Chapter 8: Urban Systems and Other Settlements

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Executive summary

Urbanisation is a major trend that will continue through the 21st century with significant implications for energy use and GHG emissions (*robust evidence, high agreement*). Every year over the past decade, the urban population has been increasing by about 70 million. The scale and speed of urbanisation are unprecedented in human history. Every week the urban population increases by about 1.3 million; every day urban land areas expand by about 102 km^2. A growing urban population will require more resources to construct urban infrastructure and more urban areas. Urbanisation levels are strongly and positively correlated with higher national incomes and thus a growing urban population will also mean more consumption associated with urban lifestyles. These trends will contribute to the increased dominance of emissions by the urban areas.

Since AR5, there is more evidence that urban areas contribute to the majority of the global carbon footprint (*medium evidence, high agreement)*. Urban areas are responsible for a large proportion of direct carbon emissions, 45–87% depending on scope and other accounting methods. Urban areas are also responsible for indirect carbon emissions through the consumption of goods and services that are produced outside of urban areas. In 2015, approximately 68% of the global carbon footprint was attributable to urban areas, and regional estimates are similar in proportion. {8.1}

Although there is large variation in urban emissions across countries and regions, the urban share of GHG emissions increased for all regions and globally between 2000 and 2015 (*high confidence).* Amongst Developed Countries, the urban share of total emissions increased from 60% in 2000 to 67% in 2015. The most significant change in emission metrics occurred in Asia and Developing Pacific and Developed Countries regions. Urban population, urban CO_2-eq emissions, and national CO_2-eq emissions increased as a share of the global total in Asia and Developing Pacific. {8.3.2}

The drivers of urban carbon emissions are complex and not simply a function of urban population size or income. The form and structure of urban areas, including land use and infrastructure shape urban GHG emissions (*medium evidence, high agreement)*. Urban form interacts with policies and regulations to influence behaviour, choice, and patterns of urban energy consumption in everyday activities. {8.1, 8.3, 8.4, 8.5, 8.6}

The expansion of urban areas to accommodate the growth in urban population through 2050 will result in significant land conversion and the loss of carbon stocks and agricultural lands (*medium evidence, high agreement***).** Urban areas are projected to increase by 0.8–2.2 million km^2 between 2015 and 2050, an increase of 14–214% over the global urban footprint in 2015, and to 1.0–3.6 million km^2 by 2100. Urban expansion by 2040 may displace almost 65 Mtonnes of crop production, which could result in an expansion of up to 350,000 km^2 of new cropland. {8.3}

Building new cities under a business-as-usual scenario could more than double annual resource requirements for raw materials to 90 billion tonnes per year by 2050, up from 40 billion tonnes in 2010 (*medium evidence, high agreement)*. Most of the yet-to-be built urban areas are in developing countries where urban GHG emissions are still low. The construction of key urban infrastructure will result in significant embodied GHG emissions and committed carbon, ranging from 8.5 $GtCO_2$ to 14 $GtCO_2$ annually up to 2030. {8.3, 8.4, 8.5, 8.6}

Urban deep decarbonisation integrates three broad strategies: (1) reducing urban demand for energy and materials, (2) switching energy supply to net-zero carbon, and (3) enhancing carbon uptake and stocks (*medium evidence, high agreement)***.** Cities can achieve net-zero through deep decarbonisation, but this requires systemic transformation. A city cannot achieve net-zero by only focusing on reducing emissions within its administrative boundaries. {8.1.6, 8.3.2.1, 8.3.4, 8.4, Box 8.1, 8.6}

Compact and resource-efficient urban growth can result in emissions savings of between 36 to 54% compared to a business as usual scenario (*medium evidence, high agreement*). Total urban emissions based on consumption-based accounting are estimated to be 28.6 $GtCO_2$-eq in 2020, representing about 70% of global CO_2 and CH_4 emissions. Resource efficient and compact urban growth will result in savings of 10.1 $GtCO_2$-eq of emissions in 2030 compared to 2020 levels under SSP1-RCP1.9 scenario. In contrast, urban emissions will increase by 2.2 $GtCO_2$-eq in 2030 from 2020 levels with moderate progress under SSP2-RCP 4.5 scenario that involves a delayed response towards net-zero (*low evidence, high agreement*). {8.1, 8.3, 8.4, 8.6}

Effective urban mitigation involves spatial planning strategies, including mixed land use, transit-oriented development, co-locating high residential and high employment densities (*robust evidence, high agreement)*. Compact cities, and policies and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and zero-emission transport, can deliver significant public health benefits and have lower emissions (*high evidence, high agreement*). {8.2, 8.3, 8.4, 8.5, 8.6, 8.7}

Nature-based solutions to mitigate climate change, such as urban forestry and green infrastructure can sequester carbon while achieving multiple co-benefits *(robust evidence, high agreement).* Urban trees offer great potential to mitigate climate change as they sequester carbon as well as permanently reduce GHG emissions through reduced energy use. Annual global urban tree carbon sequestration is on the order of 217 million tonnes. Urban trees can also help mitigate some of the impacts of climate change by reducing urban heat islands and heat stress, reducing stormwater runoff, improving air quality, and improving health. {8.1, 8.2, 8.4, 8.7}

Cities have the power to take climate action over their jurisdiction due to their ability to set regulations and policies related to land use (*medium evidence, medium agreement*). Implementation of sector-level mitigation strategies such as land use planning and building codes occur at the urban scale. Measures that are implemented at the building level can be scalable to blocks, districts, cities, and regions and offer increased energy and GHG savings. {8.1, 8.5}

Harnessing innovative informality, circular economies, and disruptive technologies in conjunction with other strategies can contribute towards low and net-zero urban development *(low evidence, medium agreement).* Realising and implementing these targets with the collective contribution of the diverse urban systems to net-zero scenarios with sufficient timing and pace of emission reductions will require a coordinated integration of all sectors, strategies, and innovations including cities in developing countries. Closing the development deficits in informal urban areas can avoid the business-as-usual trajectory of development and utilise innovations such as micro-scale technologies, decentralised utilities of water, sanitation, and service centres. {8.1.6, 8.3.2.1, 8.3.4, 8.4, Box 8.1, 8.6}

Multilevel and polycentric governance facilitates numerous policy pathways urban actors can take to achieve stabilised global temperatures *(medium evidence, high agreement).* It also illustrates that mitigation efforts are most efficient and impactful when all levels of governance and multiple nonstate actors are engaged, rendering it a key enabling condition for transformation. {8.5}

Achieving transformational changes in cities will require multilevel and polycentric governance, and substantive financing *(robust evidence, high agreement).* Large and complex infrastructure projects for decarbonisation are often beyond the capacity of local municipality budgets. To fill the funding gap in urban areas, cities play a pivotal role in debt financing for a range of low-carbon infrastructure projects and related spatial planning programs. {8.5}

8.1 Introduction

8.1.1 What is new since AR5

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) was the first IPCC report that had a dedicated, standalone chapter on urban mitigation of climate change. The starting point for that chapter was how the spatial organisation of urban settlements affects greenhouse gas (GHG) emissions and how urban form and infrastructure could facilitate mitigation. A main finding in AR5 was that urban form shapes urban energy consumption and emissions. Cities are now considered frontiers along which transformative climate change mitigation will take place. There is also considerable interest in how a systems approach – rather than a sectoral approach – to cities can accelerate mitigation of climate change.

Since AR5, there has been growing scientific literature and policy foci on urban strategies for climate change mitigation. There are three possible reasons for this. First, according to AR5, urban areas generate between 71–76 % of CO_2 emissions from global final energy use and between 67–76% of global energy use (Seto et al. 2014). Thus, focusing on urban systems addresses one of the key drivers of emissions. Second, more than half of the world population live in urban areas, and by mid-century, 7 out of 10 people on the planet will live in a town or a city (UN DESA 2019). Thus, coming up with mitigation strategies that are relevant to urban settlements is critical for successful mitigation of climate change. Third, beyond climate change, there is growing attention on cities as major catalysts of change and to help achieve the objectives outlined in multiple international frameworks and assessments.

Cities are also gaining traction within the work of the IPCC. The IPCC Special Report on Global Warming of 1.5°C (SR15) identified four systems that urgently need to change in fundamental and transformative ways: urban infrastructure, land use and ecosystems, industry, and energy. Urban infrastructure was singled out but urban systems form a pivotal part of the other three systems requiring change (IPCC 2018a). The IPCC Special Report on Climate Change and Land (SRCCL) identified cities as spatial units for land-based mitigation options but also places for managing demand for natural resources including food, fibre, and water (IPCC 2019).

Other international frameworks are highlighting the importance of cities. For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on nature's contribution to people is clear: cities straddle the biodiversity sphere in the sense that they present spatial units of ecosystem fragmentation and degradation but are at the same time spatial units where the concentration of biodiversity compares favourably with some landscapes (IPBES 2019a).

The UN Sustainable Development Goals (SDGs) further underscore the importance of cities in the international arena with the inclusion of SDG 11 on "Sustainable, Resilient and Inclusive Cities" (Queiroz et al. 2017; United Nations 2019). Furthermore, UN Habitat's New Urban Agenda (NUA) calls for integrated spatial planning at the city-regional scale to address the systemic challenges included in greening cities, among which is emissions reduction and avoidance (United Nations 2017). The New Urban Agenda also recognises the importance of urban-scale policies and transformation in urban governance.

Thus, since AR5, there is more attention on cities from the international community. At the same time, there is also significant increase in scientific literature on urban mitigation of climate change, including more diversity of mitigation strategies than covered during AR5 (Lamb et al. 2018), and focus on how strategies at the urban scale can have compounding or additive effects beyond urban areas (e.g., in rural areas, land use, and the energy sector). There is also more literature on using a systems approach to understand emissions savings and mitigation potential, including the relationship between urban mitigation and adaptation, urban mitigation and economic development, and urban mitigation and human security. In particular, the nexus approach, such as the water and energy nexus, and the water-energy-food nexus, is increasingly being used to understand potential emissions and energy savings from cross-sectoral linkages that occur in cities (Wang and Chen 2016; Engström et al. 2017; Valek et al. 2017). There is also a growing literature that aims to quantify transboundary urban GHG emissions and carbon footprint beyond administrative city and national boundaries (Chen et al. 2016; Hu et al. 2016). Such a scope provides a more complete understanding of how local urban emissions or local mitigation strategies can have effects on regions' carbon footprint or GHG emissions.

Moreover, cities around the world are putting increasing focus on tackling climate change. Since AR5:

- Cities around the world are increasing their efforts to mitigate climate change through global networks. The Global Covenant of Mayors (GCoM), a transnational network comprised of more than 10,000 cities, committed to reductions of urban GHG emissions up to 1.4 $GtCO_2$-eq annually by 2030 and 2.8 $GtCO_2$-eq annually by 2050 compared to business as usual (GCoM 2018).
- Climate leadership at the local scale and growing commitment from city decision- and policymakers to implement local-scale mitigation strategies (GCoM 2018; ICLEI 2019).
- Many cities – more than 800 – have made commitments to achieve net-zero emissions, either economy-wide or in a particular sector (NewClimate Institute and Data-Driven EnviroLab 2020).
- Climate leadership at the local scale is growing with commitment from city decision- and policymakers to implement local-scale mitigation strategies (GCoM 2018, 2019; ICLEI 2019; C40 Cities 2020a) More than 360 cities had announced at the Paris Climate Conference that the collective impact of their commitments will lead to reducing up to 3.7 $GtCO_2$-eq of urban emissions annually by 2030 (UCLG 2015). Most recently, the target is to mobilise more than 1,000 cities with science-based targets to zero-carbon futures by 2050 with the partnership of C40, the GCoM and the Carbon Disclosure Project (CDP) by UNFCCC COP26 (C40 Cities 2020a).
- Cities are increasing and amplifying their efforts to mitigate climate change through global networks. GCoM had committed to reductions of urban GHG emissions up to 1.4 $GtCO_2$-eq annually by 2030 and 2.8 $GtCO_2$-eq annually by 2050 compared to business as usual (GCoM 2018) while the savings potential is increasing and reached 2.3 $GtCO_2$-eq annually by 2030 and 4.2 $GtCO_2$-eq annually by 2050 (GCoM 2019). Using the most recent estimates of global total fossil carbon emissions for 2019 that correspond to about 36.4 $GtCO_2$, the share of these annual reductions by 2030 represents about 10% of total global emissions today (Friedlingstein et al. 2020) while the estimates differ according to the cities that are included.

8.1.2 Preparing for the Special Report on Cities and Climate Change in AR7

At the 43rd Session of the IPCC in 2016, the IPCC proposed that the seventh assessment cycle include a Special Report on Climate Change and Cities. To stimulate scientific research knowledge exchange, the IPCC co-sponsored an international Conference on Climate Change and Cities in 2018.

