planning precepts inscribed in law and implemented by bureaucrats.

Before proceeding to a discussion of urban experimentation, it is necessary to explain the link between modes of urban governance discussed in this section, and urban metabolism. In essence, governance and planning systems are responsible for the way infrastructures are configured which, in turn, conduct the flows of resources through urban systems. So, for example, during the welfarist/Keynesian period after the Second World War, urban governance in most developed countries tended to be managerial and the urban metabolic configuration was inclusive. During the period of corporatist governance, splintered urbanism tended to be the norm. Slum urbanism prevails in many cities in developing countries, especially in Africa, where urban governance norms tend to be clientelist. It follows, therefore, that if a future of entrepreneurial governance that is aimed at achieving resource efficiency within more socially inclusive cities is to be achieved, it will require a new generation of urban infrastructures to conduct resource flows in a completely differently way to what has been the norm.

Credit: Oliveira Fernandes/shutterstock.com

## 6.5. Urban experimentation

Based on the findings of this report, a new form of governance is required that can deliver on the highly ambitious SDG 11. Following Mazzucato (2011; 2015) and read together with Evans *et al.* (2016), more attention should be paid to the new 'entrepreneurial modes' of urban governance that are formed by—and emerge to drive—a wide range of 'urban experiments'. For Mazzucato, the role of the entrepreneurial state is to invest in cutting-edge research and development to create new markets *and* in the new technologies during the early high-risk stages of the familiar S-curve innovation cycle. Without this, she argues, the requisite fundamental innovations will not happen, because the private sector is averse to knowledge investments that generate returns to society in general, rather than exclusively to the primary investor. As a result, the private sector's short-term perspectives reduce its appetite for risk during the early phases of the innovation cycle. Although this approach has not been applied to the urban sector, it can be read together with the emerging literature on urban experimentation (Evans *et al.,* 2016; Castán Broto and Bulkeley, 2013). Boston's Mayor's Office of New Urban Mechanics is one example of how a city can support innovation by adopting some of the risk of research and development. Meanwhile, the University of Cambridge's Use Less Group shows how the theme of reducing consumption can be used to draw experts from multiple disciplines together to tackle global sustainability challenges, and how academia can impact on the surrounding world through partnerships with government departments, companies, research organizations and other institutions (Use Less Group, 2017).

### Boston's urban innovation lab

Shortly after winning a fifth term in office in 2010, Boston Mayor Thomas Menino created an urban innovation laboratory known as the Mayor's Office of New Urban Mechanics (MONUM) to drive his innovation agenda in the city. Situated close to the mayor's office, MONUM serves as the main champion of innovation in the city government, along with the Department of Innovation and Technology and Department of Public Works (Jacob, 2015:12).

MONUM is focused on improving service delivery, and builds partnerships with city departments, academics, entrepreneurs, non-profit organizations and civil society to design, conduct and evaluate pilot experiments that have the potential to significantly improve the quality of services provided by the city. In Boston, MONUM focuses on (1) education, (2) engagement, (3) the streetscape, and (4) economic development. Similar MONUMs have started in Philadelphia and the Utah Valley (New Urban Mechanics, 2015).

Operating with a small team, MONUM's focus on microprojects allows it to remain flexible and to bring innovations to market quickly. Projects are typically funded using a combination of city operations funds and contributions from private and non-profit partners (Trenkner 2015). It can be described as a 'risk aggregator', as one of its key roles is to create a means to manage the risks associated with local government innovation. This relies on MONUM being able to compare the risk and reward of its various projects. As its model is highly dependent on partners and their pace of progress, it works on up to 50 different projects at a time to deliver a consistent stream of innovative projects to residents (Jacob, 2015:20).

Although MONUM does not explicitly focus on resource and sustainability issues, some of the IT products it develops could be used to improve urban resource efficiency while delivering better services. For example, the Citizen Connect mobile application empowers residents to act as the city's eyes and ears, and allows them to easily report problems (e.g. faulty street lights) to the relevant official along with a photograph. Similar apps have been developed in other parts of the world to report wasteful behaviour, such as San Diego's 'Waste No Water' app for reporting water leaks, and Delhi's 'Swachh Delhi' app for reporting illegal dumping of solid waste.

Based on a recent review of the literature on urban experiments, Sengers *et al.* offer a useful definition of urban experimentation that fits neatly into the Mazzucato-type entrepreneurial governance framework. They propose that an urban experiment can be defined as follows:

> *An inclusive, practice-based and challenge-led initiative designed to promote system innovation through social learning under conditions of deep uncertainty and ambiguity. (Sengers et al., 2016)*

Under the aegis of entrepreneurial modes of urban governance that are appropriate for the early high-risk phases in the innovation cycle, the city as the laboratory of the future has become the hallmark of the global green transformation in the information age. It can, however, go either way: towards the tightly coupled algorithmic urbanism of the corporate-led smart city agenda to boost economic productivity and competitiveness that might simply result in the greening of splintered urbanism; or towards a more inclusive, well-grounded heterogeneous, creative, open-source, loosely coupled city-wide agenda of urban experiments aimed at finding ways to rebalance informational development, human well-being and sustainable resource use. However, more is required than simply registering the options.

## Fostering green innovation in Malmö

Malmö has long aspired to be a leading sustainable city, and has ambitious targets to be climate neutral by 2020 and run entirely on renewable energy by 2030. In 2010, the city's Trade and Industry Agency established the Malmö Cleantech City project to increase Malmö's appeal as a location for cleantech companies, making it an attractive place to start, operate and develop businesses in the sector. This is designed to strengthen the city's environmental profile and build its economy by attracting new business activity.

In Sweden, the cleantech sector includes waste management and recycling, bioenergy and biofuels, noise, energy efficiency, energy storage and hybrid systems, heating, sustainable buildings, refrigeration, air purification, maritime engineering, soil remediation, materials, environmental consulting, solar energy, system control engineering, transportation, water and wastewater purification, hydropower, wind power, wave power and heat pumps (Malmö Cleantech City, 2014).

Malmö Cleantech City has adopted a three-pronged approach, providing (1) business opportunities, (2) access to technology, and (3) a meeting space for collaboration and inspiration. The project is based on a triple helix model, which adds value through collaborations between the municipality, the private sector and academia. Exchange and cooperation projects are designed to enhance the development of cleantech in the Malmö region by building networks and connecting entrepreneurs with business opportunities. Malmö Cleantech City also acts as a link between existing nodes of cleantech innovation within the city, and uses these locations to pilot innovative environmentally friendly approaches through its 'Testbed' project.

Products being tested as part of the Testbed project include, among others, Orbital Systems' water-recycling showers, Alnarp Cleanwater Technology's natural water-treatment systems and Green Plank's construction materials made of plastic and natural fibres (Malmö Cleantech City, 2016).

Whereas the Paris Agreement on Climate and the SDGs operate at the global level, and national governments have country-level obligations to translate the global deals into practice, the real push for change comes from lower levels: C40, ICLEI, UCLG, Metropolis, Cities Alliance, etc. Mayors play a major role as a new set of actors on the global stage, but rooted within very local theatres of policy action (UCLG, 2016). This explains the outbreak and replication of a whole range of urban experiments that might be understood as part of a globally networked movement that shares a particular set of values.

To reiterate what many researchers and observers have argued in particularly strident ways since 2001, the dearth of policy leadership at the global and national levels has created a vacuum that helps explain the rise of local actions and initiatives. This is the primary explanation for the rise of the new social movements (from the Arab Spring, to Occupy, to the Indignadas and the African Uprising) (Castells, 2012). This also applies to the rise of globally networked urbanism and urban experimentation. While the 'rolling back' of the state has been criticized by those calling for a more interventionist 'entrepreneurial state' that is more appropriate to current conditions, little progress has been made to implement this. The resultant vacuum makes it possible to see globally networked urbanism and urban experiments as diverse ways of exploring possibilities for creating a viable 'next economy' based on the new normative commitments to SDGs.

The logical conclusion of this perspective is that the priority now needs to be on investing in the learning capacity of the network. So, for example, how can cities with insufficient service access learn from the mass-based off-grid alternatives that have started to emerge? Or from how Copenhagen's low-tech district heating system (introduced in the 1970s) now gives the city a tremendous advantage? Or from how the different examples of removing highways (e.g. Seoul) or pedestrianization of major roads (e.g. Manhattan's Broadway, entire inner cities in Europe) have worked out and their effects on greenhouse gas emissions and air pollution levels? And from how the pedestrianization and bike-friendly strategies compare and how we can speed them up or rather 'spiral up' learning?

Given these shifts away from the traditional hierarchical modernist modes of governance, this discussion has been about how a new set of change agents have, in certain cases, been able to cut through clientelism (e.g. the M-Pesa mobile-money system in Kenya) and provide better (and sometimes more sustainable) services, especially in informal areas. This is not, however, to suggest a replay of the neo-liberal free market, because there is now an ever-clearer understanding that the state will have to play a major role both in supporting research and development and in investing during the early phases of the innovation cycle, when risks are too high for the private sector (Mazzucato, 2011).

## 6.6. From competitive to well-grounded cities

Notwithstanding the strong argument made thus far that a global green transformation will depend to a large extent on the governance of sustainability-oriented urban experiments as catalysts of urban transitions, it is also necessary to recognize that urban actors do not control all the factors that determine what happens within 'city walls'. Cities and urban settlements are embedded within regional, national and global economic dynamics, resource flows and financial systems. For radical geographers associated with the 'planetary urbanization' school of thought (Brenner, 2014), this reality means it is useless to focus on what cities can do, because ultimately what matters is the structure of global capitalism and how this determines what happens within cities and urban settlements. By contrast, the new urban economists see globalization as a positive force because it makes cities compete to attract gifted people, who drive innovations, and risk-taking investors, who together stimulate growth (Glaeser, 2011). This 'competitive cities' paradigm is by far the most influential at the policy level, despite the fact that it values material wealth and economic productivity over well-being and sustainability. The 'planetary urbanization' approach is equally unhelpful as it is preoccupied with a critique of global capitalism that stands in the way of formulating policy options for what can be done now in the real world of everyday urbanism and policy formation.

Neither of these two commonly used approaches to urban economic development are helpful for understanding the transformative potential of entrepreneurial governance of urban experimentation and globally networked urbanism. What is needed is a balanced approach that accepts that although there are significant non-local 'governors' of urban dynamics that urban actors do not control, urban actors do have policy influence (both individually and collectively). They can therefore take action to 'stabilize' and 'accelerate' positive local dynamics that interact with non-local governors to catalyse what Engelen *et al.* (2016) call 'well-grounded' urban processes.

The well-grounded city approach envisages local economic development policies aimed at "a more robust city by providing foundational goods and services for the mass of the population and taxing the unearned increment in land value. The shift is away from a focus on city-versus-city competition to capture mobile resources and towards a different focus on mass welfare through using immobile and internal city resources" (Engelen *et al.,* 2016:22). Under this approach, 'stabilizers' include broad-based human development investments by a wide range of large and small public and private investors in the 'foundational economy' of basic goods and services, and in the sustainable development of the 'biophilic economy' (Beatley, 2011) (sometimes called the 'green economy'). The latter would entail a focus on local sourcing (where possible) of materials and energy from sustainably managed sources (with special reference to NBS, ecosystem restoration, locally procured and possibly organically produced food supplies, renewable energy, recycling and sustainable water use).

According to Engelen *et al.* (2016), foundational economy jobs are the ordinary everyday activities that support public/social life such as teachers who educate, carers of the very young and older people, health workers, social welfare workers, community development workers, artists and public servants. Also included are those who make/acquire the goods that are sold so that people can live, eat, communicate and stay healthy in the city. Biophilic jobs or 'green jobs' are those that arise from recycling, ecosystem restoration and decarbonization. As repairing becomes an economic necessity in the future, so more and more biophilic jobs will be created. Together, foundational and biophilic jobs make up over half of all jobs in the city, and as such they need to be prioritized by city planners and policymakers over the 'gold collar' jobs created by expensive iconic enclave developments that tend to be viable only because of hidden subsidies. Significantly, wherever foundational economies thrive there also tend to be thick interlocking local-level networks of collaboration and reciprocity, quite often expressed in the emergence of local currencies or other similar trading schemes that protect local economies from 'leakage' (Hallsmith and Liataer, 2011). These "energetic societies" (Hajer, 2010) are emerging in many places across all regions, and represent alternatives to the state-centric and market competitive models of urban development.

Complementing the stabilizers of a well-grounded city, 'accelerators' tend to focus on the construction of high-quality, socially mixed living environments where open-source informational development driven by internal and external investors and social enterprises boosts productivity and generates the surpluses needed to finance human and sustainable development. Without the productivity improvements that informational development makes possible, an over-investment in human development could lead to fiscal stress and ultimately unmanageable debt. The well-grounded city is different: it is an amalgam of the foundational and the biophilic economies underpinned by informationalism.[79] It provides the basis for a social contract between rich and poor, and gives priority to businesses, utilities, educational institutions, social enterprises, ethical banks, impact investors, creative industries, informal entrepreneurs and supermarkets whose networks and branches root them in the city so they can be subject to social licence (Engelen *et al.,* 2016:26).

Although city governments can only control non-local governors of urban development in collaboration with other levels of government (what some refer to as multilevel governance) (Betsill & Bulkeley, 2006) or via global coalitions of cities (e.g. United Cities and Local Governments, C40, ICLEI), they can focus directly on the internal stabilizers and accelerators they can control. Internal stabilizers create the conditions for one form of development or another (e.g. strategic intensification, mixed-use neighbourhoods and mass transit). Accelerators are policies aimed at accelerating a perceived set of external dynamics that if appropriately harnessed could reinforce the preferred development approach (e.g. subsidies from higher levels of government, innovation incentives from research or economic promotion agencies, competitive public funds for major infrastructure investments, or private investors with a long-term perspective). City-level policymakers can choose to use one set of stabilizers/accelerators over another, which means outcomes are contingent on rather than derived from global structural dynamics, but nevertheless constrained by the turbulent dynamics of global financial and resource flows.

The competing cities approach tells city leaders to focus on economic growth by attracting external investors into FLOR—'flats, leisure, offices and retail' (Engelen *et al.,* 2016:26). Low interest monetary regimes at global and national levels help facilitate the massive flows of cheap credit that drives FLOR investments. Internal accelerators are used to maximize the financial gains that can be derived from these investments: developer-friendly planning frameworks, attractive land deals, tax incentives and subsidies (via investments in hard infrastructures or informational infrastructures, both of which can make property developments profitable). Stabilizers tend to be limited to skills development, targeted education and particular kinds of infrastructure.

The smart city agenda being marketed aggressively by the global technology companies is in fact an accelerator for mounting competitive bids for footloose capital—as captured in the title of one influential report published by Siemens, PricewaterhouseCoopers and London-based global law firm Berwin Leighton Paisner: 'Investor Ready Cities: How cities can create and deliver infrastructure value' (Siemens *et al.,* 2014). The proposition is clear: 'smart infrastructures' attract 'smart people', thus catalysing new investments and therefore economic growth. In practice, the result is divided cities as enclaves get detached

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[79] Although the notion of a well-grounded city is borrowed from Engelen *et al.* (2016), here it is expanded to include sustainable resource use and ecosystem restoration.

from the increasingly redundant poorer areas, as seen in San Francisco and many other cities where locals are being displaced to accommodate 'smart people' employed by tech companies.

In short, to ensure that urban experimentation does not end up reinforcing competing cities at the expense of foundational and biophilic jobs, the stabilizers and accelerators of the well-grounded city will need to be enhanced. Indeed, the existing urban experiments of today can be viewed as particular constellations of stabilizers and accelerators that come together in open-ended IT-facilitated and context-responsive ways to form the lifeblood of the well-grounded city with the potential for productivity, well-being and sustainability to be evenly balanced.

## 6.7. Integrated urban planning for sustainable cities

As argued in Chapter 3, integrated planning is one of the most important internal accelerators that can be used to shape the city form and the spatial distribution of urban activities in ways that maximize the potential of the foundational and biophilic economies via strategic intensification and resource efficiency. Infrastructure investments and land-use planning decisions should be strictly aligned with these spatial guidelines. This needs to be done in a way that takes into account the fact that a city's demand for physical structures, infrastructures, housing and amenities will change with time as its population grows and demographics change. To meet new demand, city leaders and planners must have a long-term vision and strategies that are flexible and open to urban experimentation. Integrated plans should therefore avoid locking cities into physical forms that may prove over time to be dysfunctional. A city's physical structures, once established, may remain in place for more than 150 years (Hallegatte, 2009), creating an undesirable inertia that is difficult to break away from and can set a city's development back by decades, even centuries.

Learning from past planning failures will mean abandoning the notion that there is a fixed 'ideal' average density appropriate for all contexts reinforced by static plans and underutilization of large tracts of public land. It will thus entail adopting new planning tools. Granular and flexible planning that creates spaces for learning through urban experimentation allows a city to vary land-use types, densities and built forms (such as height) at the neighbourhood and block level as and when this becomes necessary for various economic, financial, environmental and social reasons, in line with long-term strategies for the city. Granular planning allows a city to increase the diversity and texture of certain neighbourhoods by promoting high densities in business districts and strategic transit nodes (for example, as is planned for Ahmedabad and Johannesburg), while preserving historic buildings through adaptive re-use. These plans must be accompanied by periodic reviews to help the city respond to external governors such as changing market conditions, demographic changes and resource constraints.

Integrated planning is essential for realizing the first two levers of change to improve urban productivity by a factor of 10, as outlined in Chapter 3, namely 'compact urban growth' and 'liveable, functionally and socially mixed neighbourhoods'. According to Salat (2016), there are eight dimensions of integrated planning that can be regarded as internal accelerators of sustainable urban forms, provided that the necessary decentralization has taken place. These are: (1) compact, articulated and polycentric intensification; (2) nodal agglomeration; (3) flexibility and alignment with market demand; (4) connectivity through scales and vibrant public realm; (5) small perimeter blocks with active edges; (6) mixed-use neighbourhoods; (7) fine-grain diversified plot patterns; (8) green spaces, natural systems and bioclimatic urban fabric (Salat, 2016).

### 6.7.1. Compact, articulated and polycentric strategic intensification

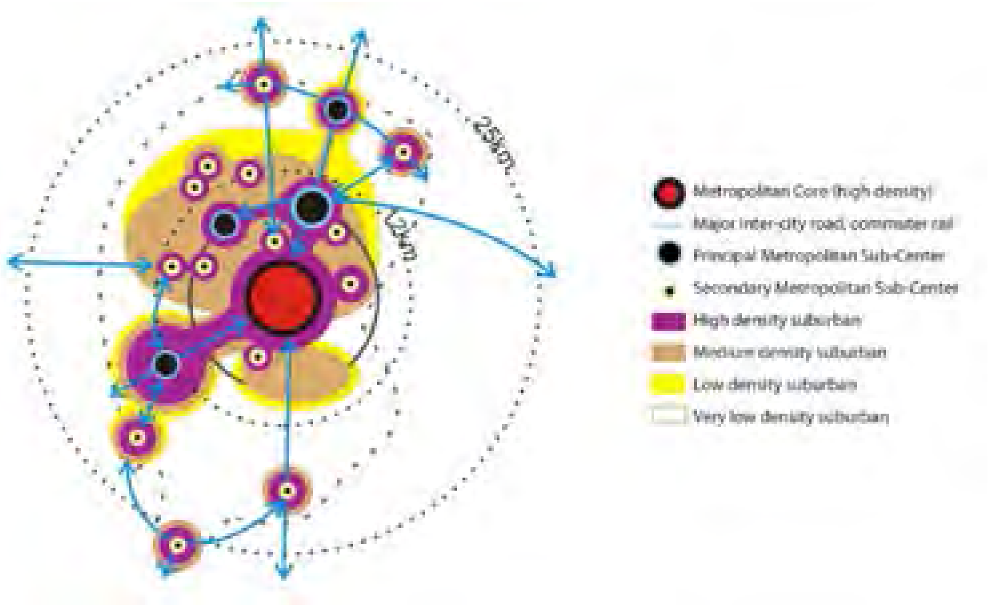
Intensification refers to an increase in the number of people and jobs in a given area (usually quantified in km$^2$). Strategic intensification and more compact forms of urban development facilitate agglomeration economies, improve access to services and improve revenue generation from property taxes. If properly implemented, strategic intensification makes efficient public transit possible. To achieve positive agglomeration and economies of scale, a minimum density of 15,000 people per km$^2$ will be required in the high-density nodes. However, as discussed in Chapter 3, what matters most is not average density across a whole city, but rather a city of well-articulated high-density nodes interconnected by high-capacity efficient and affordable transit services (supported by ecomobility infrastructure). Peaks of people numbers in economic nodes where jobs are concentrated must therefore correspond to peak connectivity to ensure efficient movement into and out of these nodes. This can only be achieved by ensuring that intensified development is only allowed where mass transit services are available. Fast-growing cities must expand by creating compact, polycentric and well-articulated spatial forms, with multiple specialized and complementary nodes able to drive the localization of economies.

Strategic intensification is different to densification. Whereas densification usually means increases in average densities across an entire urban space economy, strategic intensification is about identifying specific primary and secondary nodes that need to be densified and then interconnected via affordable and efficient mass transit. While the average density of Los Angeles is higher than the average density of New York, this does not mean that Los Angeles is the more efficient and functional urban system. This example reveals why densification, understood in terms of average densities, is problematic and therefore replaced by the notion of strategic intensification.

Credit: Nataly Reinch/shutterstok.com

## Optimizing urban form in Johannesburg with multiple compact centres

**Figure 6.1**: Johannesburg's Spatial Development Framework (SDF): compact, polycentric, spatially just city



(Source: Salat, 2016)

In anticipation that Johannesburg will grow from 4.3 million to 7 million people by 2040, the Johannesburg SDF considered three scenarios: BAU (i.e. dispersed, sprawled growth); linear development (i.e. via vast development corridors serviced by transit services to link poor areas to the city); and a compact polycentric alternative which concentrates growth in the urban core, which is connected to an articulated network of TOD nodes that are mixed use, dense and socially mixed. Modelling revealed that the third scenario performed best in economic, social and environmental terms.

### 6.7.2. Nodal agglomeration

Nodal agglomeration, rather than agglomeration in general, refers to the concentration of people and jobs in strategically selected urban nodes that are well serviced by mass transit services. The higher the number of jobs, firms and people that can be accessed within specific nodes in less than 30 minutes from outlying urban areas, the more people and jobs will tend to concentrate in these nodes. The higher the densities of these accessible nodes, the greater the economic development that will be fostered by urban development, localization, expanded public services and infrastructures, and the attraction of skilled workers and entrepreneurs. Higher densities in economic nodes can also support innovation, as ideas circulate and flow between firms, knowledge workers, social enterprises and civil society formations;[80] as well as economies of scale with respect to linkages to input and product markets, and to a diversity of audiences and networks. A doubling of job density increases economic productivity by 5–10 percent.

### 6.7.3. Flexibility and alignment with market demand

Cities must balance the need for long-term plans that align development in growing cities with investments in mass transit (including land assembly), with flexible market-responsive

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[80] This is especially so in the cultural and media sectors, where counter-hegemonic discourses generate an enormous throughput of people, money and networked ideas.

approaches to land-use change via rezoning and development control. If private developers, households and communities are not given guidance as to where they can focus their investments, development will be haphazard and inefficient. Equally, if zoning and land-use control is not flexible and responsive, constraints on available land could result in rising land prices, with ensuing exclusionary effects for the poor, start-ups, public services and social enterprises.

### 6.7.4. Connectivity through scales and vibrant public realm

Transport network planning needs to promote connectivity at three levels: inter-city, intra-metropolitan and local level. Connectivity gives producers access to input (including labour) and output markets, and provides options and choices to consumers. It also enables public spaces to be created to foster conviviality and artistic expression and host street markets and cultural events.

- Inter-city connectivity: Inter-urban connectivity stimulates the growth of secondary and tertiary cities as land- and capital-intensive operations move outward in search of cheaper land that is well-connected to the primary city. This helps prevent land prices in the primary city from being driven upward, which would have exclusionary effects. The result would be a well-articulated system of primary and secondary cities interconnected by fit-for-purpose transit systems. Dedicated transport networks such as India's freight corridors should be considered.

- Intra-metropolitan connectivity: Gridlocks and unreliable, unaffordable public transport can confine citizens to their neighbourhoods and limit livelihood prospects. Long commuting times can force people into crowded inner-city slums so they can walk to work. If a city faces both of these challenges, economic productivity will be retarded and well-being will deteriorate. Intra-metropolitan transport plans must provide for mixed transit modes that achieve two objectives: increase the supply of affordable transport options (possibly by making them compete with each other in real terms, not via false internal markets managed by monopolies to manipulate prices), and ensure congestion is minimized and pollution limited. The full cost of individual motor vehicle use should be transferred to the users (e.g. fuel levies, road levies, tolls for single-occupancy cars, traffic lanes for multi-occupancy vehicles, congestion charging, etc.), thus raising the monetary cost of this mode which, in turn, would force households and firms to relocate to access public transit services. The result would be strategic intensification, higher land rents and shorter transport distances, thus fostering urban efficiencies and a more human-scale, liveable urban environment.

- Local-level connectivity: Wide traffic-oriented neighbourhood streets connecting large superblocks of gated, low-density residences should be avoided. The street network should occupy 30 percent of the land—this would be equivalent to 18 km of street length with 80–100 street intersections per km$^2$ of residential development. Well-interconnected streets with varying widths within these parameters would create a secure but accessible, high-quality urban fabric that would save infrastructure costs, reduce energy use, enable non-motorized modes of transport and improve efficient through-flows of traffic by 25 percent compared with the wide streets/superblock model. This kind of urban fabric would support building heights of five to eight stories, with relatively small floor area per person ratios (which is only possible if the architectural designs are appropriately inspired by the need for small but highly liveable spaces with good natural lighting, effective soundproofing and a sense of privacy and security). Walkability and cycling along tree-lined attractive streets with good pavements and cycle paths, benches, outdoor cafes, kiosks, social services and other amenities holds the key to high-quality and safe neighbourhoods. Investments in streetscapes and public spaces will be

**Figure 6.2**: Map of the mixed-use Liuyun Xiaoqu neighbourhood in Guangzhou, illustrating the variety of amenities and services available

(Source: ITDP in Salat, 2016)

required to support these kinds of high-density, liveable neighbourhoods. While London, New York and Vancouver are well known for their liveable streetscapes, other cities are investing in similar ways: Colombo, Cape Town and Lagos have invested in public spaces, streetscapes and their waterfront areas, Ahmedabad has used rights of way to support pedestrianization and the BRT system, and Chennai and Johannesburg have plans for improving cycling and pedestrian walkability.

