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## Energy Transformation in Cities

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### Coordinating Lead Authors

Peter J. Marcotullio (New York), Andrea Sarzynski (Newark, DE), Joshua Sperling (Denver)

### Lead Authors

Abel Chávez (Gunnison), Hossein Estiri (Seattle), Minal Pathak (Ahmedabad), Rae Zimmerman (New York)

### Contributing Authors

Jonah Garnick (New York), Christopher Kennedy (Victoria), Edward J. Linky (New York), Claude Nahon (Paris)

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## Major Findings

- Urbanization has clear links to energy consumption in low-income countries. Urban areas in high-income countries generally use less energy per capita than non-urban areas due to economies of scale associated with higher density.
- Current trends in global urbanization and energy consumption show increasing use of fossil fuels, including coal, particularly in rapidly urbanizing parts of the world.
- Key challenges for the urban energy supply sector include reducing environmental impacts, such as air pollution, the urban heat island effect, and greenhouse gas (GHG) emissions; providing equal access to energy; and ensuring energy security and resilience in a changing climate.
- While numerous examples of energy-related mitigation policies exist across the globe, less attention has been given to adaptation policies. Research suggests that radical changes in the energy supply sector, customer behavior, and the built environment are needed to meet the key challenges.
- Scenario research that analyzes energy options requires more integrated assessment of the synergies and tradeoffs in meeting multiple goals: reducing GHGs, increasing equity in energy access, and improving energy security.

## Key Messages

In the coming decades, rapid population growth, urbanization, and climate change will impose intensifying stresses on existing and not-yet-built energy infrastructure. The rising demand for energy services (e.g., mobility, water and space

heating, refrigeration, air conditioning, communications, lighting, and construction) in an era of enhanced climate variability poses significant challenges for all cities.

Depending on the type, intensity, duration, and predictability of climate impacts on natural, social, and built and technological systems, threats to the urban energy supply sector will vary from city to city. Local jurisdictions need to evaluate vulnerability and improve resilience to multiple climate impacts and extreme weather events.

Yet future low-carbon transitions may also differ from previous energy transitions because future transitions may be motivated more by changes in governance and environmental concerns than by the socioeconomic and behavioral demands of the past. Unfortunately, the governance of urban energy supply varies dramatically across nations and sometimes within nations, making universal recommendations for institutions and policies difficult, if not impossible. Given that energy sector institutions and activities have varying boundaries and jurisdictions, there is a need for stakeholder engagement across the matrix of institutions to cope with future challenges in both the short and long term.

In order to achieve global GHG emission reductions through the modification of energy use at the urban scale, it is critical to develop an urban registry that contains a typology of cities and indicators for both energy use and GHG emissions. This will help cities benchmark and compare their accomplishments and better understand the mitigation potential of cities worldwide.

## 12.1 Introduction

Energy has enabled human development (International Energy Agency [IEA], 2010). The supply of energy to cities has been at the center of human progress since before the Roman Empire (Keirstead and Shah, 2013) when settlements required proximate sources of water, food, and fuel for cooking, warmth, and light. Modern urban life and human activities require ever greater amounts of energy. Given the tremendous projected growth in urbanization, wealth, industrialization, technological advancement, and the associated demands for vital services including electricity, water supply, transportation, buildings, communication, food, health, and parks and recreation, demands on energy supply will grow into the foreseeable future.

Meeting increasing energy demands related to urbanization given current climate change projections amplifies the challenges of the urban energy supply sector. Contemporary urban energy use is fueled largely from fossil sources, creating greenhouse gas (GHG) emissions. The energy supply sector is already one of the largest sources of GHG emissions (see, e.g., U.S. Environmental Protection Agency [U.S. EPA], 2015 for U.S. shares of emissions), and, if current urbanization trends continue, urban energy use will increase more than threefold from 2005 to 2050 (Creutzig et al., 2014). Urban energy system components are directly and indirectly vulnerable to climate change impacts. Coastal cities, for example, often have power plants located at low elevations. Moreover, with increasing urbanization, providing secure, clean, modern energy to all urban citizens is an increasingly important planning goal. Therefore, three key energy challenges motivate the focus of this chapter: (1) mitigating GHGs: over the past 20 years, the increasing demand for energy in rapidly urbanizing countries has largely been met with the burning of coal (World Coal Association, 2012), a powerful GHG producing fossil fuel. (2) Building resilient urban energy systems: extreme weather and climate risks are making cities more vulnerable to loss of electric power and damage to energy infrastructure (Evans and Fox-Penner, 2014). And (3) achieving just cities via equitable modern energy access: in 2010, approximately 179 million urban residents globally do not have access to electricity, and 447 million do not have access to modern, clean cooking fuels (World Bank, 2015).

Throughout the chapter, we focus our assessment on trends in the growth and complexity of the urban energy supply sector and the related challenges, opportunities, and barriers to moving toward low-carbon, resilient, and just energy supply systems. We use examples demonstrating reductions in environmental impacts including transitioning toward alternative technologies, fuels and changing behaviors, energy systems designed for new climatic conditions, and opportunities to increase energy access and reliability. We organize information around three key questions:

1. *What are the current states, patterns, and trends for the urban energy supply sector?*
2. *What are the mitigation, adaptation, and development challenges of the urban energy supply sector?*
3. *What are the opportunities, limits, and barriers for transforming the urban energy supply sector to reduce environmental impact and increase access and resiliency?*

To present answers to these questions, the chapter is laid out in five sections: (1) an overview of the urban energy supply sector and a framework by which the central questions can be addressed; (2) a review of trends, conditions, and drivers of urban energy supply focusing on infrastructure, energy resources, governance, and policy; (3) an evaluation of three key challenges to these systems: environmental impact, system resilience, and energy access; (4) a review of previous energy transitions and future scenarios research; and (5) options for low-carbon, resilient, and just energy supply systems and how and why they are being implemented. Throughout this chapter, Case Studies are shared to illustrate how cities with different histories, geographies, institutions, and policies address current and perceived future challenges.

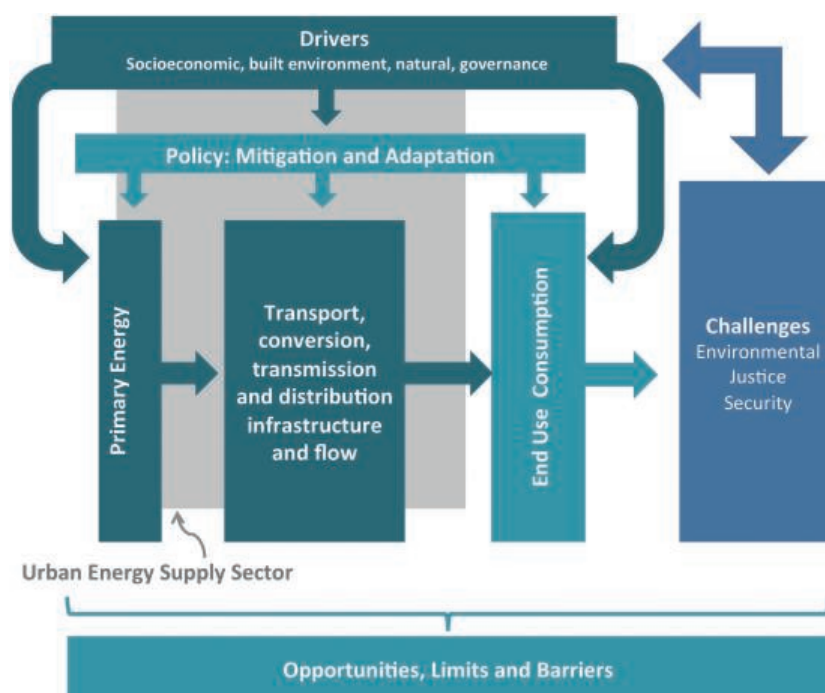
## 12.2 Overview

Urban energy systems comprise physical systems that include infrastructures and technologies, natural systems from which humans draw raw materials and services, and socioinstitutional systems involved in social relations, governance, and the management of energy services. Figure 12.1 presents a framework to explore and understand the urban energy supply sector within urban energy systems and the challenges and opportunities for transitioning to low-carbon, resilient, and just cities. The core of the urban energy supply sector is the physical infrastructure that converts primary energy resources like coal or gas or sunlight to usable energy such as electricity or heat and then delivers that energy to end-users such as businesses and residences (see Section 12.3.1 for a variety of services; e.g., heating, cooking, transportation). The design, operation, and management of the urban energy supply sector thus depend on available energy resources (see Section 12.3.2), the policy and governance context (see Section 12.3.3), and the underlying drivers of consumer energy demand (Section 12.3.4). The operation of the urban energy supply sector shapes mitigation, adaptation, and sustainable development challenges (see Section 12.4). Likewise, all components of the system face limits, barriers, and opportunities for improvement (see Section 12.5).

## 12.3 Trends and Conditions

### 12.3.1 Urban Energy Supply Infrastructure

Urban energy supply infrastructure refers to the engineered systems that provide energy to more than half of the world's population by bringing primary energy resources such as coal (often from around the world) into the city region, converting primary



**Figure 12.1** Framework for understanding the urban energy supply system.

resources into modern energy such as electricity, and transmitting and distributing this energy within and between urban areas (Bruckner et al., 2014). Supply networks can range from localized renewable energy generation to systems that span thousands of kilometers, linking mining and refining activities of solid, gas, and liquid fuels to energy conversion facilities and large manufacturing plants (Schock et al., 2012).

Urban energy supply infrastructure systems can be centralized, distributed (Hammer et al., 2011), or both. Centralized electric generation takes advantage of economies of scale offered by large power plants and the concentration of population and human activities. Large power plants can be fueled by different primary energy sources, including coal, natural gas, biomass, solid waste, or nuclear fuels, and can be located far from urban centers. Overhead wires and underground cables called *circuits* or *grids* connect electric generation technology with users. Rapidly advancing intelligent electronic technologies that enable broader consumer involvement in defining and controlling electricity needs are helping to integrate systems into “smart grids.”

Some renewable energy systems, including large wind farms, geothermal power plants, or concentrating solar power facilities, can be large-scale, allowing them to fit relatively easy into a centralized generation and distribution model. Large-scale renewable energy remains a challenge because the natural variability of supply must be balanced with demand. Small amounts of non-hydro renewable energy can be easily accommodated.

Centralized thermal power systems are common in cities with extreme temperatures in winter or summer months.

These district heating and cooling systems (DHC) produce steam or hot and cold water centrally (often also producing electricity, known as combined heat and power or CHP) and then distribute this energy via a network of underground pipes. Examples of such systems are found in cities such as Copenhagen, Seoul, Austin, Goteborg, New York, and Paris (Hammer et al., 2011).

Distributed forms of electricity generation (DG) and heat distribution include smaller power production units located at or near the point of energy use, as in buildings. DG electrical systems link directly to the building’s electric wiring system and therefore have lower transmission loss, reduced system vulnerability to service disruptions, and can more easily incorporate energy generated from renewable sources or technologies such as CHP than centralized generation (Lovins et al., 2002). DG systems are typically smaller than centralized systems, with capacities of 10 megawatts or smaller. These systems include energy storage (batteries) and sometimes connect through micro-grids for greater reliability. DG systems can also be connected to larger centralized systems.

### 12.3.2 Energy Resources

Table 12.1 presents the levels of use, available resources, and percent change over the past 20 years for the major energy carriers. The table reveals that fossil fuels (oil, gas, and coal) provide the majority of world’s energy, and the greatest recent increases in growth remain in these sources (IEA, 2013). During this period, coal (and peat) consumption has increased the most (68%), followed by natural gas (a “cleaner” fossil fuel).

**Table 12.1** *Global energy resources, 2010. Source: Schock et al., 2012; Rogner et al., 2012; Bruckner et al., 2014; World Energy Council, 2013*

Source	World Energy Supply		Reserves at current production rate (years)	Percent Growth 1993–2011 (%)
	Percent	EJ		
Oil	34.1	170	40	25
Gas	22.4	114	60	62
Coal (proven) and Peat	28.4	151	132	68
Nuclear	2	10	100	13
Hydro	2.3	12		21
Geothermal, Solar, Wind, etc	0.6	3		n/a
Combustible renewables and waste	10.2	53		23
Total	100.0	513	332	

As consumption rises, energy debates emphasize the potential for overuse (Deffeyes, 2001). The “peak debate,” as it has come to be called, has moved from a focus on conventional oil (Alekkett et al., 2010; Hubbert, 1981; Hughes and Rudolph, 2011) to include coal, gas, and uranium (Dittmar, 2013; Maggio and Cacciola, 2012; Heinberg and Fridley, 2010). Nevertheless, the primary concern for this chapter is not energy resource availability, but rather environmental impacts, disparities in energy access, and vulnerability and resilience to climate hazards (see Section 12.4).

### 12.3.3 Governance and Policy

Social, economic, and institutional mechanisms all shape demand for energy and help to oversee its supply and distribution within society. These mechanisms vary substantially from city to city depending on characteristics of the city’s governance processes, characteristics of the energy system, and other local contextual factors including geography, culture, and history (Morlet and Keirstead, 2013; Jaglin, 2014). The governance of urban energy systems varies in many ways and therefore requires localized knowledge and perspectives.

The governance of urban energy systems is particularly complex given the “public good” nature of energy and the negative externalities associated with certain forms of energy generation (Florini and Sovacool, 2009; Morlet and Keirstead, 2013). Historically, urban energy systems were limited to cooking and heating fuels and supplied through private, decentralized markets that brought fuels from the hinterland to the city (Rutter and Keirstead, 2012). Throughout the Industrial Revolution, energy demand exploded, and energy systems

were increasingly centralized and publicly supported. By the mid-20th century, many countries had nationalized electricity networks and distribution systems for fuels such as natural gas (Coase, 1950), shifting energy governance to the national scale. In some locations, aspects of energy and environmental governance are international and multilevel (i.e., Europe; Marks et al., 1996).

International institutions such as the International Energy Agency and the Asian Development Bank emerged to provide energy financing and policy support at the national and global scales (Florini and Sovacool, 2009). The International Atomic Energy Agency and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) emerged to govern the safe development of nuclear power. Today, approximately 80% of global nuclear capacity is in OECD countries (IEA, 2014).

In some countries such as Thailand, energy systems remain publicly owned and centrally operated (Kunchornrat and Phdungsilp, 2012), and energy decisions remain in the hands of national authorities. Therefore, efforts to green the energy supply and improve its resilience depend on priorities of the national government. Similarly, some countries such as South Africa may allow municipal utilities to distribute power within cities, but generation decisions remain with the central utility, leaving municipalities like Cape Town vulnerable to unreliable state-owned systems (Jaglin, 2014).

In other countries, urban energy systems are regionally coordinated, adding an additional layer of subnational governance between the market structuring functions at the national level and utility operations at the local level. In England, nine regional general-purpose governments coordinate renewable energy development among local energy providers in pursuit of national goals, although each region sets its own targets and strategies (Smith, 2007). Smooth coordination among multiple government bodies cannot be presumed, especially when urban priorities conflict with higher level goals (Jaglin, 2014). When municipal priorities diverged from their regional or national counterparts, cities like Hanover turned to transnational networks including ICLEI—Local Governments for Sustainability’s Cities for Climate Protection to help provide guidance and support for local initiatives (Emelianoff, 2014).

In yet other countries, municipal authorities have some control over energy supply where interest and institutional capacity allows. In Los Angeles, the city’s Department of Water and Power has begun to transition from using almost entirely coal-fired and nuclear power plants to a more diverse supply arrangement including purchasing from natural gas plants and wind and solar farms (Monstadt and Wolff, 2015). In Hanover, Germany, the municipal authority disinvested its share of local nuclear power and shifted its energy purchasing toward coal but also combined heat and power (CHP), wind, small hydro, solar, and biomass (Emelianoff, 2014). Likewise, in Vaxjo, Sweden, the municipal authority shifted entirely to biomass for its thermal



power generation, pushing to become a “fossil-fuel-free city” (Emelianoff, 2014).

Whereas municipal decisions are often within the context of infrastructure demands or higher level governmental choices, it is true that regional-to-local governments often have a suite of policy tools afforded to them for achieving sustainability and resilience across the energy system. The suite of policy tools can generally be articulated in three categories: regulatory, market-based, and voluntary type of instruments. Such a well-rounded set of options has proved to be an effective approach for subnational energy governance in aggregate, even though these three categories are very different in scope and outcomes.

Regulatory approaches are often associated with top-down and command-and-control actions, and they often yield high participation rates due to higher costs of noncompliance. Federally set regulations (e.g., 1990 U.S. Clean Air Act for Acid Rain) help set a standard for subnational governments (U.S. Environmental Protection Agency, 2014). For example, the United States’ public utility commissions (PUC) have set grid-wide renewable portfolio standards (RPS) that are already showing respectable carbon intensity gains (National Renewable Energy Laboratory [NREL], 2015) at the city scale (e.g., with the City of Aspen Colorado achieving 100% renewable energy; Aspen, 2015). Like the United States, the European Union (EU) also has aggressive RPS regulatory targets that are reaching community-level implementation (European Union, 2015).

Market-based approaches are centered on their incentive-based regulatory scheme to drive participation and catalyze energy development. Pollution “caps” are examples of market-based instruments often used by federal governments, and, even though they are far less obvious at community levels, they do present potentials for innovation at local government scales. Exemplary cases include China’s increased electricity prices and India’s cap-and-trade, both for energy-intensive producers (C2ES, 2014).

Voluntary policies often yield substantially lower participation than other approaches and are mostly focused on driving consumer behavior change. Actions such as behavioral feedbacks, green energy purchases, or weatherization upgrades result in minimal energy system advances (Ramaswami et al., 2012).

Over the past several decades, many countries have experimented with privatization and deregulation of energy markets, shifting the balance of power back toward the private sector and investor-owned utilities (Al-Sunaidy and Green, 2006; Wallston et al., 2004). Moves to privatize were made in response to severe fiscal challenges facing the public sector and the rise of neo-liberal ideology (Monstadt, 2007). Concurrently, many governments shifted their energy governance from governing by authority (i.e., regulation) toward enabling of voluntary private actions (Bulkeley and Kern, 2006). Such shifts reduced public control over infrastructure investments and environmental outcomes. In Berlin, voluntary agreements with private utilities

were unable to achieve intended energy efficiency and solar energy targets, even though investments increased in these areas (Monstadt, 2007).

Concern over energy security has renewed interest in decentralized and distributed modes of energy generation, such as CHP and DHC at city and small/community scales. Cities have set distributed energy targets, such as 25% by 2025 in London, and several UK municipalities have adopted the Merton Rule requiring new buildings to supply 10% of their energy using on-site renewables (Lo, 2014). UK municipalities have experimented with various forms for governing DHC, including a municipal-owned DHC company in Woking, a nonprofit-led DHC in Aberdeen, and a public–private partnership for DHC in Birmingham (Hawkey et al., 2013). Decentralized generation and provision of energy services (heating and lighting) to small communities have often been provided by individuals and small and medium enterprises termed “ecopreneurs” (Schaper, 2002; Monstadt, 2007). Community-scaled renewables show promise for promoting community energy resilience by civil society actors without requiring much or any government involvement (Aylett, 2013; Frantzeskaki et al., 2013).

#### 12.3.4 Drivers of Urban Energy Demand

Much scholarship has investigated the drivers of urban energy demand and associated impacts, from the household to city to region and global scales (Satterthwaite, 2009; Grubler et al., 2012a; Blanco et al., 2014; Marcotullio et al., 2014). These drivers can be categorized according to four sets of characteristics: socioeconomic, behavioral, geography and natural conditions, and built environment, as shown in Table 12.2.

A recent analysis of 225 cities worldwide found that affluence and fuel prices were the two most reliable predictors of total urban energy demand at end-use (Creutzig et al., 2015). Additionally, those cities could be appropriately classified as one of eight types, using indicators of the four characteristics identified earlier (gross domestic product [GDP] per capita for socioeconomic, fuel prices for behavioral, heating degree days for natural conditions, and population density for built environment). The drivers affected each city type differentially (see Section 12.4.1), indicating the importance of understanding the local context when selecting climate and energy policies for individual cities (see Section 12.5).

### 12.4 Mitigation, Adaptation, and Sustainable Development Challenges

Three key challenges emerge from the design and operation of the urban energy supply sector: (1) significant environmental impacts requiring mitigation efforts, (2) system vulnerabilities to climate change and associated impacts requiring adaptation efforts, and (3) disparities in access to modern energy requiring sustainable development efforts.

**Table 12.2** Drivers of urban energy consumption and greenhouse gas emissions. Source: Marcotullio et al., 2014

DRIVER	DEPENDENT VARIABLE	SOURCE
<b>Socioeconomic</b>	Population (+), income (+) [*income also has a + association with housing size, automobile use, heating, and industrial fuel use], urbanization (+), regional production (+), high density of energy intensive industries, service, and industrial-sector economic base (+) versus recreation-based economy (-); population ageing (-); institutional maturity and know-how on emission regulations (-); governance arrangements (-/+); race/ethnicity (+) [** race/ethnicity also influences housing characteristics]	Ciccone and Hall, 1996; Schock et al., 2012; Poumanyong and Kaneko, 2010; Schulz, 2010b; Satterthwaite, 2009; Weisz and Steinberger, 2010; Kahn, 2009; Hoornweg et al., 2011; Dhakal, 2009; Marcotullio et al., 2012; O'Neill et al., 2012; Estiri, 2014, 2015
<b>Behavioral</b>	Increasing energy prices (-), social norms and values (-/+); psychological factors [attitude, personal norm, awareness of consequences] (-/+); energy reporting (-); lifestyle-related choice including housing type (+), commuting distances (+), goods/services consumption (+), social contact (-)	Martinsen et al., 2007; Thøgersen and Olander, 2002; Schultz et al., 2007; Abrahamse and Steg, 2009; Allcott, 2011; Baiocchi et al., 2010; Heinonen et al., 2013
<b>Geography and Natural Conditions</b>	Weather and climate (-/+); geographic location of an urban area [e.g., coastal, mountainous, desert, by river or sea] (-); proximity to types of ecosystems (-) [e.g., temperate or tropical forests]	Pauchari, 2004; Pauchari and Jiang, 2008; Neumayer, 2002; Estiri et al., 2013; Kennedy et al., 2011
<b>Built Environment</b>	Technologies (-/+); physical infrastructure and related materials (-/+); design (-/+), building/infrastructure age (+); building type (-/+) and size (+); land-use mix (-); urban form; high population and employment densities (-); high connectivity street patterns; destination accessibility to jobs and services	Seto et al., 2014; Grubler et al., 2012; Chester et al., 2014; Norman et al., 2006; Estiri, 2014, 2015

Notes: Symbols in parentheses denote the direction of the relationship between each particular factor and urban energy use. The plus sign indicates a positive relationship (increases energy use), negative sign indicates a negative relationship (decreasing vulnerability), ~ (unknown).