The conference identified key research agendas including an overarching systems approach to understanding how sectors interact in cities as drivers for GHG emissions and the relationship with climate systems. The report makes a deep dive in regard to scale, informality, green-blue infrastructure, governance and transformation as well as financing climate action as areas for scientific research during the AR6 cycle and beyond (WCRP 2019).

This chapter further raises the importance of urban systems by taking the inter-sectoral approach to assessing literature on trends in urbanisation, and GHG and mitigation action. There is a dearth of literature on cities as systems and their influence on GHG emissions trends. Little literature exists that quantifies the potential of informality and for avoiding lock-in for emerging cities especially in developing countries (Nagendra et al. 2018). While there is growing literature on nature-based solutions such as green and blue infrastructure in cities, there is still a large knowledge gap in regard to how these climate mitigation actions can be integrated in urban planning and design as well as their mitigation potential, especially for cities that have yet to be built (Kavonic and Harriet Bulkeley, *submitted*).

In moving forward with the research agenda on cities and climate change science, transformation of urban systems will be critical but understanding this transformation and assessment of mitigation action remains another key knowledge gap (Estrada et al. 2021, *submitted*; Tozer et al. 2021, *submitted*). Preparation for the cities special report in AR7 highlights the knowledge gaps that have yet to be filled.

This chapter begins a transition to assessing urban systems with potential to accelerate mitigation. Although the literature on urban mitigation of climate change has increased significantly since AR5, this chapter acknowledges that significantly more knowledge is needed to understand the full suite of mitigation options available to cities and towns, especially in different geographies, income levels, and governance contexts.

8.1.3 Why focus on urban systems?

This chapter takes an urban systems approach and covers the full range of urban settlements, including towns, cities, and metropolitan areas. By urban system, this chapter refers to two related concepts. First, an urban systems approach recognises that cities do not function in isolation. Rather, cities exhibit strong interdependencies across scales, whether it is within a region, a country, a continent or worldwide. Cities are embedded in broader ecological, economic, technical, institutional, legal, and governance structures that often constrain their systemic function, which cannot be separated from wider power relations. Urban processes of physical, social, and economic nature are causally interlinked, with interactions and feedbacks that result in both intended and unintended impacts on emissions (Bai et al. 2016, 2018; Nagendra et al. 2018).

The notion of a "system of cities" has been around for nearly 100 years and recognises that cities are interdependent, such that significant changes in one city, such as economic activities, income, or population, will affect other cities in the system (Christaller 1933; Berry 1964; Marshall 1989). This perspective of an urban system emphasises the connections between a city and other cities, as well as between a city and its hinterlands (Hall and Hay 1980). An important point is that growth in one city affects growth in other cities in the global, national or regional system of cities (Gabaix 1999). Moreover, there is a well-established and empirical fact that there is a hierarchy of cities (Taylor 1997). At the top of this hierarchy are very large cities that concentrate political power and financial resources, but of which there are very few. Instead, the urban system is dominated by small and medium sized cities and towns. With globalisation and increased interconnectedness of financial flows, labour, and supply chains, cities across the world today have long-distance relationships on multiple dimensions.

The second concept of an urban system is that activities and sectors within a city are inter-connected; cities are ecosystems (Rees 1997; Grimm et al. 2000; Newman and Jennings 2008). This urban system perspective emphasises linkages and interrelations within cities. The most evident example of this is urban form and infrastructure, which refer to the patterns and spatial arrangements of land use, transportation systems, and urban design. Changes in urban form and infrastructure can simultaneously affect multiple sectors, such as buildings, energy, and transport.

This chapter kick starts a transition to assessing urban systems beyond simply jurisdictional boundaries. Using an urban systems lens has the potential to accelerate mitigation beyond a single sector or purely jurisdictional approach. The chapter draws on a growing literature using a systems approach for cities to understand emissions savings and mitigation potential, including the relationship between urban mitigation and adaptation, urban mitigation and economic development, and urban mitigation and human security. In particular, the nexus approach, such as the water and energy nexus, and the water-energy-food nexus, is increasingly being used to understand potential emissions and energy savings from cross-sectoral linkages that occur in cities (Wang and Chen 2016; Engström et al. 2017; Valek et al. 2017).

An urban systems perspective elucidates both challenges and opportunities for urban mitigation strategies. It shows that any mitigation option potentially has positive or negative consequences in other sectors, other people, or other parts of the world. Thus, formulating a truly effective mitigation option requires more careful and comprehensive considerations on the broader impacts, including equity and social justice. However, a systemic understanding of interlinkages would allow policy makers to actively seek out, and build on, synergies and co-benefits, and avoid trade-offs.

8.1.4 The urban century

The 21st century will be the urban century, defined by a massive increase in global urban populations and a significant building up of cities and towns to accommodate the growing urban population. Six trends in urbanisation are especially important in the context of climate change mitigation.

First, the size and relative proportion of the urban population is unprecedented and continues to increase. In 2018, approximately 55% of the global population lived in urban areas (UN DESA 2019). It is predicted that 68% of the world population will live in urban areas by 2050. This will mean adding 2.5 billion people to urban areas between 2018 and 2050, with 90% of this increase taking place in Africa and Asia. There is a strong correlation between the level of urbanisation and the level of national income (UN DESA 2019). In general, countries with levels of urbanisation of 75% or greater all have high national incomes, whereas countries with low levels of urbanisation under 35% have low national incomes (UN DESA 2019). There is considerable variation in the relationship between urbanisation level and national income, and the relationship is complex. However, there is a clear positive correlation between the level of urbanisation income levels (Figure 8.1).

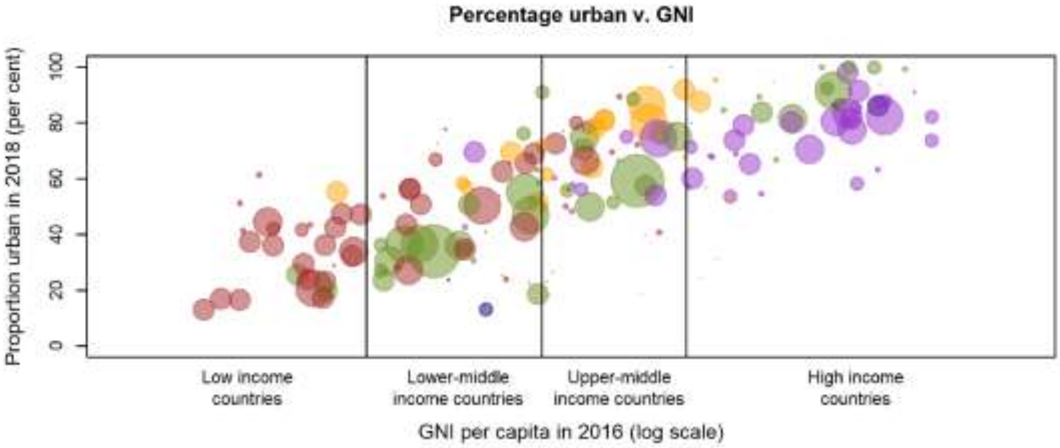


Figure 8.1. Relationship between urbanisation level and Gross National Income. There is a positive and strong correlation between the urbanisation level and gross national income. High income countries have high levels of urbanisation, on average 80%. Low income countries have low levels of urbanisation, on average 30%. Figure from UN DESA (2019, p. 42) *Permission pending.*

Second, the geographic concentration of the world's current urban population is in emerging economies and the majority of future urban population growth will take place in low- and low-to-middle-income countries. About half of the world's urban population in 2018 lives in just seven countries, and about half of the increase in urban population through 2050 is projected to be concentrated in eight countries (see Figures 8.2 and 8.3) (UN DESA 2019). Of these eight, seven are emerging economies where there will be a need for significant financing to construct housing, roads, and other urban infrastructure to accommodate the growth of the urban population. How these new cities of tomorrow will be designed and constructed will lock-in patterns of urban energy behaviour for decades if not generations. Thus, strategies for urban mitigation of climate change must include solutions appropriate for cities of varying sizes and typologies.

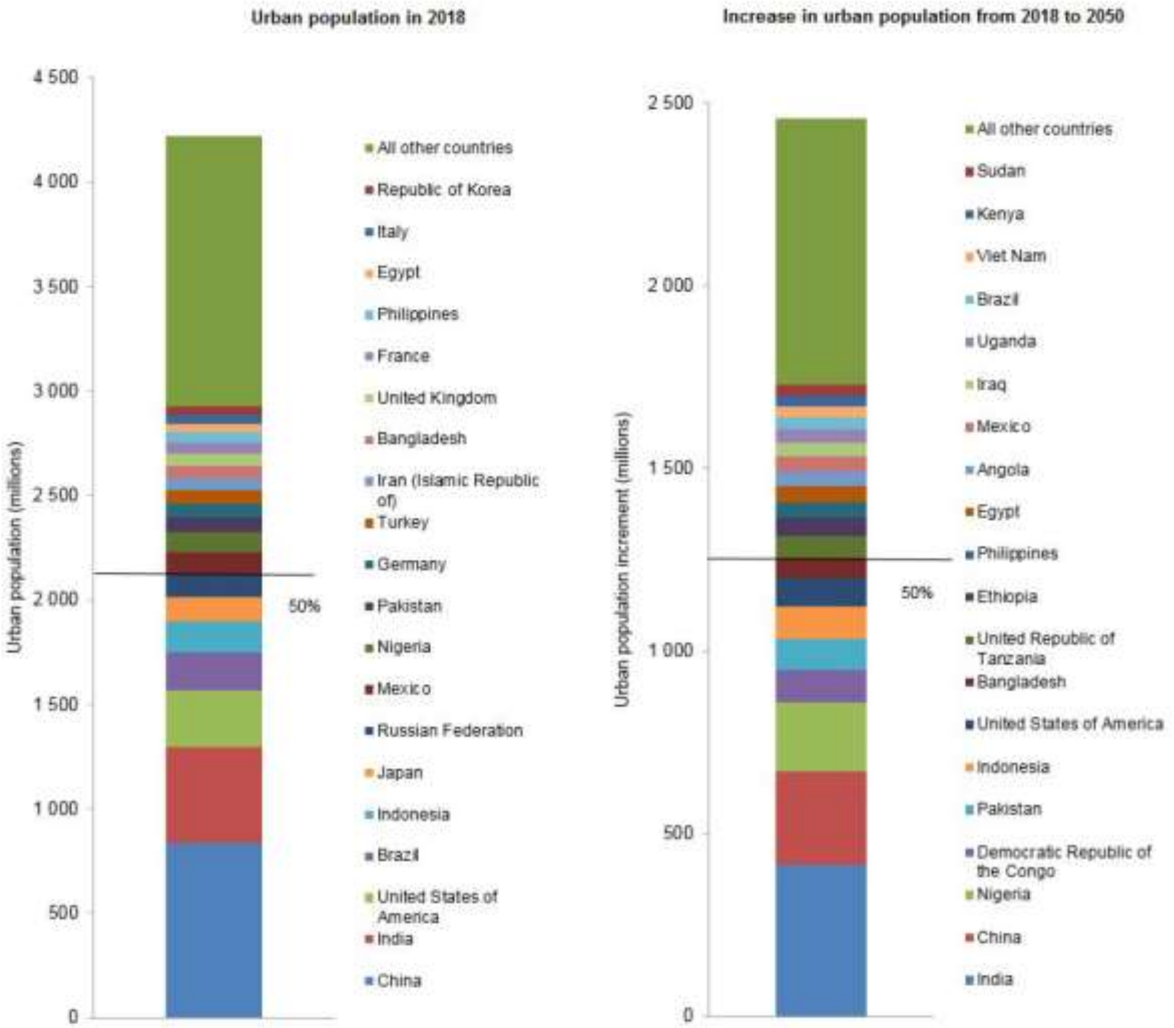


Figure 8.2. Urban population size in 2018 and increase in the projected urban population. About half of the world's urban population in 2018 lives in seven countries, and about half of the increase in urban population through 2050 is forecasted to concentrate in eight countries.
Figure from UN DESA (2019, p. 44) *Permission pending.*

Third, small and medium-sized cities and towns are a dominant type of urban settlement. More than half (58%) of the urban population live in cities and towns with fewer than 1 million inhabitants and almost half of the world's urban population (48%) live in settlements with fewer than 500,000 inhabitants (Figure 8.3). Although megacities receive a lot of attention, only about 13% of the urban population worldwide live in a megacity with more than 10 million inhabitants (UN DESA 2019). Thus, there is a need for a wide range in strategies for urban mitigation of climate change that are appropriate for cities of varying sizes, especially smaller cities which often have lower levels of financial capacities than large cities.