## 6.7.5. Small perimeter blocks with active edges

Small blocks are the essential element of an effective, human-scale and pedestrian-friendly urban fabric. A dense network of narrower streets and pathways shifts people out of cars, helps traffic flow and enables a variety of public spaces, architectures and activities to develop. Existing superblocks of 400/500 m per side separated by wide roads must be transformed, as China has decided to do. The country is also preventing new gated communities and breaking up existing ones. There is no universal rule for block size and shape (e.g. square versus rectangular). However, small-block development will mean placing entrances close to the street, with ground floor windows, appropriate signage, lighting and other architectural ways of creating pedestrian-friendly environments. Ground and first floors should be open commercial and/or socially active spaces that ensure a vibrant public realm that is human scale and interactive.

## 6.7.6. Mixed-use neighbourhoods

Mixed-use neighbourhoods can emerge in less regulated places, or can be deliberately created by changing zoning schemes to allow for the intermingling of amenities, social services, transit facilities, residential and commercial uses at the building, block and neighbourhood levels. If people have what they need close at hand, they have no need for private or public transit to do their shopping or to access amenities and services. The result is a greater sense of community, vibrant pedestrianized street life and improved safety, particularly for children. Mixed-use neighbourhoods can also support measures to ensure a greater social mix of income groups, and it can thrive on the symbiotic interdependence of the formal and informal sectors. As locating multiple activities in close proximity to one another can present challenges (e.g. noise or air pollution), mixed-use areas require different rules and regulations to single-use areas to help the various activities coexist.

### 6.7.7. Fine-grain diversified plot patterns

To ensure that urban land development is responsive to changing market and social dynamics, regulatory mechanisms that provide for a diverse pattern of plots sizes will be necessary. It must be possible to assemble plots into larger units for larger buildings, which was prevented in South African townships (former black areas under apartheid). The resulting fine grained diversified pattern fosters market responsiveness, flexible financing and creates opportunities for start-ups and social enterprise initiatives, particularly those led by younger people. This, in turn, facilitates smaller projects that require less capital to get going, or even premises with reduced rates and rentals to attract start-ups and social enterprises. This happened in New York and Brooklyn, resulting in massive land-development investments over time, although 40 percent of the Manhattan and 80 percent of the Brooklyn plots of 200 m$^2$ remain the same size as they were when established in 1811. This explains why residential neighbourhoods, dense social enterprise districts and skyscrapers are intermingled in New York. The key to this kind of flexible accelerated urban development is mechanisms and institutional arrangements that make it possible to assemble land into larger pools that can then be appropriately subdivided and developed for high-rise commercial development, upmarket residential development, subsidized housing or public amenities.

### 6.7.8. Green public spaces, natural systems and a bioclimatic urban fabric

Achieving a good quality of life in high-density urban environments depends on the establishment and maintenance of a network of public spaces of varying sizes, with an emphasis on green spaces that integrate natural systems into a bioclimatic urban fabric. Green spaces give neighbourhoods a particular identity, improve health by providing spaces for cycling, walking, jogging and quiet reflection, and help build a sense of community via community gatherings, festivals, concerts, gardens and markets. They also provide key environmental services: cooling, shading, rainwater run-off and absorption, improved air quality and reduced noise pollution. In many cases, they can also be used for small-scale food production, as is already widespread in informal settlements in the Global South, where nutrient deficiencies are high. These spaces are city assets that play important ecological, social and economic roles—particularly for the poor—and as such they need to be cherished and protected from commodification.

Planning is essential for achieving sustainable urban development, yet many cities continue to rely on outdated modes of planning, and many parts of the developing world have grossly inadequate planning capacity. For example, the UK has approximately 38 planners per 100,000 people, whereas Nigeria and India have 1.44 and 0.23 respectively (UN-Habitat, 2016). The spatial guidelines discussed here need to be integrated into a coherent governance framework that is context specific, for example the City Development Strategies being promoted by the Cities Alliance, the United Nations Human Settlements Programme, the United Nations Environment Programme and others (UNEP, 2013b). Although these strategies tend to address common themes, each city will require a unique strategy with appropriate metrics to monitor progress and support decision-making. As already suggested, infrastructure investments must not be allowed to drive spatial decisions: rather, spatial frameworks that envisage more socially inclusive, resource-efficient and sustainable urban metabolic configurations must drive the spatial location of infrastructure investments. It is also important that the spatial scale of planning for cities and infrastructure extend beyond the city to take into account resource sources and sinks, which requires cooperation with planners at higher tiers of government.

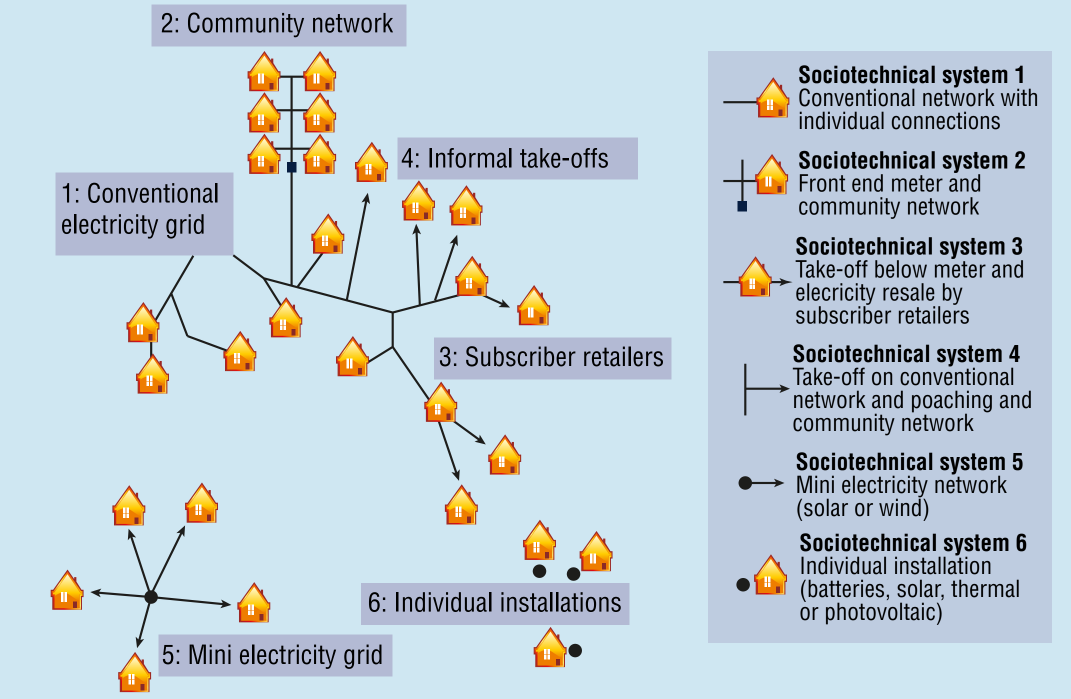
Although aspects of the eight dimensions discussed above are consistent with a competitive cities approach (e.g. the emphasis on agglomeration), when taken as a total package they can also be used to achieve a well-grounded city if there is an emphasis on mixed-use neighbourhoods, social mix, diversity, integration, accessibility, affordable mobility, publicly funded public spaces and inclusion.

## 6.8. Regulatory hegemony and hybridity

Everyone who lives in cities and urban settlements needs to somehow access basic urban services, especially energy, waste disposal, water, sanitation and mobility. For historical reasons, the generally accepted technologies and institutions that have made this possible evolved first in the developing cities of Western Europe and Northern America. The result was centrally managed public monopolies with professionally run, highly regulated bureaucracies mandated to deliver uniform services in a given area to everyone, including cross-subsidization where required. Resource constraints were defined merely as short-term technical problems for engineers to overcome via good design. These conventional service delivery institutions were part of the evolution of increasingly regulated and formalized urban systems underpinned by industrialization and economic growth, and spatially directed by urban plans.

Although these conditions do not apply in many cities and urban settlements in the Global South, the conventional service delivery system has nevertheless been regarded as the norm by both international aid agencies and local policy elites. Failure is thus defined as anything that deviates from this norm. Although neo-liberalism from the 1980s onward resulted in the privatization of many urban services in the Global North, this in fact reinforced the highly regulated nature of

**Figure 6.3**: Household access to energy: example of a delivery configuration



(Source: Jaglin, 2014)

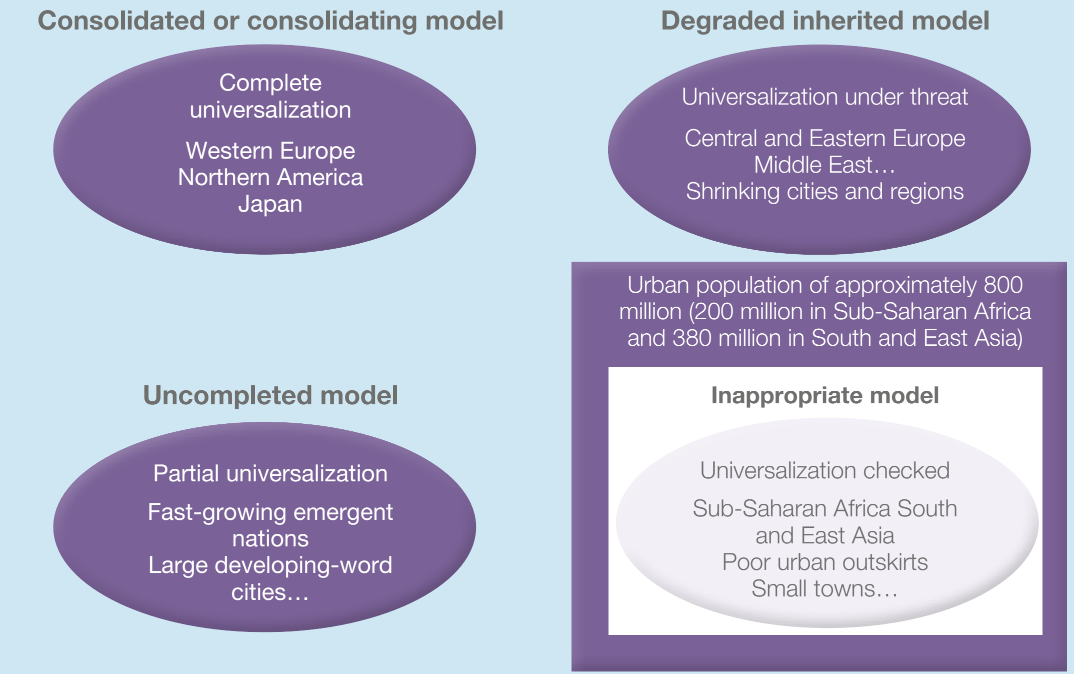
the resultant service delivery systems (albeit of a far more complex institutional configuration of interacting public and private agencies). Whether services were delivered via regulated public or private bureaucracies, both manifested what is common in nearly all urban systems in the Global North—namely the fact that they are mature urban systems where the large bulk of urban service delivery activity occurs via strictly regulated systems.

This is not true for many cities and urban settlements in the Global South. There is now a substantial body of literature that has demonstrated how complex, heterogeneous, hybridized and haphazard many urban systems in the Global South have become (Allen *et al.,* 2016; Edensor and Jayne, 2012; Parnell and Pieterse, 2014; Parnell and Oldfield, 2014; Pieterse, 2008; Swilling *et al.,* 2003). In essence, unlike formalized regulated urban systems, space and time have not been transformed into predictable regulated routines of daily urban life in the 'untamed urbanisms' of the Global South. This socio-cultural-economic heterogeneity has, in turn, resulted in a diversity of hybridized formal and informal service delivery systems that are appropriate for fast-changing, rapidly expanding and inherently unstable urbanization processes. Sylvy Jaglin provides the following description:

> *Service provision in southern cities is a combination made up of a networked infrastructure, deficient in varying degrees and offering a rationed service, and of private sector commercial initiatives, whether individual or collective, formal or informal, which are usually illegal in respect of the exclusive contracts of operators officially responsible for the service. These services fill the gaps in the conventional service and, depending on the type of urban area, target either the well-off clientele or poor clientele excluded from the main networks because of lack of resources, geographical remoteness or illegal status. These delivery configurations have one thing in common: the conventional network does not always reach the end user (Jaglin, 2014:438).*

Significantly, she concludes: "In heterogeneous cities, the diversity of service needs has been a vector for innovation" (Jaglin, 2014:439). In other words, urban experimentation in these contexts is not a marginal niche activity, but a defining feature of the way the entire urban service delivery system works in practice. It would be mistake,

**Figure 6.4**: Different outcomes in the urban service network model



(Source: Jaglin, 2014)

however, to see this as a divergence from the conventional universal service delivery model, or as a temporary step along a developmental pathway towards the final realization of this ideal. Instead, a diversity of interconnected hybridized service delivery configurations is a totally different urban service delivery approach, and it is here to stay in fast-growing, complex, heterogeneous cities and urban settlements concentrated in the Global South. Jaglin provides an example of what is commonly found in the urban energy sectors of the Global South: an ever-changing interdependent set of conventional, community-based, illegal and stand-alone non-grid systems.

Recognizing the diversity of existing and emerging interconnected service delivery configurations as the outcome of innovations in response to the unique heterogeneity of Southern cities is fundamentally different to the conventional approach. The latter analyses all systems relative to the 'consolidated' exemplary model of universal services in highly regulated environments in Western Europe, Northern America and Japan (irrespective of whether delivery is via conventional public bureaucracies or privatized entities operating in terms of enforceable regulatory frameworks). All other systems are seen as either degraded versions of this ideal (e.g. in Eastern Europe or the Middle East), or uncompleted applications that will realize the ideal in time (mainly cities in rapidly developing countries), or inappropriate applications in poorer countries, where the model is applied only in wealthier enclaves. Instead of hanging onto this old paradigm, it is much more useful to recognize the reality of hybridized diversity of service delivery in Southern cities by putting aside the historical exemplar derived from a totally different context but which remains such a powerful aspirational ideal. Indeed, it could even be argued that this hybridized multi-centred approach is more flexible and thus more resilient to the conditions that pertain in Southern cities than the exemplary conventional centralized model.

If diverse service delivery configurations are here to stay in fast-growing heterogeneous urban systems, what are the implications for urban governance and the challenge, in particular, of resource efficiency? Whereas juxtaposition of the regulated and unregulated ignores the synergies between the two, and integration is

Credit: Belish/shutterstok.com

institutionally implausible, Jaglin proposes that coordination may be feasible “depending on the quality of regulation and the consistency of incentive structures” (Jaglin, 2014:443). There are many examples of this emerging in practice, but this is not the place for further discussion.

What *is* relevant here are the implications of institutional hybridity for building inclusive resource-efficient urban metabolic configurations in Southern cities, where the large bulk of future urbanization is set to take place. The most common response is that weak governance means that sustainability challenges such as resource-efficient infrastructures and strategic intensification will not be adequately addressed. What this ignores is the way formal planning systems, when introduced, often get manipulated to act against the urban poor and further degrade the environment. For example, in Calcutta and Kampala, the wetland systems that process wastewater and provide a livelihood to thousands of urban farmers are being filled by well-connected property developers who secure ‘planning permission’, thus destroying ecosystems and the livelihoods of poor farmers who depend on them.

At the same time, a BRT system has been built in the congested city of Lagos, and in Kumasi in Ghana, the economy of a small city has been built on processing scrap vehicles shipped in from around the world. Meanwhile, thousands of off-grid solar energy systems are mushrooming across a number of African countries (e.g. Solar Sister in Uganda), allowing energy services to be accessed more quickly and avoiding the costs of extending power distribution networks to unserviced areas. Such developments suggest that by making traditional planning and governance systems that usually work to the benefit of elites unviable, the institutional hybridity of diverse service delivery systems may in fact be an appropriate response to challenges such as resource efficiency and strategic intensification. This is on the proviso that ways and means can be found to facilitate effective coordination in a sustainable direction (without aspiring to integration, and avoiding juxtaposition). Because these hybrid systems are highly responsive to market dynamics, prices and incentives will matter.

Urban governance in this context might, therefore, entail strategic interventions that take into account all the service delivery configurations active in a particular city and how they can complement each other to achieve agreed long-term socio-economic and environmental objectives. Through urban deal-making with respect to funding, access to land, incentives, procurement, taxes and (where enforcement capacity exists) regulatory controls, urban governance institutions will have to find ways to work with—rather than against—hybridity to achieve the long-term goals of inclusive resource-efficient urban development in heterogeneous urban spaces.

### Solar Sister: Providing clean, affordable energy to Africa

Founded in 2009 by Katherine Lucey, Solar Sister aims to address energy poverty and empower women in Uganda with economic opportunities, by helping them set up microbusinesses that distribute clean cookstoves and solar lanterns. To date, Solar Sister has helped produce microbusinesses for some 400 entrepreneurs in Uganda, South Sudan and Rwanda, bringing solar energy and light to more than 60,000 people (Solar Sister, 2016).

In 2014, Solar Sister reported that a typical solar lamp that costs $18 to purchase would produce up to $163 in cumulative savings for the user over a five-year timeline by displacing kerosene (Inhabitat, 2014). By avoiding approximately 600 litres of kerosene, each lamp also saves about 1.5 tonnes of $CO_2$ emissions. To date, the sale of solar products by Solar Sister entrepreneurs has helped mitigate over 10,000 tonnes of $CO_2$ emissions (UNFCC, 2016).

Over the past few years, Solar Sister has formed key partnerships with private enterprise and government, forming networks with SOSAI Renewable Energies Company, Azsa Microfinance Bank Ltd., African Wildlife Foundation and the Green Belt Movement. The company has additionally ventured into Nigeria, Tanzania and Kenya (UNFCC, 2016).

## 6.9. Governance for urban transition

As governance arrangements for urban transition are context specific, there is no general model. The narratives that drive urban transitions are a product of different power relations and different understandings of what needs to be transformed, why and how change should best be stimulated. Nevertheless, it is useful to conceptualize pathways towards urban transition as being instigated by one or a combination of the following drivers of change (Schmitz and Scoones, 2015:9-17).

### 6.9.1. State-led transformations

This pathway can be driven by local government at the city level, or by higher levels of state government pursuing a resource-efficient agenda of some sort. In such cases, governments can guide markets and investments away from BAU approaches to infrastructure, towards more sustainable alternatives such as TOD, and may take a leading role in fostering innovation in relevant fields (e.g. renewable energy). The city of Zaragoza in Spain provides one example of how local governments can work with citizens to achieve significant water savings when faced with supply constraints.

### Reducing water demand in Zaragoza

A prolonged drought in Spain during the early 1990s resulted in water shortages and public anger. Located in a semi-arid region, the city of Zaragoza used this opportunity to justify a shift in its water infrastructure focus from expanding supply to reducing demand, as a means of reducing its vulnerability to future shocks and building its resilience.

The city's Municipal Strategic Plan 1996–2010 set the ambitious goal of reducing total city water consumption from 84.7 Mm$^3$ in 1995 to 65 Mm$^3$ by 2010 (Climate-ADAPT, 2014). The Zaragoza Water Commission was established in 1996 to coordinate the city's water-saving efforts. The Commission is hosted by the city's Local Agenda 21 office, and in addition to a number of local government departments tasked with managing water, its 29 members include civil society organizations, academic institutions, businesses, professional associations and the Ebro River Basin Organization (Philip, 2011).

The three main strategies undertaken by the Water Commission were:

- Rehabilitation of water distribution infrastructure to control water losses, including the rehabilitation of distribution pipes, implementation of pressure management controls and repair of leaking water storage tanks.
- Reforming water billing from a system based partly on political criteria with little incentive to save water, towards one that covers the true cost of water services, charges users equitably and incentivizes water-saving behaviour while maintaining affordability for low-income households.
- Establishing a water-saving culture via the Zaragoza Water Saving City Programme, which works with a range of stakeholders to eliminate wasteful water use and promote the uptake of water-saving technology. The programme was initiated by a local environmental NGO, and receives support from the municipality.

In the first 15 years, the city exceeded its water-saving targets despite a 12 percent increase in population, reducing its overall water consumption by nearly 30 percent (Philip, 2011). This is mainly attributed to targeted efforts to change water consumption behaviour among specific user groups, using tailored messaging to appeal to their priorities. Users were engaged via their professional associations and neighbourhood representatives to improve the likelihood of messages being well received by the intended audience.

Following the experience of water shortages in the 1990s, the city had political support for water saving from many stakeholder groups, paving the way for their cooperation. With a supportive city council, policy commitments were made and funding was allocated to strategic activities. Authorities led by example by improving the quality of the city's water and wastewater services, which encouraged high-use groups and households who may otherwise not have responded to awareness campaigns to participate in the city-wide initiative (Philip, 2011).

### 6.9.2. Marketized transformations

Where the market is considered to be the primary mode for action on sustainability, its incentives and disincentives can be adjusted to make private businesses into agents of change that engage in beneficial behaviours. Pricing, the creation of markets, and changes in property rights regimes can be used to encourage innovation and build a greener economy that achieves economic prosperity alongside environmental goals. For instance, in Amsterdam's case, providing a platform to share information on heat supply and demand has helped grow the city's district heating market.

#### Amsterdam's 'Energy Atlas'

The city of Amsterdam has used the extensive data at its disposal to develop an open-source 'Energy Atlas' that allows the private sector to easily identify and capitalize on opportunities for district heating and cooling. These data are presented on the city's website in a clear and user-friendly manner, and are fully accessible to any interested party. Data visualization enables energy flows to be mapped, and helps potential partners connect with each other to build business cases for district energy projects based on their heat supply or demand (UNEP, 2015:54).

As the requirement that at least 70 percent of occupants need to agree to a switch from gas to district energy is an obstacle to the expansion of district energy in the city, the Energy Atlas actively involves end users in energy planning. Local businesses and land owners were involved in its design, and it includes information relevant to them (e.g. thermal and electricity production and consumption data per district; existing, proposed and potential sustainable energy projects; opportunities to connect to existing sources or networks; data on building stock; social indicators, etc.).

In the 300 hectare mixed-use Zuidoost area, the atlas has fostered cooperation between various industrial partners on energy exchange and the use of excess waste heat from data centres. The maps provide insight into the area's thermal management, linking sources of waste heat with areas of demand for heating.

### 6.9.3. Technocentric transformations

The technocentric perspective regards technology as the key to meeting growing human needs in less environmentally damaging ways, framing the challenge as one of finding the right combination of technologies to 'solve' the problem, without necessarily making changes to the systems in which they are embedded. Certain technologies are identified as being beneficial, and the focus is on enabling them to compete with incumbent technologies via targeted research and development, intellectual property policies and supportive tax and industrial policies. In Beijing, for example, innovative reverse vending machines are being rolled out to encourage the recycling of PET bottles in public places.

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## Beijing's reverse vending machines

In line with China's efforts to shift towards a more circular economy, the capital city of Beijing is using innovative 'reverse vending machine' (RVM) technology to facilitate the recycling of plastic bottles. The machines incentivize recycling behaviour by rewarding recyclers with public transport credits or airtime for their mobile phones. The value is determined by the number and type of bottles inserted into the machine (Recycling Today, 2014). These machines are conveniently located in public spaces where commuters are most likely to consume beverages from PET bottles.

Using sensors to accurately sort plastic waste, the machines help achieve higher quality recycled plastic pellets than would otherwise have been achieved by informal collection of plastic waste. This means that bottles can be recycled back into bottles instead of into lower grade products (e.g. clothing or plastic basins), helping reduce waste and pollution in the recycling process.

The reverse vending machines were developed by INCOM RECYCLE Co. Ltd, a company formed in 2008 by INCOM Resources Recovery Recycling Co. Ltd.—the largest manufacturer of regenerated bottle-grade PET chips in Asia. The machines form part of the company's Total Solution for Intelligent Solid Waste Recovery Machine and Recycling System, which integrates the Internet of things with the recycling sector to improve efficiencies (INCOM RECYCLE, 2016).

From the first 10 RVMs placed in Beijing subways in 2012, the number of machines around the city had grown to around 3,000 by the end of 2015. In 2015, INCOM estimated that it had recycled around 18 million discarded empty beverage bottles, collected from subway stations, malls, government offices, educational institutions and public spaces, and has around 400,000 citizens contributing to its collection services (Xin, 2015).

### 6.9.4. Citizen-led transformations

In cases where the public and private sector are not showing sufficient interest in urban transitions, alternative approaches can be driven from the bottom up by motivated civil society organizations. These types of transformations tend to focus on niche innovation, knowledge-sharing, and developing cultures of sustainability that shift behaviours and lifestyles in a more resource-efficient direction (e.g. from private car use towards cycling). In Kitale, citizens have led a transformation in waste management practices to reduce negative environmental impacts while improving livelihood prospects.

## Kitale's Dajopen Waste Management group

Dajopen Waste Management (DWM) was founded in 2007 as a self-help group by 30 residents of Kitale in Kenya, who wished to improve the economic, social and environmental conditions of vulnerable communities through efficient, sustainable and citizen-led waste management and recycling practices. The founders realized that while Kitale depends heavily on its agricultural sector, improper waste management practices were resulting in soil and water contamination, ruining crops and the respective livelihoods that depended on them. DWM therefore provides waste and recyclable collections, upcycles wastes (e.g. into arts and crafts items), composts, manages an organic farm and provides training on its strategy and intellectual property to other self-help and community-based groups.

Since the start of the project, 95 percent of its members have changed the way in which they dispose of waste to reduce their environmental impact. DWM has also provided training to over 21,000 people and eight self-help/community-based organizations on waste management, upcycling and organic farming (BSHF, 2016).

DWM is financially supported by its members, who contribute 30 percent of their respective revenue to the group. At the end of each year, 20 percent of the collective fund is distributed to members, and the rest remains within the group's bank account to be reinvested into new initiatives and projects (BSHF, 2016).

## 6.10. Conclusion

In conclusion, this chapter has provided a framework for understanding the future of urban governance that is appropriate for fostering socially inclusive and resource-efficient urban metabolic configurations in the information age. In the absence of an adequate set of local, national and global agreements to address both the environmental and economic crises, cities and urban settlements in all regions have become spaces where social actors can engage in creative visioning, coalition building and collaborative actions for change. The outcome is the emergence of urban experimentation, which can be harnessed to accelerate transformation towards city goals.