### 12.4.1 Environmental Impacts

The urban energy supply sector generates local and global environmental impacts, including varying levels of GHG emissions, air pollution, urban heat island (UHI) effects, and habitat and ecosystem disturbances. As the world continues to urbanize, the environmental impacts of the energy supply sector may grow by virtue of the magnitude of overall energy use (not per capita) without substantial effort toward mitigation (see Section 12.5). This chapter focuses on GHG emissions to illustrate environmental impacts most closely related to climate change, but we direct readers to other sources for additional environmental impacts (see, e.g., Apte et al., 2012, 2015; Kryzanowski et al., 2014) and for interactions with GHG emissions in forcing climate change (e.g., Pandey et al., 2006, for urban particulates).

#### *Global-Scale Impacts: GHG, Energy Patterns, and Trends*

In 2010, the energy supply sector accounted for 49% of all energy-related GHG emissions (JRC/PBL, 2013) and 35% of all anthropogenic GHG emissions, up 13% from 1970, making it the largest sectoral contributor to global emissions. According to the Emissions Database for Global Atmospheric Research (EDGAR), global energy supply sector GHG emissions increased by 35.7% from 2000 to 2010 and grew on average nearly 1% per year faster than global anthropogenic GHG emissions (Bruckner et al., 2014). Asia, Europe, and the United States contributed the most to global annual energy

GHGs, with Asia's contribution increasing rapidly in recent years.

Few studies estimate the relative urban and rural shares of global GHG emissions (Dhakal, 2010; Seto et al., 2014) due to the lack of comparable urban-scale energy and GHG emissions data. Moreover, debates remain as to the best way to inventory GHG emissions at the local level (see Box 12.2), and inconsistencies often exist among city inventories. Comparability and standard accounting protocols (e.g., the Global Protocol for Community-Scale GHG Emissions [GPC] now used by more than 100 cities globally; (ICLEI, C40 and WRI, 2012)<sup>1</sup> are needed for benchmarking, scalability, and guiding adaptive mechanisms. Box 12.1 discusses the challenges to acquiring data for these different types of accounting procedures (production and consumption). Given the lack of research infrastructure and data at the urban level, it remains difficult to rigorously quantify emissions, and this is particularly true in developing world cities. Box 12.2 gives a perspective of different tools and protocols used in cities around the world.

Nevertheless, studies suggest that cities are responsible for more than two-thirds of global energy use (IEA, 2008; Grubler et al., 2012a) and for approximately 70–75% of global energy-related CO<sub>2</sub> emissions (IEA, 2008; Grubler et al., 2012a; Marcotullio et al., 2013). When accounting for more than CO<sub>2</sub> emissions, however, studies suggest that the global urban contribution drops to less than 50% of total (Marcotullio et al., 2013), arguably owing to the largely non-urban contributions of methane worldwide (Satterthwaite, 2008).

<sup>1</sup> See <http://www.ghgprotocol.org/city-accounting>

### Box 12.1 Urban Production and Consumption and GHG Footprints: Data Challenges and Action

**Box 12.1 Table 1** Randomly selected cities from Annex 1 and non-Annex 1 economies for coupled footprints. Source: Abel Chávez

<b>Annex 1 Cities</b>	New York	Toronto	London	Berlin	Paris	
	Barcelona	Madrid	Tokyo	Sydney	Melbourne	
<b>Non-Annex 1 Cities</b>	Mexico City	São Paulo	Rio de Janeiro	Bogotá	Cape Town	Durban
	Johannesburg	Beijing	Shanghai	Delhi	Manila	Jakarta

As the world's production and consumption of goods and services continues to rise, communities, both urban and rural, are at the forefront of the innovations required to provide these needs. If communities are to develop or maintain economies that help fill global niches, it is necessary that they plan, design, and construct infrastructures that are economically feasible, environmentally benign, and socially accessible to all residents. However, in order to plan, design, and construct the necessary infrastructures, it is imperative that communities use sound material and energy flow data to identify current conditions and trends. Therefore, measuring, benchmarking, and tracking community-scale material and energy flows becomes increasingly critical.

As noted in Box 12.2, material and energy flows can come in two broad types: production and consumption. For example, production footprints account for flows associated with all in-boundary activities and trans-boundary flows of key infrastructures, whereas consumption footprints account for all in- and trans-boundary flows associated only with local household consumption. The two approaches often yield different "footprint" estimates for any one community (see Chávez and Ramaswami, 2013), yet, despite this, measuring, benchmarking, and tracking the two – coupled and side-by-side – is rarely done. Thus, the chapter authors sought to compile coupled footprints for a host of cities that included an examination of the suite of mitigation strategies afforded to cities.

The authors randomly selected a sample of 10–12 cities from Annex 1 and non-Annex 1 economies each, for a total of

20–24 cities (see Box 2.1 Table 1). The principal approach was to apply primary and publicly available data to compute the coupled footprints. The data included *production* – inventories/footprints or climate action plans; and *consumption* – household and consumer expenditure surveys. The exercise revealed, however, large and fragmented data gaps in global cities. Of the Annex 1 cities, the team located primary production and consumption data for 80% and 60% of the cities, respectively. Meanwhile, of the non-Annex 1 cities, primary production and consumption data was located for 67% and 42% of the cities, respectively. Thus, far more data investigation and development is necessary to be able to embark on the vital coupled footprint analysis. However, data needs do not end here!

Upon examining trends in community development and population growth, the need for robust production and consumption data is magnified. Although for good reason much research is devoted to megacities, smaller cities and rural communities present substantial opportunities for low-carbon, adaptive, and just development. It is noted that 51% of today's urban population live in small cities of less than 500,000 people, and that by 2030 more than 40% of the urban population will be in even smaller cities of less than 300,000 (Chávez, 2016). Thus, as communities develop, measuring, benchmarking, and tracking community-scale material and energy flows are imperative toward creating the necessary infrastructures. Crucially, action is needed to generate and compile both production- and consumption-related data at the urban scale for communities of a variety of sizes and locations, but particularly for those in the developing world.

### Urban Impacts: Energy Consumption

Many studies estimate urban energy demands and associated environmental impacts for selected cities worldwide (for reviews, Grubler et al., 2012a; Seto et al., 2014; Creutzig et al., 2015). The estimates vary extensively for reasons outlined earlier. Nevertheless, to illustrate the underlying variability, Table 12.3 provides the average per capita urban energy use from selected cities based on the Economist Intelligence Unit (EIU) data from 2002 to 2011. The table illustrates significant differences in energy use estimates among cities, recognizing,

however, that databases are not always compatible for comparative purposes. Within one region such as Asia, differences appear to be large (nearly 200 GJ per capita in Guangzhou to 5.7 GJ per capita in Calcutta). As expected, European and North American cities fall toward the upper end of the energy use spectrum and also reflect large differences, ranging from nearly 150 GJ per capita in Dublin and Atlanta to 36 GJ per capita in Istanbul and about 10 GJ per capita in Cleveland. High energy demand in some cities results from the use of older and inefficient fossil fuel-based energy technologies, heavy industry, and high automobile use. Notably, energy use in all cities in



### Box 12.2 Managing Greenhouse Gases Emissions in Cities: The Role of Inventories and Mitigation Actions Planning

Flavia Carloni, Vivien Green, Tomas Bredariol, Carolina Burle S. Dubeux, and Emilio Lèbre La Rovere

*Federal University of Rio de Janeiro*

Andrea Sarzynski

*University of Delaware, Newark*

Abel Chávez

*Western State Colorado University, Gunnison*

Apart from the differences in the institutional and political structures of cities, the majority of them may be seen as a planning unit for mitigation management purposes (Carloni, 2012). With both city specificities and similarities in mind, it is possible to profit from individual experiences that can be exchanged and define a common framework to improve mitigation actions.

Some cities' government officials think that the efforts to reduce greenhouse gas (GHG) emissions could jeopardize their economic and social agendas (Dubeaux, 2007). However, some initiatives show the opposite, combining development and climate action that results in a win-win situation.

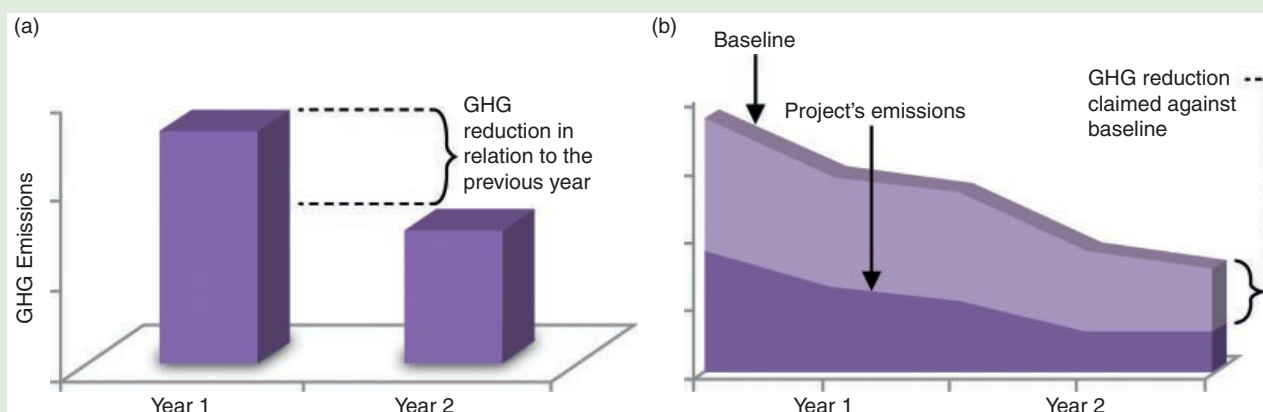
In regard to the methodologies to be applied, there are differences between accounting methods for emissions of a city (the city's GHG inventory): (1) comparison of the absolute emissions in 1 year with respect to another and (2) monitoring the mitigation effects of particular actions through the comparison of emissions from a baseline scenario with the absence of action (see Box 12.2 Figure 1) (Carloni, 2012).

In addition to the choice regarding the methods, they must follow a step-by-step methodology to ensure both a good analysis during the process and also the possibility of future comparison between different inventories. The U.S. Environmental Protection Agency (U.S. EPA, 2015) presents on its website a very simple and direct guide to conduct a GHG inventory: (1) set the boundaries, either physical, operational, or governmental; (2) define the scope, considering which emission sources should be included in the report and also which gases are going to be investigated; (3) choose the quantification approach by considering data availability and the purpose of the inventory, then adopt either a top-down, bottom-up, or hybrid approach; (4) set the baseline by determining the benchmark year; (5) engage stakeholders by bringing them into the process in the very beginning with the intention of collecting more data and information and helping construct a public acceptance; and (6) consider certification; a third-party review and certification of the methods and data is highly advisable to assure the high quality, consistency, and transparency of the report.

There are two possible approaches to monitoring: compare two or more emissions inventory data (total values or sectorial and subsectorial) or use scenario-building techniques to assess the mitigation outcomes of specific policies, projects, and measures.

It is important to acknowledge the complementarity of approaches; both must be analyzed together and in parallel. Challenges faced when applying these approaches to cities include:

- Whether and how to account for indirect emissions (leakages<sup>2</sup>)



**Box 12.2 Figure 1** Quantification of greenhouse gas emission reduction based on the analysis of an inventory (a) and based on the analyses of a mitigation action (b).

Source: Adapted from Carloni, 2012

<sup>2</sup> Carbon leakage is defined as the increase in emissions outside a region as a direct result of the policy to cap emissions in this region. Carbon leakage means that the domestic climate mitigation policy is less effective and more costly in containing emission levels, a legitimate concern for policy-makers. For example, if one city decides to create a carbon tax for a specific industry activity, companies may migrate to another city instead of improving their processes to mitigate emissions.

- How to ensure additionality<sup>3</sup> and reduction of GHG emissions by investment in projects or through the purchase of credits generated<sup>4</sup>
- Whether and how to demonstrate cause-and-effect relationships between a given action and a given emission reduction (Carloni, 2012)

## GHG INVENTORIES IN CITIES

Different methodologies and protocols for GHG inventories have been developed: the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Control [IPCC], 2006), which is frequently adapted for cities; the

**Box 12.2 Table 1** *Tools used by cities to conduct GHG emission inventories. Source: Based on data from Carloni, 2012*

Tool	Characteristics	Use
CO <sub>2</sub> Gronbolanz/ EMSIG	EMSIG (Emission Simulation in Gemeinden/Emission Simulation in Communities) was developed by Austria's energy agency. CO <sub>2</sub> Grobillanz is a simpler version. The tools comes with data from Austria regarding emission factors, goods consumption, and economic activities-related emissions. Both use geographical frontiers as boundaries.	Communities in Austria
ECO <sub>2</sub> Region	Supports the calculation of public authority and/or territory GHG emissions. The framework is mostly compatible with the IPCC (2006) methodology. It is also possible to include emissions of local pollutants such as particulate matter. Average emission factors for some countries are included.	Cities in Germany, Switzerland, and Italy
GRIP	The Greenhouse Gas Regional Inventory Protocol was developed by the University of Manchester and the United Kingdom's environmental agency. Initially, it was designed for metropolitan areas, but it has been used for smaller cities, too. The methodology used follows the IPCC Guide (2006), allowing greater comparability between cities. A tool for scenario construction is also available.	Cities in the United Kingdom as well as in some other cities in Europe and the United States
Bilan Carbone Collectivités – Territoires	This tool was developed based on work from the France Environmental Agency. It supports accountability for all gases included in the Kyoto Protocol, as well as chlorofluorocarbon (CFC) and water vapor emitted by airplanes. French cities' emission factors are available.	Municipalities in France
CO <sub>2</sub> – Beregner	A result of the work of the Denmark environmental agency in cooperation with a private consulting group, this instrument consider cities as a geographical entity – even though it may be adapted to account solely for the local authority. Only CO <sub>2</sub> , CH <sub>4</sub> , and N <sub>2</sub> O are supported, but the reporting framework follows the IPCC (2006) guidelines. It requires a great range of data, enabling complex inventories. Furthermore, the tool comes with a guide with thirty-seven possible mitigation actions, and their impacts may be calculated.	Cities in Denmark
Project 2°	This project is a cooperative effort between the Clinton Climate Initiative, ICLEI and the Microsoft Corporation. It is based on HEAT, a tool developed by ICLEI. Therefore, the resulting inventories are consistent with IEAP. All six Kyoto Protocol gases are supported, and the methodology used is in accordance with the IPCC Guide (2006). One may account emissions by the territory or the governmental authority. Additionally, emission separation in scopes (1, 2, 3) is possible.	C40 (a network of the world's megacities committed to addressing climate change)
CACPS	The Clean Air and Climate Protection Software was developed by ICLEI and follows the IEAP model. This software supports the accountability of traditional air pollutants as well as GHG. It also assists in the elaboration of emission reduction strategies through the evaluation of policies and action plans.	Mostly by cities in United States, but also elsewhere
GPC	Provides a framework for accounting and reporting citywide GHG emissions. The tool was finalized after a pilot test in 2013 and global public comments in 2012 and 2014. It replaces all previous draft versions of the GPC and supersedes the International Local Government Greenhouse Gas Emissions Analysis Protocol (community section) published by ICLEI in 2009 and the International Standard for Determining Greenhouse Gas Emissions for Cities published by the World Bank, United Nations Environment Programme (UNEP), and UN-Habitat in 2010. Several programs and initiatives have adopted the GPC, including the Compact of Mayors, Carbon Climate Registry, and CDP, among others.	To date, more than 100 cities across the globe have used the GPC (current and previous versions)

<sup>3</sup> Additionality is the requirement that GHG emissions after implementation of a clean development mechanism (CDM) project activity are lower than would have occurred in the most plausible alternative scenario to the implementation of the CDM project activity.

<sup>4</sup> Carbon credit is a commercial unity that represents a ton of CO<sub>2</sub> or CO<sub>2</sub>e removed from the atmosphere; it can be used to offset damaging carbon emissions that are or have been generated. The purchase is usually a way to get this credit from different companies or countries.

International Local Government GHG Emissions Analysis Protocol (IEAP) (ICLEI, 2009), which was a first attempt to provide a program adjusted for local inventories; and the International Standard for Determining Greenhouse Gas Emissions for Cities (UNEP, UN-HABITAT, World Bank, 2010).

Despite the progress made in the past years, there are still some questions regarding GHG accounting at the local level (e.g., How to draw the boundaries? What to measure? How to measure?).

Nikolas Bader and Raimund Bleischwitz (2009) reviewed six tools that have been used in Europe: Project 2 Degrees (developed by ICLEI, Microsoft, and the Clinton Climate Foundation; in English; used by some C40 cities); GRIP (developed by University of Manchester, UK; in English; used by several European regions); CO<sub>2</sub> Grobbilanz (developed by Austria's energy agency; in German only); Eco2Regio (developed by Ecospeed; in German, French, and Italian; used by several Climate Alliance cities); Bilan Carbone (developed by French energy agency; in French); and the CO<sub>2</sub> Calculator (developed by Danish National Environmental Research Institute; in Dutch). They explain that the six tools vary according to the GHGs included (CO<sub>2</sub> vs. other GHGs), the global warming potentials (GWP), the scope of measurement (direct vs. indirect), the definitions of sectors, how emissions were quantified (top-down vs. bottom-up), how closely the tool follows the IPCC guidelines, and the usability of the tool (e.g., simplicity of use, available languages). More recently, economic functions that result in energy and GHG flows in and across communities have been articulated as production (purely territorial), consumption, or hybrid (encompassing trans-boundary flows). In practice, the economic sector composition for communities

has been shown to follow this line of understanding, resulting in distinct planning, policy, and development pathways (Chavez and Ramaswami, 2013).

We present here some of the tools used by cities to elaborate GHG inventories (Box 12.2 Table 1):

Even with the availability of these tools, cities are still in a long way from a common framework. There are significant differences in boundary setting and reporting sectors. In addition, a number of communities do not elaborate GHG inventories regularly, thus hindering comparison in time and action planning for emissions reduction (Neves and Dopico, 2013).

At COP20, in 2014, the first widely endorsed standard for cities to measure and report their GHG emissions was launched. The Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC)<sup>5</sup> uses a robust and clear framework to establish credible emissions accounting and reporting practices, thereby helping cities develop an emissions baseline, set mitigation goals, create more targeted climate action plans, and track progress over time.

Regarding other initiatives, in 2012, in a joint initiative by the Bonn Center for Local Climate Action and Reporting (carbonn) and the carbonn Cities Climate Registry (ccCR) a platform was created to be an open space where cities could report their GHG emissions reduction and climate adaptation targets, accomplishments, and actions. Also, the Carbon Disclosure Project, another global initiative, is achieving popularity in different fields including cities, private companies, shareholders, customers and governments with its own methodology of self-report. However, it is stressed that this initiative is not a GHG inventory methodology, but, in fact, a way to report accomplishments.

African and Latin America falls below the lowest European or North American city (except for Cleveland), with African cities ranging from 18 GJ per capita in Tunis to 0.8 GJ per capita in Maputo, and Latin American cities ranging from 13 GJ per capita in Buenos Aires to 3.3 GJ per capita in Lima (Economist Intelligence Unit, 2012).

Case Studies provide additional detail on the variable sources of energy, extent of modern energy coverage, and rates of growth in demand (see Box 12.3). As demonstrated in Quito, Seattle, and Delhi, the sources of energy are diverse. Sometimes they reflect the resources of the country and the larger continent (i.e., Quito's reliance on hydro reflects the high use of hydropower throughout Latin America) and sometimes they do not (i.e., Seattle's reliance on hydro diverges with the more typical fossil fuel-powered energy in the rest of the United States).

At the metropolitan level, as distinct from the urban scale, Kennedy et al. (2015) examined energy use in twenty-seven of the world's megacities (i.e., metropolitan areas with more than 10 million residents) in 2011, revealing a similarly wide range

worldwide and within regions. Total megacity energy use varied from 2.8 TJ in New York (population 22 million) to just 0.68 TJ in Kolkata (population 14 million). On a per capita basis, Moscow led the other megacities with approximately 147 GJ per capita, followed by New York and Los Angeles (127 and 104 GJ per capita, respectively). By contrast, Mumbai and Kolkata both consumed the least energy per person (8.58 and 4.88 GJ per capita, respectively). While comparable data were not available for seven megacities, Kennedy et al. (2015) note the extraordinary growth in total energy use in Moscow, Karachi, and Los Angeles from 2001 to 2011 (1039%, 637%, and 350%, respectively). Of the studied megacities, total energy use declined only in London and Paris from 2001 to 2011 (−12% and −3% respectively), illustrating the difficulty of achieving reductions at the (mega)city scale.

Across the twenty-seven megacities assessed, electricity comprised 23.6% of the 23.4 EJ used in 2011 (Kennedy et al., 2015). Electricity comprised the majority of the total energy used in 2011 in Shenzhen and Kolkata megacities (70% and 65%, respectively), while comprising only a small share in Mexico City, Moscow, Dhaka, and Tehran (8–12%) and a tiny share in Lagos (<1%).

5 <http://www.ghgprotocol.org/city-accounting>

**Table 12.3** Selected urban area energy consumption estimates, 2011 (average gigajoules [GJ] per capita). Source: Rae Zimmerman, with data from Economist Intelligence Unit (EIU) reports (EIU, 2011a, 2011b, 2011c, 2011d, 2011e, 2011f)

Region	No. of Cities	Ave. GJ/capita	Maximum Users	Minimum Users
North America (Economist Intelligence Unit [EIU], 2011f)	27	52.2	Atlanta (152.4) Orlando (117.7) Sacramento (98.9)	Cleveland (10.3) Minneapolis (23.3) San Francisco (24.5)
Latin America <sup>a</sup> (EIU, 2011e)	17	7.2	Buenos Aires (13.0) Monterrey (12.9) Puerto Alegre (11.8)	Bogotá (3.3) Lima (3.3) Quito (4.2)
Europe <sup>b</sup> (EIU, 2011c)	30	80.9	Dublin (156.5) Ljubljana (105.9) Stockholm (104.9)	Istanbul (36.2) Belgrade (41.1) Warsaw (49.8)
Africa (EIU, 2011a)	15	6.4	Tunis (18.1) Cape Town (13.9) Durban (11.3)	Lagos (0.8) Maputo (0.8) Luanda (1.0)
Asia <sup>a</sup> (EIU, 2011b)	22	66.4	Guangzhou (197.0) Shanghai (169.7) Beijing (124.7)	Calcutta (5.7) Bangalore (9.5) Mumbai (14.2)

<sup>a</sup> Energy usage was computed from numerical values for GDP per capita and Gigajoules per capita; otherwise, they are the average of country values as given directly in the sources.

<sup>b</sup> The selection of cities in Germany for Europe are based on Economist Intelligence Unit (2011c), although there is a German report as well that includes other cities in Germany (EIU, 2011d).