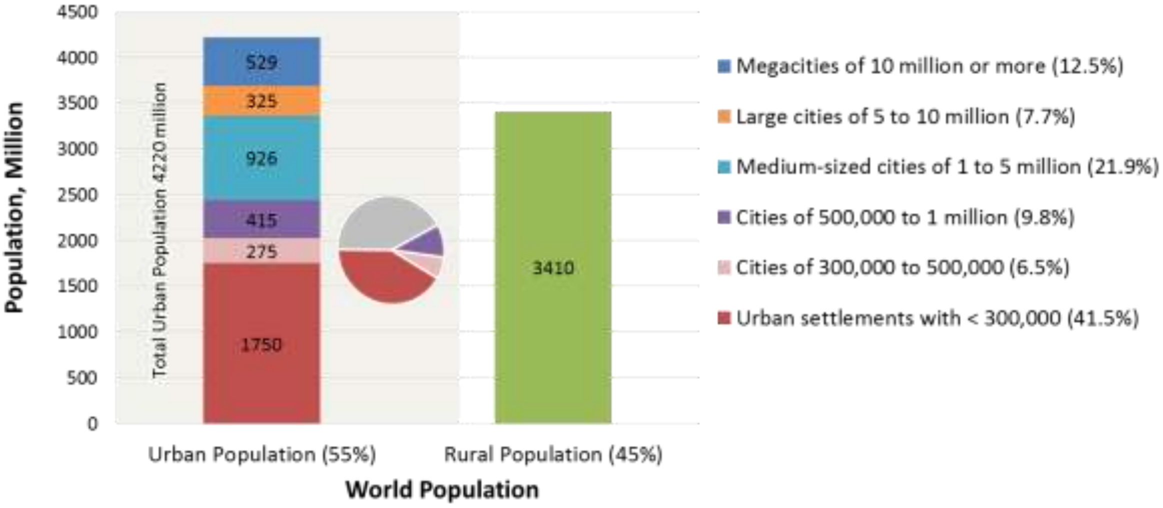


Figure 8.3. Population of the world, by area of residence and size class of urban settlement, 2018. In 2018, 4.2 billion people or 55% of the world population resided in urban settlements while 45% resided in rural areas. The coloured stacked bars for the urban population represent the total number of inhabitants for a given size class of urban settlements. Megacities of 10 million or more inhabitants had a total of only 529 million inhabitants that corresponded to 12.5% of the urban population. In contrast, about 1.8 billion inhabitants resided in urban settlements with fewer than 300,000 inhabitants that corresponded to 41.5% of the urban population. The pie chart represents the respective shares with 42% of the urban population residing in settlements with more than 1 million inhabitants while 58% of the urban population is residing in settlements with fewer than 1 million inhabitants.

Figure adapted from UN DESA (2019) *Permission pending.*

Fourth, another trend is the rise of mega-cities and extended metropolitan regions. The largest cities around the world are becoming even larger, and there is a growing divergence in economic power between megacities and other large cities (Kourtit et al. 2015; Hoornweg and Pope 2017; Zhao et al. 2017b). Moreover, there is evidence that the largest city in each country has an increasing share of national population and economy.

Fifth, population declines have been observed for cities and towns across the world, including in Poland, Republic of Korea, Japan, US, Germany, and the Ukraine. The majority of cities that have experienced population declines are concentrated in Europe. Multiple factors contribute to the decline in cities, including declining industries and the economy, and outmigration to larger cities. Shrinking urban populations could offer retrofitting opportunities (UNEP 2019a), but the challenges for these cities differ in scope and magnitude from rapidly expanding cities.

Sixth, urbanisation in many emerging economies is characterised by informality and an informal economy (Brown and McGranahan 2016). The urban informal economy includes a wide array of activities, including but not limited to street vending, home-based enterprises, unreported income from self-employment, informal commerce, domestic service, waste-picking, urban agriculture. The urban informal economy is large and growing. Globally, about 44% of the urban economy is informal, although there is much variation between countries and regions (ILO 2018). Emerging and developing economies have the highest percentage of urban informal economy, with Africa (76%) and the Arab States (64%) with the largest proportion (ILO 2018). Urban informality also extends to planning, governance and institutions (Roy 2009; EU 2016; Lamson-Hall et al. 2019). Given its prevalence, urban strategies for climate change mitigation, especially in emerging and developing countries, must account for informality.

Unlike nation, there is no internationally agreed upon definition of urban, urban population, or urban area. Countries develop their own definitions of urban, often based a combination of population size or density, and other criteria including the percentage of population not employed in agriculture, the availability of electricity, piped water, or other infrastructures, and characteristics of the built environment such as dwellings and built structures. This chapter assesses urban systems, which includes cities and towns. It uses a similar framework as Chapter 6 of AR6 IPCC WGII, referring to cities and urban settlements as "concentrated human habituation centres that exist along a continuum" (Dodman et al. 2021).

8.1.5 Urbanisation in developing countries

Urbanisation in the 21st century will be dominated by developing countries, and as such it is important to highlight aspects of it that are unique and especially relevant for climate change mitigation. Literature on urbanisation and sustainability in developing countries identifies three common elements. First, urbanisation will increase in speed and magnitude. Given their significant impact on emissions, mitigation action in Asian cities will have significant implications on global ambitions.

Second, a number of cities in developing countries lack institutional, financial and technical capacities to enable local climate change action (Sharifi et al. 2017; Fuhr et al. 2018). While these capacities differ across contexts (Hickmann et al. 2017), several governance challenges are similar across cities (Gouldson et al. 2015). These factors also influence the ability of cities to innovate and effectively implement mitigation action (Nagendra et al. 2018; Chapter 17).

And third, there are sizeable economic benefits in developing country cities that can provide an opportunity to enhance political momentum and institutions (Colenbrander et al. 2016). The co-benefits approach (Section 8.2), which frames climate objectives alongside other development benefits, is increasingly seen as an important concept justifying and driving climate change action in developing countries (Sethi and Puppim de Oliveira 2018).

Transformative action in cities in developing countries may not be realised without effective governance mechanisms resulting in high carbon lock-ins (Gouldson et al. 2015, 2016). While cities are undertaking mitigation and adaptation actions, a nuanced understanding of how climate change mitigation and development objectives interact at different governance levels is still lacking (Beermann et al. 2016; Gouldson et al. 2016; Pathak and Mahadevia 2018; Khosla and Bhardwaj 2019).

Large-scale system transformations are also deeply influenced factors outside governance and institutions such as private interests and power dynamics (Jaglin 2014; Tyfield 2014). In India, adaptation plans involving networks of private actors and mitigation actions have resulted in the dominance of private interests. This has led to trade-offs and adverse impacts on the poor (Chu 2016; Mehta et al. 2019a). Low carbon transitions are rooted in socio-economic context and engaging non-state actors including businesses, research organisations, non-profit organisations and citizens has been emphasised (Lee and Painter 2015). Engaging people in defining locally relevant mitigation targets and actions has enabled successful transformations in China (Engels 2018), Africa (Göpfert et al. 2019) and Malaysia (Ho et al. 2015). An active research and government collaboration through multiple stakeholder interactions in Iskandar, a large economic corridor in Malaysia, has resulted in the development and implementation of a low-carbon blueprint for the region (Ho et al. 2013).

Several of these cities in the global south are underserved with infrastructure and lack adequate housing. An equitable transformation in these cities entails prioritising energy access and infrastructure to meet basic needs of their populations.

8.1.6 Urban carbon footprint

Urban areas concentrate carbon fluxes because of the size of the urban population, the size of the urban economy, and the energy embodied in the goods and services used in cities (USGCRP 2018). Urban areas depend on ecosystems outside of their jurisdictional boundaries – the hinterland – to acquire energy, food, and other resources and also to discharge waste. Urban areas are a net source of both direct and indirect GHG emissions because they consume energy directly and because urban activities drive emissions elsewhere (Churkina 2016).

In cities, carbon cycles through natural (i.e., vegetation and soils) and anthropogenic (e.g., buildings, transportation, humans) pools (Figure 8.4). In addition, the accumulation of carbon in other urban pools such as buildings, results from carbon transfer from either local or global hinterlands from which raw materials are extracted for us in the city. The carbon cycle of a city and its footprint are intimately linked though transfers of construction materials, food, fuels, and waste (Figure 8.4) (Churkina 2008; Pichler et al. 2017; Chen et al. 2020b). Therefore, urban carbon pools and fluxes are closely linked with carbon pools and fluxes of ecosystems in the hinterland and the respective amounts of materials and energy are essential for accurate urban carbon accounting (USGCRP 2018).

Burning fossil fuels to generate energy for buildings, transportation, industry, etc. is the major source of carbon emissions (Gurney et al. 2015). Infrastructures containing cement also uptake carbon through the process of carbonation. The uptake of carbon by urban trees is at least two orders of magnitude faster than by cement containing infrastructures. Accumulation of carbon occurs in urban vegetation, soils, buildings, and landfills.

Urban parks, forests and street trees actively uptake carbon through the process of photosynthesis of green plants (see Section 8.4.4). They become a net source of carbon during heat waves or dormant season. Photosynthesis of urban vegetation is the only significant pathway for carbon uptake within a city. Some of the sequestered carbon is stored in biomass of urban trees and soils (see Section 8.4.4).

Urban mitigation strategies can be divided into two broad categories: reducing urban GHG emissions and enhancing accumulation of carbon in urban pools. This goal to store carbon per each unit of emitted carbon is best illustrated through the urban carbon cycle (USGCRP 2018).

Local government policies can encourage accumulation of carbon in the abovementioned carbon pools through management of urban green areas and encouraging building design with biomass-based materials. Potential carbon accumulation in landfills can be beneficial if it is accompanied by tapping CH_4 and CO_2 emissions for gas or flare although it would still have negative effects on groundwater pollution (Wang et al. 2013).

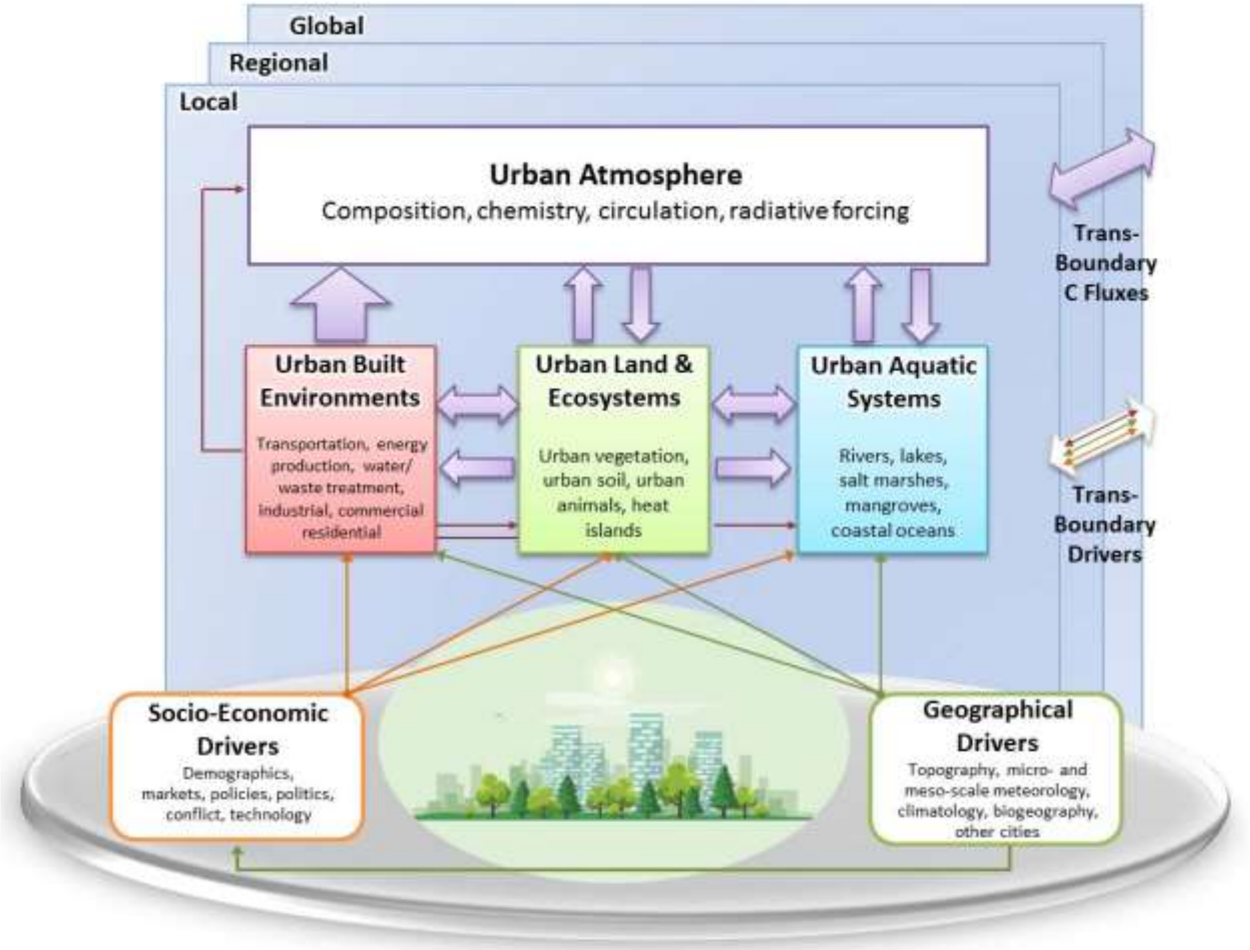


Figure 8.4. Key components of urban carbon cycling. Urban carbon budget schematic showing key urban carbon reservoirs and processes (coloured boxes), carbon emission and removal fluxes (purple block arrows), major drivers (rounded rectangles), and examples of process linkages (coloured thin arrows). Key urban reservoirs include the atmosphere, built environments, land and terrestrial ecosystems, and aquatic systems (including waters and aquatic ecosystems). Examples of key emission and removal processes are given within each box. The outer boxes represent the relationship between the local scale carbon budget of a given city and surrounding region and, ultimately, the globe through transboundary (lateral) carbon fluxes as well as interconnected drivers (socio-economic, geographical, and built systems).
Figure adapted from Hutyra et al. (2014) and Marcotullio et al. (2018) *permission pending*.