However, for urban experimentation to be replicated and go to scale, a multilevel governance framework will be required that defines a specific role for certain state institutions at different levels: supporting radical innovations as well as investments in (and/or subsidizing of) early-cycle high-risk ventures. This entrepreneurial role for state institutions would result in city-wide urban governance coalitions between government policymakers, knowledge networks, social entrepreneurs, innovators, investors and civil society organizations who share a commitment to innovations that result in greater resource efficiency (through infrastructure reconfigurations and strategic intensification via a network of interconnected high-density nodes) and well-being for all (via expansions of the foundational and biophilic economies).

Integrated urban planning should become a key implementation instrument for achieving this vision. However, it must also be recognized that in many cities in the Global South, there is an all-pervasive heterogeneity that has given rise to a hybridized and diverse set of service delivery systems. These differ from the highly regulated modes of service delivery that have evolved in many developed nations in the Global North. Dropping any attachment to the conventional exemplary model and then recognizing institutional diversity across world regions holds the key to developing context-specific urban governance approaches for catalysing urban experimentation in pursuit of decoupling.

# Chapter

# 7


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# Conclusions and recommendations

## 7.1. Introduction: The hidden costs of resource ignorance

This report is the first of its kind, detailing the expected consequences of future urbanization (2015–2050) in terms of resource requirements. Its **first main conclusion** is that if a BAU scenario is followed, cities will need more natural resources (from water to materials, from fuels to food) than the planet can sustainably provide.

Notably:

- The proportion of the global population living in cities and towns is expected to rise from 54 percent in 2015 to 60 percent by 2030 and to 66 percent by 2050. Most of this transition will take place in the Global South, requiring the significant expansion of existing cities and the construction of new cities.
- The long-term historic de-densification trend threatens to increase global urban land use from just below 1 million km$^2$ to over 2.5 million km$^2$, putting agricultural land and food supplies at risk.
- For sustainable use of global resources by 2050, the average material intensity of consumption per capita needs to be reduced from the forecasted 8–17 tonnes to 6–8 tonnes per capita per year.
- BAU could result in the resource requirements of urban areas growing from 40 billion tonnes in 2010 to nearly 90 billion tonnes by 2050.

The hidden costs of 'resource ignorance' are tremendous. We therefore need a new strategy for 21st Century urbanization.

The **second main conclusion** is that cities have the potential to deliver on the promise of a transition towards sustainability, but only if key assumptions are reconsidered. The title, 'The Weight of Cities', refers to the quantification we have made of the total resource requirements of future urbanization, both in terms of a BAU scenario as well as in an alternative scenario whereby we would draw on an integrated set of known technologies and policy options. We call this 'resource-efficient urbanization'. **Resources should now become a central policy concern**, in addition to concerns over $CO_2$, which are now well recognized.

Yet our argument goes well beyond that quantification. Our **third main conclusion** is that an alternative strategy can only be successful if we approach cities as agents of change and think about ways in which city governments, the business community and local communities can significantly improve their collaboration to shift onto this alternative trajectory. Moreover, it requires us to organize city collaborations, both within cities as well as in networks of cities. Given the limited amount of time available, this must be a dynamic strategy, propelled by current successes and strong imaginaries of possible success. Governments—international, national and local alike—should think of **cities as an interconnected urban system** and should invest in networks of cities to enhance the transformative capacity of each individual city. We suggest moving away from a model of 'competitive cities' and towards a model of 'collaborative cities'. This would require capturing and connecting the productive energy of policymakers, insights from academics and initiatives from civil society, designers, business and finance. This requires policymakers to step up their efforts to put resource flows (inputs, usages and outputs) firmly on their agenda. If we want to connect the ideal of resource-efficient urbanism to that of a city that is fair and just, the data must be developed, not only to understand each stream, but also to understand *who* is using *what* flows *where* to do *what* (Pincetl *et al.*, 2012:199).

Our **fourth main conclusion**, then, is that the future of cities does not rest on resource efficiency alone; it is about how to meet the twin goals of ensuring sufficient resources for the future and social inclusion. This is reflected by SDG 11: 'Make cities and human settlements inclusive, safe, resilient and sustainable'. The New Urban Agenda places a similar emphasis on a broader approach, connecting environmental, economic and social goals. Promoting environmental interests without addressing the well-being of all does little to create liveable, socially vibrant and creative cities. Our plea is to rethink existing cities as well as to create new cities that give consideration to layout (urban planning and morphology), resource use (infrastructures) and social organization in order to overcome social and environmental challenges.

Social injustices often take a very spatial form. For instance, in cities in developing countries, the poor can have great difficulty in reaching workplaces, having to spend more time and money due to a lack of spatial planning that could have ensured that the locations for living and working were in closer proximity. Bad spatial planning creates mobility demand, which stands in the way of healthy urban living and a prosperous future for all. A new strategy has to break with the lock-in into car-based urban infrastructures. This is particularly important in those parts of the world where the bulk of new urbanization is going to take place. A new strategy must be about connecting and enhancing the social and cultural energies to further this transition.

In this report focused on urban metabolism and resource-efficient cities, we have shown how a failure to address the resource issue will hit cities directly and fiercely. These concepts, and this report itself, facilitate collaboration between actors with different interests and distinct but intersecting world views.

This final chapter discusses recommendations to policymakers, and suggests some elements of a new governance model to make the global quest for cities that are both environmentally sustainable and socially just into a joint success.

## 7.2. Rethinking urbanism

Looking at cities through the lens of natural resources reveals an omission of historic proportions: although cities are fundamentally dependent on their interaction with the natural environment, this is not reflected in their management strategies, which are inherited from the 20th Century. While cities have always massively drawn on their rural ‘hinterlands’, whether for fuels, construction materials or food, it is the 20th Century *industrialization* of this resource extraction and use that should be held responsible for the current predicament. Instead, 21st Century urbanism and urban strategies will have to be based on a profound understanding of the interdependence between man and nature. Cities that fail to develop such strategies will pay a high price, as the costs of inaction will be much higher than those of restructuring urban interactions now.

A historical perspective helps explain this imbalance in our relation to nature and natural resources. First of all, the historic origins of current imbalances lie to a large extent in the *great acceleration* that commenced in the 1950s. During this period, the post-war modern economy started to accelerate, spreading across the Western world and creating completely new social expectations and aspirations. Significantly, the huge increases in resource use went hand in hand with the new dynamics of urbanization that resulted in the commencement of the second urbanization wave (1950–2030). New industrial production techniques allowed for massive employment of steel and cement, creating different building stock and mobility options. While expectations at the time anticipated the new energy to be nuclear, it was in fact the massive exploitation of fossil fuels that really shaped the character of urbanization. This was most notably due to the introduction of the combustion engine-powered car, which resulted in ‘de-densification’—a spatial spreading out of urban functions.

Secondly, and related to the above, from the late 1970s onward the focus was on the privatization of services that, until then, had often been provided as public goods. All over the Western world and in many colonial enclaves, the combustion engine-powered car pushed aside a complex infrastructure of coaches, trams and trains. As soon as the private car was affordable, it allowed project developers to separate functions in space. Living in suburban neighbourhoods of single-family dwellings became the aspirational goal. Suburbanization allowed people to escape the difficulties of urban life. Hence the new cheap fossil energy also created a 'time-space distantiation' (Harvey, 1989) in terms of sourcing the city with products and produce from ever-expanding hinterlands. Needless to say, the environmental costs have never been integrated into the price of fossil fuels.

The task ahead is to rethink the city for the era without cheap fossil fuels. It is now well recognized that the days of the combustion engine car are numbered, which will have consequences for the optimal shape of cities (Economist, 2017). Now it is important to think beyond fossils and in terms of the timescales that envisage a low-carbon future that delimits warming to 1.5°C. Developing sustainable cities should be a focal point for new, technologically innovative economic activity that offers great employment opportunities. It is important to remember that the spike in resource use of our urban way of living is a relatively recent phenomenon, with the 'modern' car-oriented city based on imaginaries from the 1920s that were then realized in built form over the last 70 years. Renewable energy technologies are developing and proliferating to replace fossil fuels, beating the old fossil technologies both in terms of costs and real employment. Subsequently it is only logical to think of reducing demand.

We suggest combining 'post-fossil' strategies with strategies to achieve socially inclusive cities. This approach requires us to rethink the city in terms of its layout, infrastructure and social organization, its definition of privilege and spatiality of expectations and aspirations. Moreover, we should revisit the negative consequences of the urban pattern that has emerged. Traffic congestion is not simply a 'nuisance' and health hazard, but also places a heavy burden on workers that need to spend a great deal of time and money to reach their jobs. Similarly, if we want to help reach the goal of socially inclusive cities, we need to rethink the city to create spaces that are attractive, shared and safe.

Although it may be difficult to think beyond the present when many of the solutions to current challenges are yet to be invented, this is precisely what will ensure that the sustainability transition is a success. It is proposed that the push to truly break away from fossil fuels and the current rates of material resource consumption will create a spike of sustainability-oriented innovations, from techno-infrastructures to modes of organization. If done well, sustainability will become an aspirational good in itself—a way to promote cities, focusing on quality of life—as can be seen in many cities already. Singapore, for instance, is aiming to becoming a 'car-lite' city and is investing massive research and development funds into new energy strategies and into 'greening' the city, aiming to combat the UHI effect as well as to create amenity. Meanwhile, Addis is the first city in sub-Saharan Africa to introduce a light rail transport technology to provide an alternative to the car-based default.

The good news is that the timing is about right. The enormity of the required sustainability transition should be regarded as the carrier of a new Kondratieff wave. The fundamental importance of attending to the unsustainable systems of the present goes hand in hand with the need to create new demands for productivity and innovation. Requiring massive financial funds and basically also actively 'destroying value' (Schumpeter's 'creative destruction'), it is an opportunity to help the economy at a time when demand is low and a sense of strategic direction is missing.

Considering that nearly 60 percent of the built urban stock that is anticipated by 2030 has not yet been built, this is a 'make-or-break' proposition. This is especially so for cities in developing countries that have severe social challenges to overcome, and where a new consuming middle class could exacerbate the environmental crisis, if this middle class were to emerge within urban systems designed according to the 20th Century principles. Some strategic interventions are therefore presented here that are crucial for the transition to succeed. They should not be seen as a recipe, but rather as a set of guideposts that can help a new urban strategy lift off.

## 7.3. Strategic orientations

### 7.3.1. Urban metabolisms must shift from 'linear' to 'circular'

The 20th Century will go down in history as the age of the modern, car-oriented fossil city. It was an orientation in which the costs to nature were not properly taken into account. In terms of metabolisms, it implied a conceptual approach to nature, which was regarded as subordinate to science, culture and technology. Nature was assumed to provide goods and services in perpetuity at no cost. In urban planning and architecture, this led to the idea of a 'tabula rasa' (blank slate), according to which natural elements were literally erased to allow for the idea of geometrically ordered cityscapes. This science-led system sought to improve on nature by thinking in terms of differentiated 'compartments' (water, air, soil, etc.), often overlooking the complex interactions between components.

In contrast, the future lies in NBS that follow nature in its logics and flows. We **recommend** a shift from linear urban economies to circular ones by extracting more utility from so-called 'waste' streams. For cities, this implies new approaches to managing the movement of resources through the city—both in terms of stocks (e.g. building materials) and flows that service the city (e.g. water). Concepts such as 'urban mining', 'resource cascading', 'industrial symbiosis' and the various manifestations of 're-economy' (reduce, reuse, recycle) will define the new urbanism. Sanitation and solid waste systems will have to shift from being collectors of pollutants for disposal towards being providers of water, energy, materials, nutrients and employment. The era of the car-oriented fossil city will soon be viewed as a mere stepping stone to a more sophisticated notion of urban dynamics. There is already substantial evidence that circular economics can work. Businesses and cities will have to focus on offering high value *services* rather than selling *artefacts*; providing heat instead of heaters, mobility instead of highways and cars, light instead of light bulbs. Building codes will need to be reconsidered to allow them to remain functional after the first lender has left. Most sustainable may be those cities and neighbourhoods that can constantly adapt to new demands: as Chapter 5 demonstrated, good cities are adaptable.

### 7.3.2. Urban metabolisms must be monitored to assist strategic planning at local government level

In order to succeed, the urban metabolic configuration of cities must be understood and local governments must use this to develop resource strategies. Cities depend on massive inputs of biomaterials (from fuels to food) and also produce solid waste, liquid waste and airborne emissions. Yet most cities do not have an overview of their urban resource flows. In order to manage the urban metabolism better, local governments will need dashboards that allow them to monitor their progress from linear towards circular urban metabolisms. Research on $CO_2$ monitoring has shown that even simply measuring inputs and outputs (i.e. without setting target levels) helps a transition. We therefore **recommend** introducing a system of *'green accounting'* of material flows and environmental emissions as a first step to rethinking the resource balance sheet in business and public service.[81] Awareness of resource use is a significant driver of change towards resource efficiency, often simply because it shows the hidden (often financial) costs of resource ignorance.

While some cities will be able to make use of advanced technologies to monitor resource use in real time, different approaches will be required for other cities, based on their capacities and resources. At a minimum, we **recommend** a standard set of easily measurable *indicators* to allow cities to monitor their progress. The launch of the ISO37120 standard for city indicators in 2014 is a useful starting point, but there is

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[81] See, for example, ICLEI's ecoBUDGET (www.ecobudget.org).

potential for further indicators to be added to promote thinking on circular metabolisms. In light of this report, we **recommend** that these indicators be refined to *include measures relating to the re-use of waste streams, including waste heat, captured methane, non-potable water, construction materials and food waste.*

### 7.3.3. The relationship between GDP and material flows, global land use and GHG emissions must be measured, and targets must be set

To achieve a sustainable city, the externalities of various resource usages must be priced in. Cityscapes are the reflection of the prices of key natural resources such as fuel, land and water. Putting a high price on carbon would have a significant effect, but this cannot be achieved at the local level, requiring rather national or even international policies. It is important to keep in mind that, when it comes to $CO_2$ in urban construction and building, we can speak of 'sheltered' sectors that are less vulnerable to carbon leakage, for example house prices may become somewhat more expensive but this will not make people leave the city. Pricing in the effects of unsustainable water depletion would have a marked effect on the cityscape as well.

Particular attention should be given to land economics. The urban economic-geographical literature has detailed how the global market for real estate is intertwined with economic cycles. In some regions, local governments are dependent on the sale of land for their revenues, which encourages increasingly sprawling cities with ever-diminishing returns on the costs of servicing more distant areas. We **recommend** further investigation into the alternative of *a land value added tax*. This would put a premium on building cities that keep or increase their value. Environmental and economic sustainability can go hand in hand. A system of land value added tax generally helps local governments to recoup the money they spend on building and maintaining public infrastructure.

### 7.3.4. City planning 'defaults' must be changed

Society's ecological overshoot is no longer based on active decisions, but is a function of the non-decisions of all sorts of routinized social practices. In recent decades, urban infrastructure and spatial planning have created many lock-ins. Norms and aspirations have been created around low-density suburban lifestyles, single-user cars and air-conditioning; all of which assume that electricity and oil prices will remain low. While technology has allowed for customization and the proliferation of choices, cities have many routinized sets of behaviour built into them that severely limit consumer choice and stand in the way of more sustainable behaviour.

No more is this so than in the design of cities to meet the needs of car drivers, which has become commonplace over the past 70 years. Cars are not individual technologies but constitute one of the most powerful sociotechnological systems in society. The power of such systems is in the routine behaviour they bring with them, in the many related jobs (from car mechanics to miners), in the contribution of cars to marketing and commerce, and in the role of cars as a status symbol. The morphological requirements of resource-efficient urbanism suggest a cityscape that makes people far less dependent on cars (see Chapter 3), allowing the poor in particular to access the opportunities of the city without needing to own a car. We **recommend** a radical *change in default approaches* to urban planning to prevent uncontrolled sprawl and promote high-density, mixed-use nodes with safe and inviting streetscapes, connected by reliable and affordable public transport. Imaginative examples include the removal of motorways to make way for parks and public spaces in Seoul, or the pedestrianization of European inner cities, later mimicked at Times Square and Broadway in New York City. Changing the default fosters new appropriate behaviour and possibilities, such as adapting the rail infrastructure in catchment areas by swapping heavy trains for more frequent light rail vehicles, which can increase ridership dramatically in urban regions. In order to be able to change, we must first appreciate that alternatives are available.

We **recommend** *revisiting urban planning* at metropolitan and neighbourhood scales, and mobilizing expertise to create well-designed urban forms. Here we also see a role for national governments that can facilitate innovation and learning, set targets for resource use, or promote TOD by ensuring new developments are always connected to the appropriate infrastructure. We also **recommend** *planning urban metabolic flows*, in order to capture cross-sectoral advantages, and consulting urban statistics in order to take control of actual losses and possible gains. These are strong levers for decoupling improvements in human well-being from increases in resource consumption and environmental degradation. Research shows that urban resource efficiency can be achieved via strategic planning focusing on four levers of change (see Chapter 3). We therefore **recommend**:

1. *Compact urban growth with higher densities, contiguous development and a well-articulated network of strategically intensified nodes interconnected by efficient and affordable mass transit systems.*

2. *Liveable, functionally and socially mixed neighbourhoods, with a rich mix of housing types, jobs and social amenities for different income groups; dense and connected grids of streets defining small perimeter blocks.*

   The size and shape of buildings can have a significant impact on their energy consumption, and that of the city as a whole. As Chapter 3 showed, larger superblocks surrounded by private manicured gardens are not only energy inefficient, but they also impact negatively on mobility through the city and on the liveability of neighbouring streetscapes. By limiting the perimeters of street blocks and encouraging the use of internal courtyards and parks to welcome sunshine and fresh air, architects would be better able to design passive buildings that required less energy to operate. Similarly, requiring active edges on the ground floor of large buildings would help each building contribute to more human-scale streetscapes, which in turn would encourage walking or cycling.

   In creating these new city districts, we should respect knowledge about successful mobility chains, such as 'walk-metro-walk', 'cycle-train-walk' or 'car-train-walk'. The devil is in the detail, as the distance from homes to metro stations can stand in the way of offering a viable alternative to using the car (known as the 'first mile' problem). Similarly, a chain that aims to get people out of cars and onto public transport requires substantial 'park & ride' facilities, whereas a 'bike-train-bike' system requires sufficient and safe bicycle storage. Dutch railway stations are taking the lead by constructing high-quality storage facilities for up to 12,500 bikes in close proximity to the platforms. A bike rental scheme, run by the railway company, provides a solution to the 'first mile' problem.

3. *Resource-efficient smart buildings and urban energy, waste and water systems; revisit sector-based regulation*.

   Resource-efficient building should become the standard. Similarly, traditional systems of energy generation, wastewater treatment and freshwater supply should be brought up-to-date. This requires national and sometimes supranational regulation to be revisited. In many cases, existing regulation is sector-based, which potentially stands in the way of achieving truly radical innovations. The move towards a circular economy allows for many cross-sectoral benefits and cost reductions. Yet current regulations often stand in the way of capturing these profits, as they are seen as pre-competitive agreements or even cartels. In order to facilitate the transition, it is recommended to create units that oversee regulatory experimentation, to identify regulatory barriers early on. As shown in Chapter 5, cross-infrastructure interactions—such as the exchange of waste materials and energy across infrastructure sectors—can contribute significantly to resource efficiency in general, in addition to single-sector efficiency.

The case studies in Chapter 5 show how cross-sectoral interactions such as industrial symbiosis and reusing waste heat from industries for residential or commercial sectors can reduce energy use in case cities by over 50 percent. We **recommend** urban planning to support co-location of diverse activities and networks (physical and social) to achieve this. Moreover, we **recommend** regulatory innovation.

We **recommend** targeted research funding schemes to facilitate research into resource-efficient smart buildings as well as into waste, wastewater and freshwater supply systems. While many experiments are under way, we currently lack a high-quality system for policy analysis to help assess the performance of particular experiments. In order to speed up the transition, we therefore **recommend** institutionalizing this policy analysis function for urban metabolisms soon. This is something that national governments should facilitate.

4. *Sustainable behaviours*

There is no calculation that allows the world to stay within a 2°C, let alone a 1.5°C temperature increase, that does not include a change in behaviour. Currently, many of the benefits of energy efficiency are lost due to new unsustainable behaviour. This ‘green paradox’ or ‘rebound effect’ manifests itself in the use of money saved by fuel-efficient transport to drive further or fly more often, etc. While behaviour change is one of the most complicated dynamics, we suggest building relationships with key social groups where a value change is emerging. For example, we note that highly skilled workers in the Global North tend to prefer to live close to work and avoid daily car usage. This has caused major tech companies to relocate offices to downtown locations in order to secure the top personnel.

International research suggests that each of these four levers of change has, by itself, the potential to at least halve energy and resource use compared to BAU urban development. However, these interventions are multiplicative: if they are implemented in mutually reinforcing ways, they can decrease resource use by 80–90 percent compared to sprawl and BAU levels of efficiency. We thus recommend an integrated approach.

Promotion of resource-efficient technologies such as BRT, district energy systems and green buildings can also contribute to significant reductions in the life-cycle environmental and resource impacts of cities by 2050, when accompanied by a transition towards low-carbon electricity generation. When combined, this sample of important resource-efficient technologies can contribute to 24–47 percent reductions by 2050 in the life-cycle GHG emissions, water consumption, metal consumption and land use required to provide key urban services compared to baseline projections. Reducing transportation demand by reversing the trend of declining urban densities could further reduce the environmental and resource impacts of providing all these services by another 2–12 percent.

### 7.3.5. Use urban infrastructure as a catalyst for sustainable cities

The philosopher Isaiah Berlin famously differentiated between ‘negative’ and ‘positive’ freedoms. Negative freedoms refer to the freedom from others interfering in one’s personal affairs, while positive freedoms refer to being in a position to live a good life, with good education being a key example of how to achieve this. Resource-efficient urbanism may result in cities that are sustainable and fair, creating new positive freedoms. Here, infrastructure is key to unlocking these options for many people who are now caught because infrastructure does not realistically allow them to safely and affordably use alternatives to cars or fossil fuels.

The amount of upfront investment that is expected to be required between 2015 and 2030 to maintain or strengthen economic growth as the middle class expands is in the order of $89 trillion. This is not necessarily new money, but money that has been assigned to be spent on replacing existing sanitation, roads and water supply systems. In order for cities to shift their defaults towards sustainability, it is crucial that these funds are channelled in new directions. Achieving a low-carbon scenario would require adding only 5 percent to infrastructure spending. We **recommend** judging the massive investments in urban infrastructure in the next decades based on a set of criteria and goals that are drawn up to make achieving the SDGs realistic.[82]

### 7.3.6. Urban infrastructure and land-use policy must be strategically linked to achieve sustainability goals

Urban infrastructure includes roadworks, train tracks, energy systems and ICT networks—hardware that makes for the big investments. However, this report highlights that infrastructure is more than just hardware: it orders cities and also opens up new potential in surrounding areas. This is particularly so in the case of transport infrastructure. TOD has the potential to significantly change the way people and goods move through the city, thus reducing dependence on fossil fuels and potentially improving quality of life for city inhabitants in a number of ways. We **recommend** approaching TOD and area development as integrated portfolios. Instead of allowing private developers to claim most of the benefit of public transport investments (e.g. better accessibility), the integration of infrastructure and spatial planning strategies via TOD would benefit society at large, and could help reduce urban inequities.

### 7.3.7. Develop appealing mixed-use and socially mixed inner-city neighbourhoods

Enclave urbanism stands in the way of achieving socially inclusive cities. At present, enclave urbanism takes a variety of forms, with markedly different manifestations in the developed and developing world. The well-known American and European suburbanization of the middle class that started in the 1950s has driven significant resource-intensive urban sprawl. In the developing world, manifestations of well-protected gated communities lie in close proximity to informal cities, but often slums develop on the edges of cities, with the inner cities being almost out of reach to their inhabitants. We therefore **recommend** investing in developing mixed-use neighbourhoods that are attractive and remove the incentive to escape 'urban blight' and invest in the urbanization of the suburbs, focusing development instead around high-access 'nodes' of the transport network. This requires an integrative approach in which such mixed-use and socially mixed neighbourhoods also house the top schools, cultural amenities, sporting and recreation facilities, and pavements that are safe and clean. While there is nothing particularly new about this recommendation, the emphasis is on mixed-use and socially mixed neighbourhoods not only supporting the SDG goal of social inclusion, but also helping reduce the resource requirements of urban life by locating activities closer together and avoiding long commutes.

Then there is the more recent enclavism based on the return of the (upper) middle class to the city centres. New 'urban professionals' favour a more urban lifestyle, prefer to cycle to work and like to have urban amenities such as concert halls and urban parks close by. Yet in many cities, they are also the only ones that can afford to live in the centre. So a potentially new divide is one in which wealthy green urbanites contrast with

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[82] See, for example, Global Infrastructure Basel's SuRe Standard for Sustainable and Resilient Infrastructure (http://www.gib-foundation.org/sure-standard/).

struggling suburbanites that are caught in high-fossil dependency and increasing costs of travel and energy. We consequently **recommend** working to rethink the urban fringe in terms of TOD and integrated mixed-use urban areas.

In order for the SDGs to be achieved to the full, we **recommend** combining consistent thinking about resource-efficient urbanism with concern for social inclusiveness. The ideal of a well-grounded city that looks at the economic value of the many interrelationships within urban regions fits this integrated approach to urban governance.

In cities with high inequity in infrastructure provision, Chapter 5 indicates that providing improved infrastructure up to the median service level, to the most disadvantaged, does not increase the city's overall resource demand proportionally. Thus, more inclusive city development (e.g. providing shelter to 40 percent of city populations living in slums) increases direct resource demand by less than 40 percent. We **recommend** taking on the optimistic strategy that single-sector efficiencies, cross-sectoral strategies and inclusive development can together yield a sustainable urban development pathway.

### 7.3.8. We need new imaginative business propositions to guide strategic planning for vibrant, green and socially inclusive cities

Routine behaviour drives much urbanization, with many of these routines requiring fossil fuel usage. Sprawling suburbs connected by motorways to isolated shopping malls and mono-functional office blocks, serviced by centralized electricity and waterworks, are the key components of the modern city. They now constitute the 'normal' cityscape. In the developing world, the routine development of enclave urbanism, malls and business districts, combined with sprawling slums lacking access to basic infrastructure, are similarly based on a logic of routines. They are developed because they are 'products' that are well understood in terms of investment strategies, with many buildings being built because of the underlying 'business proposition'. They often do not live up to expectations but, by that time, the developer has often already recouped the initial investment. Cities need to be rethought in terms of real estate propositions, with new business models that can work to reduce the resource requirements, reach the SDGs and be financially profitable at the same time.