### Urban Impacts: GHG Emissions

The environmental impact from urban energy use in terms of GHG emissions requires assessment of both total energy consumption as well as life cycle assessment of the types of fuels and technologies used for energy generation (Heath and Mann, 2012). Cities with similarly sized energy consumption can have dramatically different carbon emissions depending on the carbon intensity of the fuel source (i.e., gCO<sub>2</sub>/MJ) (Brown et al., 2008). Cities powered predominantly by hydropower (São Paulo, Rio de Janeiro) or nuclear electricity (Paris) have low carbon intensity and thus low total GHG emissions compared to cities powered predominantly by fossil fuels, and, among fossil fuels, coal-fired electricity (Kolkata, Shenzhen, Guangzhou) has a much higher carbon intensity than does gas-powered electricity (Moscow, Istanbul, Delhi). Comparisons of GHG emissions across cities are challenging not only due to variations in energy use and carbon intensity, as well as electrification rates, but also based on economic typologies (e.g., net-producer, net-consumer, and trade-balanced cities) (Chavez, 2012; Seto et al., 2014).

Table 12.4 highlights selected GHG emissions for cities using data from the EIU reports. The table reveals high variability across cities around the world and the need for better standardization of data. Within Asian cities, for example, there is variation between city GHG emissions levels (8–9 tCO<sub>2</sub> per capita in Beijing, Guangzhou, and Shanghai compared with 0.5–1.1 tCO<sub>2</sub> per capita in Bangalore, Mumbai and Delhi). In Latin American and African cities, urban GHG emissions are remarkably lower. Notably, however, the Latin American and African city data reported by EIU are only carbon emissions from electricity use

and thus underestimate total GHG emissions from all energy production. In places with low electrification rates like Lagos, the noted GHG emissions exclude nearly all emissions associated with energy use in the city.

Energy use and GHG emissions reported by the EIU are closely associated among Asian and among African cities, moderately associated in European and Latin American cities, and not associated in North American cities. The high association among Asian cities appears to reflect the carbon intensity of their electricity sources and the city's development status, with higher income Chinese cities having larger energy use and carbon emissions while lower income Indian cities have lower energy use and carbon emissions. The lack of association among North American cities reflects the wide variability in carbon intensity among all relatively high-income cities. Cleveland in particular illustrates the dichotomy: its energy use is quite low compared to other U.S. cities (10.3 GJ/capita) but its carbon emissions are very high (29.1 tCO<sub>2</sub>/capita), reflecting its reliance on carbon-intensive fuels. The generally lower carbon emissions in Canadian cities compared to American cities also reflects source fuel availability and policy choices of Canadian cities to limit environmental impact (see also Section 12.5).

### 12.4.2 Urban Energy Supply Sector Vulnerabilities to Climate Change

The latest IPCC report suggests that climate change-related vulnerabilities are increasing across the world's urban centers (Revi et al., 2014). That is, cities are increasingly predisposed to be adversely affected by climate impacts (Eakin and Lynd Luers, 2006,



### Box 12.3 Energy Supply in Quito, Seattle, and Delhi

**Daniel Carrion**

*Mailman School of Public Health, Columbia University, New York*

**Hossein Estiri**

*University of Washington, Seattle*

*Harvard Medical School, Cambridge, MA*

**Joshua Sperling**

*National Renewable Energy Laboratory, Denver*

The electrical grid is vast in Quito, reaching 98% of the population. Empresa Electrica de Quito (EEQ), the region's energy provider, planned a grid expansion to 99.5% of the population by 2016 (EEQ, 2012). Overall energy consumption is 3,066.4 GWh per year (United Nations Development Program [UNEP], 2011). Hydroelectric and diesel combustion are the two principal sources of energy production (EEQ, 2012). Only one diesel plant currently operates, with an electrical capacity of 31.2 MW. Five hydroelectric plants carry the remaining load, with one more forthcoming (EEQ, 2014). It is a timely expansion of the electrical grid because population growth and increasing reliance on electrical infrastructure are evident.

Two utility companies supply energy for the City of Seattle: Seattle City Light (SCL) and Puget Sound Energy (PSE). Seattle City Light, a department of the City of Seattle, is one of the largest municipally owned utilities in the United States and is the primary electricity supplier for the city, servicing 340,000 residential and 40,000 commercial customers, with a service area of 340 square kilometers. In general, most of the net electricity generation (more than 45%) in the state of Washington is from hydropower and other non-nuclear clean energy sources. According to the U.S. Energy Information

Administration, in 2013, the state of Washington was the leading producer of electricity from hydropower in the United States, where 29% of the net hydroelectricity is generated. As a result, energy sector emissions are lower in Washington than in most other states. Seattle has the lowest electric rates of all twenty-five largest cities in the United States. In 2013, 88.9% of SCL's electricity was generated from hydropower and 8.4% from other clean resources (i.e., nuclear, wind, and landfill gas), while only 1.7% comes from coal.

In 2011, the Central Electric Authority of India projected that Delhi's power requirements would nearly double over a 5-year period (2009–2014) from an average requirement of 4,500 MW to 8,700 MW and therefore began planning ahead. As of April 2013, the North Capital Territory (NCT) of Delhi was estimated to have installed electricity generation capacity of 7,163 MW, with central, state, and private sectors constituting 75%, 23%, and 2% of total capacity, respectively, and with renewable power (including small hydro) representing 10% of the mix. At the state level, total system power capacity reached 18,007 MW by 2012, with roughly 70% of power from coal, 8% from natural gas, 19% hydro, and 3% nuclear.

Between 2005 and 2013, peak electricity demand in the NCT of Delhi grew at a compound annual growth rate of 7%, and peak demand deficit in the state has increased from 2% to 5% over that same period, often resulting in daily power cuts. According to the Delhi Statistical Handbook, the number of Delhi electricity consumers increased from 2,565,000 in 2002–2003 to 4,301,000 in 2011–2012. This included a total of nearly 3,465,000 domestic consumers. Only a year later, the National Sample Survey (administered in July–December 2012) showed that 99% of urban households in Delhi now had electricity access (*note*: this may be an overestimate due to the survey missing harder-to-reach informal/slum households lacking reliable access).

IPCC, 2014b). These impacts are important for the energy sector (see Figure 12.2a), and some countries including the Philippines are conducting vulnerability assessments for the energy supply sector and identifying and pursuing climate-proofing programs to upgrade standards for energy systems and facilities (Petilla, 2014).

Climate-related vulnerability is comprised of three elements: exposure to a hazard, sensitivity to that exposure, and capacity to adapt to the hazard (Fussler and Klein, 2006). The *hazard* or shock is measured in terms of its size, intensity, and duration. Weather- and climate-related hazards could include an increased number or intensity of tropical cyclones, sea level rise, duration and intensity of heat waves, and droughts. *Exposure* refers to the inventory of people, property, or other valued items in areas where hazards may occur (United Nations Office for Disaster Risk Reduction [UNISDR], 2009; Cardona et al., 2012). The *sensitivity* includes the degree to which the agent or system is affected by a hazard (Olmos, 2001). Portions of the population (i.e., the elderly, young

and poor) are typically more sensitive to the effects of climate change, such as extreme temperature events. *Adaptive capacity* is defined as the ability of an agent or system to prepare for stresses and changes in advance of the shock or to adjust in the response to the effects of the shock (Smit and Wandel, 2006).

Prior assessments have noted that climate change presents vulnerabilities to urban energy supply in at least three different ways: to primary energy feedstocks, to power generation, and to transmission and distribution networks (Hammer et al., 2011).

*Feedstocks*: In developing countries, areas heavily dependent on different types of biomass as primary energy feedstocks may be vulnerable if climate change affects the availability of the material. Biomass is sensitive to changing temperature levels if plants reach the threshold of their biological heat tolerance or if storms or drought reduce plant or tree growth levels (Williamson et al., 2009).



**Table 12.4** Selected Urban Area Carbon Dioxide Emissions (Average tCO<sub>2</sub>/capita)<sup>a</sup>. Source: Rae Zimmerman, with data from Economist Intelligence Unit (EIU) reports (EIU, 2011a, 2011b, 2011c, 2011d, 2011e, 2011f)

Region	No. of Cities	Average annual tCO <sub>2</sub> /capita <sup>b</sup>	Maximum Emitters (tCO <sub>2</sub> /capita)	Minimum Emitters (tCO <sub>2</sub> /capita)
North America (EIU, 2011f)	27	14.51	Cleveland (29.1) St. Louis (27.1) Houston (25.8)	Vancouver (4.2) Ottawa (6.9) Toronto (7.6)
Latin America (EIU, 2011e)	17	0.20 <sup>c</sup>	Monterrey (0.72) Buenos Aires (0.53) Santiago (0.46)	São Paulo (0) Brasilia (0.01) Curitiba (0.07)
Europe (EIU, 2011c)	30	5.21	Dublin (9.79) Prague (8.05) Lisbon (7.47)	Oslo (2.19) Istanbul (3.25) Ljubljana (3.41)
Africa (EIU, 2011a)	15	0.98 <sup>c</sup>	Cape Town (4.10) Durban (3.50) Pretoria (3.05)	Maputo (0.000) Luanda (.003) Addis Ababa (.016)
Asia (EIU, 2011b)	22	4.62	Shanghai (9.4) Guangzhou (9.2) Beijing (8.2)	Bengaluru (0.5) Delhi (1.1) Mumbai (1.0)

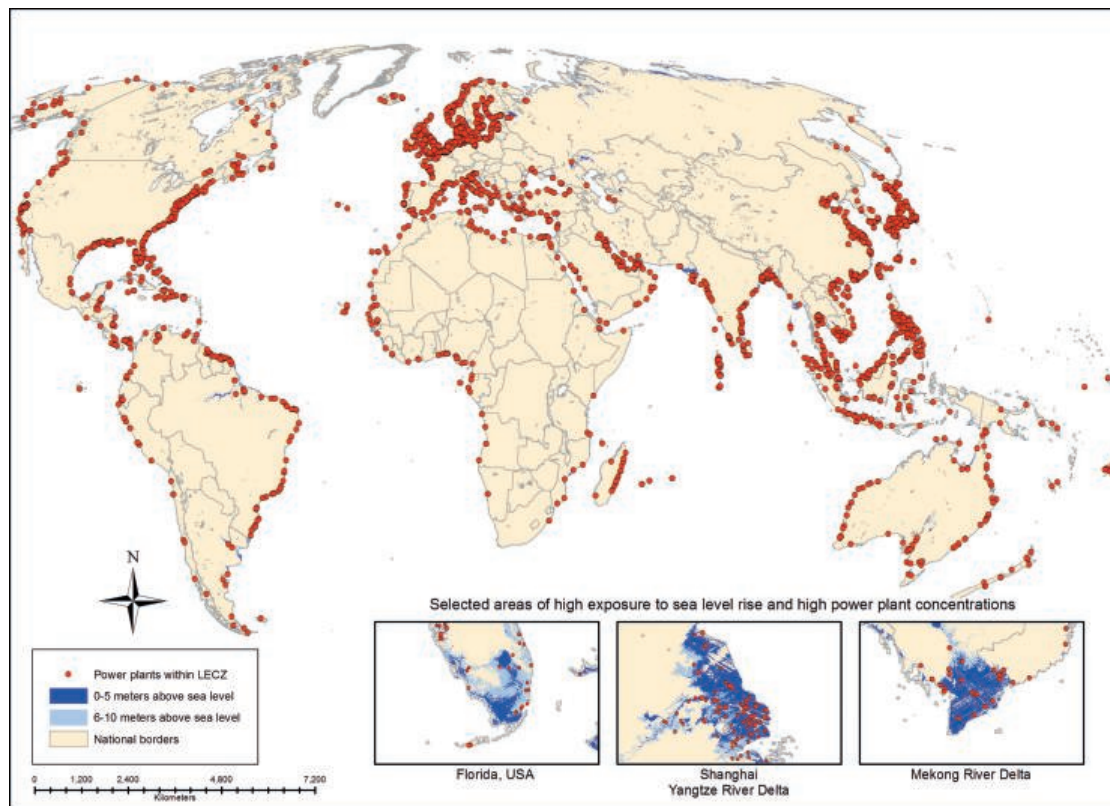
Notes:

<sup>a</sup> Units and the base used can differ across regions; therefore, comparisons among cities should only be drawn within regions not between them.

<sup>b</sup> Units for carbon dioxide are in tons (t) for total energy emissions from all sources; in some cases, other units were given and converted to tons (see notes for Latin America and Africa).

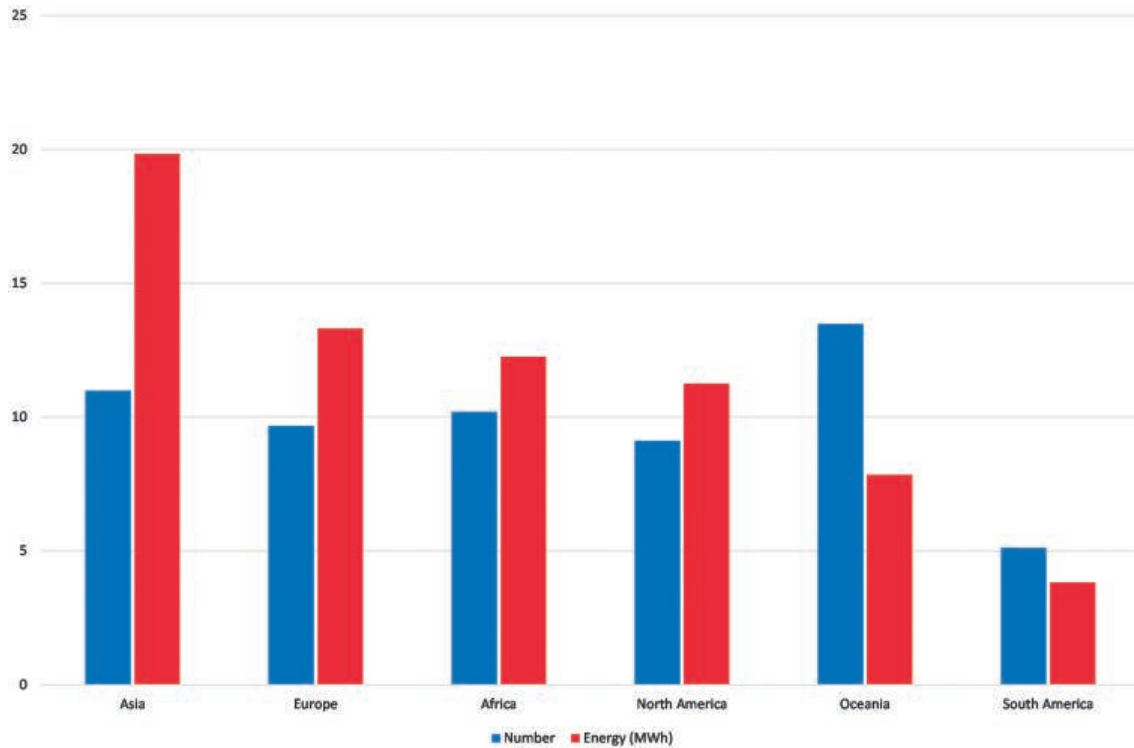
Figures are based on data generally from 2005 to 2009 with some data from 2002, and the dates vary for different cities. For example, the Economist Intelligence Unit (2011f: 16) notes that U.S. city data is from 2002, whereas Canada city data is from 2008.

<sup>c</sup> For Latin America and Africa, carbon dioxide emission figures are for electricity use only. They were originally in terms of kilograms per capita and converted to tons for comparability for the average and city figures listed.



**Figure 12.2a** Map of power plants around the world within 10 meters of sea level, 2009.

Source: This map was constructed using the USGS Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) digital elevation model at 15 arc seconds resolution using mean elevation per cell and power plant data point file from the Carbon Monitoring for Action (CARMA v.3, 2012). Elevation was extracted between 0 and 10 meters above sea level and identified those power plants within the zone



**Figure 12.2b** Percent of number and power generation of thermal power plants within 10 meters of sea level, by, region, 2009.

Source: Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), The Carbon Monitoring for Action (CARMA v.3, 2012)

Oil and gas drilling operations and refineries are also subject to exposure to extreme events, including flooding and high winds, and are vulnerable to thawing permafrost that can cause damage to infrastructure as well as decreasing water availability given the volumes of water required for enhanced oil recovery, hydraulic fracturing, and refining (Bull et al., 2007; U.S. Department of Energy, 2014). Closure of these facilities and fuel terminals in the Gulf of Mexico during and after Hurricane Katrina were linked to fuel price increases across the United States.

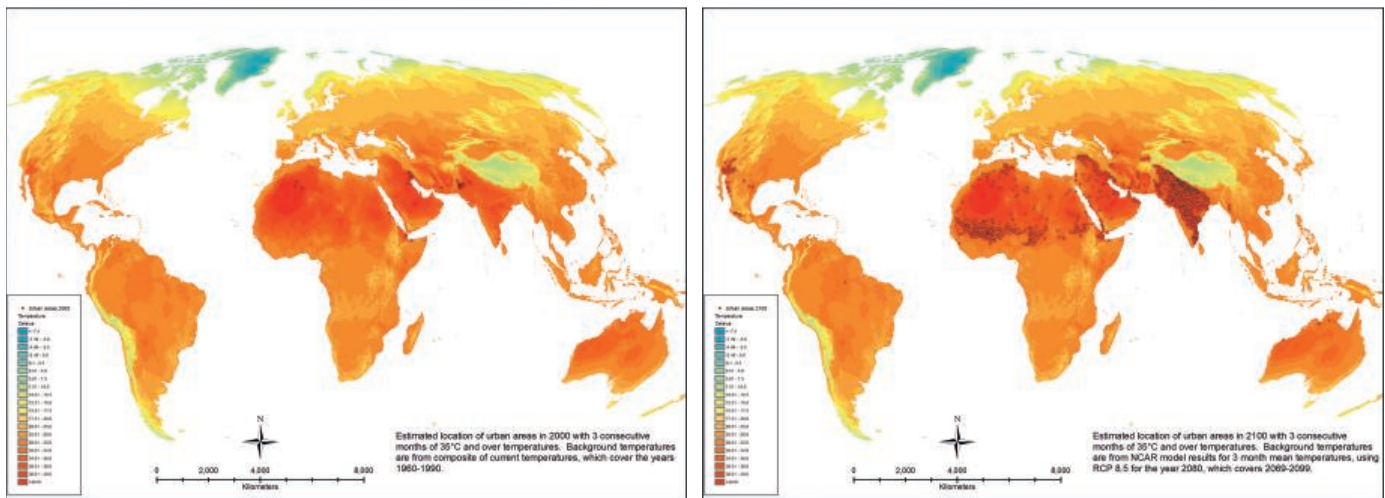
**Energy generation:** Sea level rise may also expose populations and energy and other infrastructure to risk (see, e.g., McGranahan et al., 2007; Nicholls et al., 2008; Hanson, 2011). The low elevation coastal zone (LECZ), defined as contiguous land areas along the coast that are within 10 meters of sea level, may be exposed to flooding risks, including, for example, storm surge, high tides, and extreme precipitation events, all of which are compounded by increases in sea level over the coming decades. As the map in Figure 12.2a demonstrates, across the world, more than 6,700 power generation plants that provided almost 15% of power generation in 2009 are within this zone. Figure 12.2b suggests that Asia has the highest percent of plant generation within the LECZ; almost 20% of Asian power generation. South America has the lowest share; approximately 4% of Latin American power generation.

Both total electricity demand and peak electricity demand will increase with rising temperatures, although peak demand

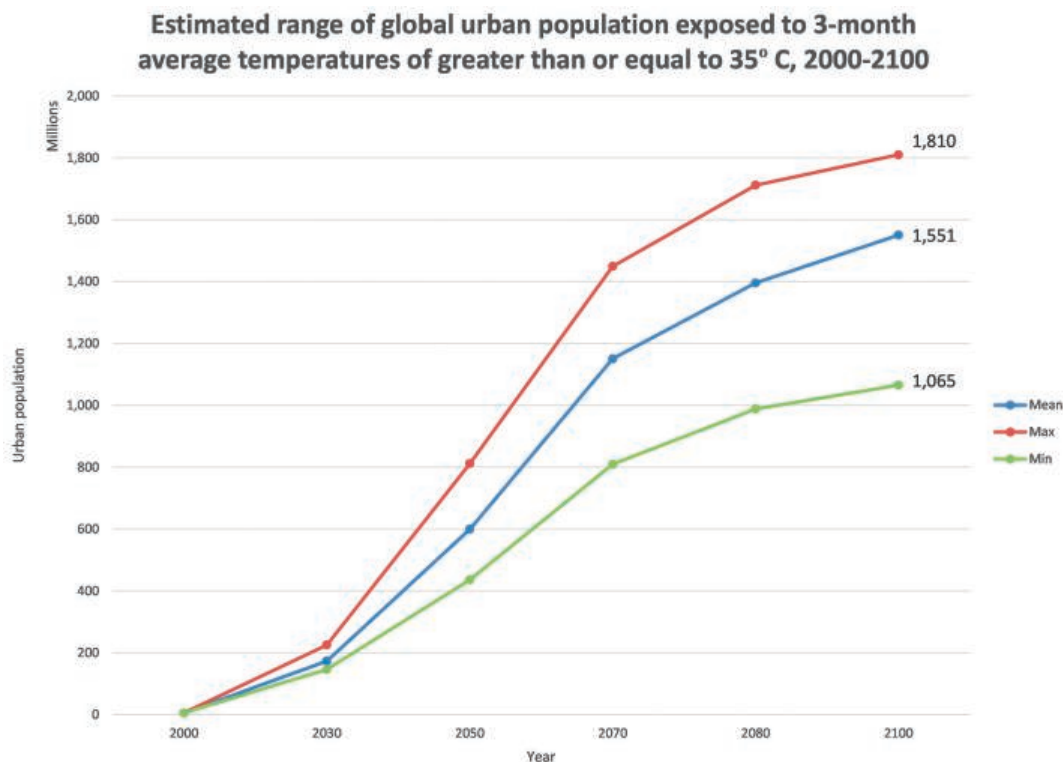
will increase at a much faster rate (Smith and Tirpak, 1989; Baxter and Calandri, 1992; ICF, 1995; Franco and Sanstad, 2008). Increasing temperatures are associated with higher air conditioning (U.S. Department of Energy, 2013). Research for Boston, Massachusetts, suggests per capita energy demand will be at least 20% higher in 2030 compared to the 1960–2000 average (Kirshen et al., 2008). In developing cities, air conditioning increases rapidly with income. Under modest assumptions about income growth, all warm areas around the globe will reach near universal saturation of air conditioners (Davis and Gertler, 2015). Moreover, heavy use of further air conditioning raises nighttime temperatures by as much as 1°C (Salamanca et al., 2014).

Future high temperatures may affect large urban populations and hence energy demand. As Figure 12.3a and 12.3b suggest, a significant number of cities with large populations may experience extremely warm summers by the end of the century. These estimates suggest that if trends remain unchanged, by 2050, more than 9% of the world's urban population will experience average summer temperatures of more than 35°C. By 2100, the share will increase to approximately 17% of the global urban population and include approximately 1.5 billion people. Of this number, more than 99% are predicted to live in Africa and Asia.