8.1.6.1 Urban emissions accounting

Urban GHG accounting is inherently complex. Over the past 15 years, a number of different approaches have emerged to account for urban GHG emissions (Chen et al. 2019; Chavez and Ramaswami 2020). Numerous studies have shown that a vast majority of cities import basic requirements of electricity, natural gas, transportation fuels, as well as water, food and construction materials—produced in powerplants, cement factories, refineries and farms located outside city boundaries, and, generating GHGs in those locations. In addition, carbon is embodied in other goods and services imported/exported from cities. There is also potential for CO_2 emissions to be sequestered in urban trees; urban land expansion can also release carbon stored in forests and agricultural lands that are displaced by impervious surface.

The in- and transboundary GHG flows and stocks can be allocated to different units of analyses, resulting in four broad urban GHG accounting approaches that have emerged over the past two decades (Table 8.1). These broad approaches or methods are: 1) Purely territorial accounting; 2) Communitywide infrastructure supply chain footprinting; 3) Consumption-based footprinting with focus on household consumption; 4) Total supply chain footprinting. While previous efforts have largely sought to position one accounting approach as more/less complete than the other, a recent synthesis review by the Global Carbon Project concludes that: a) No method is both comprehensive and locally-accurate; b) Each method seeks to be complete in the context of its stated purpose; c) The four methods are well-aligned with different policy goals; d) The choice of GHG accounting method must therefore be guided by the policy goal as demonstrated in Table 8.1; adapted from Ramaswami et al. (2020, *submitted*). Each of the four GHG accounting methods also articulates an associated vision of a net zero city, which shown in Table 8.1.

Advances in tracking carbon or GHGs in each method can support the other. For example, novel monitoring methods to directly track territorial fossil fuel CO_2 emissions (e.g., using remote sensing data and field sensors) can improve locally specific emissions factors that will enhance all the other methods. Likewise, improved understanding of spatially granular community wide infrastructure and food supply chains will also inform household supply chains and the total supply chain approaches. Most critically, from a net-zero emissions perspective, efforts to decarbonise community-wide provisioning systems across all cities (i.e., decarbonising energy, mobility-communications, food, building materials, waste, water supply and green infrastructure) will automatically result in decarbonising trade across cities.

The concept of Scopes, borrowed from the WRI GHG protocols for businesses, allow cities to delineate emission computed in each of the methods into “buckets”, separating those emissions directly released within a city’s administrative boundaries (scope 1) from transboundary emissions associated with various activities occurring in that city. Transboundary emissions are categorised into two types: GHG emissions from imported electricity (scope 2), and from other imports broadly (referred to as scope 3). GHG emissions from each method can be classified/allocated into different Scopes as shown in Table 8.1, in a manner consistent with the unit of analysis that each method is focused on. Some scholars have initiated the concept of a fourth Scope, i.e., emissions generated within the city that are exported; others have proposed further binning of emissions into five or more scopes. Such detailed delineation of Scopes can only be accomplished with reliable economic input-output tables for cities that are largely unavailable at high quality across all urban areas of the world. Furthermore, household consumption based GHG accounting using household surveys are not readily mappable to cities in since the location of industries and businesses serving homes are unknown relative to the geography of the city of interest.

The choice of method and delineation of Scopes was previously conflated with which entity is assumed to have control over the emissions, (i.e., in-boundary emissions were assumed to be controlled by cities). However, the past decade has shown that very few carbon mitigation actions can be solely implemented by cities alone; most require multi-level collaboration. Further, city policies rarely control Scope 1 industrial emissions within their jurisdiction, while most city policies can influence mobility and electricity use, both of which shape transboundary power (Scope 2) and fuel supply GHGs. Therefore, focusing first on the policy goal provides important clarity on the choice of accounting methodology, recognising that each method is complete in its stated purpose, and no method is more comprehensive and locally representative.

All approaches are related to, and can inform each other, particularly in efforts to verify reductions in GHG emissions from city-scale cations.

Table 8.1. Policy goals drive choice of urban GHG accounting approaches. Each approach is represented by its unit of analysis with associated accounting tools and example applications, and conceptualisation of net-zero GHG emissions. Adapted from Ramaswami et al. (2020, *submitted*).

Policy goal	**Carbon Accounting Approach**	**Unit of Analysis [& Scopes]**	**Associated Examples of Accounting Tools/Protocols [& Use in Practice]**	**Associated Concept of Net-Zero Carbon Emissions of a city**
Monitor location-specific sources of GHG	***Territorial Approach***: Track direct GHG emission sources; in-boundary only.	Land bounded by administrative boundary. [Scope 1 GHGs only]	Vulcan Data Tool: for territorial fossil fuel use Scope 1 GHGs Practice Example: Very few cities do only Scope 1 accounting (e.g., only 8 cities among 343 in (Nangini et al. 2019). Research studies: (Gurney et al. 2020b).	Net-zero territorial emissions, sources minus sinks (without supply chains)
Inform community-wide integrated urban infrastructure transition planning across "Key sectors*" to advance multiple agendas: Net Zero Carbon City, Resilient City, Healthy City, Smart City, Nature based solutions etc.	***Communitywide Infrastructure supply chain footprinting:*** *In-boundary plus Transboundary supply chain GHGs* of key provisioning sectors* to the whole community (consumers and all producers): supply of energy, mobility, buildings, water, waste/sewage management, green infrastructure and food systems. Includes changes in biogenic C from land/green infrastructure.	Community-wide provisioning key sectors. [Scope 1 + Scope 2 (GHG imported electricity); + Scope 3 (GHGs in supply chains of other provisioning sectors)]	Scope 1 & 2 Tools: ICLEI USA Protocol (27 cities from (Nangini et al. 2019)). GPC Basic (Scopes 1+2+3): Buildings, energy, mobility & Waste (73 cities among 350 in (Nangini et al. 2019). GPC Basic+ & ICLEI-USA Advanced (Scopes 1+2+3): All seven provisioning systems (> 20 US cities in (Hillman and Ramaswami 2010); and additional cities in Australia, China, and India) Research studies: (Baynes et al. 2011; Kennedy et al. 2014; Chavez and Ramaswami 2020)	Net-zero carbon community-wide infrastructure and food provisioning systems** (including nexus interactions and supply chains)
Mitigate household carbon footprint analysing all consumer expenditures	***Consumption-based carbon footprint***: Tracks in- plus transboundary GHGs linking production-to-final consumption	Household expenses and household fuel combustion in a boundary #.	Tool: Cool climate calculator Research Studies: (Jones and Kammen 2014; Moran et al. 2018a).	Net-zero carbon household expenditures

beyond those for key provisioning systems	only by homes; excludes exporting businesses in a city)	[Scopes not easily mapped to city boundaries##]		
Global Carbon Governance with Local-to-Global Trade Linkages	***Total Supply Chain Foot-printing*** (Transboundary; links production-to-consumption and exports; all sectors)	All imports and exports to homes, businesses and industry in a boundary [Same as Method 2, with all transboundary GHGs linked with all supply chains included as Scope 3.]	<u>Example</u>: Research study of 79 C40 cities (Wiedmann et al. 2020)	Net-zero carbon trade

*: Eight infrastructure provisioning sectors account for >90% of global GHGs; excluding only de-forestation and industrial processes for chemicals & petrochemicals production

**: Decarbonising the key physical provisioning systems will result in decarbonised trade.

#: Where input-output tables are used, final consumption by government and business capital expenses (e.g., construction expenditures) can also be computed.

8.1.6.2 Urban emissions measurement and estimation

New research since AR5 has continued to establish the importance of urban areas to total global GHG emissions and the differing proportions throughout the world. Work by Moran et al. (2018a) found that 68% of the global carbon footprint (CF) was attributable to urban areas in 2015 based on downscaling from national CF estimates (Figure 8.5).

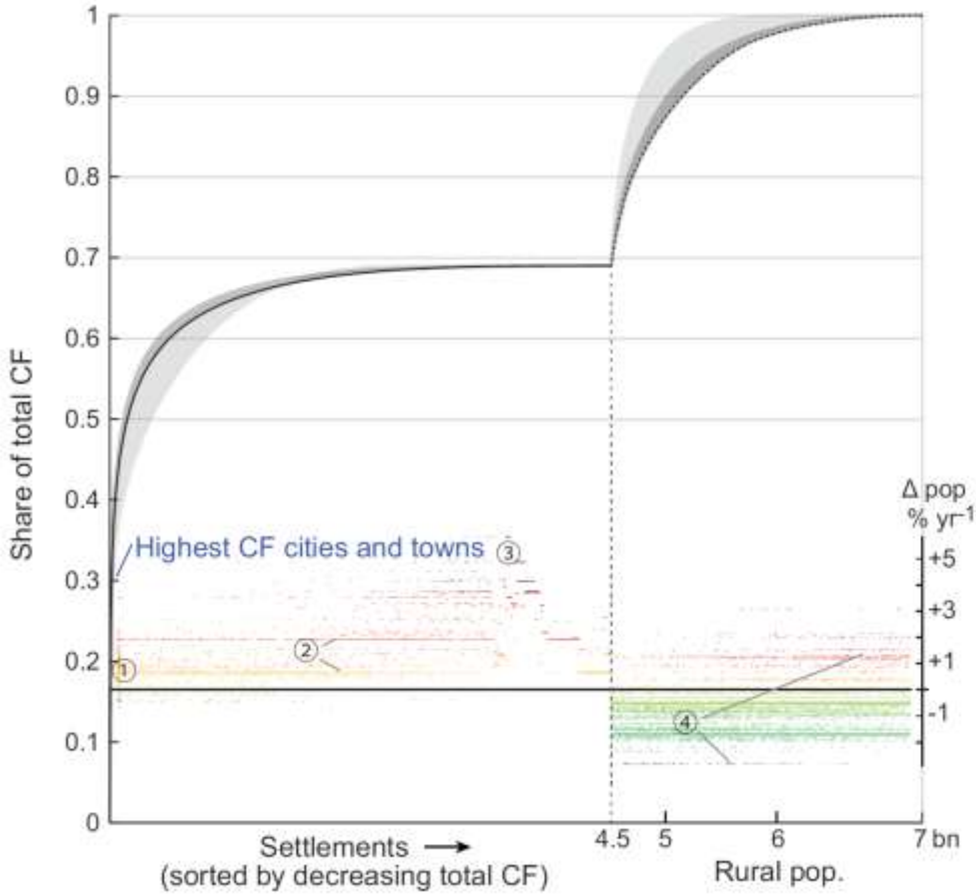


Figure 8.5. Urban share of total CF.
Figure from Moran et al. (2018a). *Permission Pending.*

Regional estimates have found similarly large proportions. For example, Wiedenhofer et al. (2017) found that the 2012 urban household CF in China accounted for 75% of national CF while Feng and Hubacek (2016) indicate that urban residents account for "more than three-quarters of the total household consumption-related CO_2 emissions" (p. 41). In the US, Jones and Kammen (2014) estimated that the CF of urban areas ("metropolitan statistical areas") accounted for 80% of the national CF in the year 2007. Also in the US, Gurney et al. (2020b) explored the urban share of CO_2 emissions as a function of the assumed urban boundary and the definition of emissions accounting scope. Using the "urbanised area" definition (most closely aligned with metropolitan areas) the direct territorial emissions accounted for 45% in 2011, which increases to 55% when including scope 2 emissions. However, the share of the total territorial emissions increases to 87% of the national total when using a more expansive definition of the urban boundary which include all settlements economically linked to a central urban area (Gurney et al. 2020b). These results are consistent with the AR5 estimate of urban share but highlight the importance of the urban boundary definitions and accounting scope in understanding the role of urban areas within global GHG emissions.