What is often forgotten is that interventions such as shopping malls, motorways and waterborne sanitation were once inventions, and existed as visions or imaginaries long before they materialized in cities. For example, the car-oriented city was promoted in the 1920s and 1930s before it really took off in practice in the 1950s. Hence, we **recommend** using the power of imaginaries to create an appetite for the sustainable city (cf. Davoudi, 2014). Unlike in the modern age, these imaginaries are not likely to be 'blueprints' for alternative cities. Rather, imaginaries can be taken from the multiplicity of successful examples. We **recommend** using good presentations of successful case studies (e.g. new transport systems, providing renewable electricity to informal settings, planning metabolic urban flows, new collective schemes to combine solar photovoltaics (PV), car-sharing of electric cars and improved Internet) as the driving force of the sustainability transition.

Combining these results can create appealing visions of post-carbon, highly resource-efficient and liveable cities that can build the appetite of both investors and politicians for sustainable urban futures. The history of urbanism shows that such imaginaries of new possible worlds can have powerful effects on rethinking and reordering cities. Creating and sharing new 'real utopias' helps cities to break away from default routines. The power of new design is thus not a gimmick or simply a visual rendering, but rather a thoughtful attempt to show what is already under way and possibilities for the future. Visual representations, such as the graphic illustrations of Blake Robinson and Karl Schulschenk on the potential futures of African cities, can help make people aware of the choices available.[83] The visuals show different possible futures, comparing a sustainable future against unsustainable defaults, so that citizens can better articulate and pursue their desired future.

### 7.3.9. A politics of experimentation can provide hope for a better future

Resource-efficient urbanism can connect to a new politics of experimentation that is seen emerging in cities around the world. Concepts such as 'living labs', city deals, innovation hubs and special zones indicate that cities are now thinking much more in terms of 'learning by doing' than focusing on one solution and trying to apply it everywhere. The old modern idea of 'analysis and instruction' has made way for a new logic of 'variation and selection', according to which the best solutions for wider application can be selected from diverse experiments. Most likely it is this politics of experimentation that will provide the inspiration and mutual learning that can really drive a broader transition. In order to ensure that experimentation is not purely for the achievement of economic ends, it is important that it is channelled towards overcoming social and environmental challenges as part of the city's strategic vision.

### 7.3.10. Cities must learn from the experiences of other cities to hasten transition

The transformative power of a politics of experimentation depends on the recognition that together, cities form a system. We thereby **recommend** investing in city networks to build a strong policy analysis of urban experiments, and 'twin town' or 'sister city' initiatives to promote learning between similar cities. Current engagement in investments must go further, through grounded research involving policymakers, academic researchers and local communities alike. This would give city networks the potential to speed up learning on the system of cities. For example, the complexity of financing investment in sustainable infrastructure requires new business cases to be developed. This research could be commissioned by various research councils and distributed via city networks for the benefit of all cities. This would allow local policymakers to work with spreadsheets showing how particular investments could be recouped and thus legitimized.

In our view, city networks can then extend their role as horizontal communication and learning platforms. Network organizations allow cities to truly start to be considered as an interconnected system and, luckily, there is no real interest on the part of individual cities to keep solutions to themselves. Indeed, some cities have seen economic advantages in sharing their knowledge with others. The learning capacity of cities can be enhanced by investing in networks of cities at various scales: nationally, internationally or even globally. In order for this to be effective, we **recommend** that investments be made to build institutions that can help these networks to work better and build solidarity between cities. At the moment, too much emphasis is placed on direct imitation of 'best practices', typically of little relevance to resource-constrained cities. Rather, investing in the type of policy research we recommend would allow an understanding to be gained of 'best principles': it would explain why certain interventions were successful in a particular context and under which conditions, so as to facilitate contextually appropriate adaptation to other localities. We therefore **recommend** investing more in actual *policy analysis* of stories of success and failure in order to enhance momentum.

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[83] http://postfossil.city/en/finalists/african-alternatives

## C40 Bus Rapid Transit (BRT) network[84]

C40 plays an important role in developing and disseminating urban practices of BRT, by actively bringing BRT cities together in a collaborative network, by collecting and showcasing best practices of BRT, and by providing expertise on BRT design and implementation (C40, 2017).

C40 has developed a series of Good Practice Guides that give an overview of the benefits of BRT and other climate actions. They “outline successful approaches and strategies cities can employ to implement or effectively scale up these actions. These Guides are based on the experience and lessons learned from C40 cities and on the findings and recommendations of leading organizations and research institutions engaged in these areas. The good practice approaches are relevant for cities engaged in C40 Networks as well as for other cities around the world” (C40, 2016).

## Building Efficiency Accelerator

The Building Efficiency Accelerator (BEA) is a public-private collaborative network that turns global expertise into action to accelerate local government implementation of building efficiency policies and programmes. It is linked to the United Nations Sustainable Energy for All (SE4ALL) initiative (United Nations Foundation, 2015). The network is led by the World Resources Institute, with ICLEI engaging to support local and subnational governments (ICLEI, 2017a). A total of 28 cities from all over the world participate (Building Efficiency Accelerator, 2017).

According to ICLEI: “Participating cities have access to a global network of over 30 businesses, governments, and technical experts who specialize in improving building energy efficiency. The BEA facilitates local collaboration and planning to improve buildings, lower energy costs, and make people more comfortable and productive where they live, work, and play.”(2017b)

One example of the impact of this initiative on cities is the case of Mexico City, which through BEA was able to implement new building regulations. “The SE4All Building Efficiency Accelerator (BEA), led by the WRI Ross Center for Sustainable Cities provided support for the new regulations, specifically for the adoption of energy-efficiency components. The BEA also helped the Mexican Government establish a national building energy code, which provided a solid foundation for Mexico City’s energy-efficiency work in buildings.” (Copenhagen Centre, 2016)

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[84] C40 has many different networks that operate in a similar way to the BRT Network. Examples include networks for District Energy, Municipal Building Efficiency, Private Building Efficiency and Sustainable Waste Management. See http://www.c40.org/networks

### 7.3.11. Higher levels of government must support city-level innovation for resource efficiency

Cities are highly dependent on higher levels of government. The resources cities receive from the national treasury influence their level of ambition to take up innovative projects, and the regulations imposed on them determine how much space and flexibility they have to experiment. Cities and networks of cities are unlikely to overcome regulatory or resource barriers by themselves, so it is important that they are able to collaborate with other levels of government to arrive at mutually beneficial solutions. To optimize resource management, it is important that the spatial scale of urban planning and infrastructure planning extends beyond the urban or peri-urban to take into account resource sources and sinks, and that systematic medium- and long-term planning and regulation by all tiers of government are aligned with the resource-efficiency agenda.

Regulations and standards set at the national level can play an important role in supporting cities in their transition towards resource efficiency, for example building regulations that promote passive solar design to save energy. Regulation is connected to reinforcement, which has become more lenient in recent years in the West, with consequences that are becoming increasingly apparent. Reinforcement, inspection and compliance are mostly national responsibilities, and should serve to support cities in achieving resource-efficiency goals rather than impeding them. Similarly, prices and taxes set at the national level can contribute significantly to providing incentives and disincentives for behaviours that support resource efficiency, and should be used strategically as tools for change.

A politics of experimentation can be fostered by higher levels of government to ensure that cities collaborate and learn from each other to accelerate innovation. State, national or even regional governments can play an important role in creating the right conditions for city-level experimentation, and can support cities by providing relevant stakeholders with the resources, space and flexibility they need to experiment and share their findings with other cities. In addition, they can formulate overarching goals for city governments to meet, so that there is a clear understanding of the role of cities in addressing global challenges such as climate change. Coordinating authorities that stand 'outside' the experiments can help ensure that they learn from each other to reach overarching goals. This coordination can be made flexible through a two-way interaction in which experiments help achieve policy goals, and policies are periodically reviewed and refined based on practical experience.

Urbanization poses very different challenges on different continents, indeed in different cities, depending on their history, location and unique combination of internal opportunities and challenges. We **recommend** mobilizing the future as a vehicle for change. This requires investing in realistic pathways as part of the resource-efficient urbanism movement. This will be markedly different from the future work of the modern city; one of the hallmarks of the modernists was their advocacy of general, universally applicable solutions to urban planning. While this report has used global trends to understand a global problem, we emphasize that the particular issues that cities face may differ markedly. The Global South will see the development of many newly built cities and incrementally growing cities, whereas other parts of the world have an agenda to retrofit existing cities. We therefore **recommend** combining analysis at the global level with constant, in-depth exploration of local and regional strategies. Resource-efficient urbanism thus promotes an approach that mobilizes local ingenuity in a manner that recognizes local contexts and allows for the creation of new forward-thinking engines of growth and development that may not yet have been imagined.

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# Appendix A — Scenarios and key assumptions

**Table A1**: List of 84 cities and their regions included in analysis

| City | Country | IEA region |
|---|---|---|
| Tel Aviv | Israel | Africa and Middle East |
| Cairo | Egypt | Africa and Middle East |
| Tehran | Iran | Africa and Middle East |
| Kuala Lumpur | Malaysia | Africa and Middle East |
| Manila | Philippines | Africa and Middle East |
| Riyadh | Saudi Arabia | Africa and Middle East |
| Dakar | Senegal | Africa and Middle East |
| Cape Town | South Africa | Africa and Middle East |
| Johannesburg | South Africa | Africa and Middle East |
| Tunis | Tunisia | Africa and Middle East |
| Harare | Zimbabwe | Africa and Middle East |
| Hong Kong | China | China |
| Taipei | China | China |
| Beijing | China | China |
| Guangzhou | China | China |
| Shanghai | China | China |
| Chennai | India | India |
| Mumbai | India | India |
| Curitiba | Brazil | Latin America |
| São Paulo | Brazil | Latin America |
| Bogotá | Colombia | Latin America |
| Graz | Austria | OECD Europe |
| Vienna | Austria | OECD Europe |
| Brussels | Belgium | OECD Europe |
| Copenhagen | Denmark | OECD Europe |
| Helsinki | Finland | OECD Europe |
| Paris | France | OECD Europe |
| Lyon | France | OECD Europe |
| Marseille | France | OECD Europe |
| Nantes | France | OECD Europe |
| Berlin | Germany | OECD Europe |
| Dusseldorf | Germany | OECD Europe |
| Frankfurt | Germany | OECD Europe |
| Hamburg | Germany | OECD Europe |
| Munich | Germany | OECD Europe |
| Ruhr | Germany | OECD Europe |
| Stuttgart | Germany | OECD Europe |

| City | Country | IEA region |
|---|---|---|
| Rome | Italy | OECD Europe |
| Milan | Italy | OECD Europe |
| Bologna | Italy | OECD Europe |
| Amsterdam | Netherlands | OECD Europe |
| Oslo | Norway | OECD Europe |
| Madrid | Spain | OECD Europe |
| Barcelona | Spain | OECD Europe |
| Stockholm | Sweden | OECD Europe |
| Berne | Switzerland | OECD Europe |
| Geneva | Switzerland | OECD Europe |
| Zurich | Switzerland | OECD Europe |
| London | United Kingdom | OECD Europe |
| Glasgow | United Kingdom | OECD Europe |
| Newcastle | United Kingdom | OECD Europe |
| Manchester | United Kingdom | OECD Europe |
| Prague | Czech Republic | OECD Europe |
| Athens | Greece | OECD Europe |
| Budapest | Hungary | OECD Europe |
| Cracow | Poland | OECD Europe |
| Calgary | Canada | OECD North America |
| Montreal | Canada | OECD North America |
| Ottawa | Canada | OECD North America |
| Toronto | Canada | OECD North America |
| Vancouver | Canada | OECD North America |
| Atlanta | United States of America | OECD North America |
| Chicago | United States of America | OECD North America |
| Denver | United States of America | OECD North America |
| Houston | United States of America | OECD North America |
| Los Angeles | United States of America | OECD North America |
| New York | United States of America | OECD North America |
| Phoenix | United States of America | OECD North America |
| San Diego | United States of America | OECD North America |
| San Francisco | United States of America | OECD North America |
| Washington | United States of America | OECD North America |
| Brisbane | Australia | OECD Pacific |
| Melbourne | Australia | OECD Pacific |
| Perth | Australia | OECD Pacific |
| Sydney | Australia | OECD Pacific |
| Osaka | Japan | OECD Pacific |
| Sapporo | Japan | OECD Pacific |
| Tokyo | Japan | OECD Pacific |
| Wellington | New Zealand | OECD Pacific |
| Singapore | Singapore | OECD Pacific |
| Seoul | Republic of Korea | OECD Pacific |
| Jakarta | Indonesia | Other Developing Asia |
| Bangkok | Thailand | Other Developing Asia |
| Ho Chi Minh City | Viet Nam | Other Developing Asia |

**Table A2**: Selected cities and regions presented in main report

| Region | Country | City |
|---|---|---|
| Africa and Middle East | South Africa | Cape Town |
| | Saudi Arabia | Riyadh |
| China | China | Hong Kong |
| | | Beijing |
| Latin America | Brazil | São Paolo |
| | Colombia | Bogotá |
| OECD Europe | Hungary | Budapest |
| | Germany | Berlin |
| India | India | Chennai |
| | | Mumbai |
| OECD North America | United States | Los Angeles |
| | Canada | Toronto |
| OECD Pacific | Korea | Seoul |
| | Australia | Sydney |
| Other Developing Asia | Indonesia | Jakarta |
| | Thailand | Bangkok |

**Table A3**: City scenarios

| City | Country | IEA region |
|---|---|---|
| Tel Aviv | Israel | Africa and Middle East |
| Cairo | Egypt | Africa and Middle East |
| Tehran | Iran | Africa and Middle East |
| Kuala Lumpur | Malaysia | Africa and Middle East |
| Manila | Philippines | Africa and Middle East |
| Riyadh | Saudi Arabia | Africa and Middle East |
| Dakar | Senegal | Africa and Middle East |
| Cape Town | South Africa | Africa and Middle East |
| Johannesburg | South Africa | Africa and Middle East |
| Tunis | Tunisia | Africa and Middle East |
| Harare | Zimbabwe | Africa and Middle East |
| Hong Kong | China | China |
| Taipei | China | China |
| Beijing | China | China |
| Guangzhou | China | China |
| Shanghai | China | China |
| Chennai | India | India |
| Mumbai | India | India |
| Curitiba | Brazil | Latin America |
| São Paulo | Brazil | Latin America |
| Bogotá | Colombia | Latin America |
| Graz | Austria | OECD Europe |
| Vienna | Austria | OECD Europe |
| Brussels | Belgium | OECD Europe |
| Copenhagen | Denmark | OECD Europe |
| Helsinki | Finland | OECD Europe |
| Paris | France | OECD Europe |
| Lyon | France | OECD Europe |
| Marseille | France | OECD Europe |

| City | Country | IEA region |
|---|---|---|
| Nantes | France | OECD Europe |
| Berlin | Germany | OECD Europe |
| Dusseldorf | Germany | OECD Europe |
| Frankfurt | Germany | OECD Europe |
| Hamburg | Germany | OECD Europe |
| Munich | Germany | OECD Europe |
| Ruhr | Germany | OECD Europe |
| Stuttgart | Germany | OECD Europe |
| Rome | Italy | OECD Europe |
| Milan | Italy | OECD Europe |
| Bologna | Italy | OECD Europe |
| Amsterdam | Netherlands | OECD Europe |
| Oslo | Norway | OECD Europe |
| Madrid | Spain | OECD Europe |
| Barcelona | Spain | OECD Europe |
| Stockholm | Sweden | OECD Europe |
| Berne | Switzerland | OECD Europe |
| Geneva | Switzerland | OECD Europe |
| Zurich | Switzerland | OECD Europe |
| London | United Kingdom | OECD Europe |
| Glasgow | United Kingdom | OECD Europe |
| Newcastle | United Kingdom | OECD Europe |
| Manchester | United Kingdom | OECD Europe |
| Prague | Czech Republic | OECD Europe |
| Athens | Greece | OECD Europe |
| Budapest | Hungary | OECD Europe |
| Cracow | Poland | OECD Europe |
| Calgary | Canada | OECD North America |
| Montreal | Canada | OECD North America |
| Ottawa | Canada | OECD North America |
| Toronto | Canada | OECD North America |
| Vancouver | Canada | OECD North America |
| Atlanta | United States of America | OECD North America |
| Chicago | United States of America | OECD North America |
| Denver | United States of America | OECD North America |
| Houston | United States of America | OECD North America |
| Los Angeles | United States of America | OECD North America |
| New York | United States of America | OECD North America |
| Phoenix | United States of America | OECD North America |
| San Diego | United States of America | OECD North America |
| San Francisco | United States of America | OECD North America |
| Washington | United States of America | OECD North America |
| Brisbane | Australia | OECD Pacific |
| Melbourne | Australia | OECD Pacific |
| Perth | Australia | OECD Pacific |
| Sydney | Australia | OECD Pacific |

| City | Country | IEA region |
|---|---|---|
| Osaka | Japan | OECD Pacific |
| Sapporo | Japan | OECD Pacific |
| Tokyo | Japan | OECD Pacific |
| Wellington | New Zealand | OECD Pacific |
| Singapore | Singapore | OECD Pacific |
| Seoul | Republic of Korea | OECD Pacific |
| Jakarta | Indonesia | Other Developing Asia |
| Bangkok | Thailand | Other Developing Asia |
| Ho Chi Minh City | Viet Nam | Other Developing Asia |

**Table A4**: Assumed market share of district heating under baseline and resource-efficient scenarios (percentage of heating load)

| Region | Baseline | | | Resource-efficient | | |
|---|---|---|---|---|---|---|
| | 2010 | 2030 | 2050 | 2010 | 2030 | 2050 |
| China | 20% | 20% | 20% | 20% | 50% | 50% |
| India | 0% | 0% | 0% | 0% | 20% | 20% |
| Europe | 30% | 30% | 30% | 30% | 80% | 80% |
| United States | 10% | 10% | 10% | 10% | 50% | 50% |
| OECD Pacific | 10% | 10% | 10% | 10% | 50% | 50% |
| Economies in transition | 50% | 50% | 50% | 50% | 80% | 80% |
| Latin America | 10% | 10% | 10% | 10% | 40% | 40% |
| Developing Asia | 20% | 20% | 20% | 20% | 60% | 60% |
| Africa and Middle East | 0% | 0% | 0% | 0% | 20% | 20% |

**Table A5**: Assumed market share of district cooling under baseline and resource-efficient scenarios (percentage of cooling load)

| Region | Baseline | | | Resource-efficient | | |
|---|---|---|---|---|---|---|
| | 2010 | 2030 | 2050 | 2010 | 2030 | 2050 |
| China | 20% | 20% | 20% | 20% | 50% | 50% |
| India | 20% | 20% | 20% | 20% | 50% | 50% |
| Europe | 10% | 10% | 10% | 10% | 40% | 40% |
| United States | 10% | 10% | 10% | 10% | 60% | 60% |
| OECD Pacific | 10% | 10% | 10% | 10% | 60% | 60% |
| Economies in transition | 10% | 10% | 10% | 10% | 30% | 30% |
| Latin America | 10% | 10% | 10% | 10% | 60% | 60% |
| Developing Asia | 20% | 20% | 20% | 20% | 60% | 60% |
| Africa and Middle East | 30% | 30% | 30% | 30% | 60% | 60% |

# Appendix B — City-level results

## B.1. Africa and Middle East

### B.1.1. BRT

**Figure 1**: Resource-efficiency potential of Bus Rapid Transit in Cape Town

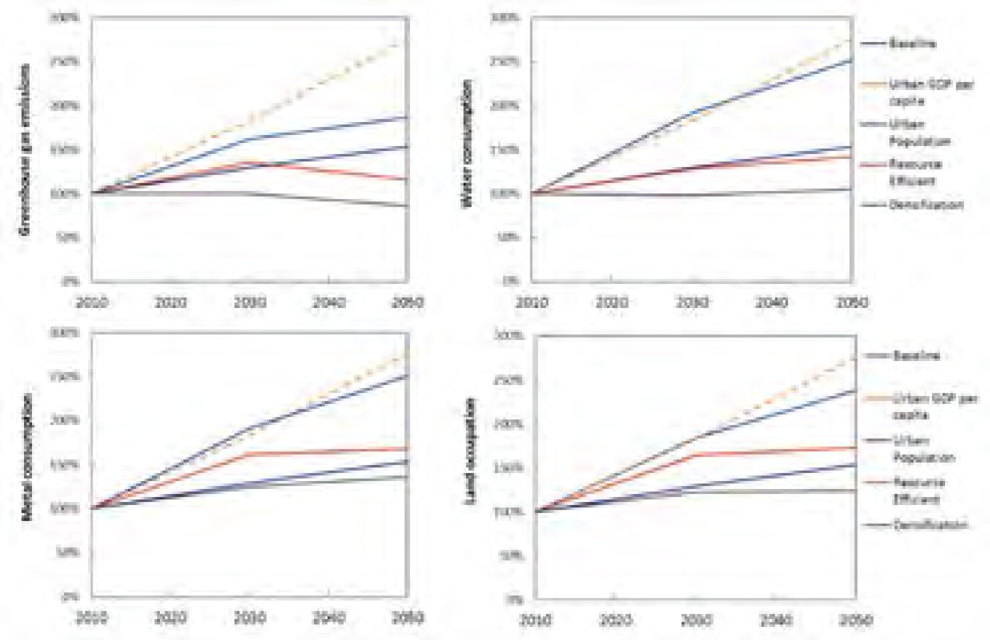
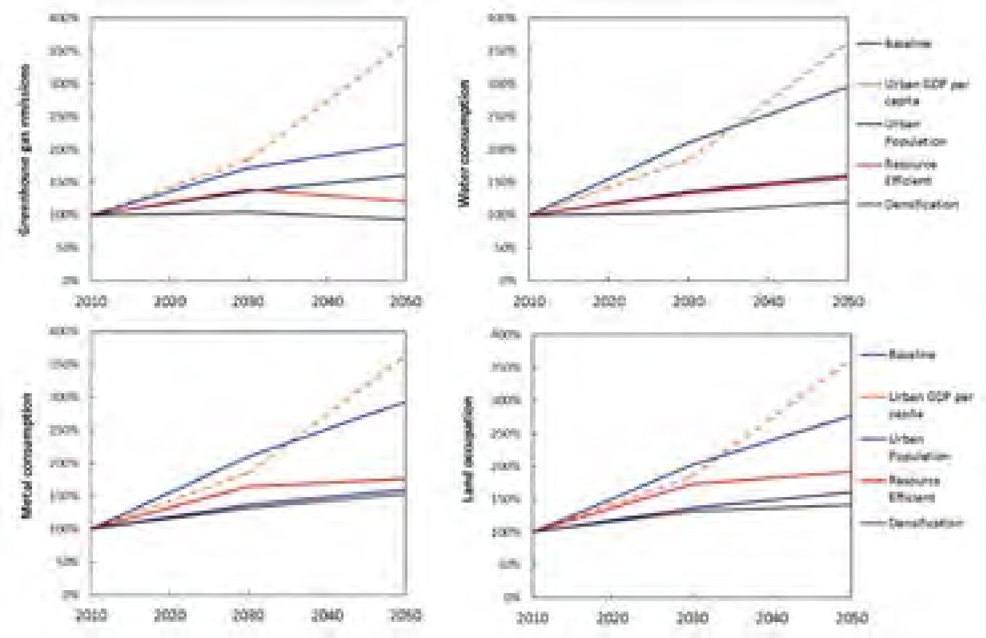