A city's power generation capacity is sized to meet the highest summertime peak demand. By contrast, when peak demand growth outpaces total demand growth, spare capacity is in short supply, increasing the risk of blackouts and brownouts (Miller



**Figure 12.3a** Maps of estimates for cities under extreme summer temperatures (35°C and higher) in 2000 (left) and 2100 (right). The maps were produced by identifying the highest three consecutive mean monthly temperatures for each cell, averaged from 32 global climate models for 2080 (covering 2070–2099) and a composite map for the current temperature (1960–1990). For 2000, the background colors are the averages for the three highest consecutive monthly means for each cell for that year. The 2100 background values are presented using only the NCAR climate model (ccsm4) for Representative Concentration Pathway (RCP) 8.5. Grid cells are 2.5 arc minutes, approximately 5 km<sup>2</sup>. The 2100 map demonstrates the concentration of cities in Africa and Asia that may experience extreme summer temperatures under the RCP8.5 scenario.



**Figure 12.3b** Chart of estimated urban population under different summer temperature conditions, 2000–2100. The figure presents the growth in numbers of global urban residents over time for cities experiencing three consecutive months of 35°C and higher temperatures, with mean, minimum, and maximum estimates of population.

et al., 2008). In California, a summer 2006 heat wave led to blackouts across the state because sustained high nighttime temperatures prevented the transformers from cooling down before demand increased again the next morning (Miller et al., 2008; Vine, 2012). In developing countries, during 2005, hot and cold

weather explained 13% of the variability in energy productivity (Farrell and Remes, 2009).

Drought can affect power generation due to the cooling needs of plants. Three potential impacts include (1) reduction of stream flow, (2) increase in temperatures downstream

of power plants beyond allowable limits due to waste heat exhaust, and (3) increase of water temperature into plants (ICF, 1995; U.S. Department of Energy, 2013). In some situations, power plants may be asked to scale back operations. Moreover, drought is associated with wildfire and increased temperatures that damage energy supply infrastructure (CDP, C40, and AECOM, 2014).

Power generation facilities reliant on renewable resources may be affected by climate change. Hydroelectric facilities fed by glacial and snow-melt have historically benefited from the ability of glaciers to regulate and maintain the water levels of rivers and streams throughout the summer. With increasing temperatures, snow levels are decreasing and glaciers are shrinking, thus jeopardizing the amount of hydroelectric production available to serve many urban areas (Markoff and Cullen, 2008; Madnani, 2009). The densely populated Mediterranean region may face a 20–50% decrease in hydropower potential by the 2070s, although changing precipitation patterns are expected to increase hydropower production by roughly 15–30% in northern and eastern Europe over the same period (Lehner et al., 2001). The elevation at which precipitation occurs is key because retention dams serve different functions based on their elevation and have different water release rules that could affect the availability of power at different times of the year (Aspen Environmental Group and M Cubed, 2005; Franco, 2005; Vine, 2012).

Alternatively, as mentioned earlier, power generation facilities are also affected by too much rainfall. Geojje, South Korea, reported that frequent and intense rainfall reduced operational hours at the company shipyard resulting in delayed deliveries. Typhoon Maemi, in 2003, caused approximately US\$20 million in damages (CDP, C40 and AECOM, 2014).

Climate-induced changes may be important in limiting solar and wind production in certain areas. More cloudy days may result in a decline in solar radiation in the United States by 20% (Pan et al., 2004) but only a 2% decline in solar radiation in Norway (Fidje and Martinsen, 2006). Wind patterns may also change. Research finds no clear signal in the Baltic Sea (Fenger, 2007), although onshore wind speeds in the United Kingdom and Ireland are expected to decrease in summer and increase in winter (Harrison et al., 2008). In the United States, wind speeds may decline from 1% to 15% (Breslow and Sailor, 2002).

*Energy transmission and distribution networks:* Typical electrical transmission losses range from 6% to 15% of net electricity produced (Lovins et al., 2002; International Electrotechnical Commission [IEC], 2007). The effect on aboveground lines is moderated by cooler ambient air, while wires below the ground are cooled by moisture in the soil. As temperatures increase, the cooling capacity of the ambient air and soil declines, conductivity declines, and lines may begin to fail (Hewer, 2006; Mansanet-Bataller et al., 2008; U.S. Department of Energy, 2013). Extreme events take a toll on transmission, including intense precipitation, flooding, storm surge, and high winds (McKinley, 2008;

U.S. Department of Energy, 2013). For example, heavy snows in central and southern China in 2008 blocked rail networks and highways used for delivering coal to power plants, forcing seventeen of China's thirty-one provinces to ration power and affecting hundreds of millions of people in cities across the country (French, 2008).

Increased size and intensity of hurricanes can affect oil and gas transmission. Hurricane Katrina caused the shutdown of major pipelines from the Gulf region resulting in a full disruption of the supply of gas, crude oil, and refined products to other U.S. regions (Hibbard, 2006). On the other hand, Larsen et al. (2008) note that Arctic transport routes and energy infrastructure for moving oil and gas across Alaska are located across areas at high risk of permafrost thaw as temperature rise. System stresses from this impact not only slow supply to cities, but also increase also energy prices.

The result of extreme event impacts on the energy supply sector appears in the form of outages. Understanding recovery patterns and trends is critical to identifying adaptation measures. Simonoff, Restrepo, and Zimmerman (2007) analyzed U.S. electric power outages from a variety of causes and found not only an increasing trend over the years but, since the early 2000s, increasing duration of the outages as well. The ability of electric power systems to recover varies across different types of facilities and circumstances. Zimmerman (2014) analyzed the recovery of electric power in New York citywide and by borough and found high levels of restoration within a couple of weeks after super storm Sandy.

*Critical interdependencies with other infrastructure:* as mentioned in Hammer et al. (2011), energy systems provide the “life blood” to cities. Energy supply is a critical resilience priority: if energy systems fail, results pose additional stresses on the ability to provide potable water supply, food, transportation, sanitation, communications, health care, and so on. Energy supply disruptions can lead to cascading failures across the economy, government, communities, and multiple other infrastructure sectors. This is not to mention the disproportional impacts of power outages and lack of access to modern energy services on the elderly and poor, especially during periods of extreme heat or other hazard events, as demonstrated by the recent heat waves in India and Pakistan and Hurricane Sandy in New York (see also Section 12.4.2).

Since the urban energy supply sector provides multiple benefits to society and enables improved standards of living (Pasternak, 2000), reducing vulnerabilities can help to avoid cascading failures ranging from reduced hours and services for hospitals (Hess et al., 2011; Schwartz et al., 2011), disruptions of critical human activities (cooking, boiling water, space heating, cooling), reduced transport that enables access to livelihoods, breaks in social networks, and reduction in industrial production and communication (McMichael et al., 1994; Saatkamp et al., 2000; Wilkinson et al., 2007).



## Box 12.4 A Framework to Evaluate Climate Vulnerability of Urban Energy Systems

Hossein Estiri

*University of Washington, Seattle*

*Harvard Medical School, Cambridge, MA*

This box proposes a framework for evaluating the vulnerability of the urban energy supply sector to climate change impacts. Climate impacts can be categorized into two types: gradual and spontaneous. Gradual impacts occur slowly over time (e.g., incremental changes in temperature and precipitation), and, depending on severity of the effects, local jurisdictions should have enough time to plan for them. These effects can be considered as causing low vulnerability for the energy supply sector unless they are of high severity. In contrast, spontaneous impacts are often extreme and hard to predict (e.g., hurricanes, floods, heat waves, and prolonged droughts). Any spontaneous climate impact can raise the urban energy supply sector's vulnerability. In addition, climate impacts on urban energy systems can be characterized as having both direct and indirect effects (Box 12.4 Figure 1). This framework can be used to evaluate the vulnerability of components of the energy supply sector and the entire system as a whole.

Gradual impacts:

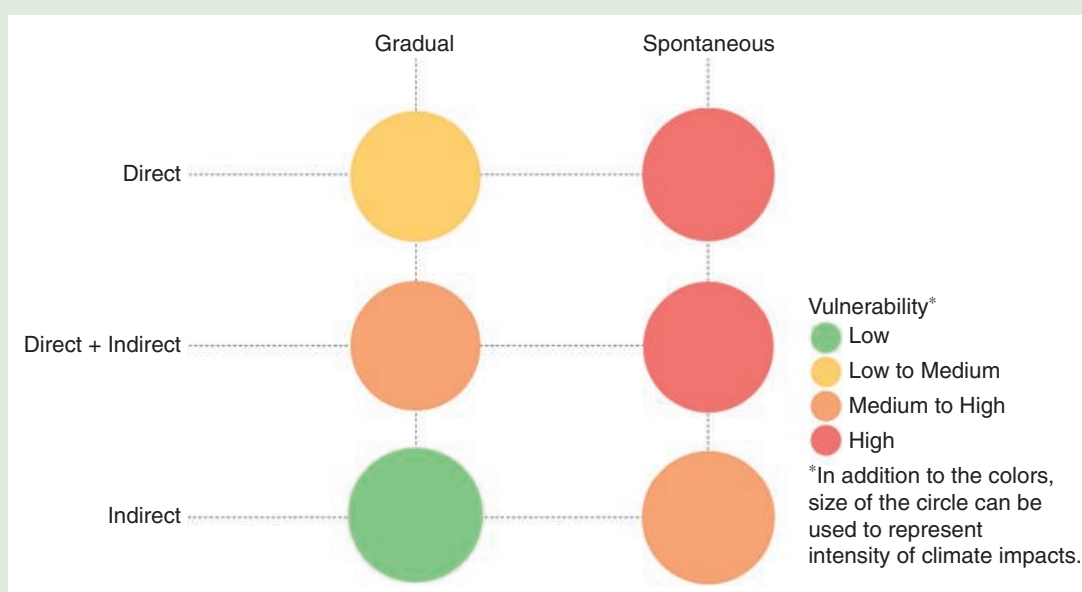
- Gradual damages to energy production and transmission equipment and structures that decrease efficiency and increase distribution losses
- Increases in energy demand for cooling
- Decreases in capacity to generate hydropower resulting in limited ability for cooling thermal plants as a result of changes in snow and rain dynamics

- Availability of biomass for energy generation due to adverse impacts of climate change on agricultural yields

Spontaneous impacts:

- Increases in frequency of extreme events such as hurricanes and floods can directly damage energy production, transmission, and distribution infrastructures, such as nuclear plants, offshore oil drilling platforms, and energy distribution systems and power lines – high vulnerability
- Sea-level rise can also pose a major direct threat to energy supply facilities such as coastal power plants – high vulnerability
- Extreme climate events can influence the urban energy supply sector. For instance:
  - Droughts and floods can produce shifting paradigms in availability of water resources used for cooling thermal plants – medium vulnerability
  - Heat waves can pose significant shocks to the urban energy supply sector by producing temporal peaks in energy demand – high vulnerability

Climate change is a complex phenomenon and so is predicting its impacts. In most cases, the urban energy supply sector is highly vulnerable to spontaneous climate impacts and less so to climate change's gradual effects. Highest vulnerabilities happen when both demand and supply of energy change in reverse directions (i.e., simultaneous increase in demand and decrease in supply). It is crucial for local and regional jurisdictions around the world to systematically evaluate possible impacts of changes in local, regional, and global climate on their energy systems and on other systems dependent on these energy systems, and adopt suitable adaptation strategies to improve their resilience.



**Box 12.4 Figure 1** A framework to evaluate vulnerability of the urban energy supply sector.



### 12.4.3 Urban Energy Supply Access Challenges

Energy access is critical for human development (Modi et al., 2005). Better provision of electricity and clean fuels improves health, literacy, and primary school completion rates. Similarly, better access to electricity lowers costs for businesses and increases trade and investment, driving economic growth and helping to reduce poverty.

Worldwide in 2010, however, more than 179 million urban residents lacked access to electricity and nearly 477 million urban residents lacked access to non-solid fuels (see Table 12.5). The urban population share without electricity has dropped slightly from around 5.7% to 5.1% over the past 20 years, but the large urbanization that has occurred has pushed up the absolute numbers. From 1990 to 2010, the numbers of urban population *with* access electricity jumped from 2.1 to almost 3.4 billion. At the same time, the number without electricity jumped from 127 to 179 million. The greatest gains in access over the past 20 years were in Asia, which also experienced the most intense urbanization. For example, from 1990 to 2010, the percentage without access in South Asia dropped from 13.9% to 6.9%.

Figure 12.4 demonstrates the gains made in populations with electricity access, with a focus on urban households in selected countries from 1990 to 2015 and using data from the USAID Demographic and Health Survey program. For the purposes of comparison, and from just these 13 randomly selected countries – including Indonesia, Peru, Philippines, Ghana, Bangladesh, Senegal, Rwanda, Zambia, Madagascar, Burkina Faso, Uganda, Tanzania, and Malawi –total gains (from 1990 to 2015) for urban residents now having electricity exceeds the

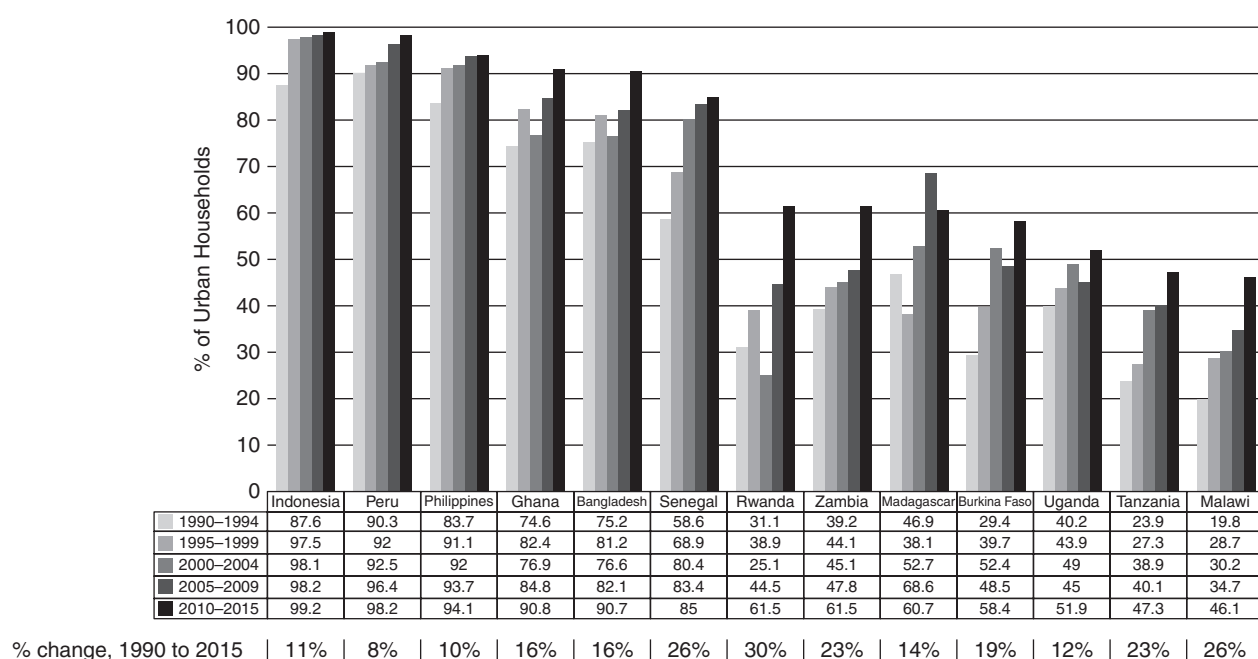
**Table 12.5** Urban population without access to energy, 1990–2010 (millions).

Source: World Bank, 2015; UN, 2014

Region	Electricity			Non-solid fuels
	1990	2000	2010	2010
<b>Developing</b>	127	132	179	442
<b>Least developed</b>	44	68	85	177
<b>Developed</b>	2.0	1.1	0.0	5.0
<b>Africa</b>	56	84	112	191
<b>Asia</b>	63	39	54	223
<b>Europe</b>	2.0	1.1	0.0	5.0
<b>Latin American and Caribbean</b>	8	8	12	28
<b>North America</b>	0.0	0.0	0.0	0.0
<b>Oceania</b>	0.6	0.7	0.8	0.2
<b>Total</b>	<b>129</b>	<b>134</b>	<b>179</b>	<b>447</b>

Note: Calculations were based upon the national percentage of urban population with access to electricity and non-solid fuels (World Bank) and total national urban population (UN).

total urban population of the largest 50 cities in the United States in 2014 (~48.4 million; U.S. Census Bureau). Figure 12.4 also shows that in 1990, the majority of African nations remained well below 50% coverage in terms of urban households with electricity access. Positive trends are recognizable for all selected countries across Asia, Latin America, and Africa, with



**Figure 12.4** Increases in electricity access for urban households of select countries of the Global South: 1990 to 2015. Approximately 53.5M more urban residents in these countries may have access to electricity. Reliable 24-hour access is likely lower.

Source: USAID, 2016; the Demographic and Health Survey Program. Data accessed at: <http://beta.statcompiler.com/>

almost a doubling in urban coverage in the countries of Rwanda, Tanzania, and Malawi (from 1990 to 2015).

At the same time, the most significant problems with energy access still remains in Sub-Saharan Africa, where in 2010, approximately 36.8% of urban residents lacked access to electricity and nearly 64% of urban residents lacked access to non-solid fuels (World Bank, 2015). The combined power generation capacity of the forty-eight countries of Sub-Saharan Africa is 68 gigawatts (GW), no more than that of Spain. Currently, the installed capacity per capita in Sub-Saharan Africa (excluding South Africa) is a little more than one-third of South Asia's (the two regions were equal in 1980) and about one-tenth of that of Latin America.

Moreover, electricity coverage in Sub-Saharan Africa is skewed to more affluent households. Among the poorest 40% of the population, coverage of electricity services is well below 10%. Conversely, the vast majority of households with coverage belong to the more affluent 40% of the population (Eberhard et al., 2011).

In recent years, external factors have exacerbated the already precarious power situation in Sub-Saharan Africa. Drought has seriously reduced the power available to hydro-dependent countries in western and eastern Africa. Countries with significant hydropower installations in affected catchments – Burundi, Ghana, Kenya, Madagascar, Rwanda, Tanzania, and Uganda – have switched to expensive and highly polluting diesel power (Eberhard et al., 2011).

Access to clean (non-solid) fuels is lowest among poor households in urban areas, especially in slums or informal settlements, and also in peri-urban areas. The types of energy sources used by the urban poor vary with very-low-income households relying exclusively on fuel wood, charcoal, animal dung, and waste materials, and with slightly better-off households using coal, kerosene, and some electricity. Only a small proportion of urban households in low-income nations use electricity or liquid propane gas (LPG) for cooking (Karekezi et al., 2012). Since many informal fuels do not have organized markets, limited information exists on supply chains for biomass and informal fuels in cities (Satterthwaite and Sverdluk, 2013). Sources such as animal dung may be available in the immediate vicinity; however, fuel wood supply can extend to the hinterland, especially for peri-urban households. In Malawi, nearly 60% of charcoal wood for the four major cities came from surrounding areas, including protected areas, forest reserves, and national parks in 2007 (Zulu, 2010). If current trends continue, the number of people in Sub-Saharan Africa relying on traditional biomass for cooking will increase sharply over the next two decades (Brew-Hammond, 2010). Important to note is that energy justice issues are not only an issue in developing-country cities. Even in the United States, survey results of residents in the city of Detroit show “almost 27 percent of low-income households have fallen behind on utility payments and an additional seven percent have experienced a utility shut-off” (Hernandez, 2015).

Considering that traditional sources will remain in the urban energy mix in the near future, near-term efforts are needed to formalize the sustainable production, promotion, and distribution

processes of informal fuels and to transform cook stoves and available fuel infrastructure choices (Karekezi et al., 2008; Karekezi et al., 2012). In the mid-term, the supply of clean and affordable energy in cities should be prioritized and embedded in local and national development plans. This effort will require investments in commercialization of clean energy complemented with strategies to improve affordability through financial reforms including targeted subsidies, micro-financing to spread upfront costs, and other innovative mechanisms.

Despite or rather because of current trends, energy justice for the world's urban population is high on the international agenda. The new Sustainable Development Goals (7 and 11) elevate energy justice and access to basic services to a high priority. Specifically, Target 7.1 calls for ensuring universal access to affordable, reliable, and modern energy services, whereas Target 11.1 calls for ensuring access for all to adequate, safe, and affordable housing and basic services and to upgrading slums, both by 2030 (UN, 2015).

While there were 17 goals, 169 targets, and more than 200 indicators as of January 2016, and a headline goal on climate, there was no headline goal on air pollution. With many areas undergoing transitions in access to electricity and industrialization, rapid growth in air pollution has emerged as a major challenge affecting urban populations today. From coal briquettes to oil-fired heating, energy and air pollution in cities is arguably more important than GHG emissions, at least in the near term. While climate impacts (e.g., heat and sea level rise) will have direct impacts on infrastructure, people, and energy systems, current challenges in the context of air pollution, especially in cities not meeting air quality standards (e.g., Los Angeles, Beijing, Mexico City) are critical.

## 12.5 Opportunities, Limitations, and Barriers to Achieving Adaptation, Mitigation, and Sustainable Development Goals for the Urban Energy Supply Sector

### 12.5.1 Energy Transitions and the Urban Energy Supply Sector

Transitions are breaks or inflections in long-term trends involving complex sociotechnical systems (National Research Academy, 1999). Energy supply transitions are crucial to development. For example, in countries such as China and India, sharp increases in the human development index are being achieved via relatively small increases in energy use (Sperling and Ramaswami, 2013; Steinberger and Roberts, 2009).

Historical transitions in energy supply systems reflect significant shifts in the role of different primary fuels, such as the transition from wood and water power to coal in the 19th century, or innovations in conversion technologies such as electrification in the late 19th century (Verbong and Geels, 2007; Smith, 2010; Grin et al., 2012; Justo, 2009). These transitions were due to a combination of the increased efficiency of the new carrier (higher energy

intensity), the convenience of its use due to increased supply, the expansion of technologies that facilitated the use of the energy in a variety of forms, and its lower price (Grubler, 2004, 2012; Smil, 2010; Fouquet and Pearson, 2012), and they unfolded over long periods of time (40–70 years) (Fouquet, 2010; Grubler, 2012).

Contemporary energy transitions may not be driven by the same factors as those in the past (Grubler et al., 2012b). Recent urban energy supply transitions are fundamentally different from those of the past. When measured against the developed world experience, cities in the developing world demonstrate consistent and clear patterns of divergence. In developing world cities, the staged transitions between primary fuels (biomass to coal to liquid fossil fuels to natural gas) are occurring sooner during development (at lower levels of economic income), changing faster, and emerging simultaneously as opposed to sequentially (Marcotullio et al., 2005). Given these changes, how long future transitions might take is not well understood.