The approaches taken to quantifying urban emissions have similarly expanded rapidly in the last decade. Distinct from the accounting framework used to conceptualise an urban GHG budget, the methods used to quantify urban carbon fluxes, and thereby evaluate policy outcomes and emission trends, can be classified into two measurement approaches or perspectives: top-down and bottom-up.

“Top-down” approaches evaluate or infer fluxes from observations based in the atmosphere. When coupled to atmospheric transport modelling algorithms, the top-down approach can perform an atmospheric inversion, inferring fluxes from concentration measurements given assumed transport by the atmosphere (Breón et al. 2015; McKain et al. 2015; Feng et al. 2016; Lauvaux et al. 2016; Sargent et al. 2018). However, atmospheric measurements can be used to infer fluxes in alternative ways via simple mass balance calculations or via tracer ratio procedures (Cambaliza et al. 2014; Moore and Jacobson 2015; Turnbull et al. 2015).

“Bottom-up” approaches, by contrast, include a mixture of direct flux measurement, indirect estimation, and modelling. For example, a common estimation method uses a combination of socioeconomic activity data (e.g., population, number of vehicles, and building floor area) and associated emissions factors (e.g., amount of GHG emitted per activity), socioeconomic regression modelling, or scaling from aggregate fuel consumption (Jones and Kammen 2014; Pincetl et al. 2014; Porse et al. 2016; Shan et al. 2017). Direct end-of-pipe flux monitoring often is used for large facility-scale emitters such as power plants (Gurney et al. 2016). Indirect fluxes, as often represented in consumption-based accounting frameworks, can be estimated through either direct atmospheric measurement (and apportioned to the domain of interest) or modelled through process-based models (Clark and Chester 2017) or economic input-output models (Mi et al. 2016; Pichler et al. 2017; Moran et al. 2018a).

Despite the growth in research on urban emissions measurement, significant gaps remain in standardisation, comprehensiveness, timeliness, and practical application (see Section 8.7.3).

Cross-Working Group Box in WGII and Cross-Working Group Box 2 in WGIII

Cross Working Group Box 2: Climate Change and Urban Areas

Bronwyn Hayward (New Zealand), David Dodman (Jamaica/United Kingdom), Shuaib Lwasa (Uganda), Mark Pelling (United Kingdom), Karen Seto (the United States of America), Xuemei Bai (Australia), Vanesa Castán Broto (United Kingdom/Spain), Winston Chow (Singapore), Felix Creutzig (Germany), Rafiq Hamdi (Belgium), Şiir Kılkış (Turkey), Timon McPhearson (the United States of America), Minal Pathak (India), Diana Reckien (the Netherlands/Germany), Ayyoob Sharifi (Iran/Japan), Peter Newman (Australia), Paolo Bertoldi (Italy), Diána Ürge-Vorsatz (Hungary)

A cross-Working Group Box on climate change and urban areas appears in Chapter 8 of Working Group III and Chapter 6 of Working Group II. These boxes convey the same core messages- the global urgency, the real opportunity for rapid decarbonisation and climate risk reduction in urban contexts. Although the content and emphasis of the two boxes differs, both build on the IPCC Special Report on Global Warming of 1.5°C, and indicate potential approaches that will enable the Paris Agreement objectives and Sustainable Development Goals to be met.

Three key points are particularly important: the urgency for climate action in cities; cities as catalysts for cascading risks and carbon lock-ins; and the role of governance and finance to enable inclusive, urgent and systemic action.

i) The Need for Urgency

Responding to climate change in cities and urban systems by decarbonising and reducing risk to residents and infrastructure is urgent (Wilson and Orlove, 2019). What happens in urban areas – both as they are, and as they will develop in coming decades – is highly significant to achieving the Paris Climate Agreement. Cities currently are estimated to be the sites of 45-87% of direct carbon emissions depending on accounting methods and approximately 68% of the global carbon footprint in 2015 (WGIII Chapter 8 ES).

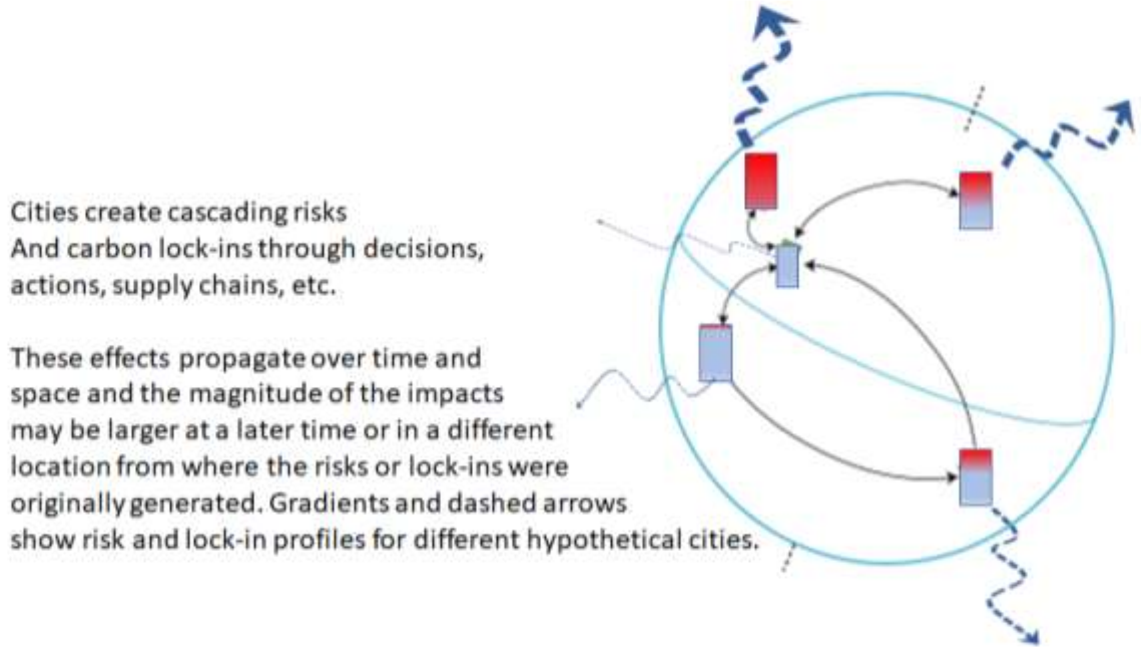
The urban share of global emissions is projected to increase significantly in the coming decades due to the scale and speed of urbanisation and the new infrastructure necessary to accommodate this new growth (Gurney et al., 2020; WGIII Ch 8 ES, n.d.). Every five days, the urban population increases by about 1 million (UN DESA, 2019) and urban areas will expand by about 100 km^2 every day through 2050 (Huang et al., 2019). The growth of urban areas will necessitate the construction of buildings and roads, water and sanitation facilities, energy and transport systems that will be energy and emissions intensive in both their construction and operation, unless major changes are made in how these are designed and implemented (Swilling et al., 2018). How and where new urban areas will be developed will lock-in place patterns of energy consumption and behaviour, deepening inequalities and path dependencies that are difficult to change once in place (Erickson and Tempest, 2015; Ürge-Vorsatz et al., 2018). Thus, while there is a need to develop climate actions for existing cities, there is an equally urgent need to ensure that newly built cities and expanded urban areas are climate neutral and have low climate change vulnerability and exposure.

The urgency to act is not only due to impending and growing urban areas and resulting emissions but also due to the growing climate risk to urban populations, infrastructure and economies. Recent estimates suggest 1.6 billion people will be regularly exposed to extreme high temperatures by 2050; an additional 800 million will be vulnerable to sea-level rise and coastal flooding; 650 million will be at risk of water shortages (C40 and UCCRN, 2018). Under SSP1-2.6 and SSP5-8.5, respectively, by end-of-century, exposure of urban population to deadly heat will increase from 600 million to 3-4.75 billion and extreme rainfall will increase 564 million to 2.9-5 billion. Nearly 20% of power generation globally lies at risk in 0-5m Low Elevation Coastal zones (LECZ) and projections show severe disruption and risk to urban transportation, human mobility, social and health infrastructures and economies particularly in the Global South (McPhearson et al. submitted).

Action in the Global South is particularly urgent. It is here that urban growth is most rapid and that transformative climate action can have some of the most far-reaching impact and significant co-benefits for sustainable development (Bai et al., 2018; Sotto et al., 2019). Half of the projected urban population growth through 2050 will occur in just eight countries, seven of which are Developing Countries or Emerging Economies (UN DESA, 2019). Half of the world's urban population in 2050 will live in regions with urban expansion-induced warming of 0.5 °C–0.7 °C, up to~3 °C (Huang et al., 2019). Any actions that are taken also need to keep in mind the potential for unintended consequences of mitigation and adaptation actions that may exacerbate inequality and reduce the capacity of urban populations to respond to the increasing frequency of climate-related disasters (Keenan et al., 2018; Shokry et al., 2020).

ii) Cities as Catalysts for Cascading Risks and Carbon Lock-Ins

Cities and urban regions extend their influence deep into rural places, oceans and the atmosphere. Climate change impacts and action can cascade across these connected places. As climate impacts and opportunities for risk and carbon reduction spread they can also concentrate. The result is that urban places become catalysts for the emergence of, as well as the concentration of, climate change impacts, risks and opportunities for risk reduction and deep decarbonisation (Pescaroli and Alexander, 2018). The resulting geographical distribution of costs, benefits and opportunity is uneven with social justice consequences. Common to all though is the recognition that for climate change adaptation, mitigation and loss and damage, cities do not function alone. This is the interconnected and truly global promise that cities bring to climate change.



Cities create cascading risks
And carbon lock-ins through decisions, actions, supply chains, etc.

These effects propagate over time and space and the magnitude of the impacts may be larger at a later time or in a different location from where the risks or lock-ins were originally generated. Gradients and dashed arrows show risk and lock-in profiles for different hypothetical cities.

Figure CWGB CCUA.1: Cities, cascading risks, and carbon lock-ins

While city planning and administration is place-based, risk and mitigation require cross-site and cross-scale action. Repurposing urban planning and management to achieve deep decarbonisation, or risk reduction cannot easily be achieved by only focusing on reducing emissions or risk within administrative boundaries (WGIII Ch 8 ES). The interconnection of cities and public and private sector supply chains creates conditions of cascading novel risks and carbon lock-in that require innovative governance responses such as through empowering and raising the profile of local and urban policies in national decision-making process and knowledge networks linking municipalities (Binder and Massaro, 2020).

The extension of observed climate risk and loss from individual places and events to cascading climate change impacts is an outcome of the challenge faced by interconnected infrastructure trying to keep pace with growing urban populations and an intensification of climate change associated hazards. This can lead to apparently localised events having much wider impact - for example where flooding damages power generation or transmission systems with potentially city-wide consequences for business, social and health sectors. Recent research shows that the impacts of climate hazards propagate across cities around the world, and that indirect impacts can be larger than the site of the direct impact (Shughrue et al., 2020). Urban centres are especially catalytic of cascading losses where local closures (e.g. airports, ports, etc.) can have global or regional consequences for trade or supply chains with knock-on consequences for urban food security and livelihoods. This underscores that no city is resilient to climate change until all cities are resilient. Lower capacity, often smaller urban centres and those with higher proportions of informal settlements have less extensive connectivity but also less capacity to maintain and manage systemic risk especially when facing rapid population growth as in many small and medium sized centres in Asia and Africa. This can serve to concentrate and localise risk, loss and opportunity (Paterson et al., 2017).

COVID-19 has made very visible many of the processes and outcomes of cascades. Climate change brings a global, unrelenting if more slowly building set pressures, any of which could set-off rapidly cascading and multiplying economic and social impacts. COVID-19 has also shown the depth of inequality and vulnerability that has been allowed to accumulate in urban settlements through locked-in policy processes and market institutions (for example in overcrowded and underserviced living conditions). These vulnerabilities lie at the heart of climate change risk - and point to opportunities for interventions at reducing multiple risks - pandemic, climate, public health and poverty. The interconnectedness of cities and their catalysing possibility then offers global opportunities for building resilience with multiple benefits through targeted action that can break locked-in processes of risk accumulation.

iii) Governance and Finance as Enabling Conditions for Urban Climate Action

Effective multilevel governance is more likely to enable rapid and inclusive systemic change for climate action when there is institutional capacity, political will and local agency, frameworks for inclusion of residents' views, supportive national and federal policies, rapid transfer of knowledge and access to finance to meet the urgent needs of cities (Koop et al 2017, IPCC SR 1.5). Attention to human rights, inclusion, oversight, monitoring and evaluation may address the potential for maladaptation and equity trade-off risks inherent in urgent action (Hulme 2019; Maddon 2019).

Working at speed and scale cannot dislodge sustainability, inclusion and accountability. These safeguards can draw on a burgeoning experience of urban resilience planning and action across many urban contexts. Such safeguards are central to maintaining the link between urgent climate action and the core aim of the Sustainable Development Goals that no-one be left behind, and of the Sendai Framework that risk is responded to by Building Back Better.