**Figure 2**: Resource-efficiency potential of Bus Rapid Transit in Riyadh



## B.1.2. District energy

**Figure 3**: Resource-efficiency potential of district energy in Cape Town

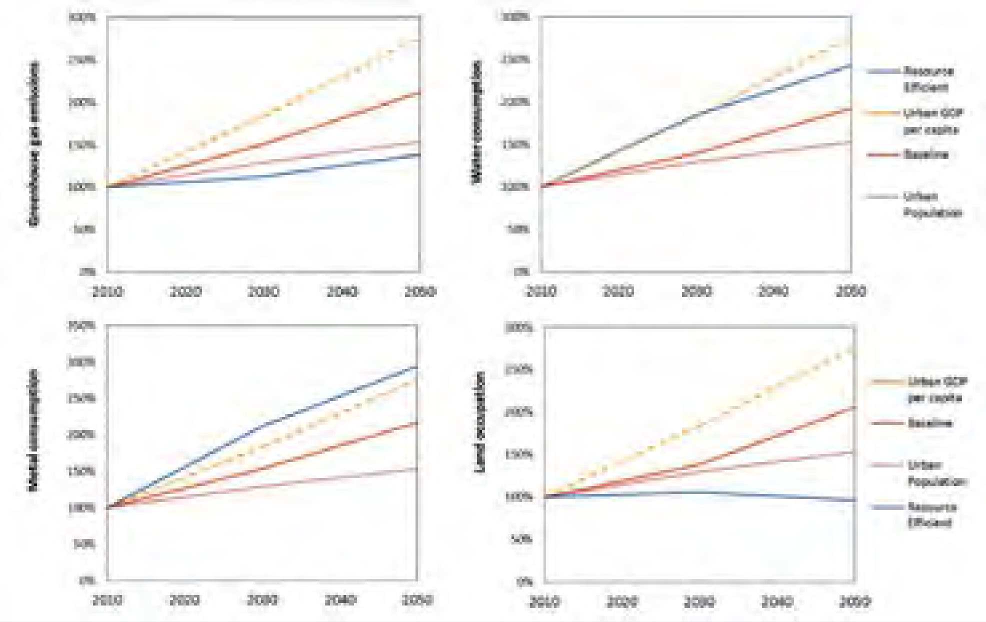
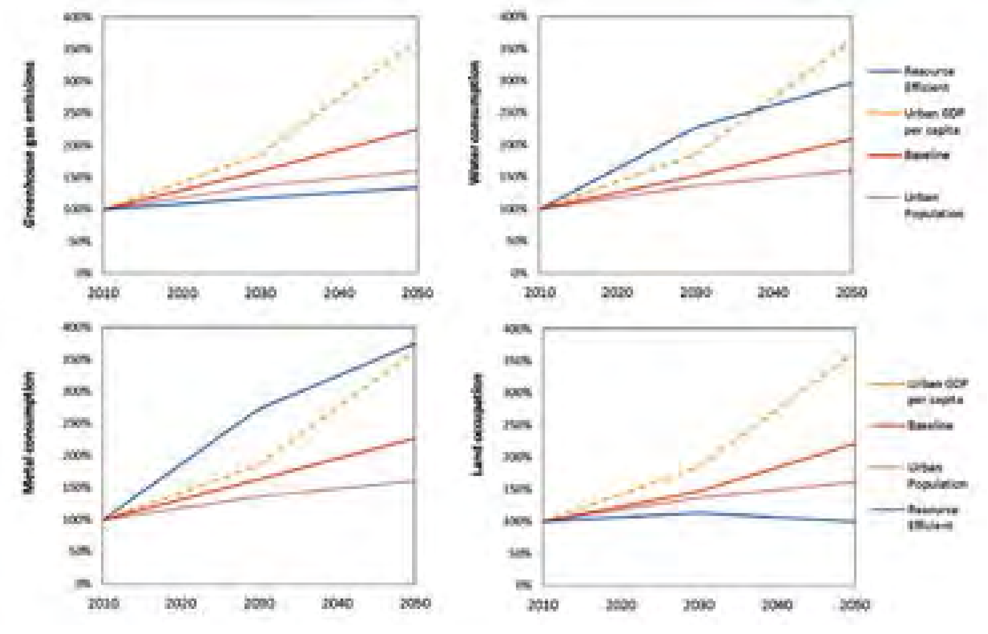
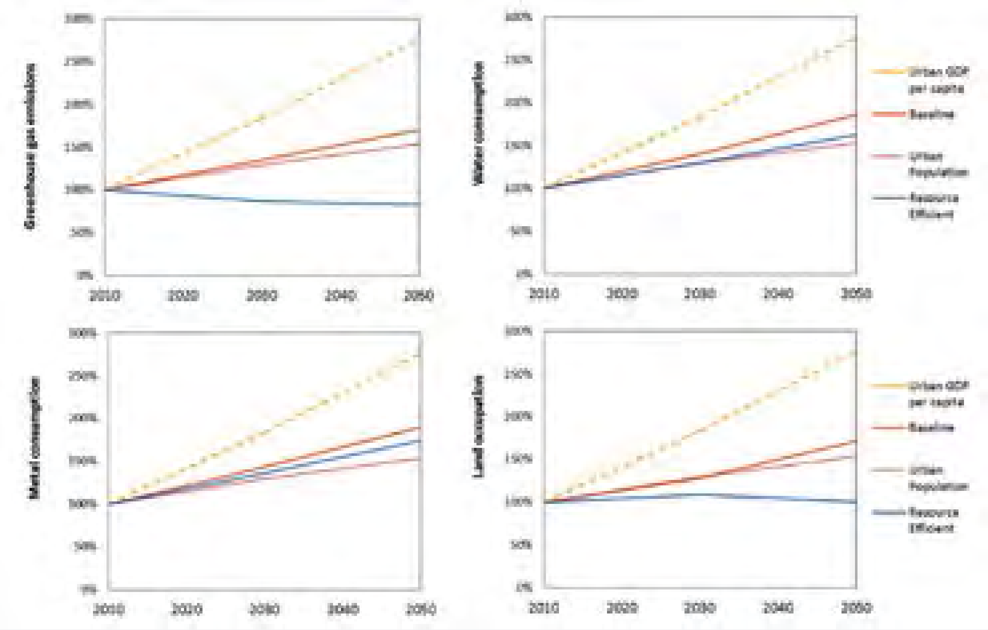


**Figure 4**: Resource-efficiency potential of district energy in Riyadh



## B.1.3. Green buildings

**Figure 5**: Resource-efficiency potential of green buildings in Cape Town



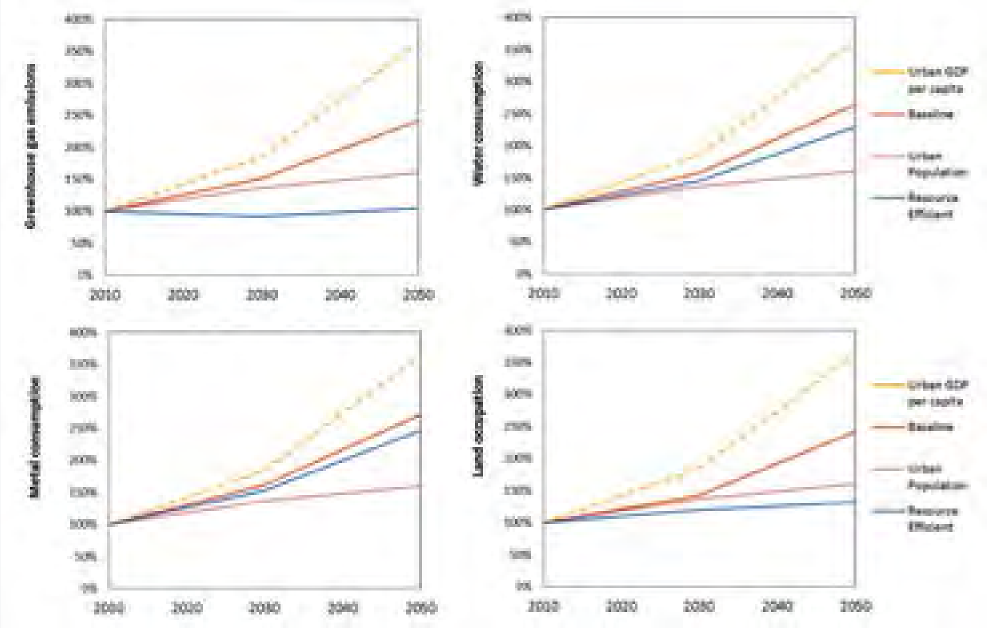


**Figure 6**: Resource-efficiency potential of green buildings in Riyadh

## B.2. China

### B.1.4. BRT

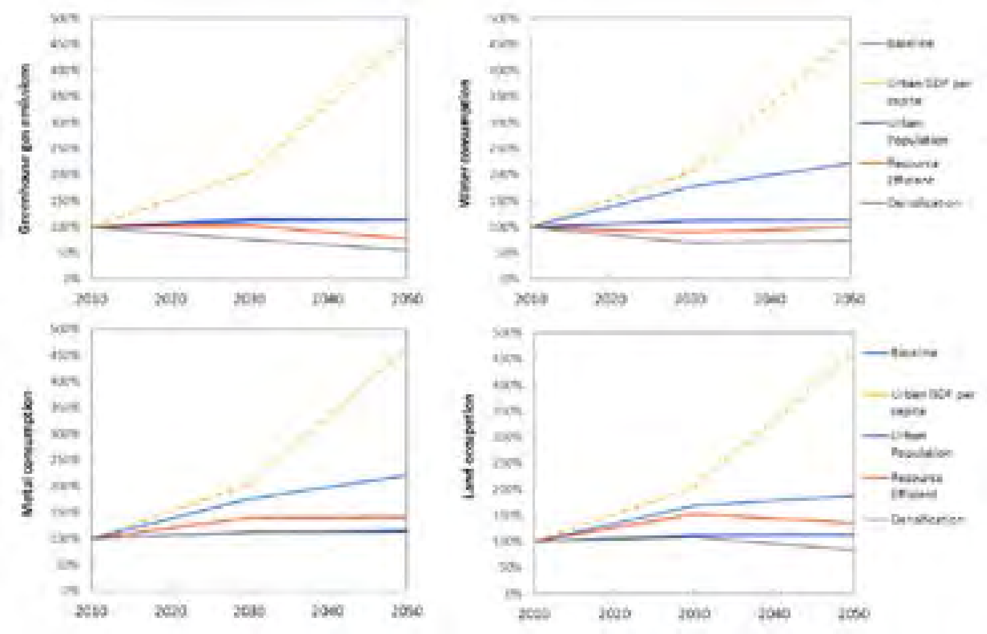


**Figure 7**: Resource-efficiency potential of Bus Rapid Transit in Hong Kong

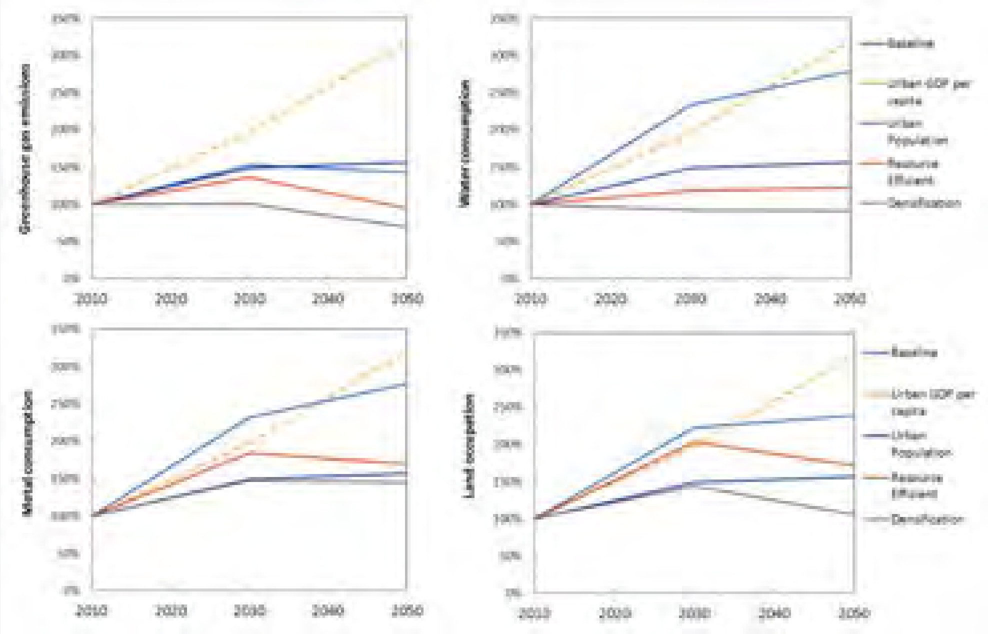


**Figure 8**: Resource-efficiency potential of Bus Rapid Transit in Beijing

## B.1.5. District energy

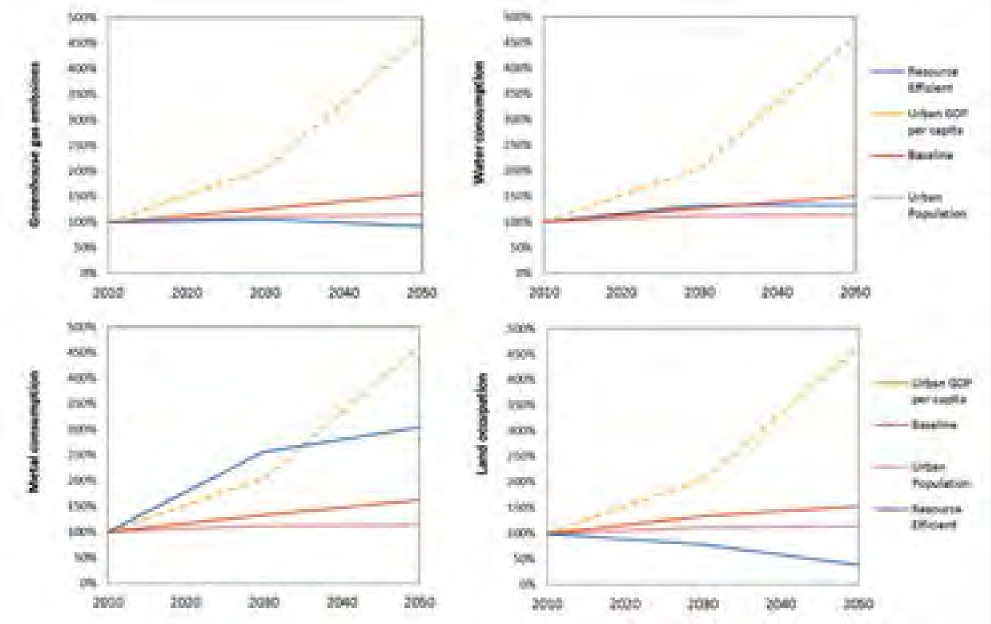
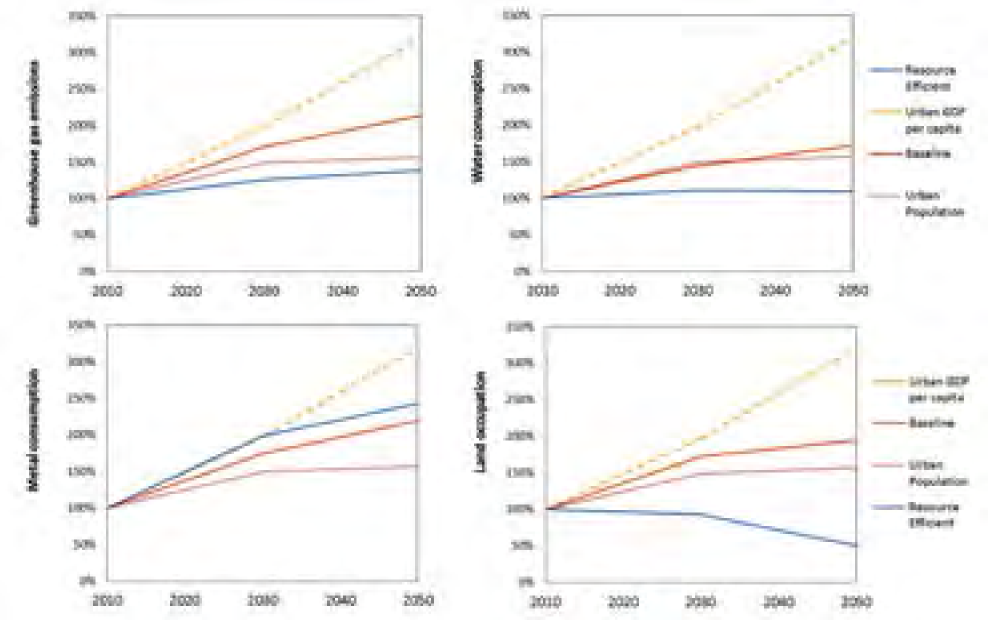


**Figure 9**: Resource-efficiency potential of district energy in Hong Kong

**Figure 10**: Resource-efficiency potential of district energy in Beijing



## B.1.6. Green buildings

**Figure 11**: Resource efficiency potential of green buildings in Hong Kong

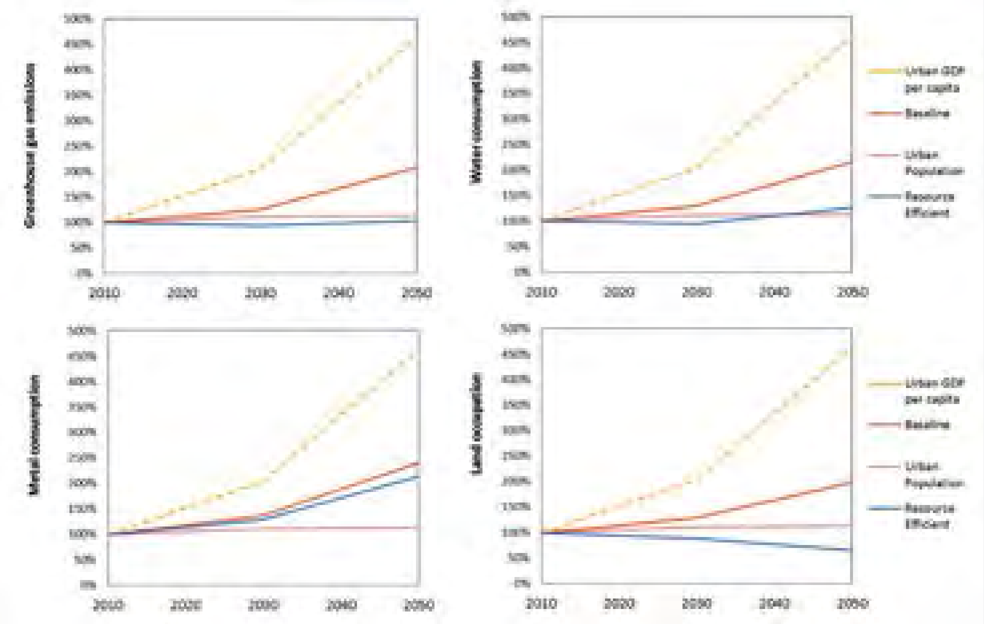
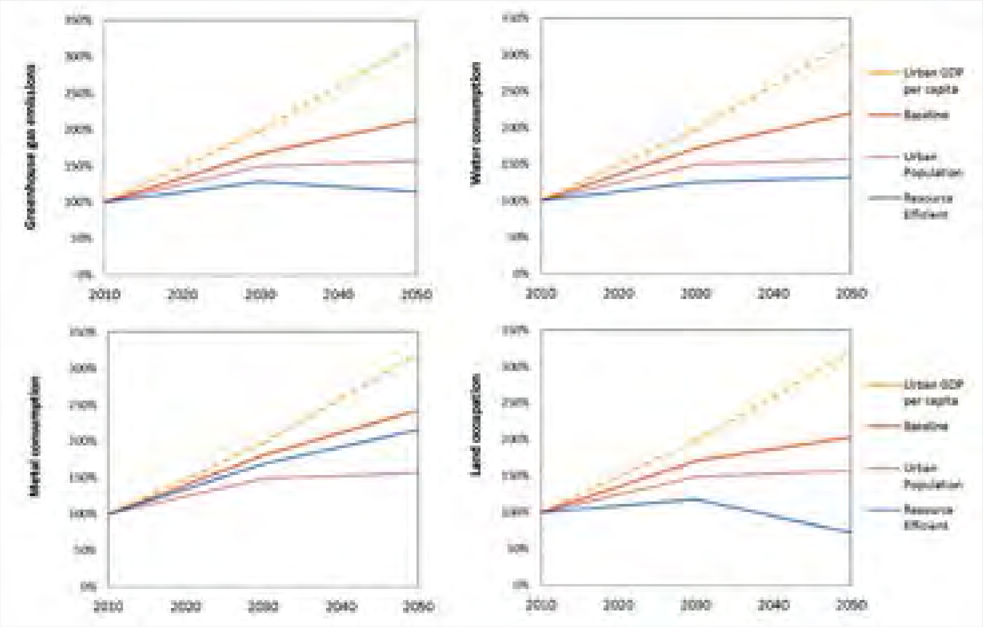


**Figure 12**: Resource-efficiency potential of green buildings in Beijing



## B.3. Latin America

### B.1.7. BRT

**Figure 13**: Resource-efficiency potential of Bus Rapid Transit in São Paulo

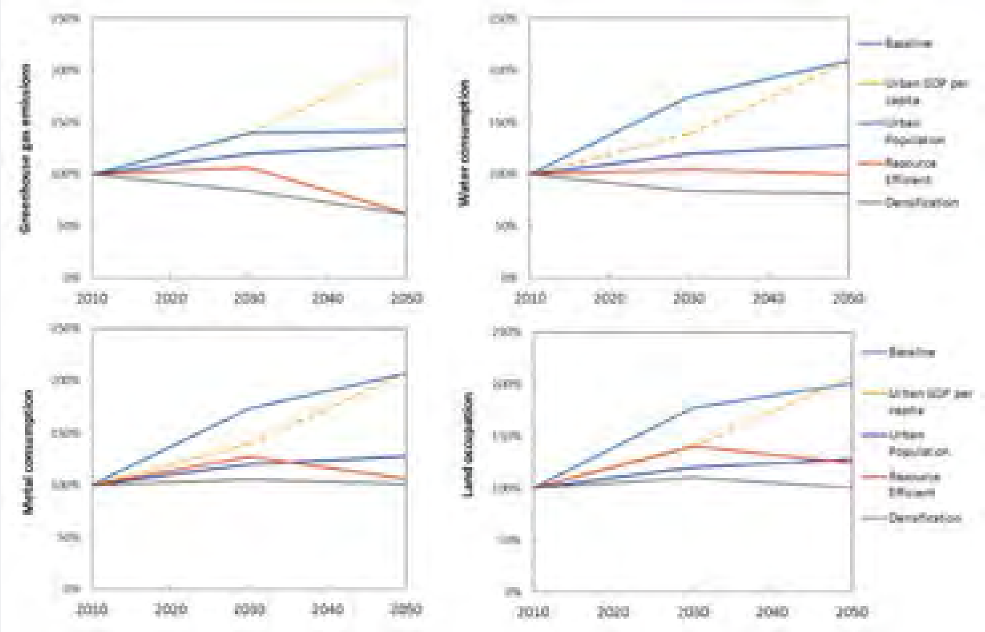
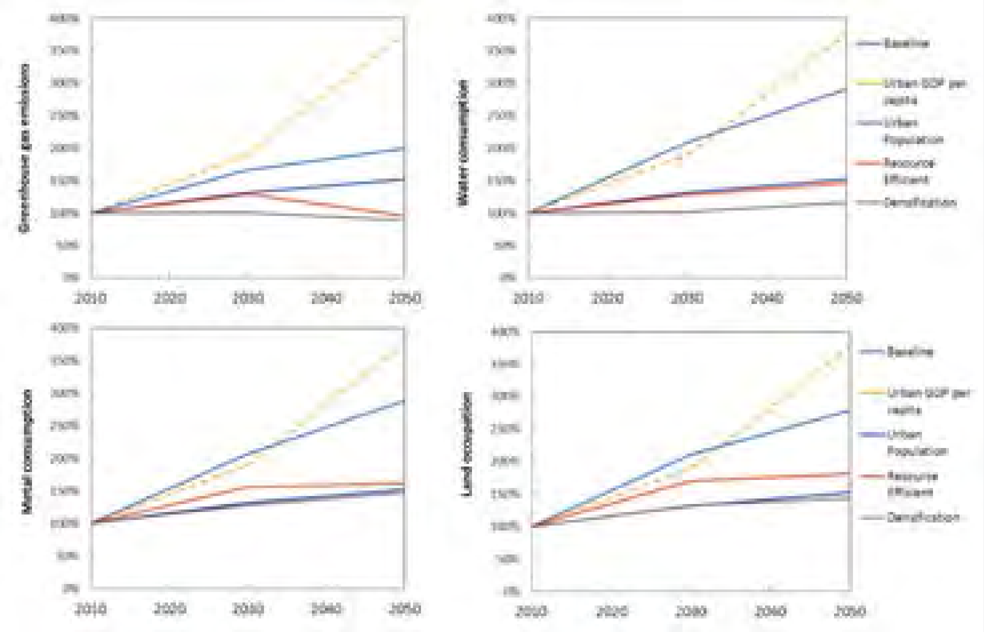


**Figure 14**: Resource-efficiency potential of Bus Rapid Transit in Bogotá



## B.1.8. District energy

**Figure 15**: Resource-efficiency potential of district energy in São Paulo

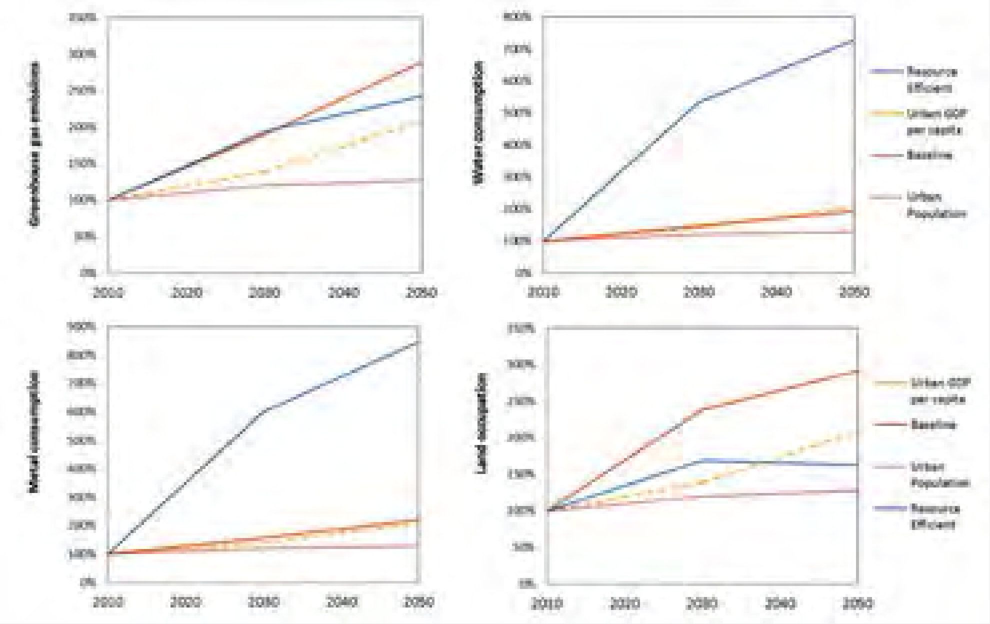
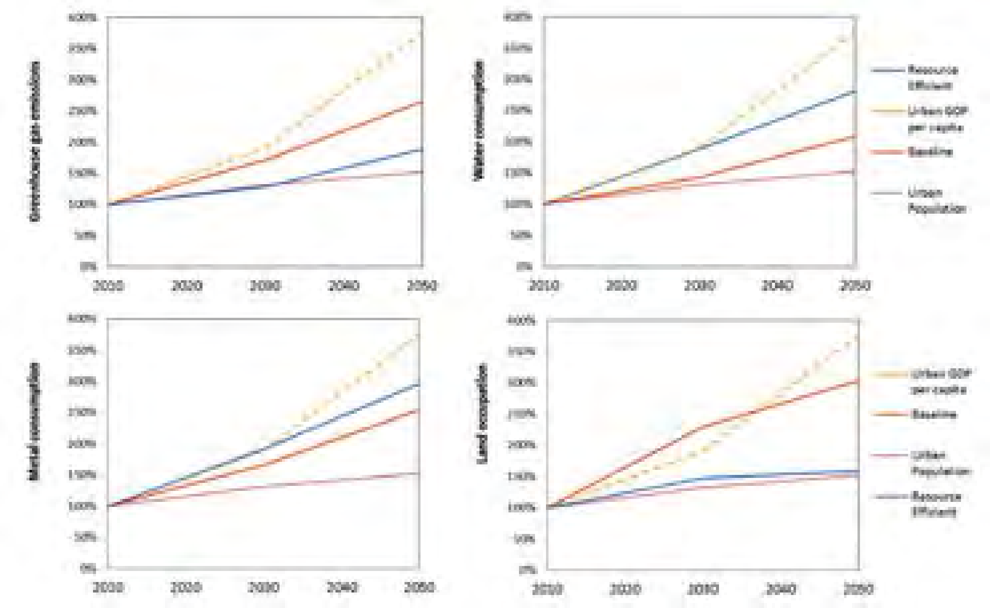