### 12.5.2 Energy Scenarios and the Urban Energy Supply Sector

Scenario efforts seek to predict future global energy demands, trajectories, uncertainties, and alternative futures. Examples include the World Energy Outlook (IEA, 2012), the Global Energy Assessment (GEA) (2012), the IPCC's latest concentration pathways (2014a), and the World Energy Council (WEC, 2013). All recent scenarios predict increased demand for energy in the future with the majority of the increase from non-OECD countries.

As the world urbanizes, energy systems increasingly exist to supply energy to urban residents and businesses. Global urban energy demand (end-use) in 2005 was estimated at 240 EJ, serving 3.2 billion urban residents (Creutzig et al., 2015). If current trends continue, including a doubling of the urban population and a dramatic increase in economic development worldwide, global urban energy use may increase more than threefold to 730 EJ in 2050 (Creutzig et al., 2015). Policy and planning interventions, including increasing fuel prices and population density, may enable reduction of that global urban energy demand by 180 EJ, resulting in only 540 EJ by 2050 (Creutzig et al., 2015). Nearly all the potential reductions from this “urban mitigation wedge” are expected in Asia, Africa, and the Middle East, with only minimal reductions likely in OECD nation cities given their expected slow growth.

In addition, more than half of the land area expected to be urban in 2030 remains to be built (Seto et al., 2012), and this has important implications for energy supply, especially at current rates of declining densities among developing-country cities where a doubling of urban population over the next 30 years may require a tripling of built-up areas (Angel, 2012).

As a result, all energy scenarios suggest that how the world's cities develop will be critical to achieving global sustainability (WEC, 2010; Calderon et al., 2014; Seto et al., 2014). In fact, cities have always been at the center of social, technological, and environmental change, and, by 2020, the world's rural population

will begin decreasing, thus making all subsequent future population changes occur in metropolitan areas (UN, 2014). Importantly, the technological, sociopolitical, cultural, and ecological drivers of energy transitions will increasingly be urban-related.

Whether cities will aid in the just and resilient development of energy resources is an open question. According to the GEA (2012), energy resources pose no inherent limitation to meeting the rapidly growing global energy demand as long as adequate upstream investment is forthcoming in exploration, production technology, and capacity for renewable technologies (Rogner et al., 2012). The problem is not the amount but the uneven distribution of resources, resource use, and related environmental impacts.

Energy scenarios differ as to whether mitigation, adaptation, and sustainable development goals can be simultaneously achieved, with most scenarios not yet focused on adaptation. The GEA (2012) states that achieving the objectives of providing almost universal access to affordable clean cooking fuel and electricity for the poor, limiting air pollution and health damages from energy use, improving energy security throughout the world, and limiting climate change are simultaneously possible using a variety of different pathways. Yet the IEA (2012) argues that about a billion people will remain without electricity in 2030 (using their middle range scenario) and that the United States is the only country that may achieve energy security by 2030, given its wealth, technological level, and energy resources. Many plausible futures suggest that business as usual will put the world on a course of high warming by the end of the century, with extreme and potentially irreversible impacts (Calderon et al., 2014). These impacts require new types of energy scenarios addressing not only mitigation, but also adaptation concerns.

### 12.5.3 Climate Mitigation and the Urban Energy Supply Sector

Urban areas play a key role in global climate stabilization as demand centers for power generation. Four categories of mitigation actions, as described in Chester et al. (2014), are available to governments, households, the private sector, civil society, and communities, and these have shown potential to position the urban energy supply sector on low-carbon trajectories, often with co-benefits for public health, economic development, and other city goals:

1. *Planning actions*: The IPCC describes the planning of low-carbon development patterns as: (1) high population and employment densities that are co-located, (2) compact urban form, (3) mixed land uses, (4) high connectivity street patterns, and (5) destination accessibility to jobs and services
2. *Policy actions*: Regulatory, market-based, and voluntary policy instruments make up the range of policy approaches to mitigation; efforts can include renewable portfolio standards, new pricing structures, smart growth policies, new codes for design and operation of infrastructures, and distribution of home energy meters (Davis and Weible, 2011)
3. *Technology actions*: Such as fuel switching, energy-efficiency upgrades, changing electricity generation mix to rely on lower to no-carbon sources (Jacobson and Delucchi, 2011),

increasing cost-effectiveness of renewables, electric vehicles, and improving storage

4. *Behavior change actions*: Such as residential and commercial building occupant behavior; active transport choices recycling; and shifting diets, lifestyles, purchasing habits, and values (Semenza et al., 2008)

Local plans aimed at energy and its impacts occur in a number of different forms: climate action plans (CAPs), energy plans, and sustainability plans. The existence and coverage of local plans has been sporadic (for a review, see Zimmerman, 2012). For example, in the United States, climate plans exist in 31 states; of those, only 19 had both state and local plans and 5 had local plans only (U.S. EPA, 2011; Zimmerman and Faris, 2011). Although the coverage of CAPs has been controversial (Zimmerman, 2012), many localities, such as Beijing, have adopted energy use and emission reduction policies without a local climate plan (Zhao, 2010). Aznar et al. (2015: 3) point out that “While the CAPs are a good indication of cities’ planned actions and goals, they do not fully capture what actions cities actually implement.” They also recognize the need to study CAPs more fully to ascertain what they are accomplishing (Aznar et al., 2015). However, they do conclude that the existence of climate, energy, and sustainability plans does spur action (Aznar et al., 2015).

Integrating actions in the development of the urban energy supply sector can reap great benefits. For example, in Shanghai, an international team of experts are designing a distributed low-carbon energy system that matches specific local challenges, using technologically mature and economically viable solutions (see Box 12.5).

While the Shanghai case demonstrates a few types of mitigation actions, all four types of mitigation actions are present in New York’s efforts (Table 12.6), where plans, policies, and technologies for urban energy supply sector components (production, transformation, transmission, and end use) are reducing GHG emissions. Given that electricity systems cannot be viewed as isolated from social and institutional systems, behavior change efforts in government incentive programs or utility pricing schemes are also described.

Although these examples demonstrate the wide range of mitigation responses for locations like Shanghai and New York and options that are commercially available now, no single “silver bullet” solution to achieve low-carbon development exists. Instead, cities and energy suppliers must consider multiple approaches for achieving mitigation goals (see Section 12.5.5.4). Listed here are illustrative (not comprehensive) mitigation actions being adopted by cities (Aylett, 2014; NREL, 2015).

Small-scale actions for urban residents and businesses for mitigation in energy supply sector:

- Use less carbon-based energy
- Reuse and recycle goods
- Live close to work
- Walk, bike, carpool instead of driving solo
- Take public transportation
- Consume less meat
- Design buildings to use less energy
- Undertake weatherization and energy audits
- Upgrade heating/air conditioning
- Purchase energy-efficient appliances
- Install/increase use of renewables

### Box 12.5 Shanghai, Lingang: An Innovative Local Energy Concept to cut CO<sub>2</sub> Emissions by Half

Marianne Najafi

*EDF France, Paris*

The Lingang District is one of Shanghai’s nine satellite towns, located 70 kilometers southeast of the city’s center. The initial development of this greenfield site will be started on a 1 square kilometer section, then extended to a larger district of 42 square kilometers. In order to obtain innovative green urban design proposals for this district, real estate developers launched an International Competition of Conceptual Urban Design in July 2014. The Sino-French team made up of the Urban Planning and Design Institute Tongji of Shanghai; EDF, a French electricity company; and l’AUC, a French architectural firm, won first place in the city’s urban conceptual design competition in November 2014.

By taking into account energy at the earliest stages of urban planning and by using systemic approaches, EDF, along with Tongji, and l’AUC were able to put forward a transformative new low-carbon and energy-efficient urban solution. The proposed solutions needed to address two specific local energy challenges: CO<sub>2</sub> emissions reduction and energy system optimization. Three dimensions structured the proposal:

1. *Reducing energy demand* (electricity, heat, cold): The cooperative urban design focused on low-energy solutions, leveraging mixed-space use and higher urban density. Moreover, while following Chinese “green building” standards, new technologies to reduce thermal losses and promote heat recovery were also incorporated into the proposal, which greatly improved global energy efficiency in building heating and cooling.
2. *Proposing the most appropriate local energy mix*: The proposal reduced the use of coal production while harnessing the potential of local renewable energy sources.
3. *Designing the local energy system*: The team’s energy system design spatially coupled heating and cooling networks with specifically sized energy centers to optimize efficiency and allow for the solution’s easy scaling to the 42 square kilometer Comprehensive Zone during the next phase of construction.

The result of these designs is an estimated 50% reduction in CO<sub>2</sub> emissions, 50% reduction of electricity peak load, and 10% reduction in consumer energy bills.



**Table 12.6** Summary of four types of mitigation actions from New York. Source: Chester et al., 2014

Mitigation Strategies in Energy Sector:	Planning	Governance/Policy	Technology	Behavior Change
Key Learning, Knowledge, and Policy Networks: Carbonn Climate Registry ICLEI C40	Rezoning for denser development and affordable transit-oriented housing; planning for large-scale wind turbines in federal offshore waters 20 miles outside NYC (anticipated output of 350–700 MW), and renewable biogas from anaerobic digesters at wastewater treatment plants	Local Law 84 (requiring annual large buildings energy use benchmarking) Local Law 85 (meeting energy codes for major renovations), Local Law 87 (requiring energy audits and retro-commissioning once every 10 years), Local Law 88 (requiring lighting upgrades and submeters by 2025) for large buildings	Reducing fossil fuel combustion via construction of new transmission lines providing 1,000 MW of new hydropower; Solar PV growth from 1 MW (2007) to nearly 20 MW (in mid-2013) with SunEdison developing its largest solar PV system of 10 MW and more soon to be added at Freshkills	Pricing, demand-side management; options for customer-sited clean and distributed energy resources (NY State Public Service Commission)

Larger-scale actions (directly or indirectly) achieving mitigation in the energy supply sector include:

- Switch to higher mix of renewables
- Use cleaner fossil fuels (e.g., coal to natural gas)
- Increase use of large carbon-neutral technologies, carbon capture and sequestration (CCS) or carbon capture utilization and storage (CCUS) (see below), and shifts to nuclear power (Zwaan, 2013)
- Increase production efficiencies and minimize transmission losses
- Enforce environmental labeling and use policies (e.g., use of EnergyStar equipment in the United States)
- Target financing (e.g., tax carbon usage according to its social impact)
- Plan urban areas to reduce spatial inefficiencies
- Undertake energy audits of existing buildings and upgrade/retrofit (e.g., to higher energy efficiency office lighting, energy management systems to control heating/cooling in buildings)
- Increase purchase of and city targets for fuel-efficient vehicle fleets, hybrid electric vehicles, low-carbon transportation fuels, charging stations for electric vehicles
- Increase biking/walking trails, expand dedicated bike lanes on streets and bike parking facilities, improve public transport, install showers/changing facilities for employees, create car free zones, use congestion charging and other travel demand management strategies (Note: such transportation strategies may increase in relevance for the energy supply sector; as for the U.S. electric power industry, projections indicate “a 400% growth in annual sales of plug-in electric vehicles by 2023 may substantially increase electricity usage and peak demand in high adoption areas.” (U.S. Department of Energy, 2014)

Whereas the actions listed here show a wide variety of options, which set of policies might work in specific locations is not well understood. Research is needed to demonstrate the range of local contextual factors that are key to usable science for implementation (Dilling and Lemos, 2011), large participation and adoption (Ramawami et al., 2012), and increased effectiveness of programs (Stern et al., 1985).

### 12.5.3.1 Reduction in Energy Consumption and Emissions

One of the most direct strategies for reducing energy consumption and emissions is demand side management (DSM). Energy DSM programs can cut across energy and other sectors, such as buildings, transportation networks, and other infrastructure installations for heating, ventilation, and air conditioning (HVAC) and lighting. Alternatively, technological actions have also been very popular, including, for example, light-emitting diode (LED) installations in buildings and on streets. Such advances have served to reduce energy consumption in North American cities, including Calgary and Denver (EIU, 2011f: 41). Beijing estimates its “Green Lighting Programme” will save the city 39 MW of electricity per year (Zhao, 2010). Toronto has used cold water to provide air conditioning, estimating a savings of 61 MW per year (EIU, 2011f: 21). Planning of residential building retrofits combined with behavioral education resulted in a decrease in electricity and gas use in the Department for Communities and Local Government (DCLG) “low-carbon communities” program in the United Kingdom, although the wide range of demonstrated impacts illustrate the importance of broader behavioral and contextual factors in determining energy demand (Gupta et al., 2014).

Los Angeles has deployed integrated environmental, land-use, and development planning strategies to reduce overall energy consumption and has pursued infrastructure revitalization that reduces energy demand (EIU, 2011f). Similar “community energy management” strategies that combine land-use planning with community-based energy technology/infrastructure investments like DHC were estimated to result in an average energy consumption reduction of 15–30% and associated CO<sub>2</sub> emissions reduction of 30–45% from 1995 to 2010 in four communities in British Columbia (Jaccard et al., 1997). Rio de Janeiro has also sought to reduce energy consumption and associated emissions through a variety of infrastructural changes including modernization of its electricity network (see Case Study 12.1).

Globally, mitigation efforts explore the use of pricing schemes such as carbon taxes and cap-and-trade markets that discourage energy use and associated carbon emissions through



## Case Study 12.1 Urban GHG Mitigation in Rio de Janeiro

Andrea Nuñez

*Catholic University of Honduras, San Pedro Sula*

<b>Keywords</b>	Energy distribution, informal settlements, drought
<b>Population (Metropolitan Region)</b>	11,835,708 (IBGE, 2015)
<b>Area (Metropolitan Region)</b>	5,328.8 km <sup>2</sup> (IBGE, 2015)
<b>Income per capita</b>	US\$8,840 (World Bank, 2017)
<b>Climate zone</b>	Am – Tropical monsoon (Peel et al., 2007)

Rio de Janeiro represents one of the dynamic axes of the Brazilian southeast region whose economy is the second most prosperous of the country. As the energy matrix of Brazil is already rather clean, depending mostly on renewable resources, one of the key energy challenges has to do with improving efficiency in energy distribution (ENEL Foundation Research Project, 2014). At the same time, and despite the progress of the past decade, recent demonstrations and upheaval signaled that Rio still faces severe social challenges. For example, despite ongoing state programs, roughly 20% of the city's population lives in informal settlements known as *favelas* or slums, with very limited access to public services. Electricity distribution is often informally accessed. Electricity infrastructure is generally available; however, until very recently, the nontechnical losses in some favelas (largely related with electricity theft) reached 95% of the total electricity in the grid (Light, 2013).

There are manifold distribution challenges in large cities such as Rio, and wasteful consumption and nontechnical losses (e.g., energy theft) are high, imposing large costs for utilities, governments, and ratepayers (Coelho, 2010). Moreover, distribution grids require modernization to cope with societal expectations and new regulatory frameworks on smart metering, hourly tariffs, distributed generation, and the like. Apart from the costs, local government and regulators have been actively paving the way toward smart-grid solutions (e.g., through new regulations and RandD funding), but there is a long way to go (ENEL Foundation Research Project, 2014).

In the current municipal administration, climate change measures are coordinated by Rio de Janeiro's Municipal Secretariat of the Environment (Secretaria Municipal de Meio Ambiente [SMAC]) through its Climate Change Office (CCO), along with the Mayor's Office (EIA, 2013). This management involves transversality with different areas of municipal administration and partnerships with academic institutions through shared actions and innovative activities in several sectors, such as solid waste management, transport, urban planning, energy, and civil defense, among others. The goal is to achieve sustainability, mitigation of GHG emissions, and adaptation to climate change impacts (Cities, 2014). Management actions are based on the development of a regulatory framework to enable feasible actions. the CCO also develops links with institutions of excellence in the public and private sectors and with civil society organizations.

The main piece of the Regulatory Framework is Law n. 5.248/2011 that establishes the Climate Policy of the City and sets measurable, reportable, and verifiable reduction targets for GHG emissions for 2012 (8%), 2016 (16%), and 2020 (20%) based on emissions recorded in Greenhouse Gas Inventory of Rio de Janeiro City, published in 2011 (City of Rio de Janeiro, 2011). The Law also establishes city adaptation policies to face climate change effects (Cities, 2014).

Rio's GHG Inventory was developed by the Centre for Integrated Studies on Climate Change and the Environment (Centro Clima/COPPE) and Federal University of Rio de Janeiro (UFRJ), with alternative scenarios due to emissions mitigation actions in different sectors and across the city as a whole. It presents the emissions resulting from transportation and from residential and commercial buildings, public buildings, and refineries, and tracks land use and forestry; residential, industrial, and commercial wastewater; industrial processes; and solid waste (COPPE, 2011). Alternative scenarios consider projects and actions incorporated into the municipality's planning. Law n. 5.248/2011 establishes the elaboration, updating, and publication of the GHG Municipal Inventory every 4 years, but it does not determine specific targets for emissions that are the responsibility of the municipal administration. Most of the reduction in emissions will occur as a result of governmental actions, mainly infrastructural changes, such as new bus rapid transit (BRT) systems, subway expansion, and modernization of public lighting.

Despite the clean electricity matrix, new generation sources and energy efficiency policies are increasingly important issues in Brazil (Geller et al., 2004) not only because of the source of the energy but also because of the size of the facility and its impacts. For example, building new dams faces strong social and political opposition (notably in Amazonia), and dry seasons bring hydro-generation into jeopardy. Recently, one policy-supported solution is to use mini- and micro- (hydro) generation (e.g., in rivers). This issue is not only a matter of finding new sources, but is also search for better energy efficiency and innovation in electricity distribution. This search is increasingly supported by governments and the regulator Aneel (Agência Nacional de Energia Elétrica/National Agency for Electrical Energy), for example, through appliance-substitution programs for low-income households, educational initiatives, tight regulatory standards for energy losses, and technological innovation on many fronts (e.g., Aneel, 2008).

Aneel reports that:

1. 0.5% of the operational profits of distribution companies should be applied to actions and programs to fight energy inefficiency and wasteful consumption (with a special emphasis on low-income households)
2. 0.2% of the operational profits of distribution companies should be applied to research and development (including not only "pure" research and prototypes but also market applications such as smart grid/smart city projects)
3. Only a maximum amount of about 30% (e.g., for Light S.A.) of nontechnical energy losses (e.g., theft) can be transmitted to the distribution tariff, pushing the development of innovative solutions (i.e., different types of peak-off peak hourly tariff, micro- and mini-generation, and smart metering) to tackle the issue

Improving the quality of energy distribution (i.e., reliability, cost reduction, and efficiency) and reducing energy losses are the key

drivers for the country's recent investment in the development of smart grids (CGEE, 2012).

### SMART GRID PROGRAM OF LIGHT S.A.

To reduce losses and improve operational efficiency, Light Sociedade Anônima (Light S.A.), one of Brazil's main electricity distribution companies, which supplies the City of Rio, has recently formalized a smart grid program following-up on the company's past efforts to implement remote metering solutions in its concession area. The program comprises the development, prototyping, and early application of a portfolio of different technologies and solutions, including grid automation and smart metering technologies, charging stations for electric vehicles, distributed energy generation, and demand-side management. Light S.A. cooperates with other companies in the energy industry (CEMIG, AXXIOM) and other national and international technology providers and knowledge institutes (e.g., Lactec, CPqD, CAS, GE).

Currently, the Brazilian Agency for Industrial Development (Agência Brasileira De Desenvolvimento Industrial [ABDI]) is studying the development of a tailor-made industrial policy for the smart-grid field, and these regulatory efforts, first pilots, and R&D count already on strong financial support from the Brazilian Science

and Technology Policy. Another very important initiative has been the Inova Energia program, a joint initiative of Aneel, the Funding Authority for Studies and Projects (Finep), and the Brazilian Development Bank (BNDES), which supports the development of different smart city pilots in the country, including in Rio de Janeiro (where important distribution companies and technology players are located). Both Ampla – another energy company that supplies part of the metropolitan region and Rio state, but not the city – and Light S.A. have active smart grid programs benefitting from government funding and close cooperation with national and international technology partners.

Current national government policies regarding energy use go from energy loss prevention initiatives that unfolded in Rio in the past decade to current activities that aim to reduce emissions through local government operations (Case Study 12.1 Table 1).

Curbing nontechnical electricity loss in informal settlements is an issue for many cities around the world. Rio de Janeiro is an example that shows that good technical solutions are required, and the implementation of technology has necessarily to go hand-in-hand with societal embedding efforts: building utility–community relationships and instituting behavioral and cultural change.

**Case Study 12.1 Table 1** *Energy Emissions Inventory for Rio de Janeiro. Source: Carbon Disclosure Program CDP (Cities, 2014)*

Emissions reduction activity	Projected emissions reduction over lifetime (metric tons CO <sub>2</sub> e)	Action
<i>Outdoor Lighting &gt; LED / CFL / other luminaire technologies</i>	640,000	Estimated value for 2020.
<i>Other:</i>	100,000	Project Morar Carioca provides urbanization for slums, and entails full reurbanization and waste management, public lighting, water, drainage, garbage collection, slope contention and public equipment. This project "My House, My Life," is part of a federal housing project that provides homes to those previously living in high-risk areas of slums. Estimated value for 2020.
<i>Energy Supply &gt; Transmission and distribution loss reduction</i>	11,400,000	Fugitive emissions. Estimated value for 2020.
<i>Transport &gt; Improve rail, metro, and tram infrastructure, services and operations</i>	529,700,000	Establishment of four new BRT systems: TransOeste (150,000 riders / day), TransCarioca, 1st phase (380,000 riders/day), TransCarioca, 2nd phase (150,000 riders/day), TransOlimpica (100,000 riders/day), TransBrasil (900,000/day). the BRT System is being implemented in Copacabana. Subway expansion (230,000 riders/day). Acquisition of new subway trains (+550,000/day) Expansion of cycle lanes, 300 km. Estimated value for 2020.

higher energy prices. For example, the Tokyo Metropolitan Government, in 2010, developed the world's first cap-and-trade program at a city level targeting energy-related CO<sub>2</sub> as a market-based approach to mitigation. Other cities developing systems for carbon emissions trading and offsets include Chicago, London, Sydney, and Tianjin (Broto and Bulkeley, 2013). The European Union's Emission Trading Scheme provides a model and important lessons for other emissions trading efforts, the most important of which is to establish a reliable, quantitative

emissions baseline and tracking and verification system (Brown et al., 2008).

An important mitigation strategy for energy-related emissions is to lower the carbon intensity of the urban electricity supply, with efforts under way in London and Milan (Croci et al., 2010), throughout the Netherlands (Rotmans et al., 2001), in Beijing (Zhao, 2010), and now across all of China (Hsu, 2015). Kennedy, Ibrahim, and Hoornweg (2014) identify two key thresholds by

which cities will be more effective in pursuing strategies for low-carbon development (Box 12.6).