Mitigation and adaptation policies share many drivers so that accelerated solutions can be codesigned and delivered in synergy with ongoing development priorities (Rosenzweig et al 2018). Synergies can be strengthened and trade-offs managed by political leadership which acts on science and involves and engage communities from the bottom up in planning and implementing broad-scale, holistic and proactive climate risk and mitigation strategies (Palermo and Hernandez, 2020). Governance of urban-scale digitalisation will be an important enabler, or potential barrier, of municipal climate action (see digitalisation box in Ch 16, WGIII) and requires coordination between municipal climate and digitalisation services. There is a role for new, inclusive decision making institutions (Becker et al 2020; Broto 2017) and for national and international support and collaboration, such as the sharing of expertise and opportunities for continuing community learning within and between cities and urban regions (Morrison et al 2019, Melica et al, 2016). Transnational cities networks such as the Global Covenant of Mayors, C40, ICLEI, etc. offer a platform for sharing expertise, promoting multilevel governance and raising the profile of urban climate action in international fora (Domorenok, 2019).

Finance is needed to support the rapid catch-up of exposed, vulnerable and carbon intensive existing settlements, as well as for investing and constructing the new urban places needed to meet growing urban populations. Financing systemic city responses to climate presents challenges at multiple levels from funding informal and neighbourhood actions to investing in urban regional infrastructure and insuring geographically cross-cutting supply chains and underlying materials manufacturing. This requires novel financing mechanisms to reach diverse actors from low income communities to national agencies and private sector enterprises. Current finance is unevenly spread. Large and complex infrastructure projects for decarbonisation are often beyond the capacity of local municipal budgets. To fill the funding gap in urban areas, cities play a pivotal role in debt financing for a range of low-carbon infrastructure projects and related spatial planning programs. Smaller cities, informal settlements and small and medium sized enterprises find it most difficult to access finance that can enhance inclusive urgent and systemic action – even where plans are in place.

iv) Knowledge gaps

While there are opportunities associated with urban systems as a framing for emissions reduction and adaptation, below is list of knowledge gaps in regard to how urban systems can be characterised for climate action on one hand and the policy understanding of how urban systems can be represented.

- Understanding urban systems and accounting for the interconnections, systemic risk creation, embodied emissions and transfer of urban development infrastructure technologies in different geographies.
- How climate mitigation and adaptation actions can be integrated through urban planning and design (Kavonic and Harriet Bulkeley, *in press*)
- Urban systems pathways for transformation and assessment of mitigation and adaptation action (Estrada et al. 2021, *in press*; Tozer et al. 2021, *in press*).
- Potential of accumulated impact of multiple locally implemented actions and the informal sector in the Global South - and scaling up of these actions (Prieur-Richard et al. 2018).
- How governance systems can be transformative to create an enabling environment for innovation through multilevel governance for city-regions in the context of sustainable development.
- Down-scaled models of global warming and climate risks at the city-level.

8.2 Co-benefits of urban mitigation

Co-benefits are "the positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits to the society or environment" (IPCC 2018b, p. 546). Co-benefits occur when implementing mitigation (adaptation) measures that have positive effects on adaptation (mitigation) (Sharifi 2021). In contrast, the trade-offs emerge when measures aimed at improving mitigation (adaptation) undermine the ability to pursue adaptation (mitigation) targets (Sharifi 2020). The magnitude of such co-benefits and trade-offs may vary depending on various factors such as the type of mitigation measure and the scale of implementation.

AR5 reported a range of co-benefits associated with urban climate change mitigation strategies including public savings, air quality and associated health benefits, and productivity increases in urban centres (Seto et al. 2014). Since AR5, evidence continues to grow on the co-benefits of urban mitigation. In developing countries, a co-benefits approach that frames climate objectives alongside other development benefits is increasingly seen as an important concept justifying and driving climate change action in developing countries (Sethi and Puppim de Oliveira 2018). The following section discusses co-benefits of urban mitigation actions on adaptation and other sustainable development dimensions.

Communication of co-benefits could make a strong case for driving strong mitigation action where traditional methods have not succeeded (Bain et al. 2016) and it is possible to build win-win solutions through a combination of policies (Viguié and Hallegatte 2012). Methodologies for interactions of mitigation actions and their co-benefits for cities were reported by Solecki et al. (2015), Buonocore et al. (2016), Chang et al. (2017), and Helgenberger and Jänicke (2017). Figures 8.6 and 8.7 illustrate some of these interactions.

In addition, a systematic review of over 50 climate change articles by Sharifi (2019) emphasised mitigation contributing to resilience – especially to temperature changes and flooding – with varying magnitudes depending on factors such as type of mitigation measure and the scale of implementation. Categories that emerged with the most frequency include increasing density, improving urban design and land use planning, transportation, building, waste, energy, water, and NBS. As illustrated in the

Figure 8.6, several mitigation measures can deliver medium to high co-benefits of air quality, adaptation, green jobs and health while there is limited literature on equity. Based on the synthesis, there is *high agreement and medium confidence* on co-benefits delivery of mitigation measures at urban scale.

Intervention	Mitgation/Adaptation	Impacts: Air Quality	Green Jobs	Health	Equtiy
Passive building design	Mitigation H	H	L	H	
Enhance building energy efficiency (i.e., home appliances, light bulbs, etc.)	Mitigation H		M	H	
Distribution and decentralization of energy systems (district cooling and heating, CHP plants, microgrids, etc.)	Mitigation H		M	M	L
Decarbonization of the energy sector/low carbon energy sources	Mitigation H	M	M	M	
Urban agriculture and local food production	Both L	M		M	M
Dietary changes	Both L			M	
Green roof, roof garden, reen façade and green walls	Both M	M	M	H	
Network of parks, urban greenery and open spaces	Both H	M		H	
Urban nature protection (forests, green belt, protection of natural habitats, Wetlands and water bodies , etc.)	Both M	M		H	
Water-sensitive urban design (permeable surfaces, bioswales, etc.)	Both M				
Promotion of public transport and Non-Motorised Transport (NMT)	Mitigation H	M	M	H	M
Shared Mobility	Mitigation M	M	M	M	M
Electrification of urban transportation (Electric Vehciles)	Mitigation H	M	M	M	
Compactness (Appropriate levels of density)	Mitigation H	H	M	M	L

Insufficient Evidence

The colour describes the postive impact intensity of the intervention/policy measures. Darker the colour higher the impact.

H,M, L — Letter in the box indicates confidence level (H = High; M = Medium and L = Low Confidence)

Figure 8.6. Co-benefits of Urban Mitigation Actions. The first column lists urban mitigation options. The second column shows whether this influences mitigation, adaptation, or both. The subsequent columns indicate the impacts on each of the selected development objectives. Shades of colour indicate the intensity of impacts of the proposed intervention, dark blue representing high impact and light blue indicating low impact. The letters in boxes indicate confidence of the assessment findings.

8.2.1 Sustainable Development

Sustainable development is a wide concept, encompassing socioeconomic and environmental dimensions, envisaging long-term permanence and improvement. Whilst long-term effects are more related to resilience – and hence co-benefits and synergies with the mitigation of GHG emissions – some short-term milestones were defined by the post-2015 UN Sustainable Development Agenda SDGs, including a specific goal on climate change (SDG 13) and another urban goal (SDG 11) – "to make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations 2015, p. 14). Many of these interactions are discussed in this section. Klopp and Petretta (2017), Kutty et al. (2020), and Simon et al. (2016) discuss the use of SDGs and related indicators as a tool for improving cities, science-based decision-making, open and comparable data collected at local scales, inclusion of diverse voices and actors, and context-specific goals.

Evidence on the co-benefits of urban mitigation measures on human health has increased significantly since AR5, especially through the use of health impact assessments where energy savings and cleaner energy supply structures based on measures for urban planning, heating, and transport have reduced CO_2, nitrogen oxides (NO_x), and coarse particulate matter (PM10) emissions and increased opportunities for physical activity for improved health (Diallo et al. 2016). In developing countries, the co-benefits approach has been effective in justifying climate change mitigation actions at the local level (Puppim de Oliveira and Doll 2016).

There is increasing evidence that climate mitigation measures can lower health risks that are related to energy poverty, especially among vulnerable groups, such as the elderly and in informal settlements (Monforti-Ferrario et al. 2018). Measures such as renewable energy-based electrification of the energy system not only reduce outdoor air pollution, but also enhance indoor air quality through promoting smoke-free heating and cooking in buildings (Kjellstrom and McMichael 2013). The environmental and ecological benefits of electrification of the urban energy system include those on air quality based on a shift to non-polluting energy sources (Jacobson et al. 2018; Ajanovic and Haas 2019; Bagheri et al. 2019; Gai et al. 2020) including an estimated 408,270 lives per year being saved due to air quality improvements given a move to 100% renewable energy in 74 metropolitan areas around the world (Jacobson et al. 2020). Other studies indicate possibilities to reduce premature mortality by up to 7,000 people in 53 towns and cities with 93,000 net new jobs and lower global climate costs and personal energy costs based on roadmaps for renewable energy transformations (Jacobson et al. 2018).

The co-benefits of energy saving measures in 146 signatories of a city climate network due to improved air quality are quantified as 6,596 avoided premature deaths (with a 95% confidence interval of 4,356–8,572 avoided premature deaths) and 68,476 years of life saved (with a 95% confidence interval of 45,403–89,358 years of life saved) (Monforti-Ferrario et al. 2018). Better air quality further reinforces the health co-benefits of climate mitigation measures based on walking and bicycling since evidence suggests that increased physical activity in urban outdoor settings with low levels of black carbon improves lung function (Laeremans et al. 2018). Physical activity can also be fostered through urban design measures and policies that promote the development of ample and well-connected parks and open spaces, and can lead to physical and mental health benefits (Kabisch et al. 2016).

Results from cities in India, Indonesia, Vietnam, Kathmandu, and Thailand show that reducing emissions from major sources (e.g., transport, residential burning, biomass open burning and industry) could bring substantial co-benefits of avoided deaths from reduced PM2.5 (fine inhalable particulates) emissions and radiative forcing from black carbon (Pathak and Shukla 2016; Dhar et al. 2017; Permadi et al. 2017; Karlsson et al. 2020), reduced noise, and reduced traffic injuries (Kwan and Hashim 2016). Compact city policies and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emission public transport delivers significant public health benefits (Creutzig 2016; Ürge-Vorsatz et al. 2018). Trade-offs include the marginal health costs of transport air pollution (Lohrey and Creutzig 2016) and stress from traffic noise (Gruebner et al. 2017).

Urban forestry and green infrastructure such as NBS act as both climate mitigation and adaptation measures by reducing heat stress (Kim and Coseo 2018; Privitera and La Rosa 2018), improving air quality, reducing noise (Scholz et al. 2018; De la Sota et al. 2019), improving urban biodiversity (Hall et al. 2017a), and enhancing wellbeing, including contributions to local development (Lwasa et al. 2015). Health benefits from urban forestry and green infrastructure include reduced cardiovascular morbidity, improved mental health (van den Bosch and Ode Sang 2017; Vujcic et al. 2017), higher birth weight (Dzhambov et al. 2014), and increased life expectancy (Jonker et al. 2014). Urban agriculture, including urban orchards, roof-top gardens, and vertical farming contribute to enhancing food security and fostering healthier diets (Cole et al. 2018; Petit-Boix and Apul 2018; De la Sota et al. 2019). See Section 8.4.4 on NBS for a longer discussion.

8.2.2 Economic development, competitiveness, and equity

Sustainable management of urban ecosystems entail addressing economic growth, equity, and good governance. Many of these aspects are covered in the previous and forthcoming sections. Maes et al. (2019) identified 102 targets (99 synergies and 51 trade-offs) with published evidence of relationships with urban ecosystems – out of the 169 in the 2030 Agenda. The targets require action in relation to urban ecosystem management, in terms of environmental improvements, equality related to basic services, long-term economic growth, stronger governance, and policy development at multiple scales.

Policy interventions could also result in negative impacts or trade-offs with other objectives (Viguié and Hallegatte 2012; Sharifi 2020). Anti-sprawl policies that aim to increase density or introduction of large green areas in cities could increase property prices resulting in trade-offs with affordable housing and push urban poor further away from cities (Reckien et al. 2017; Alves et al. 2019).

Analysing 100 US communities over 12 years, Rousseau et al. (2019) explored the contribution of local environmental non-profit organisations to sustainable cities, and Juraschek et al. (2018) analysed the potentials and impact levels of urban factories to promote the SDGs in cities. Although sizeable economic benefits from mitigation actions in developing country cities can enhance political momentum and institutions (Colenbrander et al. 2016), these may not be realised without effective governance mechanisms, resulting in high carbon lock-ins (Gouldson et al. 2015, 2016).