**Figure 16**: Resource-efficiency potential of district energy in Bogotá



## B.1.9. Green buildings

**Figure 17**: Resource-efficiency potential of green buildings in São Paulo

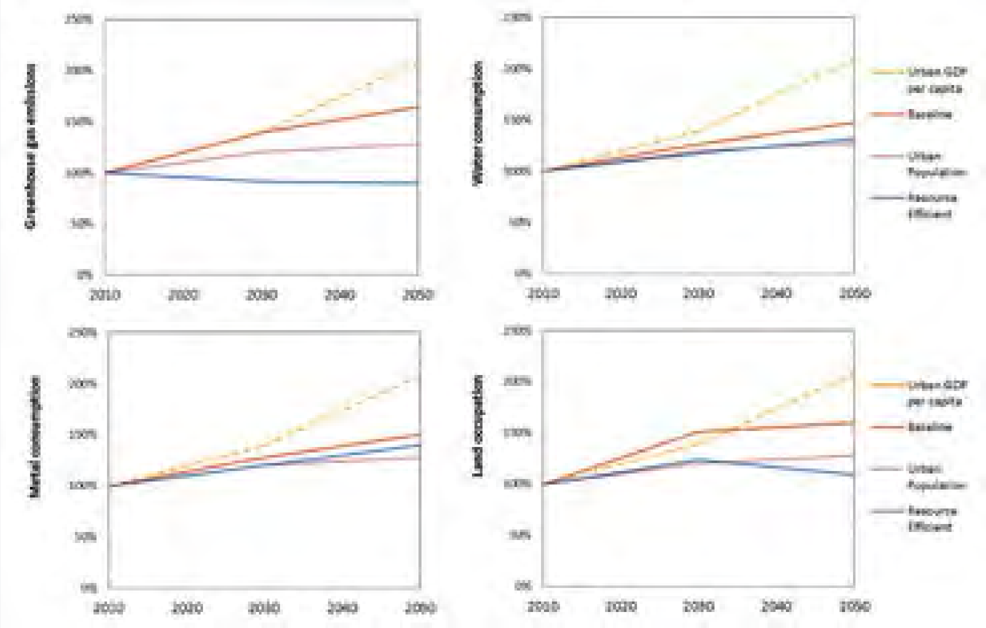
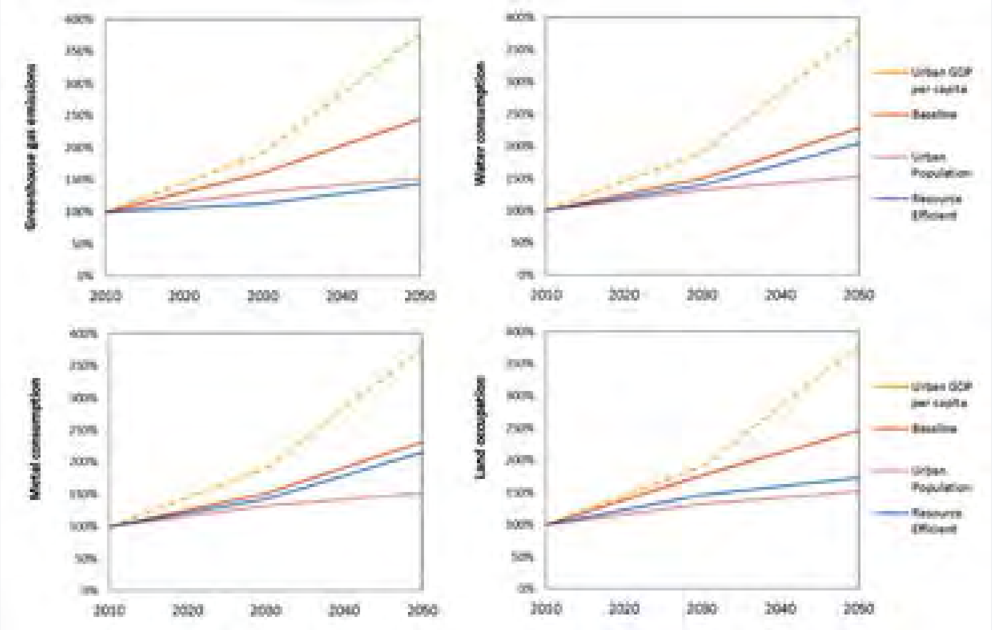


**Figure 18**: Resource-efficiency potential of green buildings in Bogotá



## B.4. OECD Europe

### B.1.10. BRT

**Figure 19**: Resource-efficiency potential of Bus Rapid Transit in Budapest

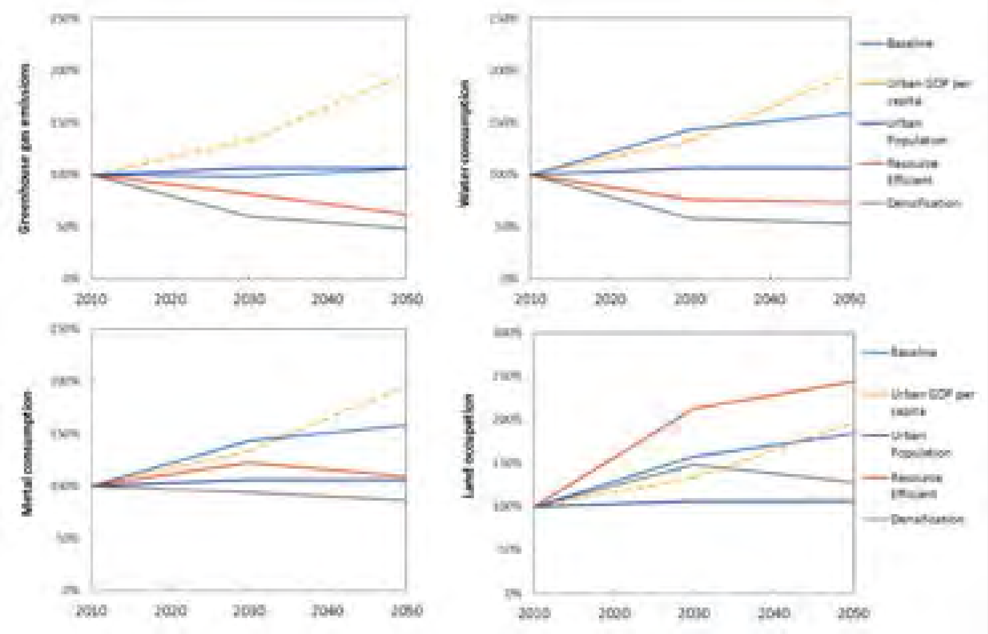
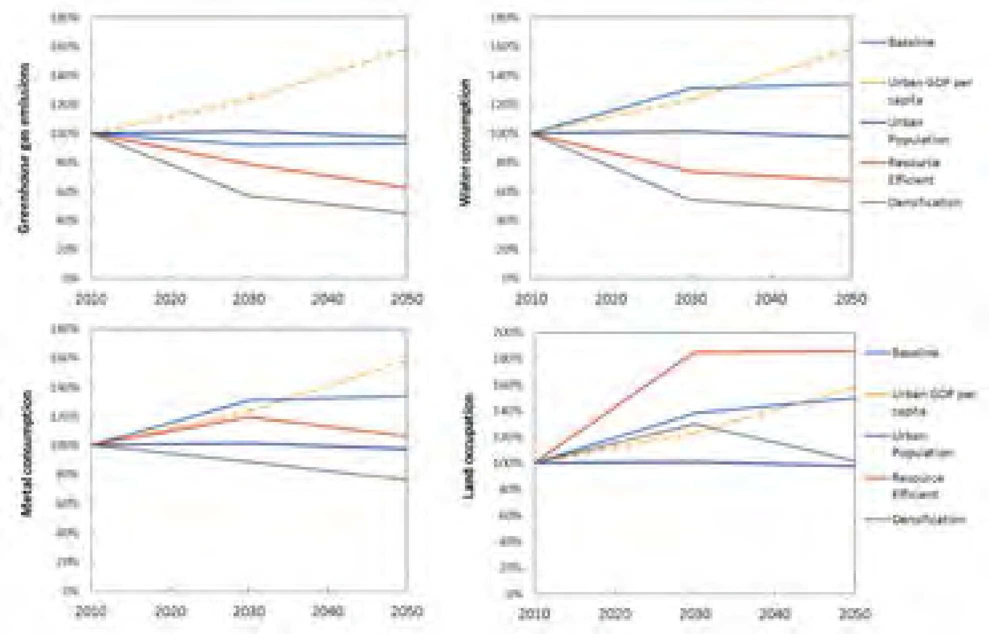


**Figure 20**: Resource-efficiency potential of Bus Rapid Transit in Berlin



## B.1.11. District energy

**Figure 21**: Resource-efficiency potential of district energy in Budapest

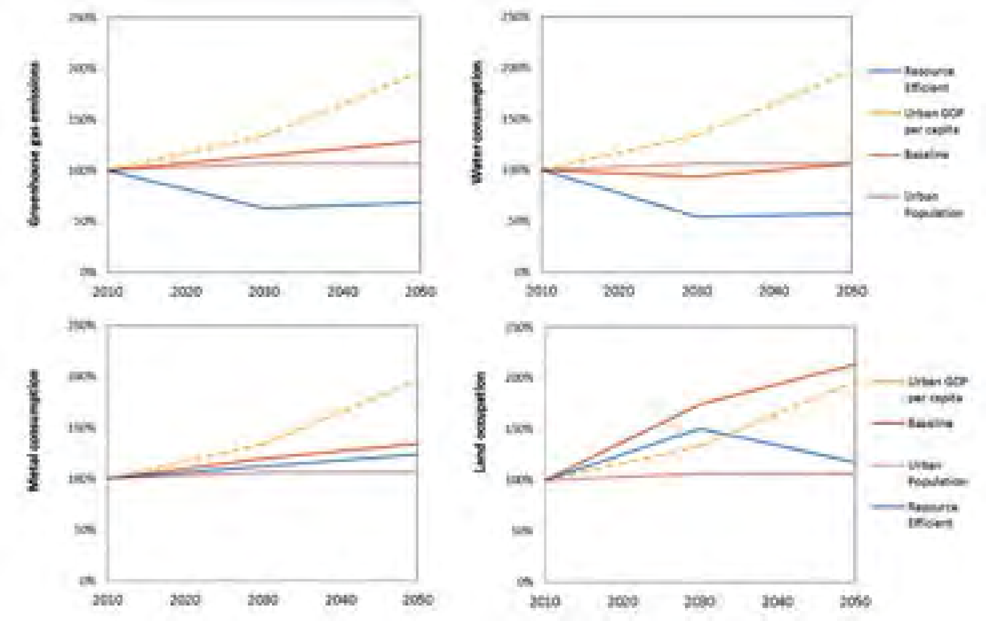
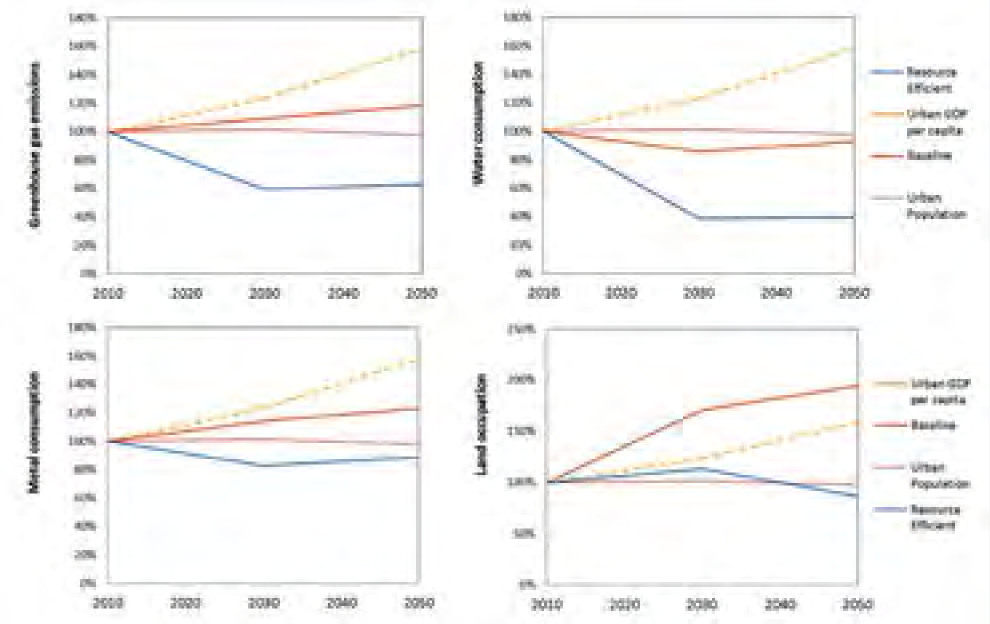


**Figure 22**: Resource-efficiency potential of district energy in Berlin



## B.1.12. Green buildings

**Figure 23**: Resource-efficiency potential of green buildings in Budapest

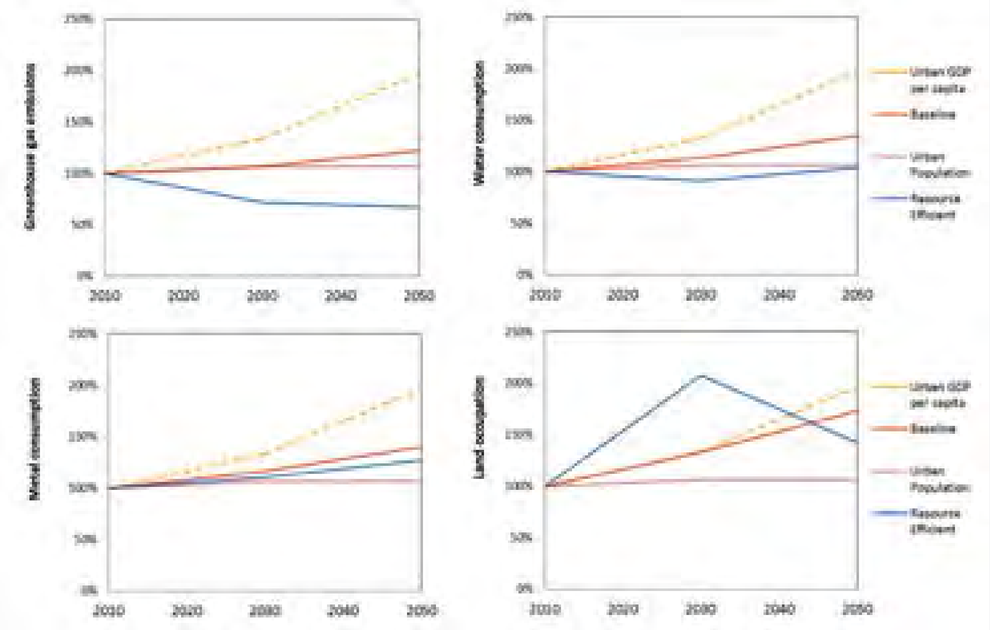
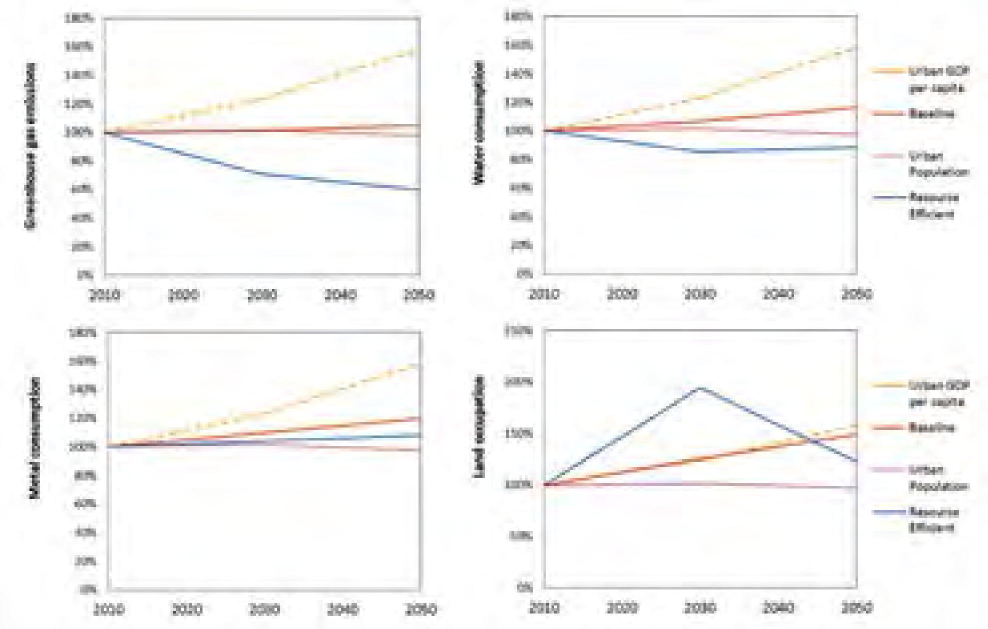


**Figure 24**: Resource-efficiency potential of green buildings in Berlin



## B.5. India

### B.1.13. BRT

**Figure 25**: Resource-efficiency potential of Bus Rapid Transit in Chennai

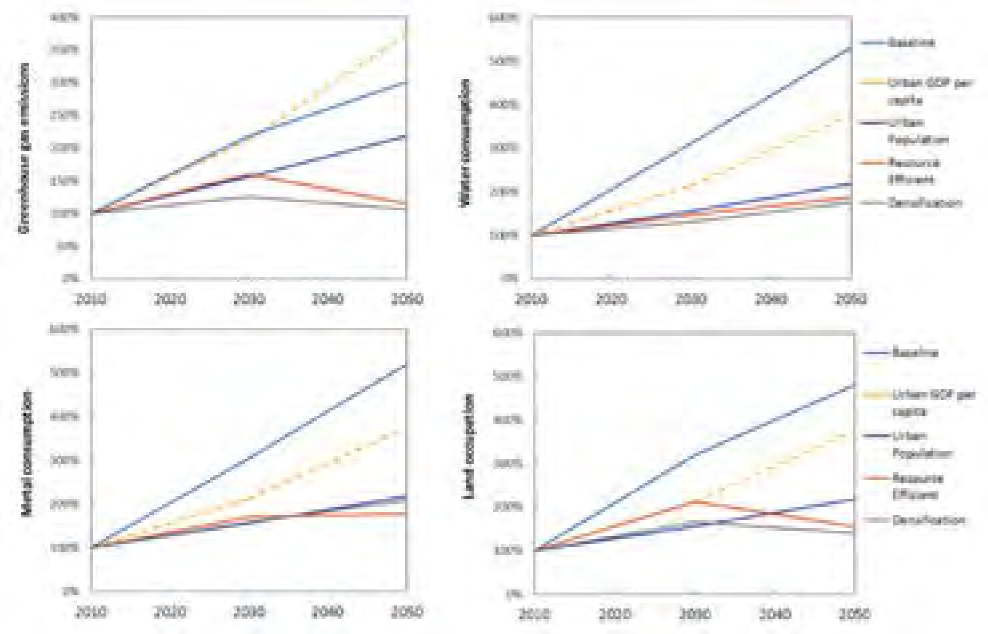
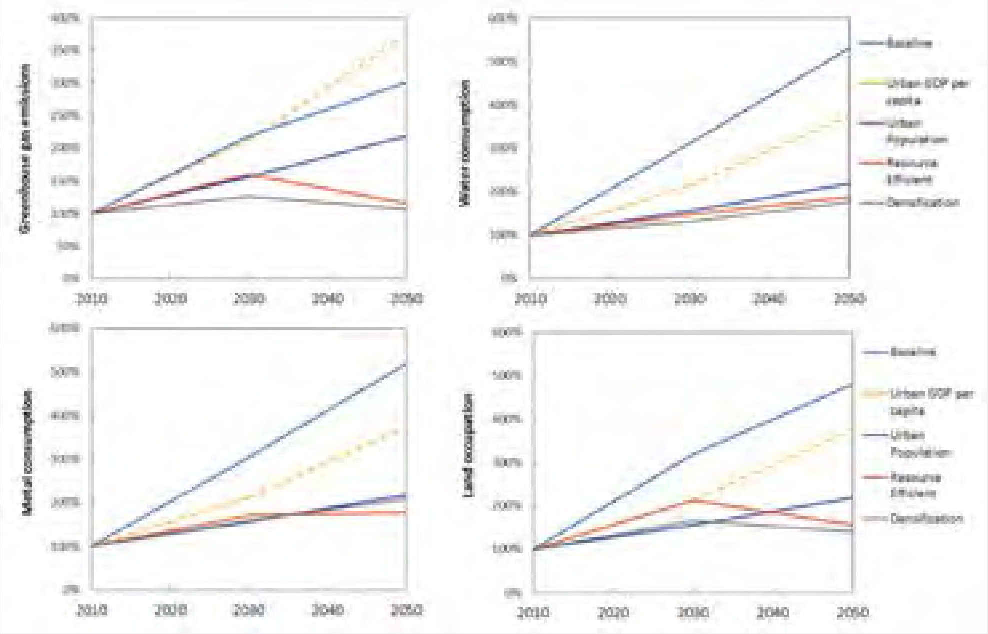


**Figure 26**: Resource-efficiency potential of Bus Rapid Transit in Mumbai



## B.1.14. District energy

**Figure 27**: Resource-efficiency potential of district energy in Chennai

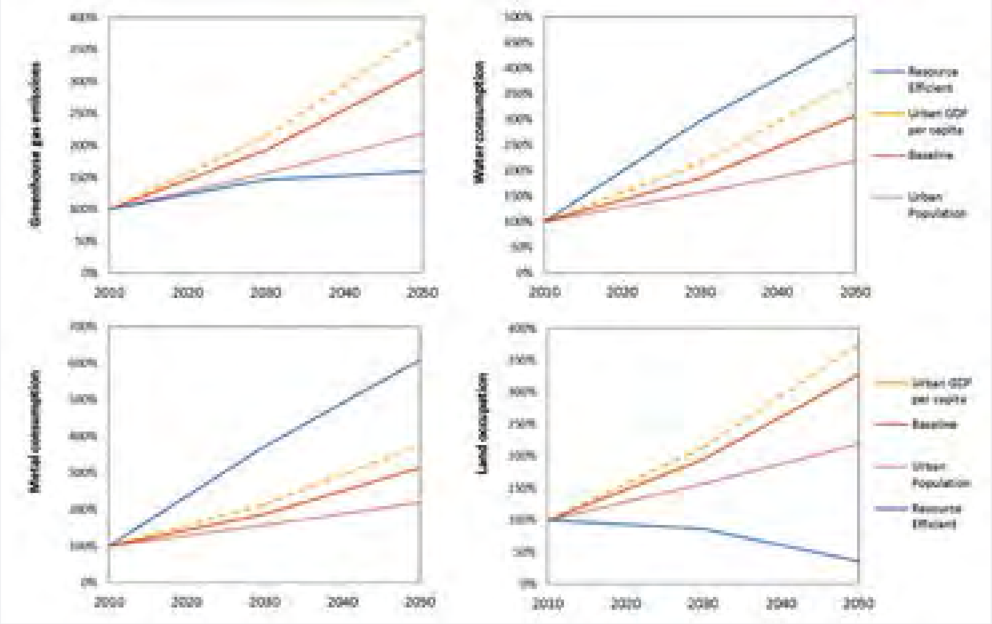
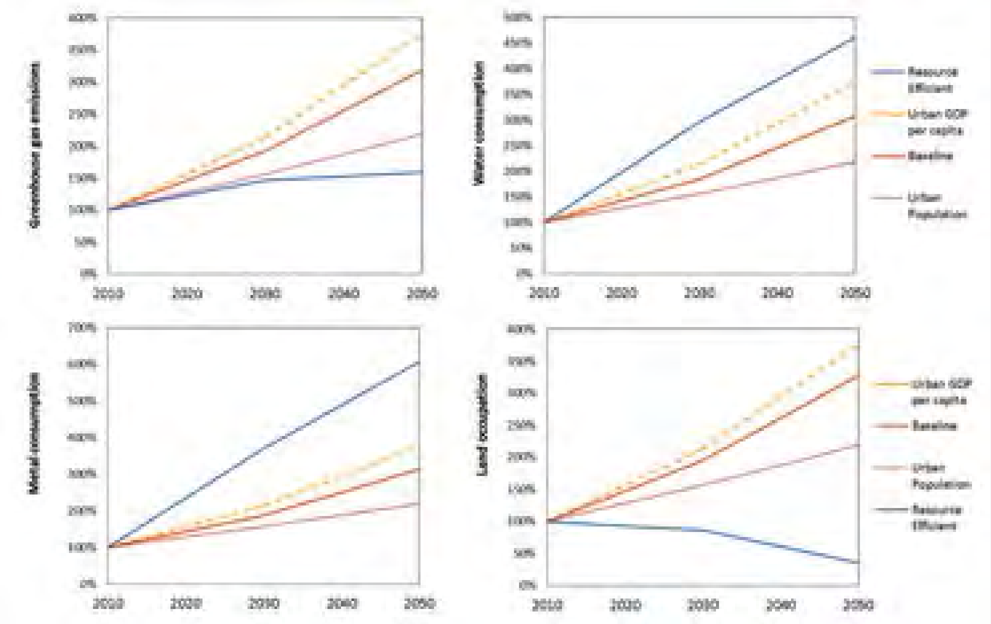