Another remediation strategy is the deployment of carbon capture and sequestration (CCS) or carbon capture utilization and storage (CCUS). These processes capture  $\text{CO}_2$  emissions from sources like coal-fired power plants, and store, reuse, and remove the emissions from the atmosphere. Storage is typically provided in geologic formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs. Today CCS and nuclear generation are the only large-scale technologies that are believed to significantly reduce the emissions from fossil fuels. CCS is, however, still at the pilot stage in places like Rotterdam and Shanghai, and its future is uncertain, mainly because of the high costs (WEC, 2013). Lower cost carbon sequestration options include urban greening and reforestation, practiced throughout the world in cities like Bogota, Quito, São Paulo, Cairo, Lagos, Johannesburg, London, Madrid, and Hong Kong (Broto and Bulkeley, 2013). Some urban greening efforts can be quite expensive, however, and thus should be given careful consideration as part of a city's mitigation plan (Kovacs et al., 2013).

### 12.5.3.2 Use of Renewables

To achieve a warming level of below  $2^\circ\text{C}$  by 2050, the recent IPCC (2014a) reports suggest that future scenario trajectories needed to reduce GHG emissions by 40–70% relative to 2010 levels are defined by a global share of low-carbon electricity supply comprising renewable energy, nuclear, natural gas, and some use of carbon capture and sequestration. Currently, in most countries, however, renewables account for less than 10% of the energy supply and usually less than 5%. The use of renewables by cities varies sharply around the world. For example, about half of the seventeen Latin American cities identified by the EIU draw more than 80% of their electricity supply from renewables (EIU, 2011e). In 2015, renewables excluding large hydro accounted for (the first time) a majority of new electricity-generating capacity (UNEP, 2016). We list here examples of a variety of renewable energy programs in cities around the world.

*Solar energy:* Solar energy is growing as a renewable source. A number of African cities are installing solar water heaters (EIU, 2011a). In the United States, Environment America (2015) identified fifty-seven cities installing solar photovoltaic systems ranging from less than 1 to 132 MW of cumulative capacity. Cities with solar installations exceeding 90 MW at the end of 2013 were Los Angeles, San Diego, Phoenix, San Jose, and Honolulu. Boston's Solar Boston initiative supports the adoption of solar power through permitting, financing, technology development, and implementation that increased capacity in 2010 to 3.1 MW with a 2015 projected increase to 25 MW (EIU, 2011f). Chicago built the United States' largest solar power plant in an urban area, estimated to provide 10 MW of power and save 14,000 tons of GHG emissions annually (EIU, 2011f). Minneapolis built the largest Midwest solar array, located at the top of its convention center and saving 540 metric tons of  $\text{CO}_2$  annually (EIU, 2011f).

*Hydropower:* A number of cities especially in Latin America and parts of Africa use hydropower as a main source of energy. Hydropower supplies 100% of São Paulo's power (EIU, 2011e). The Economist Intelligence Unit (2011a: 16) estimates the use of hydropower at 69% in seven Sub-Saharan African cities (excluding South Africa). Seattle also produces the majority (89%) of its electricity from hydropower (see Box 12.2 and Case Study 12.2), although climate change impacts in the region may force diversification of its electricity sources to accommodate less hydropower generation in summer, estimated at 12–15% by 2040s and 17–21% by the 2080s (Hamlet et al., 2010).

*Wind:* Wind energy is considered the fastest growing renewable energy source, although its share of energy is still low. Several African cities are planning wind energy facilities; for example, Cape Town will be installing its country's first commercial wind plant (EIU, 2011a). Beijing is increasing its wind generating capacity at its Guanting Wind Farm and other nearby farms to more than 115 MW capacity, expecting to reduce  $\text{CO}_2$  emissions by nearly 125 kton per year (Zhao, 2010).

*Waste:* Many areas, including Buenos Aires, Denver, Phoenix, Birmingham (UK), Dhaka, Cape Town, Hong Kong, Mumbai, Mexico City, and Ho Chi Minh City are capturing landfill gas to produce electricity or heat, serving to reduce the GHG emissions from the waste sector and reduce the demand and associated emissions from other energy fuels (Broto and Bulkeley, 2013). Beijing is recovering methane from chicken manure, reducing  $\text{CO}_2$  emissions by approximately 88 kton per year (Zhao, 2010). Similarly, New York is experimenting with producing renewable gas from wastewater (see Case Study 12.3).

*Renewable energy targets:* Many countries have adopted renewable energy targets that will influence the cities located within those countries. The targets vary from percentage share of the renewable fuels category to fuel-specific target quantities. From 2005 to 2015, the number of countries adopting such targets increased from 43 to 164 countries with 12 more in non-OECD countries (International Renewable Energy Agency, 2015). Subnational governments are also adopting renewable targets, as with the 90% renewable electricity target by 2020 adopted by Australia's capital city, Canberra (see Case Study 12.4). To date, more than 15 ICLEI — Local Governments for Sustainability cities and regions have committed to using 100% renewable energy between 2020 and 2050. A national renewable energy standard is still being debated in the United States, as well as a clean power plan rule by 2030 to limit carbon emissions from power plants.

### 12.5.3.3 Emission Reduction Targets

Many cities have now set specific GHG emissions reduction targets that could be achieved using a variety of mitigation strategies. C40, ARUP, and others (2014) estimated cumulative savings for 228 cities given the targets of 2.8, 6.1, and 13.0 Gt  $\text{CO}_2$ -equivalent by 2020, 2030, and 2050, respectively. Annual reductions estimates were 454 Mt  $\text{CO}_2$ e per year, 402 Mt  $\text{CO}_2$ e

### Box 12.6 Low-Carbon Infrastructure Strategies for Cities: Carbon Intensity and Population Density Is Key

**Christopher Kennedy**

*University of Victoria, British Columbia*

**Daniel Hoornweg**

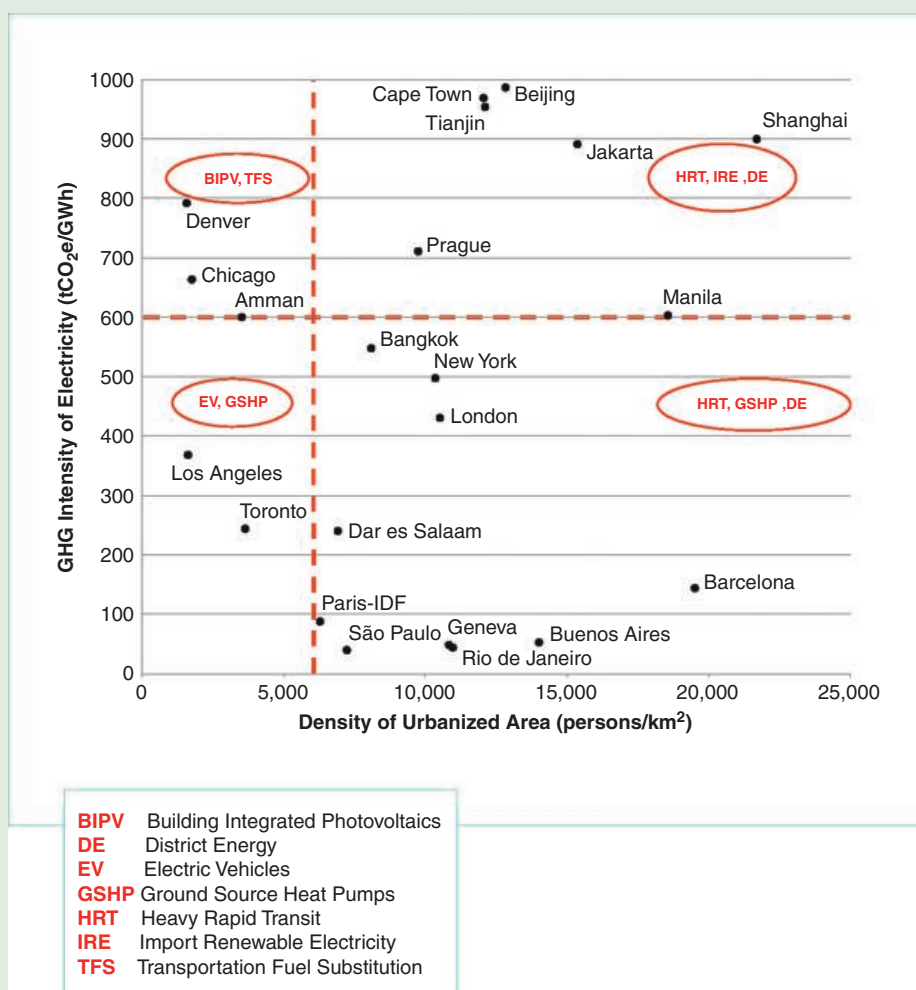
*University of Ontario Institute of Technology, Toronto*

*Sustainable Development Network, World Bank, Washington, D.C.*

The urban development and technological strategies that cities can pursue to reduce their greenhouse gas (GHG) emissions or grow with low-carbon trajectories differ depending on urban form, environment/climate, technological, economy (e.g., energy pricing), governance, and sociodemographic factors. Among the most important determining characteristics of city GHG emissions are the carbon intensity of electricity supply and the population density of the urbanized area (see Box 12.6 Figure 1). Cities where the carbon intensity of power grids is below approximately 600 tCO<sub>2</sub>e/GWh can broadly pursue electrification and alternative

space-heating strategies for low-carbon development (e.g., adopt electric vehicles or use heat pumps in the place of natural gas furnaces). Above about 600 tCO<sub>2</sub>e/GWh, electrification becomes self-defeating; overall emissions are increased due to the high carbon content of the electricity supply. Other strategies for district energy systems or substantial low-carbon public transportation systems are broadly only economically viable at medium to high urban densities of more than about 6,000 persons per square kilometer. Based on local conditions and aspirations, strategies and key leverage points for low-carbon development will differ for cities such as Denver, Toronto, Rio, and Beijing.

In cities expected to undergo rapid growth (e.g., Dar es Salaam) and with commensurate needs for increased electricity supply, the future expected GHG intensity of electricity supply needs to be considered. In many fast-growing cities potential future hydroelectric opportunities may be exhausted, and the carbon intensity of new supply could vary markedly (e.g., likely mix of coal, natural gas, nuclear, renewables).



**Figure 1** Examples of low-carbon infrastructure strategies tailored to different cities. Prioritization according to both urban population density and the average greenhouse gas intensity of existing electricity supply. Both factors need to be taken into account in developing sustainable urban energy solutions.

Source: Adapted from Kennedy et al., 2014



## Case Study 12.2 Climate Change and the Energy Supply System in Seattle

Hossein Estiri

*University of Washington, Seattle*

<b>Keywords</b>	Energy supply, adaptation, mitigation, hydro power
<b>Population (Metropolitan Region)</b>	3,043,878 (U.S. Census Bureau, 2010)
<b>Area (Metropolitan Region)</b>	15,208 km <sup>2</sup> (U.S. Census Bureau, 2010)
<b>Income per capita</b>	US\$56,180 (World Bank, 2017)
<b>Climate zone</b>	Csb – Temperature, dry summer, warm summer (Peel et al., 2007)

Situated on a narrow isthmus between Puget Sound and Lake Washington, Seattle is the seat of King County and the largest city in the state of Washington. With an estimated population of 652,405 residents (and 3.61 million in the metropolitan area) in 2013, Seattle is one of the fastest growing major cities in the United States and home to some of world's most recognized technology companies, including the Boeing Commercial Airplane Group, Microsoft, and Amazon. Seattle has a milder and wetter climate than many other parts of the world, with less extreme variations in temperature and more cloudy days.

Seattle is a leader in climate action in the United States and globally, with several incentive programs and plans dating back to 2000. In 2006, Seattle was one of the first cities in the United States to adopt a climate action plan (CAP; City of Seattle, 2013). The city is also among the nine major cities in the United States that have passed building energy benchmarking and disclosure policies.

Climate change is already taken seriously by city officials in Seattle because its impacts on the Puget Sound area are being observed. Some of the most important climate impacts on Seattle's energy supply system are more variable and generally reduced mountain snow pack, earlier and faster spring melt of mountain snow pack, and reduced summer river levels for hydro power. The City of Seattle (and Seattle City Light [SCL] as one of its departments) is taking action to reduce its impact on climate change and reduce its adverse effects on the city. Seattle's climate mitigation and adaptation strategies focused on its energy supply system. These are either part of the Seattle CAP (with a holistic approach to the entire metropolitan region) or independently developed by SCL's active climate change program.

### ENERGY SUPPLY AND CLIMATE MITIGATION IN SEATTLE

According to a report by the American Council for Energy-Efficient Economy (ACEEE) in May 2015, Seattle is the fifth most energy-efficient city in the United States (Ribeiro et al., 2015). Seattle's climate mitigation strategies for its energy supply systems focus on promoting energy conservation and clean energy resources.<sup>6</sup> In 2005, SCL was the first large electric utility in the United States to become carbon neutral. SCL's conservation program is among the longest-running

in the country. Since 1977, SCL's has been taking actions to reduce demand for fossil fuels that contribute to climate change.

To improve energy efficiency and reduce energy demand in buildings, the City of Seattle's CAP (2013) has envisioned that, by 2030, information from the Energy Benchmarking reports will be publicly accessible and disclosing home energy use or a home energy rating at the point of sale for single-family homes will be required.

By 2030, CAP also has envisioned that Seattle buildings will be using a portfolio of renewable and low- or no-carbon energy sources, and that these clean energy sources will be provided either by SCL's maintained carbon-neutral electricity or by neighborhood district energy systems that use renewable and waste heat sources, such as district energy, solar energy, and geothermal energy.

### ENERGY SUPPLY AND CLIMATE ADAPTATION IN SEATTLE

Seattle's energy supply system is highly reliant on the local climate, particularly the timing, type, and amount of precipitation. In 2009, SCL contracted with the University of Washington's Climate Impact Group to study climate change effects on regional climate, stream-flow, and stream temperature in order to support SCL's assessment of impacts of projected climate change on operations at its hydro-electric projects and on future electricity load in its service territory.

SCL has incorporated the results of its continued research on climate impacts into its Integrated Resource Plan (IRP) (Seattle City Light, 2014) and its updates. According to the SCL's 2014 IRP update, SCL hydropower generation is threatened by changes in snowpack and glaciers due to long-term climate change. River flows and generation are expected to gradually increase during the winter and decline in the summer due to the overall warming. Winter is currently the peak season for electricity use in the Puget Sound area, but climate impacts can change this seasonality. SCL is working with the National Park Service and the University of Washington to inventory and forecast future flows from the glaciers and snowpack.

SCL has identified its main concerns related to climate impacts. Due to warmer temperatures and more frequent heat waves, higher energy demand in summer and de-rating of the overhead lines, which can lead to reduced transmission capacity, are plausible. These impacts can specially create high risk for vulnerable populations. Due to the expected increase in winter rain, lower snowpack, and loss of glacier runoff, hydroelectric generation is expected to increase in winter, but decrease in the summer, when energy demand is likely to increase. Also, frequency of summer water conflicts and spilling for flood control are expected to upsurge. Due to the risk of more frequent wildfires, landslides, and floods, sea-level rise, higher frequency of transmission and distribution outages, and equipment damage (or reduced life expectancy of equipment) are likely to occur.

Some of SCL's adaptation strategies to prepare for climate impacts and reduce its adverse effects are:

- Developing a utility-wide adaptation plan
- Leveraging present tools to plan for hydro-climatic variability and prepare for high winds and storms
- Establishing a rate stabilization fund
- Relicensing with the Federal Energy Regulatory Commission (FERC)
- Upgrading with new equipment for landslides and lightning
- Assessing fire risk and preparing for greater fire frequencies

<sup>6</sup> See Box 12.3 for details on Seattle's energy supply.



## Case Study 12.3 Renewable Gas Demonstration Projects in New York

Annel Hernandez

*New York City Environmental Justice Alliance (NYC-EJA)*

<b>Keywords</b>	Renewable energy, wastewater management, organic waste management, infrastructure, Newtown Creek
<b>Population (Metropolitan Region)</b>	20,153,634 (US Census Bureau, 2016)
<b>Area (Metropolitan Region)</b>	17,319 km <sup>2</sup> (US Census Bureau, 2010)
<b>Income per capita</b>	US\$56,180 (World Bank, 2017)
<b>Climate zone</b>	Dfa – Continental, fully humid, hot summer (Peel et al., 2007)

The development of the Newtown Creek Renewable Natural Gas Project is an example of how sustainable waste management strategies can produce renewable energy. Wastewater treatment operations maintain safe and clean waterways in urban areas to address public health concerns, create more livable spaces for city residents, and protect marine ecosystems. Wastewater treatment plants (WWTP) processes also create byproducts that include sludge, biosolids, solid waste, and methane. In New York, thirteen of the fourteen Department of Environmental Protection (DEP) WWTPs utilize the methane byproduct of operations to power boilers and other plant equipment.

The largest of these plants, Newtown Creek Wastewater Treatment Plant, has the daily capacity to treat 330 million gallons of wastewater and presently produces 500 million cubic feet of biogas annually, or on average 1.37 million cubic feet of biogas daily. The biogas, otherwise known as renewable gas or biomethane, is produced in anaerobic digesters where the organic sludge removed from treated water is heated to 95°F for approximately 15–20 days. During this process, microorganisms convert organic matter into biogas, which is about 50–60% methane and 40–50% carbon dioxide. Currently, the Newtown Creek WWTP applies 40% of this excess biogas to powering the plant operations, with the remaining amount of biogas flared into the atmosphere.

New York City's DEP and the international utility company National Grid have struck a long-deliberated deal to conduct the Newtown Creek Renewable Natural Gas Project. Under the agreement, both entities have entered into a 20-year contract that states National Grid will fund the design, construction, operation, and maintenance of the new demonstration. Moreover, DEP will provide the biogas free of charge for the first 5 years after renewable gas operations commence. After the 5-year mark, any operational surplus will be divided equally between both organizations. One of the reasons this project is viable is the proximity of both operations – the Newtown Creek WWTP facility is located just a few city blocks from National Grid's Greenpoint Energy Center. Furthermore, the existing pipeline infrastructure running alongside the Newtown Creek WWTP streamlined the project because there was no additional private or public land needed to develop the project. AECOM, an international infrastructure firm with previous experience working with the Newtown Creek WWTP, was contracted by National Grid to partner

with Ennead Architects to develop the project. The project encountered various challenges and setbacks along the way due to the complex regulatory context in the state. This project is setting a new precedent for public–private partnerships between energy utilities and water utilities. The project began operations in the autumn of 2016.

The Newtown Creek Renewable Natural Gas Project is expected to reduce GHG emissions by 90,000 metric tons each year, which is equivalent to removing 19,000 cars from the city's crowded roads or planting 2 million additional trees with 10 years worth of growth and its associated carbon uptake. Furthermore, the project is estimated to produce enough renewable gas to heat 5,200 homes in the city, with more energy potential in the future. The project strives to ensure the 100% of the biogas is utilized in efficient ways (New York City Department of Environmental Protection [DEP], 2013).

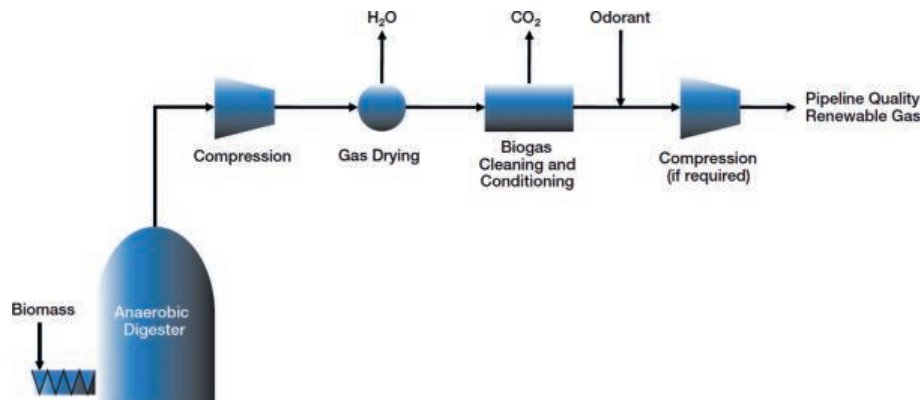
Many consumers have the perception that renewable gas is of inferior quality to the more accepted natural gas found in fossil fuel reserves, frequently alongside oil operations. Although renewable gas has a slightly different composition than natural gas it is of the same quality because both are predominantly methane and are derived from the decay of organic matter. Once the anaerobic digestion process is complete, the renewable gas enters the upgrading and cleanup process before being injected into the gas distribution pipelines. First, the renewable gas enters the compression phase, followed by the gas-drying phase that extracts any remaining water (H<sub>2</sub>O). Then the renewable gas enters the cleaning and conditioning phase where the methane (CH<sub>4</sub>) is separated from the remaining CO<sub>2</sub> through a process known as *pressure swing adsorption* (PSA). The remaining CO<sub>2</sub> or tail gas is then flared into the atmosphere. The now pipeline-quality renewable gas is odorized with the distinct gas scent, as is all natural gas for safety concerns, before being injected into the distribution system. Additionally, to maintain and monitor the quality of the renewable gas, National Grid will conduct analytical chromatography, sample gas, and install meters (National Grid, 2014).

The Newtown Creek Renewable Natural Gas Project also provides an alternative to the growing costs of local solid waste management. In recent years, the New York City Department of Sanitation (DSNY) has been expanding the collection of organic waste and investing in modern processing. The city hopes to lower costs by diverting organic waste from landfills and reducing the cost of exporting the total solid waste streams. Organic food waste management is a major issue because it accounts for approximately 25–30% of New York's entire waste stream. Previous co-digestion studies show that organic food waste coupled with organic wastewater streams increase the rates of methane production and decrease the costs of solid waste management. To support the demonstration project, Waste Management of New York (WMNY), in partnership with DEP and DSNY, opened a specifically designated organics collection facility that is not geared toward composting efforts. Instead, organic food scraps are converted into a liquefied feedstock or *engineered bioslurry* at the Varick I transfer station, also situated along Newtown Creek, and sent to the WWTP. WMNY utilizes patented technology called the Centralized Organic Recycling equipment (CORE) process, which will potentially handle about 250 tons of organic waste per day.

The Newtown Creek WWTP has the long-term potential daily capacity to process 500 tons of organic waste, with short-term potential estimated at a daily capacity 250 tons within the next few years.



**Case Study 12.3 Figure 1** *The Newton Creek Wastewater Treatment Plant. Source: National Grid*



**Case Study 12.3 Figure 2** *A diagram illustrating the process in which waste is broken down and converted into useable gas. Source: National Grid*

An organic waste diversion strategy of 153,000 tons annually would account for approximately 54,500 metric tons of GHG reductions (Waste Management of New York, 2014). In the United States, there have been various local success stories of anaerobic digestion and co-digestion applications (U.S. EPA, 2014).