Mitigation measures related to different sectors can provide co-benefits and reduce social inequities. Transport-related measures such as transportation demand management, transit-oriented development, and promotion of active transport modes provide economic co-benefits through, for example, reducing healthcare costs linked with pollution and cardiovascular diseases, improving labour productivity, and decreasing congestion costs. As a case in point, data from cities such as Bangkok, Kuala Lumpur, Jakarta, Manila, Beijing, Mexico City, Dakar, and Buenos Aires indicate that economic costs of congestion account for a considerable share of their GDP (ranging from 0.7% to 15.0%) (Dulal 2017). Safe public and non-motorised transport facilities contribute to fostering accessibility and equity among different social groups, which can improve access of low income populations to jobs and gender responsive transport systems that can enhance women's mobility and financial independence (Viguié and Hallegatte 2012; Lecompte and Juan Pablo 2017; Reckien et al. 2017; Priya Uteng and Turner 2019).

Green infrastructure can also offer considerable economic co-benefits. For example, green roofs and facades and other urban greening efforts can improve microclimatic conditions and enhance thermal comfort, thereby reducing utility and healthcare costs. The presence of green infrastructure in the vicinity of properties may increase their economic value (Votsis 2017; Alves et al. 2019). Studies in the UK show beneficiaries willing to pay (WTP) an additional GBP 1.4 to GBP 10.5 and the WTP varies depending on the size and nature of the green space (Mell et al. 2013, 2016). This could also result in trade-offs as housing prices increase and push out poorer residents from inner areas to the periphery. Other measures such as urban agriculture not only reduce household food expenditure, but provide additional sources of revenue (Ayerakwa 2017; Alves et al. 2019). Based on the assessed literature, there is high agreement but low evidence of economic co-benefit of green infrastructure.

Additional sources of income for citizens and local authorities can also be provided through implementing waste management and wastewater recycling measures. Wastewater recycling can minimise the costs linked with renewal of centralised wastewater treatment plants. Waste management and wastewater recycling is also a pathway for inclusion of the informal sector into the urban economy with high agreement and medium evidence. Additionally, authorities can sell energy generated from wastewater recycling to compensate for the wastewater management costs (Colenbrander et al. 2017;

Gondhalekar and Ramsauer 2017). Another measure that contributes to reducing household costs is promotion of behavioural measures such as dietary changes that can decrease the demand for costly food sources and reducing healthcare costs through promoting healthy diet (Hoppe et al. 2016) (see Sections 8.3.3 and 8.4 on behavioural aspects of urban mitigation).

In addition to cost savings, various measures such as stormwater management and urban greening can enhance social equity and environmental justice. For example, the thermal comfort benefits provided by green infrastructure and passive design measures can address issues related to energy poverty and unaffordability of expensive air conditioning systems for some social groups (Sharma et al. 2018; He et al. 2019). Another example is the flood mitigation benefits of stormwater management measures that can reduce impacts on urban poor who often reside in flood-prone and low-lying areas of cities (Adegun 2017; He et al. 2019). Generally, the urban poor are expected to be disproportionately affected by climate change impacts and any measures that reduce such disproportionate impacts would enhance social equity (Pandey et al. 2018; He et al. 2019).

Low-carbon urban development that triggers economic decoupling can have a positive impact on employment and local competitiveness (Dodman 2009; Kalmykova et al. 2015; Chen et al. 2018b; García-Gusano et al. 2018; Hu et al. 2018; Shen et al. 2018). Sustainable and low-carbon urban development that integrates issues of equity, inclusivity, and affordability while safeguarding urban livelihoods, providing access to basic services, lowering energy bills, addressing energy poverty, and improving public health can also improve the distributional effects of existing and future urbanisation (Friend et al. 2016; Claude et al. 2017; Colenbrander et al. 2017; Ma et al. 2018; Mrówczyńska et al. 2018; Pukšec et al. 2018; Wiktorowicz et al. 2018; Ramaswami 2020).

8.2.3 Coupling mitigation and adaptation

Simultaneous integration of adaptation and mitigation into climate action plans is essential for taking account of their interactions.

Measures related to different sectors can provide both mitigation and adaptation benefits as shown in Figure 8.7. These measures are divided into nine categories, namely: behavioural issues, building, energy, green infrastructure, transportation, urban governance, urban planning, waste, and water. In addition to their energy-saving and carbon-sequestration benefits, many measures can also enhance adaptation to climate threats such as extreme heat, energy shocks, floods, and droughts (Sharifi 2021).

As for trade-offs, some mitigation efforts may increase exposure to stressors such as flooding and the urban heat island (UHI) effect, thereby reducing the adaptive capacity of citizens. For instance, high-density areas that lack adequate provision of green and open spaces may intensify the UHI effect (Pierer and Creutzig 2019; Xu et al. 2019). There are also concerns that some mitigation efforts may diminish adaptive capacity of urban poor and marginalised groups through increasing costs of urban services and/or eroding livelihood options. For instance, environmental policies designed to meet mitigation targets through phasing out old vehicles may erode livelihood options of poor households, thereby decreasing their adaptive capacity (Colenbrander et al. 2017). Ambitious mitigation and adaptation plans could benefit private interests resulting in adverse effects on the urban poor (Chu et al. 2016; Mehta et al. 2019b).

NBS such as urban trees and greenspaces can sequester carbon and reduce energy demand, provide adaptation co-benefits by mitigating the UHI effect (see Section 8.4.4) (Berry et al. 2015; Wamsler and Pauleit 2016; WCRP 2019).

Considering these multiple interactions between mitigation and adaptation measures, it is essential to take integrated approaches that can provide insights on how to maximise co-benefits and minimise trade-offs. Some preliminary efforts have been made to develop optimised scenarios using Urban Integrated Assessment Frameworks (UIAFs) (Ford et al. 2018; Caparros-Midwood et al. 2019). There are also some scenario-based studies that demonstrate how simultaneous consideration of adaptation and mitigation can effectively reduce GHG emissions, minimise exposure to flood risk, and reduce the UHI intensity (Viguié and Hallegatte 2012; Xu et al. 2019).

Measures aimed at climate change mitigation (as well as those aimed at both mitigation and adaptation) contribute to resilience against various climate change impacts, especially to temperature changes and flooding. The magnitude of such benefits and trade-offs may vary depending on various factors such as the type of mitigation measure and the scale of implementation.

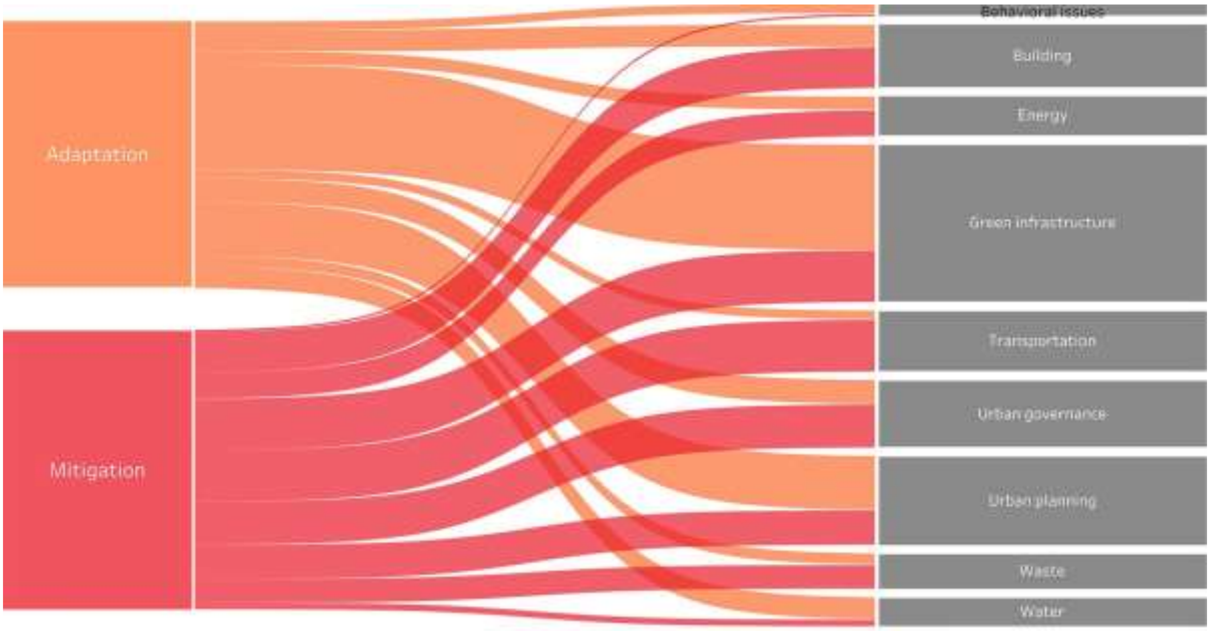


Figure 8.7. Urban sectors and their links to mitigation and adaptation benefits. A review of 56 studies shows that various urban planning and design measures across different categories can provide both mitigation and adaptation benefits. Measures related to some categories such as transportation, building, waste, and energy are primarily aimed at urban climate change mitigation. However, they can also offer adaptation benefits and enhance urban resilience. For instance, improvement of vehicle efficiency standards not only reduces emissions, but also enables better adaptation to energy shocks. Similarly, renewable-based distributed and decentralised energy systems improve resilience to energy shocks and considering the water-energy nexus may also enhance adaptation to water stress. There are also some categories that their primary focus is adaptation but can also offer mitigation co-benefits. For instance, in addition to adaptation benefits such as stormwater management and thermal comfort provision, urban green infrastructure measures provide mitigation co-benefits such through carbon sequestration and reduction of cooling energy demand. The review demonstrates that existing evidence is mainly related to certain categories such as urban green infrastructure, urban planning, transportation, and buildings. Specifically, there has been more emphasis on the potential co-benefits of measures such as proper levels of density, building energy efficiency, distributed and decentralised energy infrastructure, green roofs and facades, and public/active transport modes. By further investment on these measures, planners and decision makers can ensure enhancing achievement of mitigation/adaptation co-benefits at the urban level.

Figure from Sharifi (2021, p. 9).

8.3 Urban systems and GHG emissions

Urban systems are fundamentally open systems. Therefore, they can lower their local emissions while helping lower emissions outside of their administrative boundaries through their use of materials and resources. As a complex system, cities can increase the efficiency of infrastructure and energy use beyond what is possible with individual sectoral components. This section assesses the mitigation potential of urban systems by taking a whole systems perspective, incorporating urban metabolism and the flows of resources and energy.

8.3.1 Trends in urban land use and the built environment

Urban areas are expanding to accommodate a growing urban population. Urban land use is one of the most intensive human impacts on the planet. Urban land areas compete with agriculture and forests for land across the world, fragmenting ecosystems, reducing biodiversity, and creating mosaics of urban land use with patched nature areas and built-up areas, while in some areas new cities are created in unprecedented ways in open water bodies and deserts that have implications for GHG emissions and lock-in effects (Güneralp et al. 2017a).

Density, physical infrastructure, and other city-form patterns are factors that determine for long periods outcomes like emissions, resource consumption, land use, and other impacts on humans and the environment (Butler et al. 2014; Salat et al. 2014; Ramaswami et al. 2016; Seto et al. 2016; d’Amour et al. 2017). Thus, understanding trends in urban land use, especially growth and patterns of the built environment, is essential for assessing energy behaviour in cities as well as long-term mitigation potential.

From 1975 to 2015, urban settlements expanded in size approximately 2.5 times, accounting for 7.6% of the global land area (Pesaresi et al. 2016). By year 2015 the extent of urban and built-up lands was between 0.5–0.6% of the total 130 Mkm^2 global ice-free land use, taking up other uses such as fertile cropland and natural ecosystems. This is projected to increase two-to-threefold by 2030 (Arneth et al. 2019; Jia et al. 2019).

An analysis of 478 cities with populations of more than 1 million people found that the predominant urban growth pattern worldwide is “outward” expansion, suggesting that cities are becoming more expansive than dense (Mahtta et al. 2019).

From 1970 to 2010, North America and Europe consistently ranked high in terms of the ratio of land consumption rate to population growth rate, suggesting low levels of land-use efficiency (Güneralp et al. 2020) (Figure 8.8). This ratio, designed to reflect many dimensions of land-use efficiency, is one of the indicators of SDG target 11.3 (“by 2030, enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management in all countries”) rate (United Nations 2015, p. 21).

By this measure, however, India and China represent the most inefficient trends in urban land use (Figure 8.8). Notably, India is alone among the rest in exhibiting consistently decreasing levels of urban land-use efficiency (Güneralp et al. 2020). However, the larger cities in Southeast Asia exhibit consistently higher land-use efficiencies, while the small and medium cities in this region and those in Africa trend toward lower land-use efficiencies. Urban population densities have consistently declined only in India, China, North America, and Europe with significant exceptions across city sizes (Figure 8.8). Globally, small-medium urban areas with population less than 2 million people lead their larger counterparts in both rates of urban land expansion and decreases in urban population densities (Güneralp et al. 2020).