**Figure 28**: Resource-efficiency potential of district energy in Mumbai



## B.1.15. Green buildings

**Figure 29**: Resource-efficiency potential of green buildings in Chennai

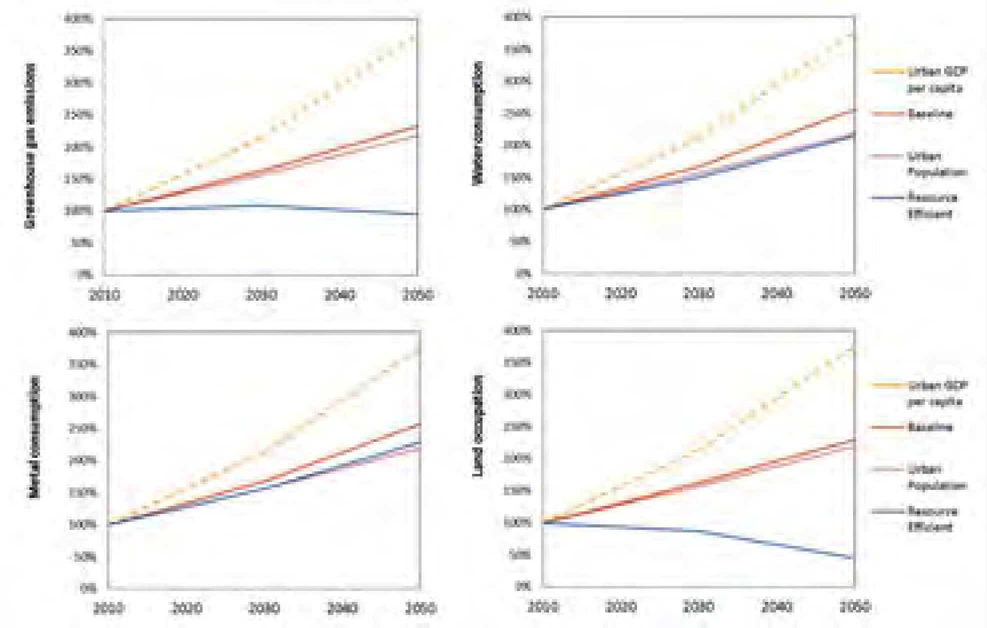
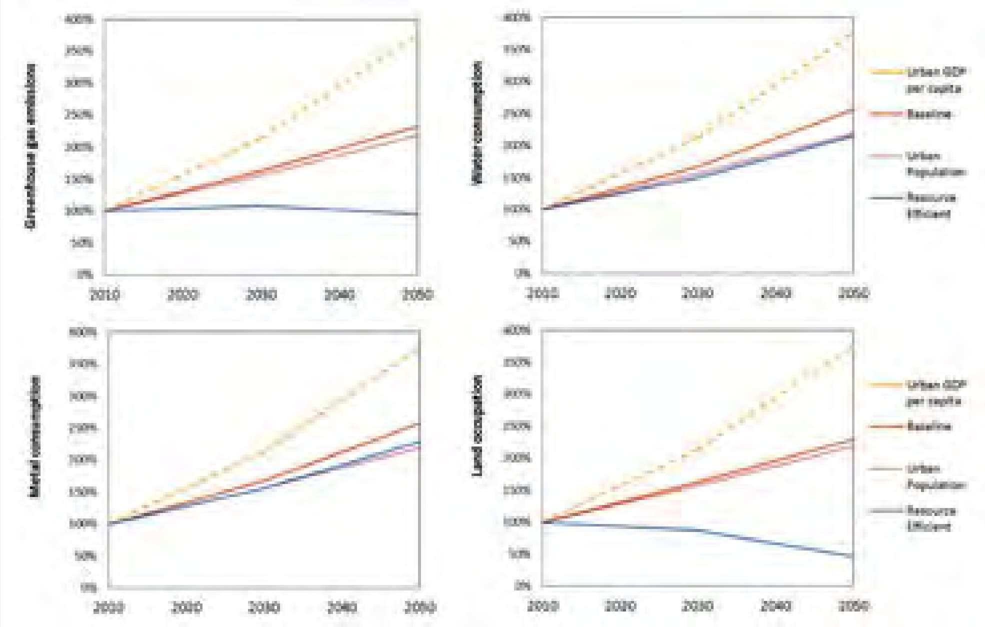


**Figure 30**: Resource-efficiency potential of green buildings in Mumbai



## B.6. OECD North America

### B.1.16. BRT

**Figure 31**: Resource-efficiency potential of Bus Rapid Transit in Los Angeles

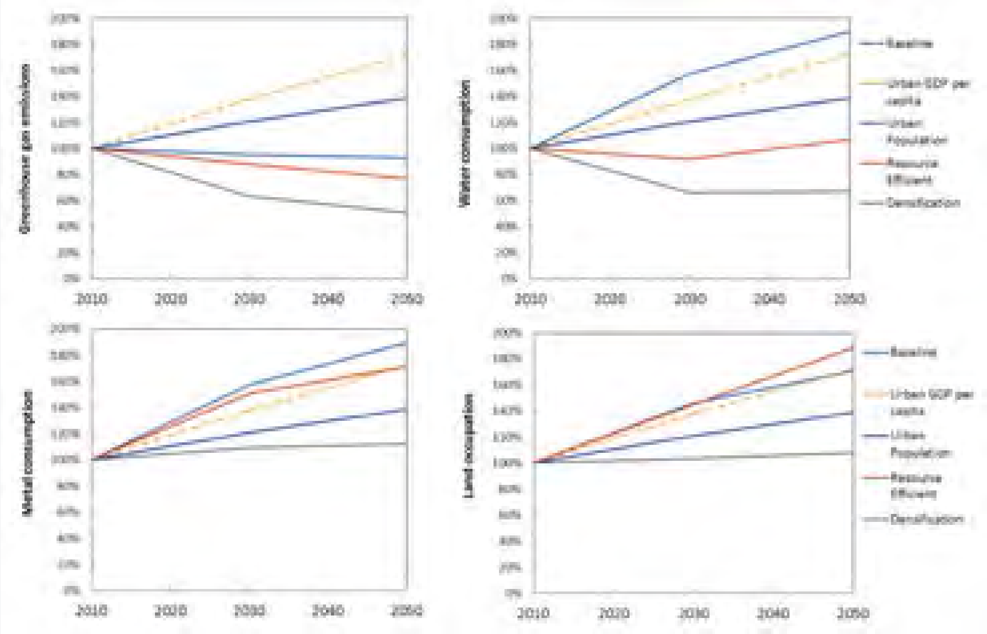
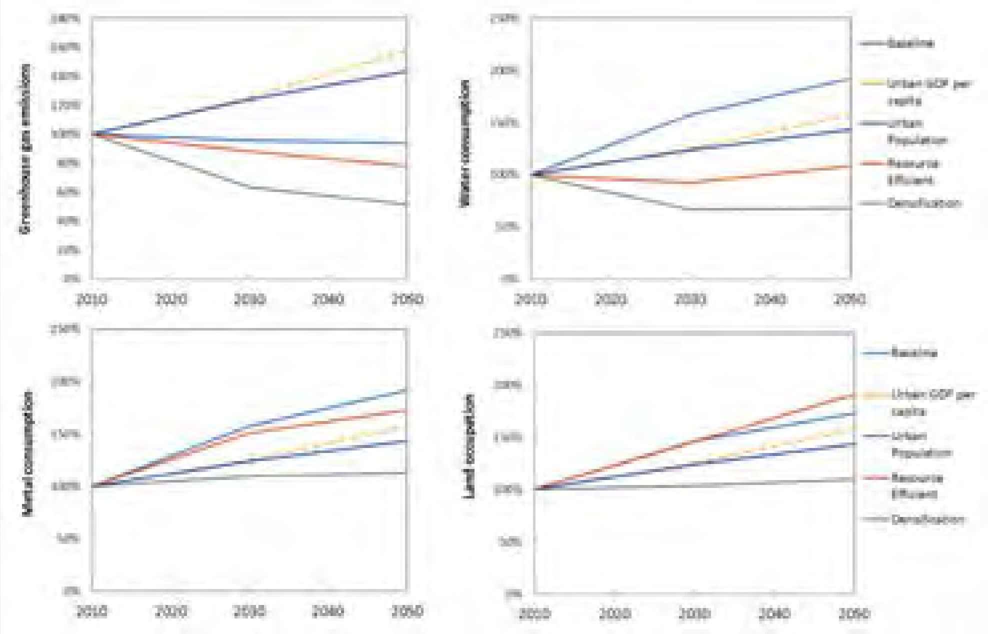


**Figure 32**: Resource-efficiency potential of Bus Rapid Transit in Toronto



## B.1.17.District energy

**Figure 33**: Resource-efficiency potential of district energy in Los Angeles

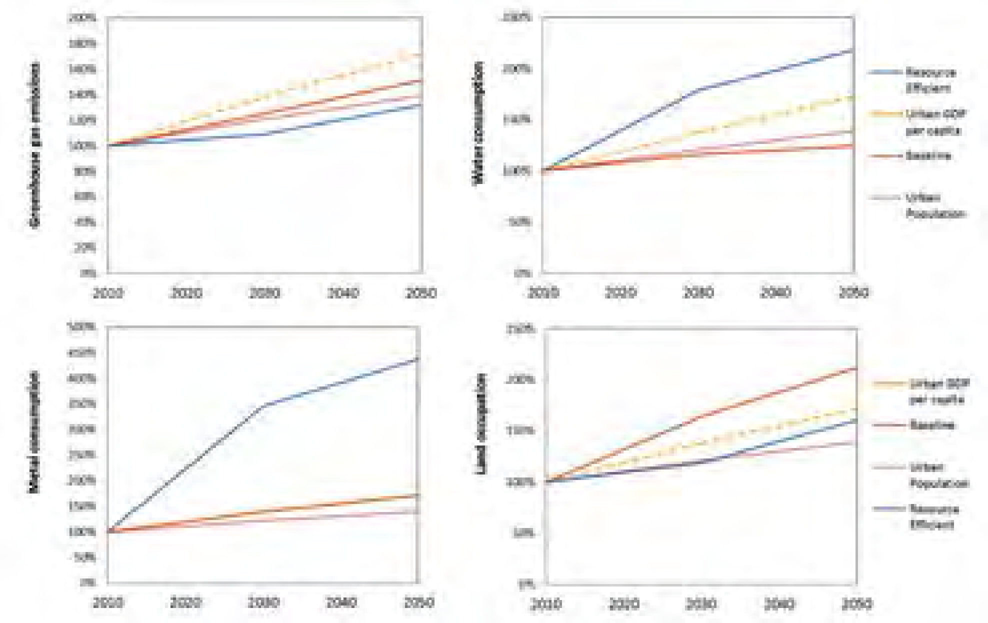
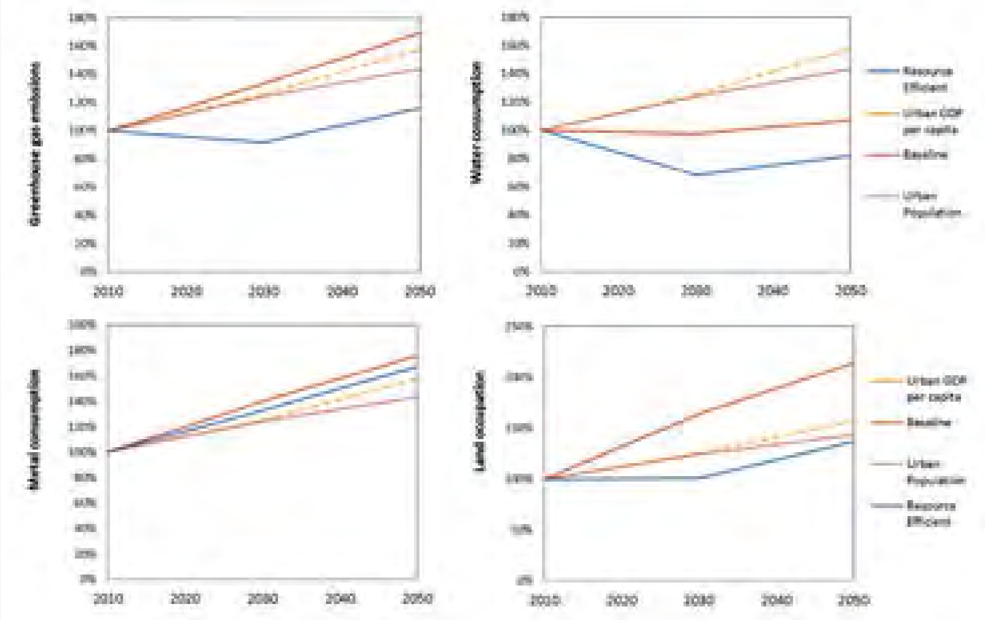


**Figure 34**: Resource-efficiency potential of district energy in Toronto



## B.1.18. Green buildings

**Figure 35**: Resource efficiency potential of green buildings in Los Angeles.

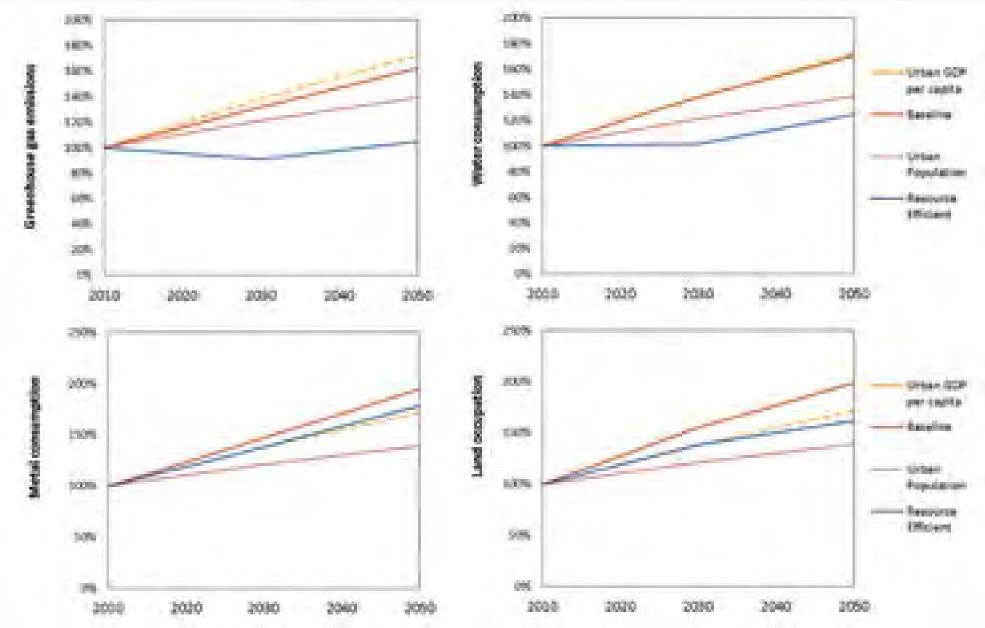
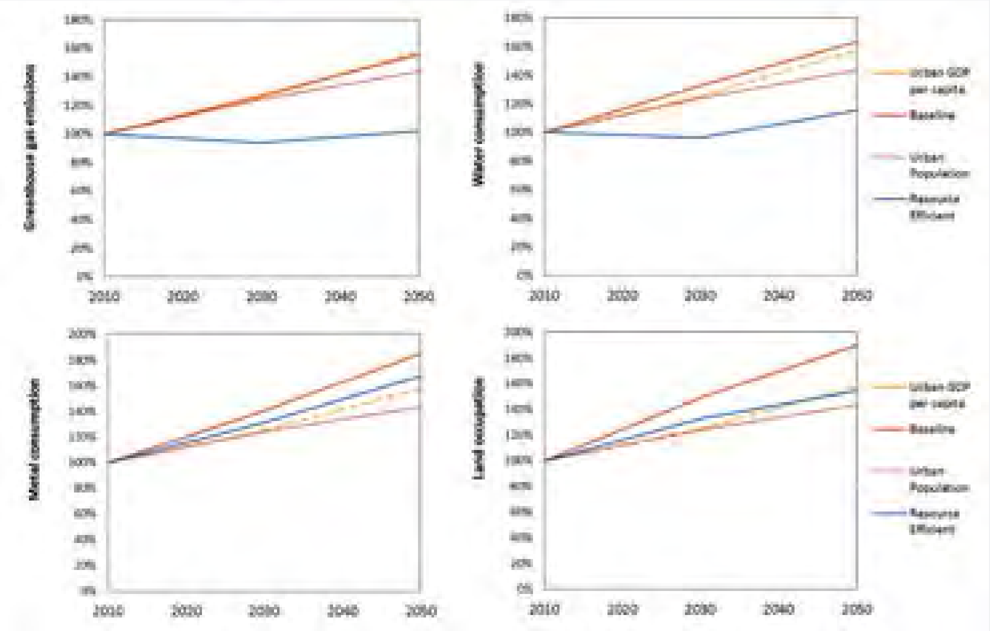


**Figure 36**: Resource-efficiency potential of green buildings in Toronto



## B.7. OECD Pacific

### B.1.19. BRT

**Figure 37**: Resource-efficiency potential of Bus Rapid Transit in Seoul

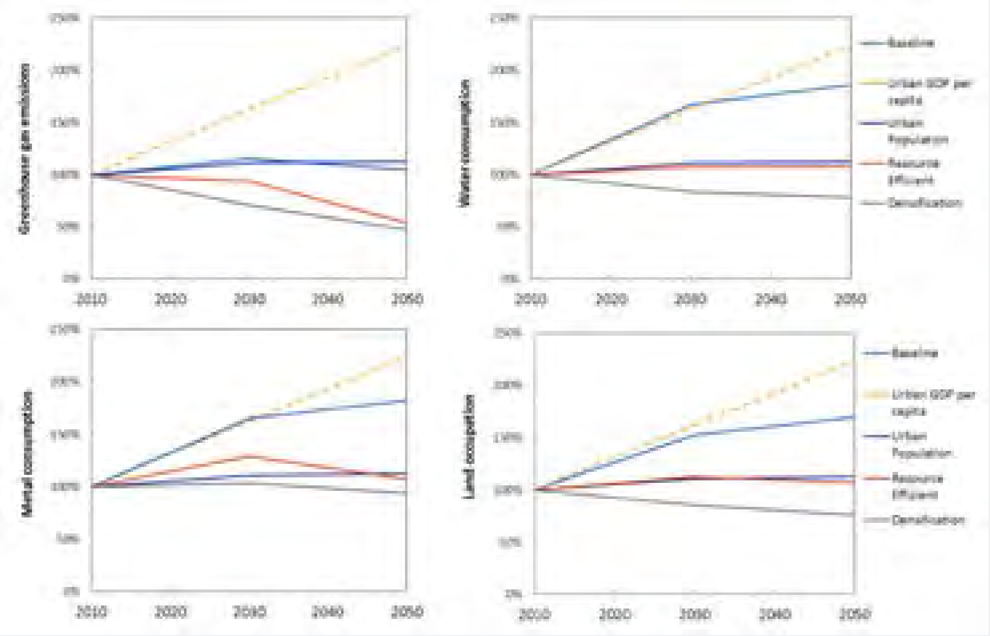
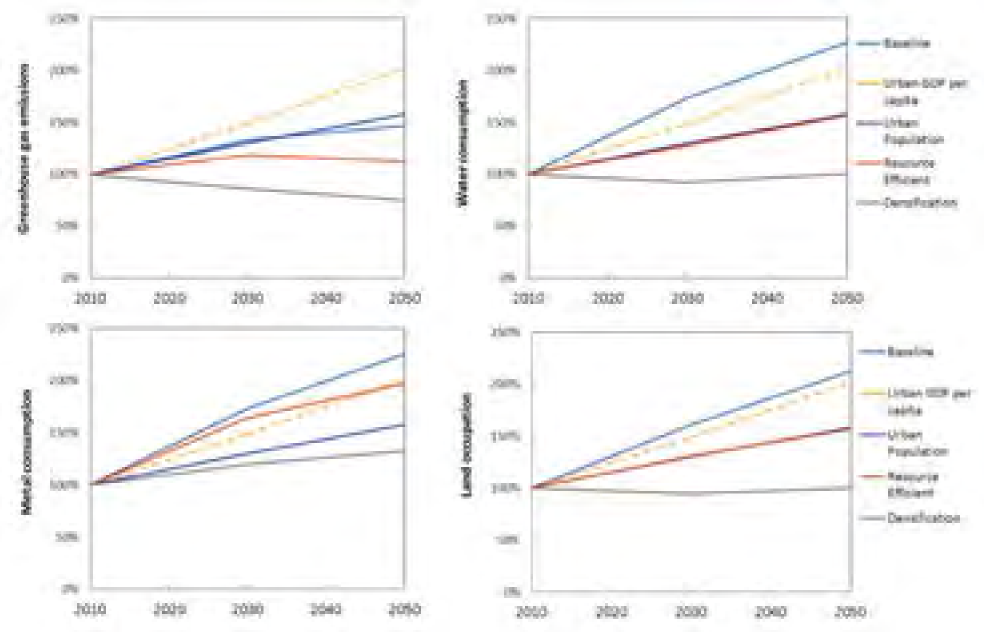


**Figure 38**: Resource-efficiency potential of Bus Rapid Transit in Sydney



## B.1.20. District energy

**Figure 39**: Resource-efficiency potential of district energy in Seoul

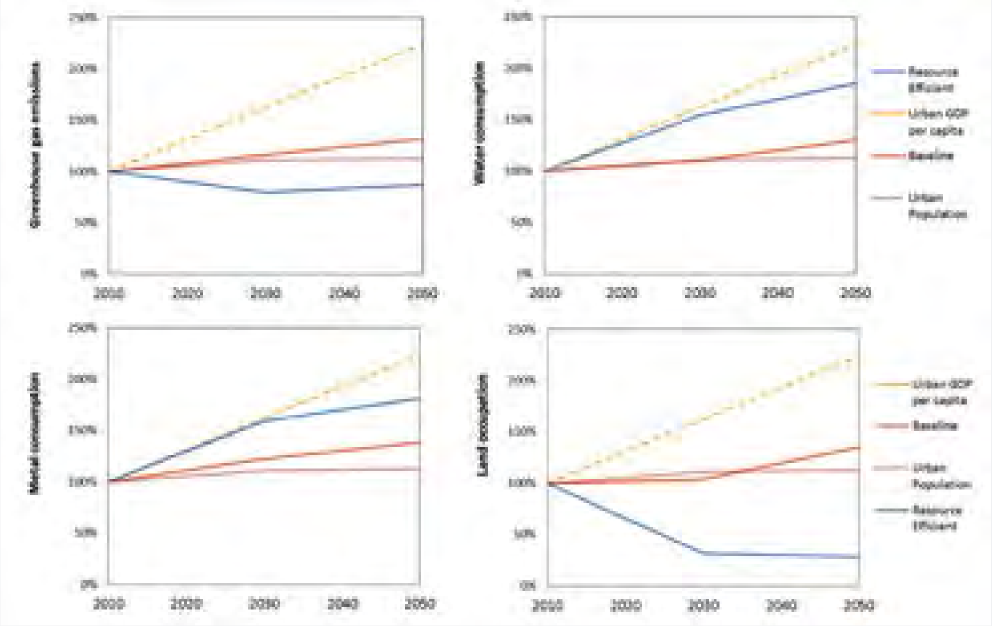
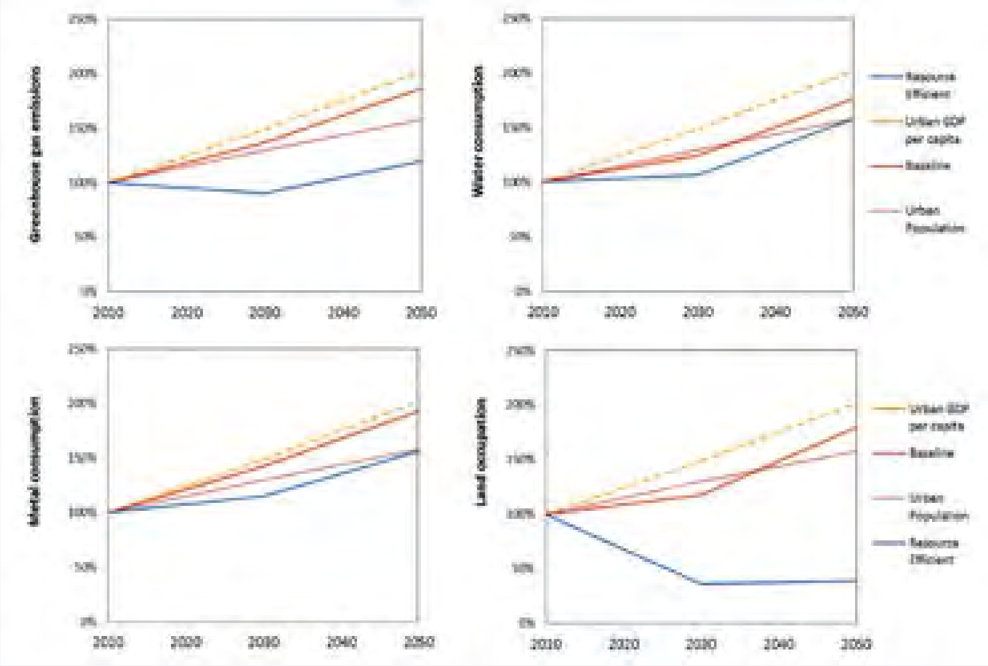