Once the Newtown Creek Renewable Natural Gas Project starts operations, the policy-making sphere and the energy industry will closely monitor progress and performance. This project presents renewable gas production as a feasible, replicable, and scalable strategy for cities internationally.

per year, and 430 Mt CO<sub>2</sub>e per year in 2020, 2030, and 2050, respectively (see Table 12.7). They provide specific emission reduction targets for 28 cities ranging from 20% to 100% over 10- to 60-year periods using baselines from 1990 to 2014 (C40 Cities and ARUP, 2014). Many cities also are covered by the emission reduction targets set by their states in subnational initiatives, including the Regional Greenhouse Gas Initiative in the northeastern United States, the Western Climate Initiative in the western United States and Canadian provinces, and the Midwestern Regional Greenhouse Gas Reduction Accord in the Midwestern United States.

#### 12.5.3.4 Measuring Effectiveness

Despite pledges to cut GHG emissions, few cities have demonstrated quantifiable reductions to date that can be verified with publicly available information (Pierce, 2015). Furthermore, many of the cities with demonstrated reductions do not face the urbanization and development pressures seen in developing-world megacities or the smaller rapidly industrializing cities. These latter types of cities are expected to dominate future urbanization and GHG mitigation opportunities.

## Case Study 12.4 The Benefits of Large-Scale Renewable Electricity Investment in Canberra

**Cameron Knight**

*Environment and Planning Directorate, ACT Government, Canberra*

**Barbara Norman**

*ACT Climate Change Council,  
Canberra Urban and Regional Futures, University of Canberra*

<b>Keywords</b>	Renewable electricity, feed-in tariff, reverse auction, mitigation, energy
<b>Population (Metropolitan Region)</b>	387,069 (ACT Government, 2015)
<b>Area (Metropolitan Region)</b>	2,358 km <sup>2</sup> (Australian Bureau of Statistics [ABS], 2007)
<b>Income per capita</b>	US\$60,070 (World Bank, 2015)
<b>Climate zone</b>	Cfb – Temperate, without dry season, warm summer (Peel et al., 2007)

In 2010, the Australian Capital Territory (ACT) government established a series of emissions reduction targets in legislation, specifically designed to meet targets of:

- 40% less than 1990 emissions by 2020
- 80% less than 1990 emissions by 2050
- Zero net greenhouse gas (GHG) emissions by 2050

Close engagement with local stakeholders and academic experts has been important to the ACT Government's pursuit of its emissions reduction targets. The ACT Climate Change Council was also established under the Act. The Council comprises a range of specialist and community interests to provide expert advice to the Minister for the Environment and Climate Change on climate change policy and implementation strategies (ACTCCC, 2015).

### ESTABLISHING A 100% RENEWABLE ELECTRICITY TARGET

Electricity is by far Canberra's greatest source of GHG emissions. Electricity in Australia is generated predominantly from fossil fuels, particularly coal, from which 74% of the national electricity market's electricity is sourced (Garnaut, 2008; AEMO, 2014).

The high emissions intensity of Australia's electricity means that it is the source of 61% of ACT's emissions. Meeting the ACT's ambitious emission reduction targets requires a significant cut to the emissions intensity of ACT electricity. In 2012, a 90% renewable energy target became the central policy of the ACT's climate change strategy and action plan, AP2. In May 2016, this target was increased to 100% by 2020 (ACT Government 2016).

### DELIVERING LARGE-SCALE RENEWABLE ELECTRICITY INVESTMENT AT THE LOWEST COST

The ACT Government estimated that 640 MW of new large-scale renewable energy investments would be required to achieve the 100% renewable energy target.

The ACT Government's first major investment in large-scale renewable electricity was the 20 MW Royalla Solar Farm, created by Fotowatio Renewable Ventures in August 2014. At the time of completion, it was the largest solar farm constructed in Australia. Feed-in tariff entitlements were also awarded to Zhenfa Australia and OneSun Capital for a 13 MW solar farm at Mugga Lane and a 7 MW solar farm at Williamsdale, respectively (ACT Government 2015b).

The ACT's investment in large-scale electricity generation has been achieved through an innovative feed-in tariff (FiT) reverse auction process. Renewable electricity project proponents are required to put forward bids against a set of criteria, including price. The winners of the auction process become eligible for a FiT at a fixed price. Because a "contract for difference" approach is applied, and because the price is fixed and not subject to inflation, the subsidy costs to Canberra will decrease as the value of wholesale electricity prices rise over time (Buckman et al., 2014).

On March 12, 2014, the Minister for the Environment, Simon Corbell MLA, announced a 200 MW Wind Auction to be conducted by a competitive reverse auction process. This was the first of three auctions offering feed-in tariff entitlements up to a total capacity of 600 MW, with a final announcement of successful tenders made in August 2016. The successful proponents were:

- 19.4 MW Coonoor Bridge wind farm being developed by Windlab situated near Bendigo, Victoria;
- 309 MW Hornsdale wind farm, stages 1, 2, and 3, being developed by developed by French renewable energy company Neoen International SAS in partnership with Australian company Megawatt Capital Investments, near Port Augusta, South Australia;
- 80.5 MW Ararat wind farm being developed by RES Australia near Ararat, Victoria;
- 100 MW Sapphire Wind Farm 1 developed by CWP Renewables in northern New South Wales; and
- 91 MW Crookwell 2 Wind Farm developed by Union Fenosa Wind Australia, 15 kilometers southeast of Crookwell NSW.

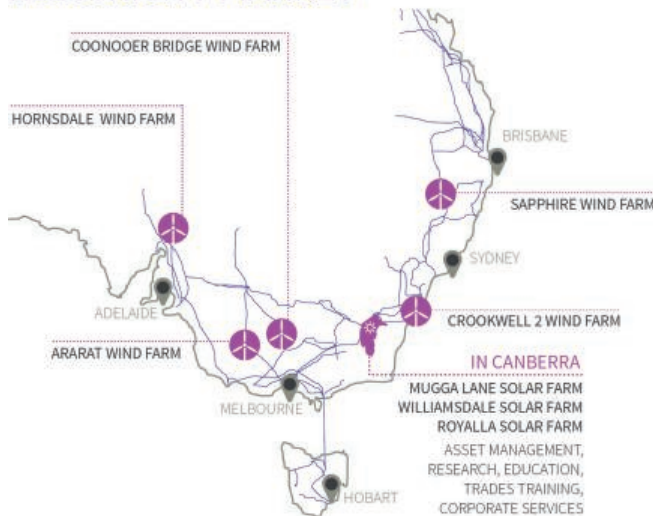
The successful proponents of this process are outlined in Case Study 12.4 Figure 1. In relative terms, this is the biggest step change reduction in greenhouse gas emissions of any Australian jurisdiction (ACT Government, 2015c).

Through competitive processes and an innovative FiT structure, the ACT government has been able to deliver this step change to renewables at an average cost of around AU\$1.79 (US\$1.44) per household per week. This is part of the estimated AU\$4.67 (US\$3.75) per week electricity price impact required to achieve the 90% renewables electricity target (ACT Government, 2015c). This demonstrates that moving to high levels of renewable electricity is both achievable and affordable.

### ECONOMIC BENEFITS OF RENEWABLE ELECTRICITY INVESTMENT

ACT's investment in renewable electricity is stimulating investment in strategic priority areas of the local economy – building local infrastructure, intellectual property, and knowledge and skills of international significance – while creating opportunities for exports and sustainable job creation. The economic benefits flowing from successful reverse auction projects total more than AU\$500 million (US\$400.92 million).

## LOCATION OF CANBERRA'S WIND AND SOLAR FARMS WITHIN THE NATIONAL ELECTRICITY MARKET



**Case Study 12.4 Figure 1** Wind farms funded under the ACT Government's reverse wind auction.

Source: ACT Government, 2015b

The ACT Renewable Energy Local Investment Framework (ACT Government, 2014b) is designed to enhance opportunities for job creation resulting from the ACT's investments in large-scale renewable projects. All developers participating in the wind auction were required to demonstrate best-practice community engagement processes for their projects and contributions to local industry development.

The three successful wind auction proponents will deliver a range of benefits for the ACT through a AU\$50 million (US\$40.09 million) economic stimulus package, including the establishment of new operations centers, research and development partnerships with local universities, a new national trades training center, an innovation fund for small Canberra renewables businesses, and a AU\$7 million (US\$5.61 million) investment in new courses at the Canberra Institute of Technology (CIT) and the Australian National University (ANU).

As a result of investment by wind auction proponent, Neoen CIT will be developing its new Renewable Energy Skills Centre of Excellence to target national and international students looking for hands-on learning in renewable energy asset development and management.

The ACT government is also targeting skilled professionals around the country, transitioning from work in decommissioned coal and gas generation assets across Australia's national electricity market. Supported by WindLab and Renewable Energy Systems, the ANU is expanding its renewables programs and will establish Australia's first master's degree course in wind energy development, complementing the existing master's degree in energy change program. This is reinforcing the international reputation of the ANU and its Energy

Change Institute as leaders in education and applied research in the energy field and in creating new opportunities for business–research collaborations.

Important for the ACT is the continued growth of renewable electricity investment in the region. A key partner in this is the South East Region of Renewable Energy Excellence (SERREE), which is working to develop a vibrant cluster of renewable energy businesses in Canberra and the surrounding region. A requirement of the wind auction was for proponents to invite tenders from and to contract with local businesses in the asset development and operational stages of the wind farms. SERREE will provide an important vehicle for this investment, supporting local jobs and creating international exposure for small business in the ACT and its surrounds.

All wind farms will be run from new management and operations headquarters in Canberra. In the short term, it is expected that these operations hubs will directly employ eleven highly skilled, full-time personnel, with employee numbers expected to grow substantially over time as new wind farms in Australia and overseas are developed and managed from these facilities. Local small businesses and start-ups will be supported through a new AU\$1.2 million (US\$0.96 million) Renewable Energy Innovation Fund supported by Neoen.

A big local winner out of the wind auction process is the Canberra-based company, WindLab. As a result of the wind auction, WindLab projects that investment in salaries and related costs are expected to grow to in excess of AU\$240 million (US\$192.49 million) over the 20-year FiT period.

To offer pathways for young people, WindLab and RES have partnered to deliver a Renewables in Schools program, introducing Canberra high school students – both government and nongovernmental – to the world of renewable energy. The program will outline to students opportunities to contribute to the growth of this exciting field through further tertiary education, research, or trades training.

## CONCLUSION

Canberra exemplifies the increasingly important role of cities in responding to rising global GHG emissions. Its goal of supplying 100% of its electricity from renewable sources by 2020 has minimal impacts on local energy prices and has already generated significant benefits for the local economy.

The Territory's wind auctions have received significant industry attention, attracting both domestic and international proposals. Competition was intense, both in terms of FiT price and contributions to the Local Investment Framework.

Under the Renewable Energy Local Investment Framework, the government has recognized that renewable energy industries provide a strategic growth opportunity for the Canberra economy. The Framework sets out a vision of Canberra as an internationally recognized center for renewable electricity innovation and investment, and the city is well on the way to achieving that goal. The local investment benefits achieved through the wind auction demonstrate a concerted effort by the ACT government to develop renewable electricity as a strategic opportunity for Canberra. It also reflects a recognition by industry of Canberra as a good place to invest – a high-skills economy well placed in the global renewable energy revolution.



**Table 12.7** Urban carbon emission reduction targets. Computed from C40, ARUP and others, 2015.

Number of cities	Percent of total	Target Year	Target: Percent of cumulative emission reductions
144	63	2020	12
27	12	2012–2030	13
57	25	2050	15

Efforts to maximize GHG mitigation potential need further research, especially into how multiple actions that transcend political/institutional boundaries are being implemented, as well as which mitigation options are cost-effective, scalable, align with existing local priorities or conditions, have high participation rates and leadership, and/or result in undesirable “rebound” effects. To assist with some of these types of analyses, efforts are needed to calculate the expected (or potential) and monitor the actual effectiveness of mitigation strategies over time. Equation 1 illustrates how effectiveness can be quantitatively assessed as a product of the baseline emissions from the city, the anticipated savings from the activity change, and the participation rate in the activity:

$$\text{Mitigated Amount} = \text{Baseline} \times \text{Anticipated Savings} \times \text{Participation Rate}$$

(Equation 1)

Future research that measures and “ground-truths” GHG reduction effectiveness via randomized case-control trials can generate information for decision-makers to better understand actual emission reductions and participation rates in GHG mitigation action programs that are voluntary or market- or regulatory-based (see Section 12.3.3).

Singapore, and specifically the Housing and Development Board of Singapore (HDB), serves as one model for using quantitative scenario-based urban information modeling comparing climate mitigation potential of various urban planning strategies to inform decision-making (see Case Study 12.5).

Many cities have begun to use quantitative analyses and tools to compare the effectiveness of various mitigation actions, and here we highlight two examples from China:

- *Changing commercial district in Shanghai*: Identified 58 actions for reducing energy use and emissions, including building retrofits, greening the energy supply, improving building codes, and clean transport. Each action was assessed according to its cost to implement and energy and GHG savings potential. The energy supply improvements from purchasing renewable energy, on-site distributed generation, and “phasing out” transformers together were estimated to reduce GHG emissions by 57 kton CO<sub>2</sub>e during 2011–2015,

compared to a total estimated reduction potential from all 58 actions of 177 kilotons CO<sub>2</sub>e, although improving building energy efficiency had a larger overall potential for emissions mitigation in the district (World Bank, 2013).

- *Xiamen City, China*: Found fuel switching toward lower carbon options had by far the most energy and emissions reduction potential in 2007–2020 as compared with other reduction strategies such as improving industrial energy efficiency, improving large public building efficiency, expanding public transit, or investing in renewable energy sources (Lin et al., 2010).

Results from these studies indicate that the relative effectiveness of different reductions strategies depends on the characteristics of the studied community and the drivers reviewed earlier (Section 12.3.4), and thus it is difficult to generate “best practices” that apply in all communities. Nevertheless, interest in identifying “no- and low-regrets” policies is high (Ostertag, 2012; Ruester et al., 2013). No- or low-regrets policies are those in which the benefits to society from energy or emissions reductions (and other goals such as job creation or reducing conventional air pollution) outweigh the implementation costs, regardless of the severity of future climate change impacts, including some energy-efficiency and demand-side management (Prasad et al., 2008; Ebinger and Vergara, 2011).

### 12.5.3.5 Institutional Barriers and Ways of Overcoming Them

Reducing the environmental impact of the urban energy supply sector requires substantial institutional capacity to identify and implement appropriate mitigation strategies. Twelve types of institutional barriers to effective environmental management are uncoordinated institutional framework; limited community engagement, empowerment, and participation; limits of regulatory framework; insufficient resources (capital and human); unclear, fragmented roles and responsibilities; poor organizational commitment; lack of information, knowledge, and understanding in applying integrated adaptive forms of management; poor communication; no long-term vision, strategy; technocratic path dependencies; little or no monitoring and evaluation; and lack of political and public will (Brown and Farrelly, 2009). Insufficient resources is relevant to all cities but especially smaller cities not having the same capacity and resources of the megacities of the world: less training to assess and mitigate urban energy-related GHG emissions, less financing, fewer knowledge networks, and often a higher need to prioritize investments in economic development relative to environmental conservation.

Furthermore, higher population growth and spatial expansion in small and medium-sized cities is often accompanied by fewer planning resources and weaker capacities to ensure provisions of public services and infrastructure, leaving GHG mitigation to be lower on the priority list unless it aligns with other local development priorities (see Case Study 12.6).

## Case Study 12.5 The City of Singapore's 3D Energy Planning Tool as a Means to Reduce CO<sub>2</sub> Emissions Effectively

Marianne Najafi

*EDF France, Paris*

<b>Keywords</b>	Emissions, urban energy, technology, 3D modeling, EDF
<b>Population (Metropolitan Region)</b>	5,607,300 (Department of Statistics Singapore, 2016)
<b>Area (Metropolitan Region)</b>	719.2 km <sup>2</sup> (Department of Statistics Singapore, 2016)
<b>Income per capita</b>	US\$72,711 (Department of Statistics Singapore, 2017)
<b>Climate zone</b>	Af – Tropical rainforest (Peel et al., 2007)

The Housing and Development Board of Singapore (HDB), Singapore's biggest public housing provider, uses a ground-breaking urban modeling tool to compare various urban planning strategies and select the most appropriate one for achieving the city's goals. This analysis allows the city to harness clean technology and, by doing so, reduce its CO<sub>2</sub> emissions.

EDF, a major electricity company, has developed the IT tool to facilitate a system's approach to energy and urban systems and their interactions at the very early stage of the planning process. Based on this systemic approach and expert advice, energy systems and CO<sub>2</sub> emissions can be optimized during the planning phase by using effective levers of action such as urban morphology, density, mixed land use (commercial and residential uses), renewable energy potential, efficient cooling and heating networks, and optimization of building consumption and emissions related to mobility.

The tool simultaneously maps three energy system dimensions:

- **Energy demand and its evolution:** Energy demand in buildings and energy efficiency actions, mobility and electric mobility development, public lighting
- **Local energy supply:** Distributed energy production and local renewable potentials
- **Electric and thermal networks:** Enablers of the integration of renewables and giving flexibility to the energy systems thanks to demand response and energy storage

The systemic approach of the tool facilitates collaboration between the Singaporean authorities and other industrial partners, incorporating location maps and 3D representations of buildings as well as

graphs and tables of consumption data. The planning approach, in combination with use of the tool, is stakeholder inclusive and provides understanding of co-benefits or the positive externalities related to enhancing quality of life and air quality.

### THE FIRST RESULTS

This IT tool was initially developed for the new residential district of Yuhua, Jurong East, in Western Singapore, in 2014. Results suggest a potential reduction of energy consumption by half in 2030 as compared to 2010 and a potential for photovoltaic (PV) renewable energy use of approximately 20% to 30% of energy consumption. In one plausible scenario, GHG emissions could be cut by more than half with simulations showing approximately 21,000 tons of GHG avoided over 15 years of PV operation. Measures include energy efficiency in building air conditioning systems, integration of solar panels, green roof development, water and domestic waste management, and improved urban mobility.

### THE LESSONS LEARNED FROM THE DEPLOYMENT OF THE TOOL

#### Adapting to the Local Specificities

Each city or territory is highly specific and has its own characteristics in terms of natural resources, history, culture, and local energy production. Urban energy reduction solutions therefore must vary. However, for all cities, the global approach is the same: first look at energy demand and energy efficiency, then evaluate the potential for energy resources and specifically renewables, and finally design efficient, reliable, affordable energy supply networks. The approach must be cognizant of the challenges of balancing different interests, and it must focus on the ongoing operation and maintenance of facilities to meet initial design goals.

#### Thinking Long-Term

Analyzing energy needs and energy resources over a 20- to 30-year horizon provides the context for good energy decision-making, in addition to determining early on positive and negative impacts, costs and benefits, and both negative and positive externalities (local energy production, sustainable mobility). While there are many uncertainties, comparing different strategies and impacts in the long run helps decision-makers to think of both today's cost and longer term benefits.

#### Acceptability and Stakeholder Engagement

Energy projects can only succeed if they rely on strong political will across scales capable of mobilizing the various stakeholders around a shared vision and trajectory. Given stretched municipal budgets, greater stakeholder engagement and public-private partnership are increasingly attractive.

### 12.5.4 Climate Adaptation and the Urban Energy Supply Sector

Vulnerability and risk assessment of energy systems are critical to inform adaptation strategies that improve the resilience of cities and their inhabitants to energy system stresses. Appropriate

adaptation strategies depend on the specific climate hazards and vulnerabilities facing each city, as well as on the adaptive capacity of its residents.

The capacity of urban residents to adapt to climate vulnerabilities is embodied in both the physical infrastructure within

the urban environment as well as the urban socioeconomic and political processes and structures. The adaptive capacity of residents, for example, is a function of the quality of provision and coverage of infrastructure and services, investment capacity, and land-use management (Revi et al., 2014). Urban adaptive capacity during extreme events depends on: (1) proper and simultaneous functioning of lifeline systems including transportation, water, communications, and power; (2) the robustness of critical facilities for public health, public safety, and education; and (3) preparedness programs and response and relief capabilities (Wenzel et al., 2007).

In the short term, parts of energy supply systems have been designed to cope with climate-related risks. For example, substation sites in San Diego are graded to divert waters away from facilities and to prevent erosion (ICLEI, 2012). Facilities including oil and gas drilling operations; thermal power plants; and hydro, wind, solar, and biomass generation can be better designed or managed on-site to withstand climate hazards such as higher winds, storm surge, or drought (Ebinger and Vergera, 2011). In the long-term, relocation of distribution lines and generation facilities will be required (Wilbanks et al., 2007) as well as increasing levels of redundancy, flexibility, and reliance on distributed generation systems that allow for avoiding certain design or service deficiencies involved with citywide or regional distribution grids, blackouts, and other types of service disruptions (Lovins et al., 2002). New facility siting decisions, water-efficient energy generation systems, community-based renewables, back-up diesel generators, early warning systems,

and hazard preparedness plans are other forms of adaptations (Tyler and Moench, 2012).

Table 12.8 identifies examples of energy system adaptation strategies that include reducing exposures and sensitivity and improving adaptive capacities via planning, policy, technology, and behavior change approaches. As with mitigation, these four categories of urban adaptation approaches are pathways to more resilient energy systems, defined by characteristics of having spare capacity, flexibility, limited or “safe” failure, rapid rebound, and planning/policy processes that catalyze constant learning. Importantly, these strategies will vary in relevance by city, region, and local contextual factors such as weather. In the future, integrated approaches toward low-carbon, climate-resilient, and just energy systems will require planning, policy, technology, and behavior change suited to local contexts. Meanwhile, city exchange of ideas, knowledge, and resources toward these goals – sharing what has worked and what has not worked – is increasing (e.g., ICLEI, C40, 100RC) although further mapping efforts can help to catalyze co-benefits integration (see Section 12.5.7), scaling, and replication.

A recent survey of 350 global cities (Aylett, 2014) identified that, of those cities with local government-operated electrical utilities, only 15% are focusing on adaptation planning. Therefore, we provide an illustrative list of options that can be adopted in cities. These options are gathered from a review of several reports and studies (World Bank, 2011; Royal Academy of Engineering, 2011).