**Figure 40**: Resource-efficiency potential of district energy in Sydney



## B.1.21. Green buildings

**Figure 41**: Resource-efficiency potential of green buildings in Seoul

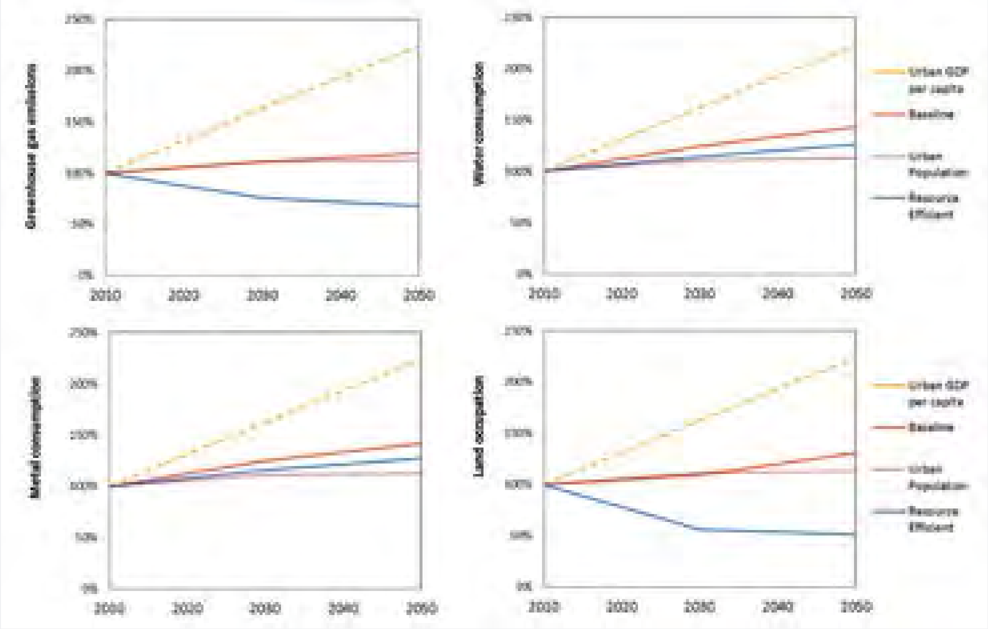
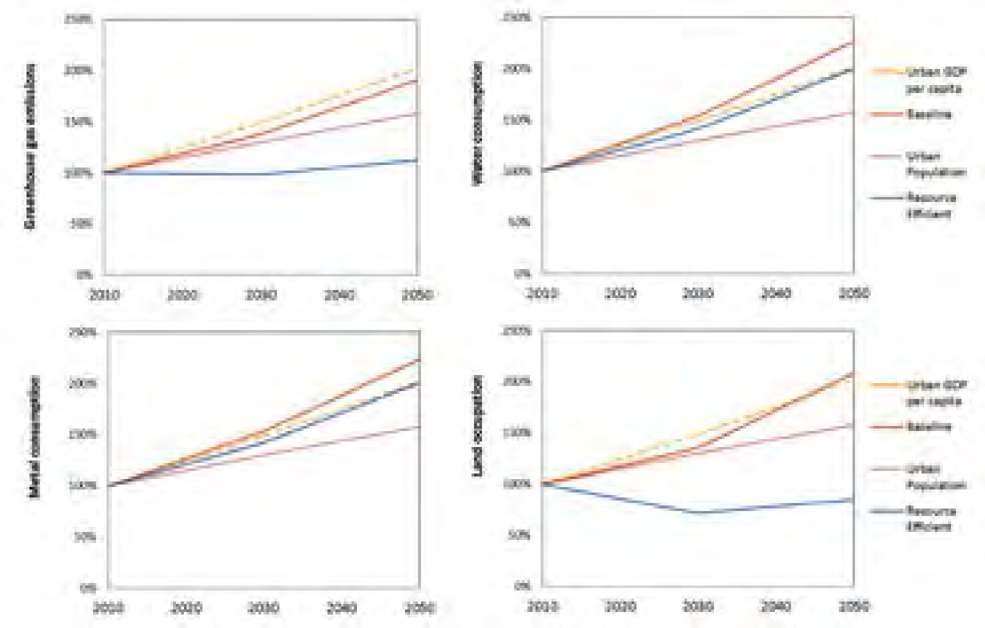


**Figure 42**: Resource-efficiency potential of green buildings in Sydney



## B.8. Other Developing Asia

### B.1.22. BRT

**Figure 43**: Resource-efficiency potential of Bus Rapid Transit in Jakarta

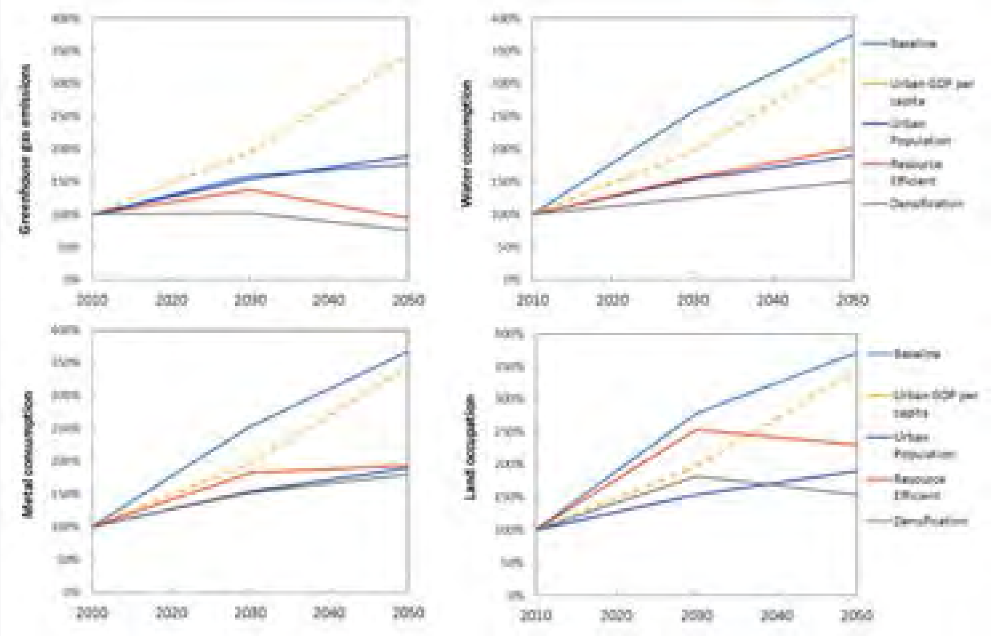
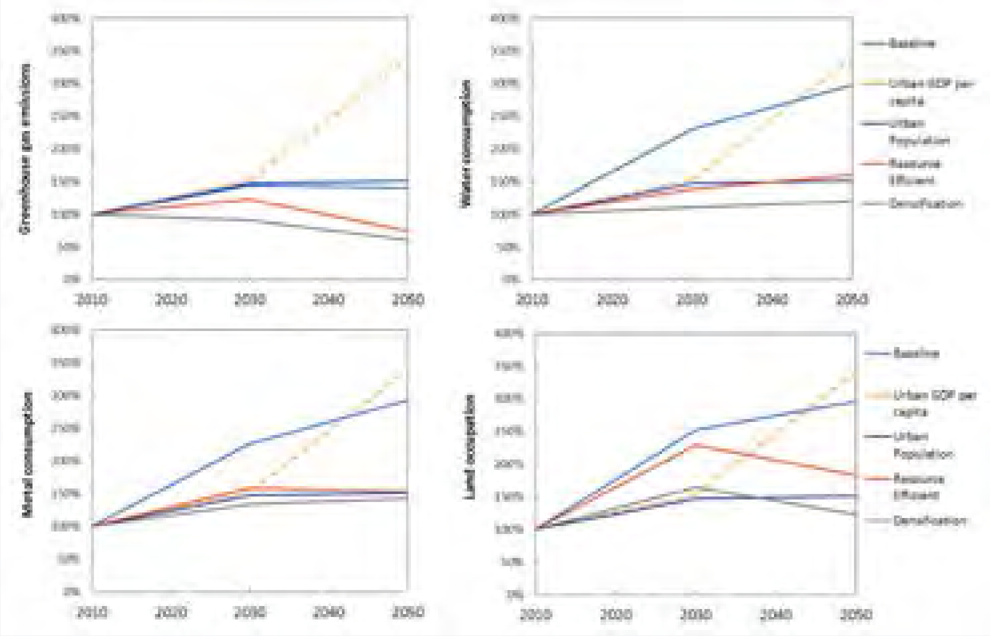


**Figure 44**: Resource-efficiency potential of Bus Rapid Transit in Bangkok



## B.1.23. District energy

**Figure 45**: Resource-efficiency potential of district energy in Jakarta

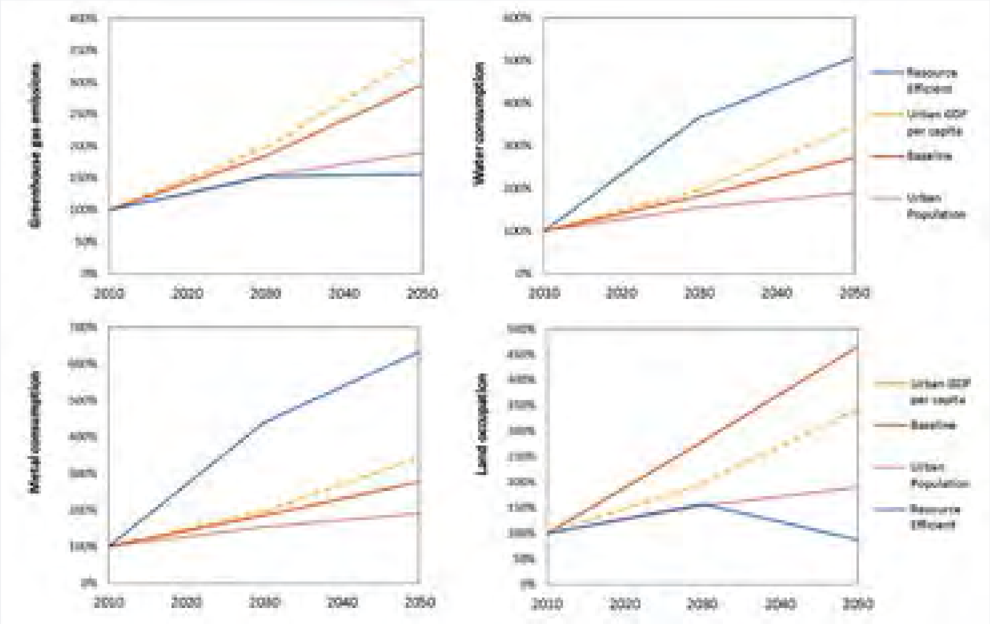
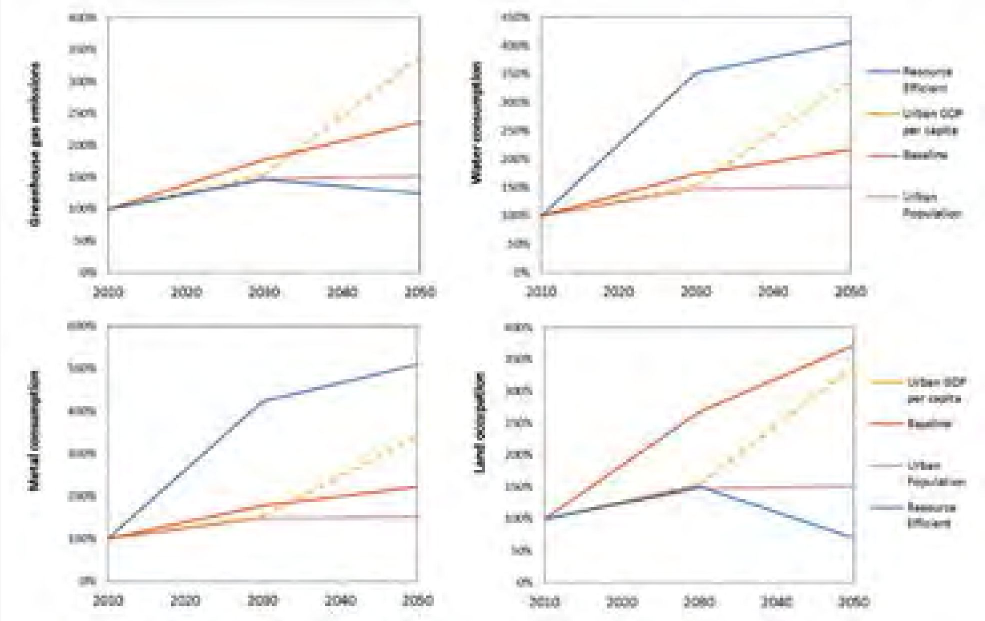


**Figure 46**: Resource-efficiency potential of district energy in Bangkok



## B.1.24. Green buildings

**Figure 47**: Resource-efficiency potential of green buildings in Jakarta

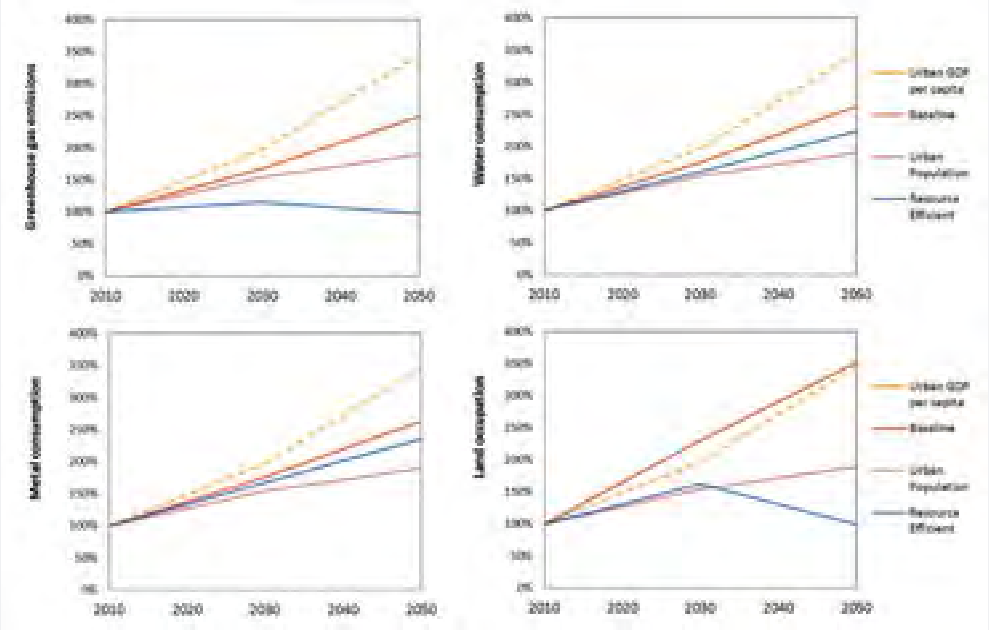
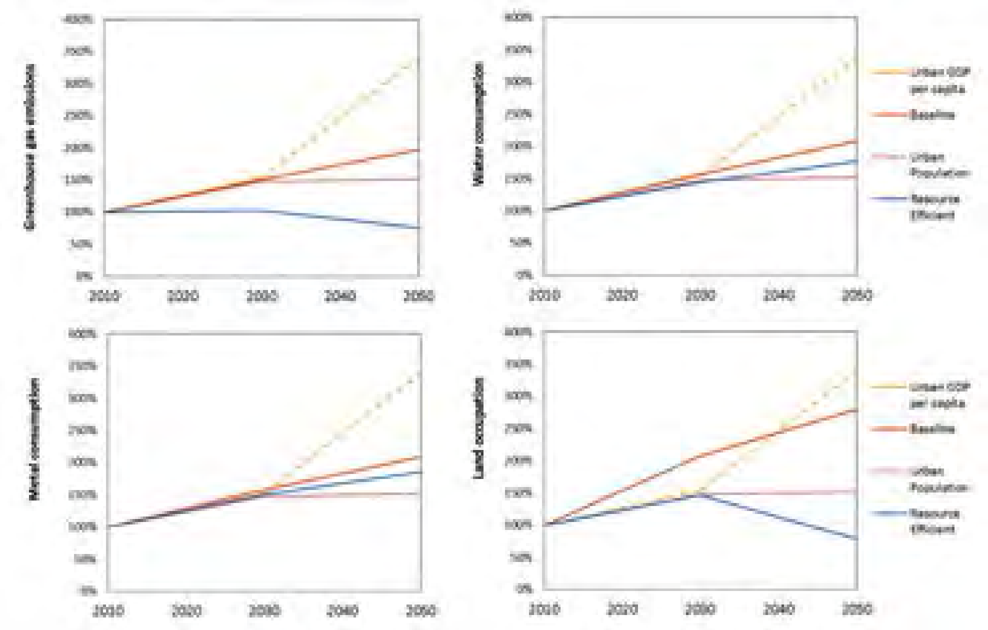


**Figure 48**: Resource-efficiency potential of green buildings in Bangkok



# Appendix C — Additional results

The figures in this appendix show the resource impacts of meeting demand projections in all 84 cities under each scenario. In the scatter plots, cities are classified according to their income (i.e. total urban GDP per capita) in 2010, 2030 and 2050 and the total life-cycle GHG emissions, water consumption, land use and metal consumption are shown for each year in each scenario. In these graphs, a general comparison of the placement of the green and blue (resource-efficient and densification) points with the placement of the orange points (baseline) can provide insight into the potential for decoupling impacts from economic growth in cities from the present to 2050.

**Figure 49**: Transportation: the relationship between resource impacts and GDP per capita in 84 cities under baseline (BL), resource-efficient (RE) and resource-efficient with strategic densification (RE_dense) scenarios

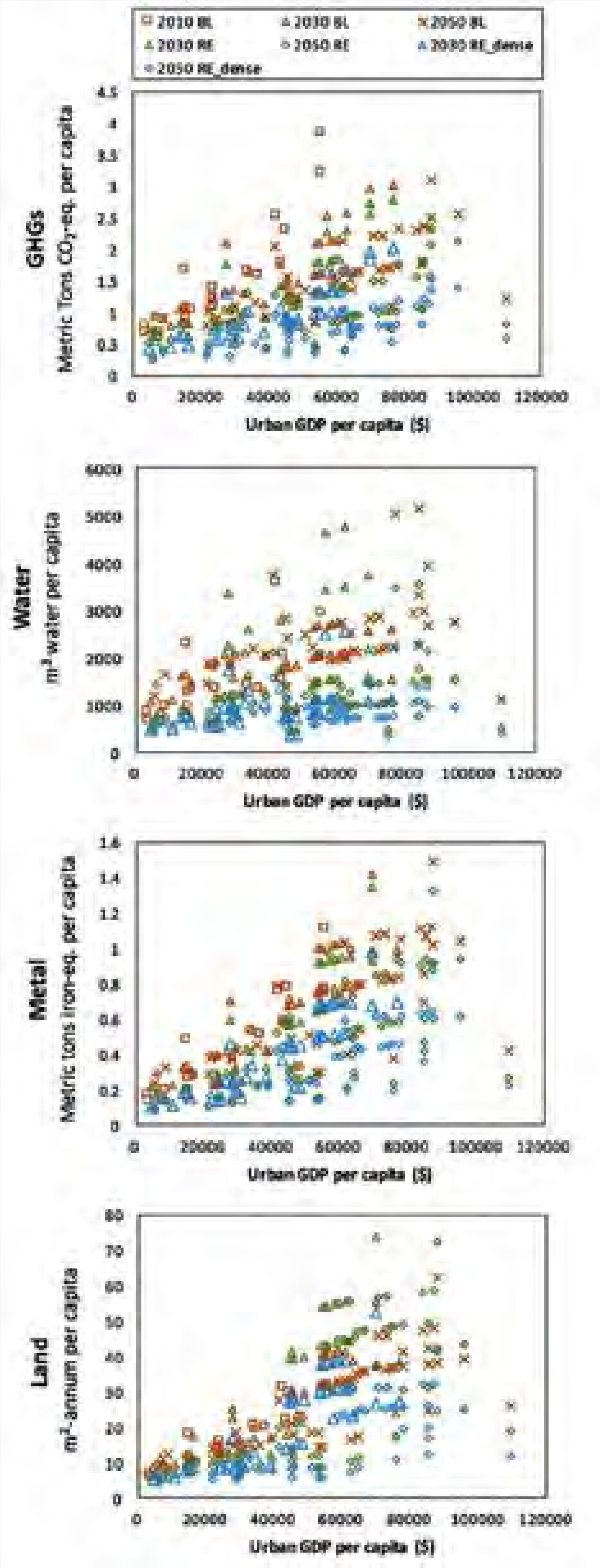


**Figure 50**: District energy: the relationship between resource impacts and GDP per capita in 84 cities under baseline (BL) and resource-efficient (RE) scenarios

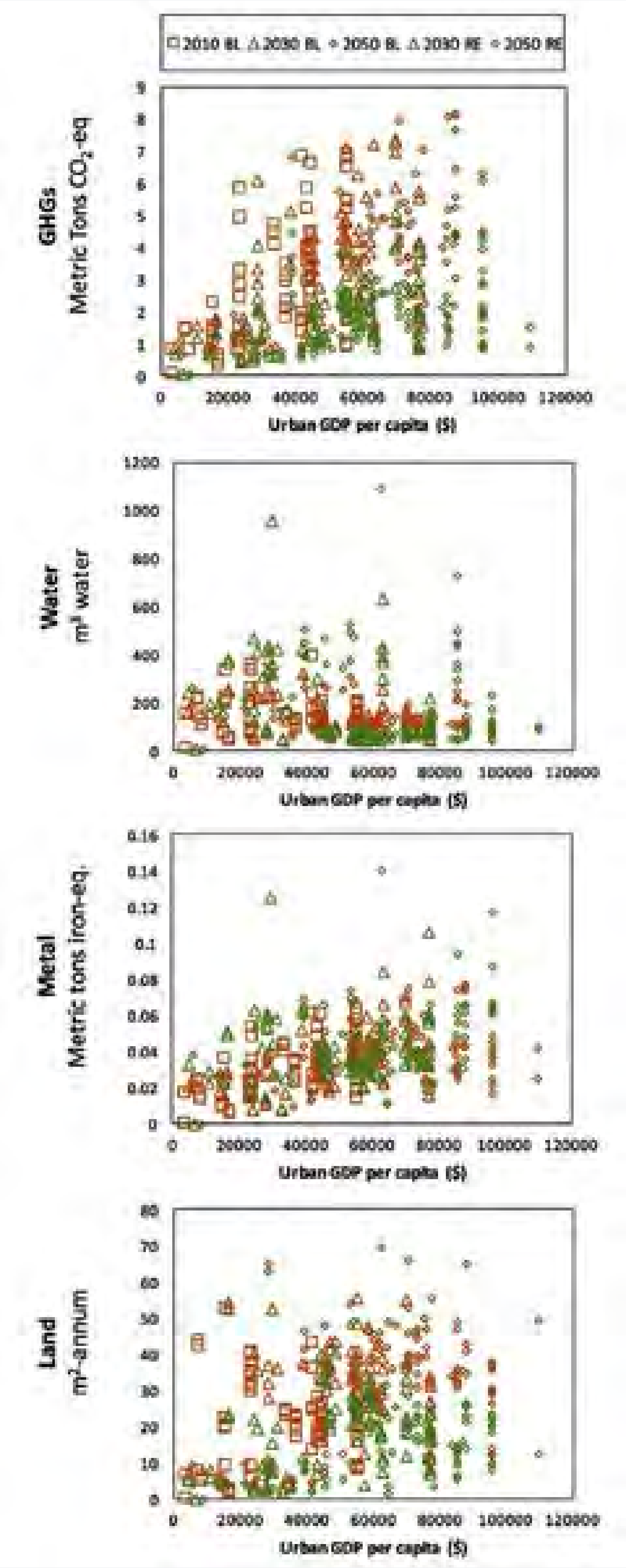
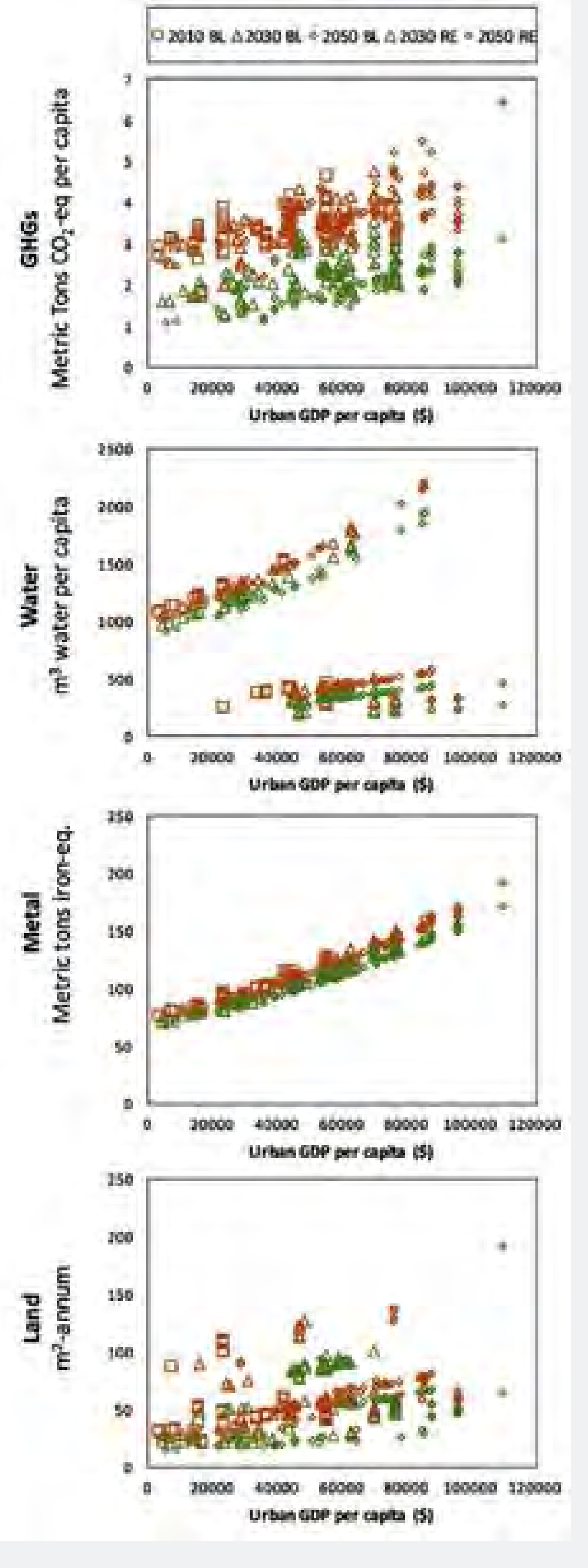


**Figure 51**: Green buildings: the relationship between resource impacts and GDP per capita in 84 cities under baseline (BL) and resource-efficient (RE) scenarios



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UN environment

United Nations
Environment Programme

The proportion of the global population living in cities and towns is expected to rise from 54 percent in 2015 to 66 percent by 2050; which will result in a significant expansion of existing cities, as well as the construction of new cities. Without a new approach to urbanization the material consumption by the world's cities will grow from 40 billion tonnes in 2010 to about 90 billion tonnes by 2050. Therefore the resource use implications and environmental impacts of urbanization are significant. Resources should now become a central policy concern, in addition to concerns over climate change.

We have a once-in-a-lifetime opportunity to shift the expected urbanization onto a more environmentally sustainable and socially just path. Decisions made today on urbanization and land use models, as well as on critical infrastructure, will determine whether our investments are future-proof or whether they in fact lock us into an unsustainable path.

This report calls for a new strategy for 21st Century urbanization and presents the parallel actions on urban planning, sustainable design, resource efficient components, and infrastructure for cross-sector efficiency that are required for a transition towards low-carbon, resource-efficient and socially just cities. It also presents the new governance model and politics of new imaginative business propositions and experimentation that will make possible such transition.

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