## Case Study 12.6 Managing Polluting and Inadequate Infrastructure Systems and Multiple Environmental Health Risks in Delhi

Joshua Sperling

*National Renewable Energy Laboratory, Denver*

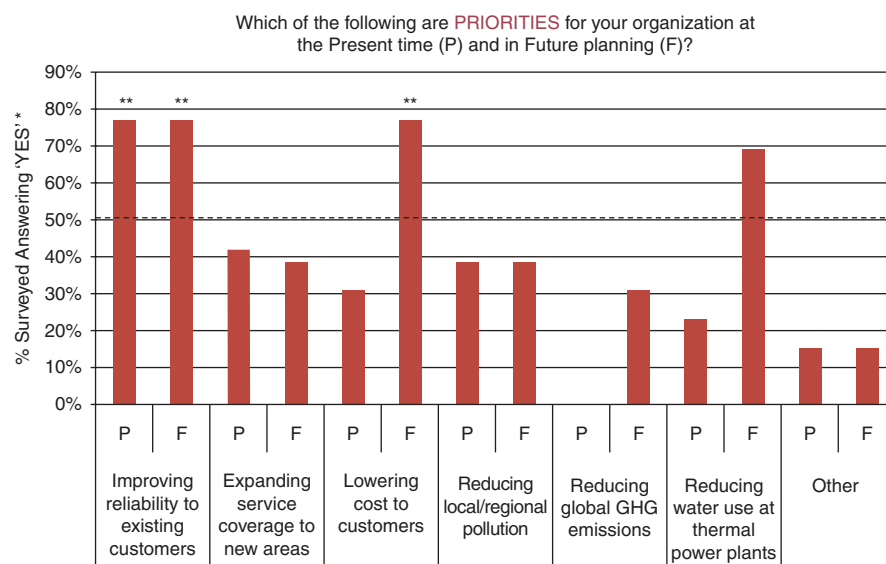
<b>Keywords</b>	Energy supply, heat wave, GHG emissions reduction
<b>Population (Metropolitan Region)</b>	21,753,486 (IndiaStat, 2015)
<b>Area (Metropolitan Region)</b>	1,483 km <sup>2</sup> (Delhi Government, 2015)
<b>Income per capita</b>	US\$1,680 (World Bank, 2017)
<b>Climate zone</b>	BSh – Arid, steppe, hot (Peel et al., 2007)

Current energy infrastructure conditions in Delhi are poor, with unscheduled power cuts, 8% still using solid fuels for cooking, many

lacking access to reliable/affordable electricity, and average pollutant concentrates up to four times higher than national outdoor air quality standards. Actions adopted by the Delhi government underline the importance of managing energy infrastructure systems given multiple environmental health risks that can be driven by urbanization, air pollution, and climate-related extreme weather (e.g., the rolling blackouts and more than 2,000 deaths in the North India heat wave early in the summer of 2016).

The local government has proactively planned for a number of activities contributing to improved management of energy systems, including conversion of coal-based to gas-based power plants, use of clean natural gas (CNG) for transportation, and reductions in supply losses. Stand-by loss reduction (Prakash, 2014) can have significant impacts, especially as these power losses make up 25% of the total Delhi electricity produced.<sup>7</sup> On the demand side, efficiency standards for appliances and lighting that make up the bulk of Delhi's residential energy demand have also been a focus, as well as Delhi's Transportation Department vision aiming to implement a comprehensive multimodal system of approximately 500 kilometers of metro rail, bus priority lanes, and use of CNG across the entire

<sup>7</sup> See Box 12.3 for details on Delhi's energy supply.



**Footnotes:**

\* Computed based on "yes/no" responses from 12 of 14 EOs; remaining two will be captured (n = 12).

\*\* Ranked in the Top-3 by >50% of respondents who provided a ranking in addition to a 'yes/no' (n = 7).

### Case Study 12.6 Figure 1 Priorities of electricity infrastructure operators.

Source: Cohen, 2014

bus fleet. However, the twin goals of reduced emissions and risks to populations in Delhi remain critical, and challenges remain including poorly maintained transmission lines, extreme heat, and overloaded grids (in general) due to the struggle to meet rapidly rising demand. Plans for heat wave-proof transmission and distribution systems are fundamental to reliable electricity and the heat action plans under development should consider use of cooling centers in public transit stations during extreme heat events. New policies under consideration for net metering, reducing supply losses, and achieving air pollution and GHG mitigation co-benefits are critical and will require long-term planning efforts.

In the short term, and despite these laudable efforts,– Delhi was ranked by the World Health Organization (WHO) in 2014 as the worst city globally among 1,600 cities worldwide in terms of particulate (PM<sub>2.5</sub>) air pollution concentrations, and many inhabitants continue to lack basic infrastructure so that a focus on reducing current health burdens due to civil infrastructure (e.g., energy, water, transport) or infrastructure-related environmental factors (e.g., air and water quality, extreme weather events) could be a significant opportunity and strong motivator for low-carbon development, especially with 19% of classified deaths in Delhi (in 2008) potentially related to such factors. In fact, infrastructure intervention at present could reduce mortality by about 4% even through one action to reduce PM<sub>10</sub> levels in the city (Sperling, 2014). Specifically in the context of electricity infrastructure operators (EOs), surveys by Cohen (2014) indicate that among seven identified priorities,

improving reliability, expanding service, and reducing pollution were highest present priorities, with reliability, lowering costs, and reducing water use at thermal power plants highest priority for future planning; note that reducing GHG emissions was not considered a priority for any of the surveyed EOs at present (see Case Study 12.6 Figure 1). The same survey also found that the factors contributing most to current power outages are insufficient generating capacity, heat waves/drought, and fuel supply disruptions to thermal power stations.

These examples, challenges, and opportunities illuminate important questions going forward:

1. What is the potential for energy and emissions mitigation for Delhi's energy system given such EO priorities?
2. Can mitigation actions in Delhi have pollution and health risk reduction co-benefits?
3. How and why are growing cities such as Delhi introducing technology, planning, policy, and behavioral change approaches to both mitigate and adapt to climate change?
4. What new studies, actions, and programs are needed to improve understanding of and develop solutions for the urban energy supply sector in Delhi?
5. What will future demands look like, and which risks to Delhi energy systems and local populations are highest priority, especially under rapid growth conditions and a changing climate where increased frequency and intensity of extreme events impact energy systems?

Small-scale adaptation actions of energy supply systems:

- Move to distributed generating capacity and systems
- Create public cooling centers, emergency shelters, health facilities with on-site and back-up power supplies to provide safe places to go during heat waves, wildfires, floods, and other extreme events
- Create on-site renewable energy generation for community-based resilience centers that help ensure on-site communications, alternative water treatment/sewer capacity, and on-site food and medicine refrigeration capabilities
- Ensure redundant power systems for operation of critical infrastructures, government buildings, health/disease



**Table 12.8** Summary of four types of adaptation actions. Source: Adapted from Chester et al., 2014

Adaptation Strategies in Energy Sector	Planning	Policy	Technological	Behavior Change
Key Learning, Knowledge, and Policy Networks: 100 Resilient Cities, Asian Cities Climate Change Resilience Network, ICLEI, C40, UCCRN, Mayor's Adaptation Forum, and others	Heat-Health Action Plans (Knowlton et al., 2014) focused on maintaining power to critical facilities/vulnerable groups; cooling centers in public transit stations during extreme heat	Renewables and energy efficiency incentive programs; early warning systems such as heat/flooding alerts to mobile phones and other forms of media/communications (TV, radio, short online videos, door-to-door)	Expanding capacity and reducing stand-by losses (Prakash, 2014) to avoid overloaded energy systems in the longer term due to rising temperatures and increasing energy demand (Archer et al., 2014)	Use of home heating and cooling systems (Stern, 2016); infographics, dashboards, and real-time energy meters; community-based social marketing techniques; social norming (Schultz et al., 2007; Goldstein et al., 2008)

surveillance monitoring systems, and surge health care services

- Redesign/shift renewable power site locations or change operations to minimize hazards
- Improve severe weather early warning systems and prediction capabilities so utility operators can better prepare for and manage extreme events
- Use smart meters and grids to play a part in managing variability in demand and supply

Larger scale actions (directly or indirectly) for adaptation in the energy supply sector:

- Create detailed risk assessments for energy assets and facilities to examine the likely conditions they will be exposed to (e.g., floods, storms, drought)
- Combine the use of centralized and distributed energy supply systems
- Apply efficiency measures and prioritization of critical infrastructures during supply shortages
- Use strategic siting or relocation of electric power generation plants (e.g., due to sea level rise)
- Institute river basin management to protect hydropower potential
- Track needs for greater generating capacity during times of peak demand
- Make changes in regulation to allow for electricity operator cooperation/coordination
- Determine dependencies of energy infrastructure (e.g., on water infrastructure for cooling; ICT infrastructure for control, management, and communications; and transport infrastructure for the supply of fuel for power generation and the distribution of oil and gas, as well as to enable access for energy infrastructure operators and maintenance staff)

As with mitigation, context is critical to the adoption of any of the listed measures, and few studies illustrate the effectiveness of different adaptation strategies. The effectiveness of adaptation may be estimated quantitatively by the number of buildings that are removed from risk, although more often such estimates depend on context, sequencing and interaction of adaptation actions, and behavioral responses that are difficult to anticipate

(Adger et al., 2005). Some effort has been made in estimating the effects of urban greening strategies, which may provide both mitigation and adaptation benefits. For instance, urban trees in Beijing in 2002 were estimated to reduce average air temperatures by 1.6°C, store 0.2 million tons of CO<sub>2</sub>, and reduce summertime electricity demand from coal-fired power plants, subsequently reducing emissions (Yang et al., 2005). Even relatively small investments in “green” infrastructure within cities through planning and design (such as urban parks of approximately 1 hectare with widely spaced shade trees and good water sources) can effectively reduce the urban heat island and reduce cooling energy demand in urban neighborhoods (Müller et al., 2014). Likewise, adding 10% more green space in high-density urban environments through green roofs was estimated to adequately maintain urban temperatures at baseline levels in the Greater Manchester region despite projected increased temperatures through 2080 from climate change (Gill et al., 2007). These examples illustrate the need for increased attention to mitigation and adaptation synergies and tradeoffs.

### 12.5.5 Mitigation and Adaptation Co-Benefits and Interactions

There are both benefits and risks posed by urban energy infrastructure systems (Sperling and Ramaswami, 2013). Complementing the four categories described of mitigation and adaptation options, a key focus area for cities in terms of policy development has been regulation, economic/fiscal instruments/investments, and capacity-building focused on several key areas of the urban energy supply sector including efficiency; greater use of clean fuels and processes; access, reliability, and energy security; and resilience.

With these multiple key areas for decision-making, measuring both synergistic and antagonistic electricity supply pathways toward low-carbon, resilient, and just cities is of great importance. As just one example of energy for just cities in the context of public health, a perhaps antagonistic pathway could be defined as the need to provide clean drinking water systems placing new energy demands on cities by requiring new water treatment plant facilities, resulting in increases in GHG emissions, meanwhile

reducing waterborne diseases. As such, it is worth exploring synergistic pathways that reduce GHG emissions, improve urban air quality, and generate social justice co-benefits (such as in Beijing leading up to the Olympics; Zhao, 2010) and antagonistic pathways that may increase health benefits while worsening GHG emissions or lead to “maladaptations” (Noble et al., 2014). Similarly, efforts to build long-term resilience may reduce GHG emissions yet do little for current health or pressing development issues.

New scenario tools are needed, and a few are under development that estimate quantitative impacts for health and carbon emissions while also mapping/monitoring the vulnerability and resilience of the energy supply sector. At a minimum, actual performance assessment is needed. Equally important are the multiple qualitative tools such as the “action impact matrix” that allows comparison of various policy options against co-benefits criteria, including poverty alleviation, biodiversity, air quality, and water scarcity (Munasinghe and Swart, 2000) and the “adaptation matrix” that illustrates co-dependencies among urban systems including energy, transport, health, and water (Kirshen et al., 2007).

While significant complexity exists, interdisciplinary and systems-based efforts are still needed that help identify synergies, co-benefits, interactions, and tradeoffs that have yet to be evaluated. Some mitigation and adaptation co-benefit assessments have been conducted and have proved enlightening for decision-making in select cities (e.g., Harlan and Rudell, 2011; Ruth, 2010). Urban infrastructure sectors are described as a key area where opportunities for synergies are greater (Wilbanks et al., 2007) (see Table 12.9). Data availability and a lack of

**Table 12.9** Energy supply examples of co-benefits (top row) and tradeoffs (bottom row).

Mitigation	Adaptation
Reduce emissions by expanding use of renewable sources	Reduce vulnerability to widespread power grid outages by encouraging distributed generation from multiple renewable sources.
Reduce emissions by improving efficiency of energy and water delivery systems	Reduce potential for grid overload and failure by decreasing demand.
Energy shifts to low-carbon natural gas or nuclear electricity production	Water constraints during periods of drought exacerbated by new low-carbon energy supply and generation systems

standard assessment methods remain key challenges to increasing the comparability of efforts and effectiveness.

A recent survey of more than 412 local and regional governments by the ICLEI (2015) reports that the majority of mitigation and adaptation actions are focused on policy, action planning, and infrastructure investments. The top five ranked co-benefits for local climate mitigation and adaptation actions, taken together, include improving air quality and urban livelihoods, boosting the urban economy, protecting urban ecosystems, and safeguarding urban health.

Quito, Ecuador, has sought to integrate its mitigation and adaptation efforts with its overall urban development strategy and thus pursue co-benefits, especially from improvements in its urban energy system (see Case Study 12.7).

## Case Study 12.7 Energy and Climate Change in Quito

**Daniel Carrion**

*Mailman School of Public Health, Columbia University, New York*

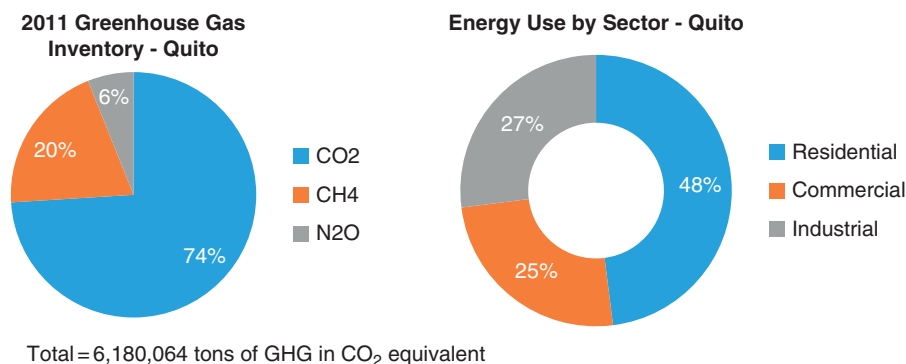
<b>Keywords</b>	Mitigation, energy efficiency, methane capture, renewable energy, adaptation
<b>Population (Metropolitan Region)</b>	2,239,191 (Secretario Metropolitano de Territorio, Habitat y Vivienda [STHV], 2010)
<b>Area (Metropolitan Region)</b>	4,230 km <sup>2</sup> (STHV, 2010)
<b>Income per capita</b>	US\$5,820 (World Bank, 2017)
<b>Climate zone</b>	Cfb– Temperate, without dry season, warm summer (Peel et al., 2007)

Quito is a leader among cities worldwide, evidenced by its involvement with horizontal government leadership initiatives such as C40 and ICLEI. The country as a whole has twenty-five registered Clean Development Mechanisms, many in Quito (UNEP, 2011). In 2009, the city introduced a robust and coherent framework to address climate change via targeted mitigation and adaptation strategies (Municipio del Distrito Metropolitano de Quito [MDMQ], 2009). This plan is known as the Estrategia Quiteña al Cambio Climática (EQCC) or Quito's Climate Change Strategy.

### GREENHOUSE GAS INVENTORY

A 2011 report found that Quito was responsible for 4.5% of Ecuador's total greenhouse gas (GHG) emissions (MDMQ, 2011). CO<sub>2</sub> was the most abundantly emitted of the three GHGs measured in 2011. Total GHG emissions by sector were: 57% energy, 7% agriculture, 18% waste, and 18% in biomass use and land-use change (MDMQ, 2011). These classifications follow Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). Total emissions are estimated at 2.55 tons CO<sub>2</sub> equivalent per person per year (MDMQ, 2014).<sup>8</sup>

<sup>8</sup> See Box 12.3 for details on Quito's energy supply.



**Case Study 12.7 Figures 1 and 2** *The 2011 Greenhouse Gas Inventory for Quito and Quito's energy use by sector.*

### MITIGATION EFFORTS

GHG mitigation projects are well under way in Quito. Ecuador is estimated to contribute less than 1% of the world's GHG emissions annually (MDMQ, 2014). Quito only comprises a fraction of that 1%. Despite this, the city demonstrates a strong commitment to sustainable development and leadership. Quito upholds initiatives pertaining to citizen education, transparency, and awareness, as outlined in the EQCC. The city has countless documents, presentations, reports, educational materials, curricula, and more ready for download on its website, further indicating this commitment. The EQCC seeks community support, but also encourages adaptation and mitigation starting in the home.

*Energy efficiency and alternative energy initiatives:* Quito has begun to incentivize both. The city's public housing and government buildings have begun implementation of mixed energy improvements, including photovoltaics and energy efficiency upgrades (MDMQ, 2010). These efforts may also be used to encourage private residential and commercial adoption, through incentivizing the use of clean energies in new construction. Key urban infrastructure has been targeted for implementation of photovoltaics, namely at bus stops (MDMQ, 2010). Photovoltaics may be one of Quito's best alternative energy options if done correctly because its high altitude and moderate temperatures may improve solar panel efficiency (Kawajiri et al., 2011). The Empresa Electrica de Quito (EEQ) is currently monitoring wind characterization throughout the region to determine the viability of wind power (EEQ, 2014b).

In 2011, Quito's waste sector had an annual output of 1,100,155 tons CO<sub>2</sub>-equivalent GHGs. None of those emissions consisted of CO<sub>2</sub>. Instead, almost 97% of those emissions were of methane. Despite some recent objections, methane is regarded as an efficient and clean combustible (Brandt et al., 2014). The City of Quito has decided to capture methane from waste (i.e., landfills) for energy. This technique demonstrates Quito's innovative methods to mitigate and promote development (MDMQ, 2010).

The municipality has created an admirable goal of 9 square meters of green space per city resident called La Red Verde Urbana (Green Urban Network). Furthermore, the construction or implementation of green roofs on new or existing infrastructures is being incentivized (MDMQ, 2010, 2012).

Green space can yield substantial energy-related paybacks. Research has found that green space in cities can counter traditional urban heat island effects caused by dark, impervious surfaces (Vasilakopoulou et al., 2014). This would attenuate the need for cooling during summer months. Maintenance of porous surfaces

allows for natural drainage of water, reducing the need for man-made drainage and energy-intensive wastewater treatment systems (Berndtsson, 2010). The Green Urban Network demonstrates that urban planning strategies offer highly effective tools against climate change.

Another urban planning technique with powerful mitigation potential is the concept of urban containment (Seto et al., 2014). Within Quito's 2011–2016 Climate Plans is a strategy for the collaboration of architects, regional planners, contractors, and real estate professionals to identify vacant or underutilized areas for (re)development within the city. Doing so offers planned densification throughout the city (MDMQ, 2012). This type of planning can reduce energy use and ecological footprint while avoiding unnecessary deforestation (Seto et al., 2014).

### ADAPTATION STRATEGIES

Quito has already witnessed a 1.2–1.4°C increase in temperature from 1891 to 1999. In addition, changes in precipitation patterns have also been observed and more are expected (Zambrano-Barragan et al., 2010). In response, the city is involved in creating a metropolitan atmospheric network, mitigating risk and vulnerability to extreme weather events, reconfiguring the urban landscape, and diversifying its energy portfolio.

The Metropolitan Atmospheric Network of Quito (REMMAQ) collects and generates data on ozone, glaciers, carbon flows, and other climate-relevant factors that would inform short- and long-term decision-making. Such information would be essential to operationalizing any form of climate-resilient energy planning, especially in the context of disaster-prone areas (MDMQ, 2012).

Quito has a sizeable population living in informal settlements and disaster-vulnerable sections of the city, often at its outskirts. A 2011 UNEP report estimates that 53% of all settlements were informal and 443 neighborhoods were illegal (UNEP, 2011). The high electrical coverage of the population coupled with a large number of precarious houses implies an electrical grid under equally vulnerable conditions. The municipality has created programs to identify, prioritize, and manage high-risk areas. Threats can be addressed via engineering in some cases, while in others families must be relocated. An estimated US\$10 million has been used to relocate 1,500 families between 2011 and 2012 (MDMQ, 2010). Those families may be best served if redirected toward the core of the city as part of the urban containment efforts.

In Quito, renewables are recognized simultaneously as mitigation and adaptation via “energy diversification” (MDMQ, 2009). The city's

energy supply comes largely from hydroelectric, which may be vulnerable to the predicted precipitation changes and decreased glacier runoff (Zambrano-Barragan et al., 2010). Notable proportions of energy do still come from a diesel combustion plant (EEQ, 2012). The city, and country, is planning to replace diesel with natural

gas (Ludeña and Wilk, 2013; Ministerio del Ambiente de Ecuador [MAE], 2000; MDMQ, 2012). Plans even include promotion of natural gas-powered vehicles alongside electric and hybrid (MAE, 2000). These adaptations, while not entirely shock-resistant, will offer some stability against the specter of climate phenomena.

## 12.6 Conclusions

This chapter reviews the urban energy supply sector in the context of the major challenges and opportunities for climate change mitigation, adaptation, and sustainable development.

The main challenges to the urban energy supply sector include environmental impacts and energy access and the vulnerabilities of energy systems to weather- and climate-related events. Given trends in urbanization, energy consumption, inequality, and climate change, these challenges will only increase if nothing is done to improve access, resilience, and lower impact.

The review cites both significant barriers and incentives to changing urban supply systems to meet these challenges. While previous transitions may not provide a good roadmap of what might happen in the future because the nature of change is significantly different now than in the past, there remain key indicators that help to provide insight. The length of the transition cycle has probably not changed so we can expect the process to take several decades to occur. This may be even more true today than in the past because in the current era the shift to low-carbon fuels will largely be driven by governance and natural influences because socioeconomically and behaviorally both the price and the convenience of non-hydro renewables is not more attractive than current fossil fuel options.

Moreover, given the diversity of urban conditions and demands, the review suggests that there will not be one single solution to energy supply challenges, but rather there will be numerous solutions to fit unique local needs. This does not mean that localities cannot learn from one another's successes and failure, but rather that the search for a one-size-fits-all set of policies may not be fruitful.

The diversity of urban energy supply solutions is already demonstrated in the large and growing number of efforts emerging across cities globally to mitigate the environmental impact of the energy supply sector and adapt it to climate impacts. This chapter identified a few of these efforts from Rio de Janeiro to Seattle, to Canberra, to Delhi. These policies have generated much interest, but also demonstrate that there remains much to do to transition away from the current trajectory of increasing GHG emissions, vulnerability, and energy inequity. Radical changes in institutions may be required, and, in some instances, cities are responding.

Finally, future scenarios all predict greater urbanization and energy consumption. While some future scenario research points to the possibility of lower carbon cities, but where many urban residents remain without access and few have energy security, there is also research that suggests it is possible to overcome

current barriers and meet all three key challenges. We conclude that while there is much to be done, with greater participation, better technologies, political will, and institutions that support low-carbon, equity, and resilience, there is no reason why the urban future cannot support globally sustainable development and access to resilient, clean, modern energy supplies for all.

## Chapter 12 Urban Energy

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