Another analysis on a global sample of 194 cities also identified small to medium-sized cities as the most dynamic in terms of their expansion and change in their forms (Lemoine-Rodriguez et al. 2020). Nevertheless, there is an overall trend toward more homogeneous urban forms under the simultaneous influence of the processes of both fragmentation and compactness. The exception to this trend is a group of large cities in Australia, New Zealand, and the United States that are still predominantly fragmented. These findings on the evolving form of cities of varying sizes from different parts of the world have significant implications for energy use and GHG emissions and point to a need for carefully crafted policy recommendations depending on the type of the city and its geographical location.

Over 60% of the reported urban expansion (nearly 40,000 km^2) was formerly agricultural land. In terms of percent of total urban land expansion, largest conversions of agricultural lands to urban land uses from 1970 to 2010 took place in Europe, China, and Southeast Asia (Figure 8.9). The largest proportional losses of natural land cover were reported for North America and Oceania, which are followed by Southwest Asia, Latin America, and India (Güneralp et al. 2020). Future urban expansion in the future through 2040 may displace almost 65 Mtonnes of crop production, which could result in an expansion of up to 350,000 km^2 of new cropland (van Vliet et al. 2017).

Committed emissions from urban infrastructure include buildings and road networks, strongly influenced by built environment layouts, densities and specific uses. However, quantifications of such lock-ins are rare, ranging around 10–14 GtCO$_2$ annually (see Chapters 2 and 7; Erickson et al. 2015).

The drivers of urban land area increase are multiple including an increase in urban incomes, a shift in population with higher incomes in fast growing economies, and new state or privately built cities targeting a particular class of people (Delgado-Ramos 2019).

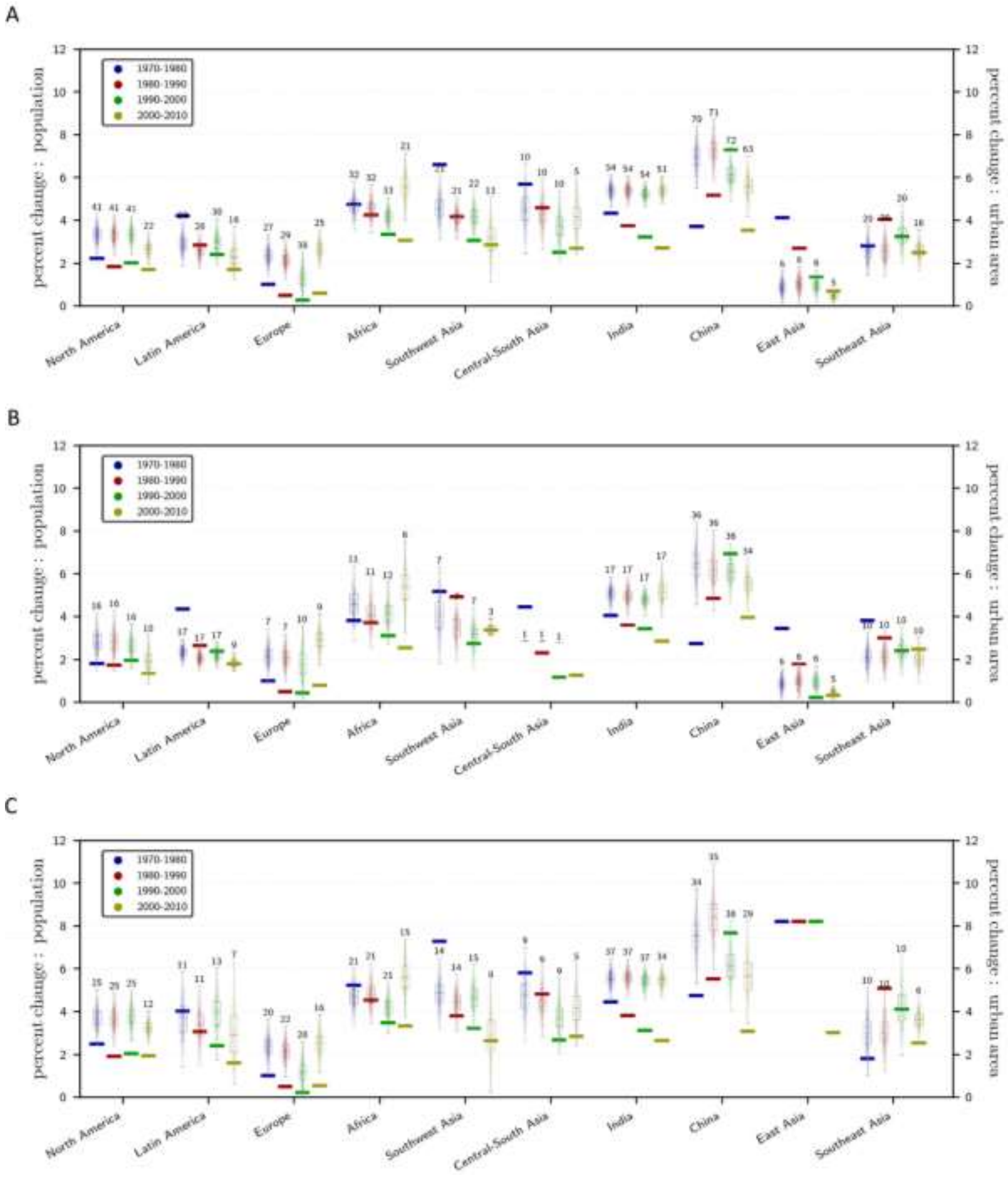


Figure 8.8. Comparison of two different urban growth measures, urban land and urban population, by region and by decade. Average annual rate of change for urban land and for urban population for (A), all case study locations in our synthesis with a population >300 000; (B), those with a population>2million (large urban centres), and (C), those with a population>300 000 but<2million (small-medium urban centres).Box plots show the median, 1st and 3rd quartiles, and lower and upper mild outlier thresholds of bootstrapped averages of annual rate of change for urban land. Population data, aggregated from individual case study locations to the geographic regions in the synthesis, are derived from the UN data on populations of urban agglomerations with a population of 300, 000 people or more. Number of locations used in each decadal bootstrapped estimate is shown above the respective box plot. Dashes represent the percent change in urban population. Oceania has too few data points for any trend to emerge and is hence omitted.

Figure from Güneralp et al. (2020, p. 4).

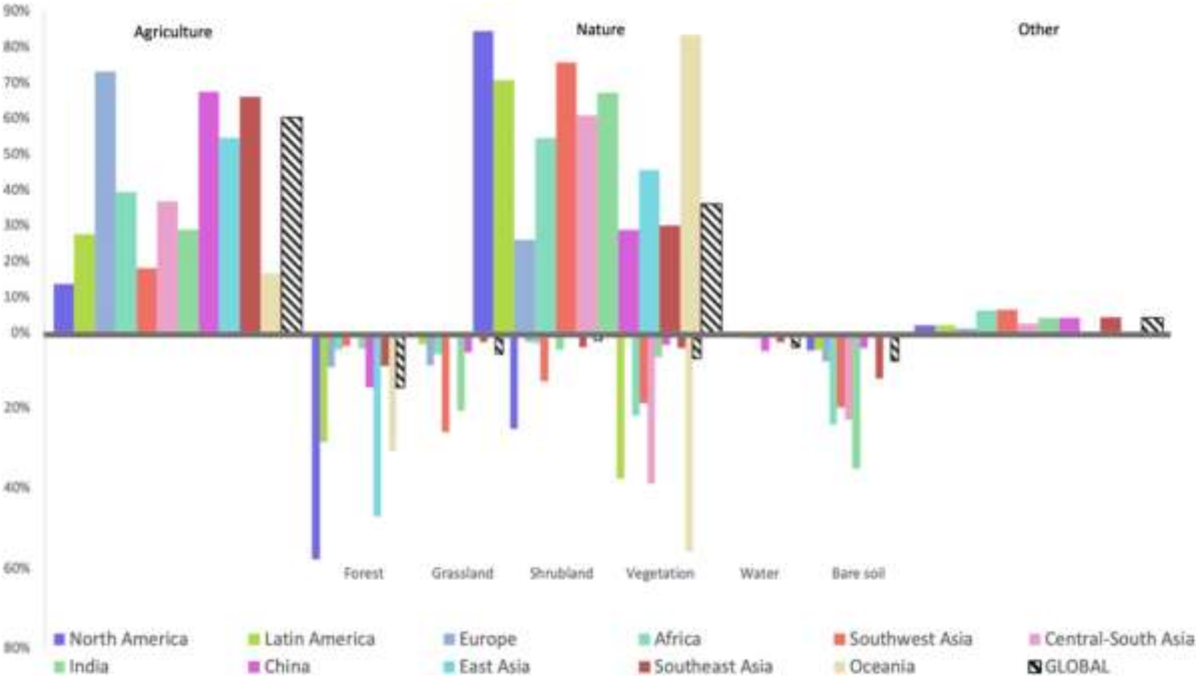


Figure 8.9. Percent of total urban land expansion from other land covers (1970–2010). The bottom half of the plot disaggregates the "Nature" category into forest, grassland, shrubland, vegetation, water, and bare soil. Figure from Güneralp et al. (2020, p. 9).

8.3.1.1 *Informal settlements*

Informal settlements have potential to accelerate transitions to low carbon urban development. There are several key reasons for a huge potential to mitigate GHG emissions in these areas. First, informal urban areas may not require large investments in retrofitting as they have developed with minimal investment in large scale infrastructure. Second, these areas exhibit flexibility of development and can potentially be transformed into urban form and use with low- or neutral-carbon intensity in respect to transportation, energy use in residential buildings, and renewable energy (Baurzhan and Jenkins 2016; Henneman et al. 2016; Byrne et al. 2017; Oyewo et al. 2019).

There are many possibilities for the potential of informal urban areas to mitigate climate change. If informal urban areas avoid the business-as-usual trajectory of urban development and utilise innovations regarding micro-scale technologies, decentralised utilities of water, sanitation, and service centres, emissions associated with treating wastes and vehicle miles can be avoided (Tongwane et al. 2015; Yang et al. 2018a). The various options include spatial adjustments for walkability of neighbourhoods, low energy intensive mobility, low energy intensive residential areas, harnessing of renewable energy at city-scale, adoption of off-grid utilities, and electrification and enhancement of the urban ecology – all of which have multiple potential benefits (Colenbrander et al. 2017; Fang et al. 2017; Laramee et al. 2018; van der Zwaan et al. 2018; Wu et al. 2018; Silveti and Andersson 2019). Some of the co-benefits of the various mitigation options include more job opportunities, increased incomes, more business start-ups, air quality improvement, and enhanced health and wellbeing (Gebreegziabher et al. 2014; Dagnachew et al. 2018; Keramidas et al. 2018; Adams et al. 2019; Ambole et al. 2019; Boltz et al. 2019; Moncada et al. 2019; Weimann and Oni 2019; Manga et al. 2020).

Informality has demonstrated that there are possibilities for a diversity of urban services and infrastructure that are non-networked, non-centralised, including sanitation, waste, water, and electricity serving over 60% of the urban population in developing country cities (Lawhon et al. 2018). The alternatives of disruptive, hybrid, largely non-networked multiplicity of technologies applicable from micro- to meso-scale are dominant systems of urban services and infrastructure in urban areas of developing countries that have potential for low emissions development (Narayana 2009; Dávila and Daste 2012; Radomes Jr and Arango 2015; Potdar et al. 2016; Grové et al. 2018). These technologies can be applied in short-term as responses with long-term influence on emissions reduction. Assessed literature indicates that a cumulative impact of the disruptive technologies on emissions reduction with robust evidence but medium confidence can reduce emissions sources by 15–25% through enhanced emissions sinks small and medium sized cities. (Tongwane et al. 2015; du Toit et al. 2018; Nero et al. 2018, 2019; Frantzeskaki et al. 2019; Mantey and Sakyi 2019; Singh and G. 2019).

8.3.2 Trends in urban emissions and drivers

Luqman et al. (2020, *submitted*) explored trends in CO_2 emissions and their key drivers across 109 global cities for the period spanning 1998 to 2018. They found that while urban CO_2 emissions were increasing in all urban areas, the dominant drivers were dependent upon development level. Emissions growth in developing country urban areas was driven by increases in area and per capita emissions. Developed country urban areas, by contrast, exhibit declining per capita emissions with moderate increases in urban area. Across all cities, increases in population density lead to declines in per capita emissions.

Figure 8.10 presents key urban emission metrics for five global regions in the years 2000 and 2015. The most significant change in emission metrics occurred between the Asia and Developing Pacific and the Developed Countries regions. Urban population, urban CO_2-eq emissions and national CO_2-eq emissions are increased as a share of the global total in the Asia and Developing Pacific while the same metrics declines for the Developing Countries. All regions witnessed an increase in the urban share of CO_2-eq emissions. Urban per capita CO_2-eq and national per capita CO_2-eq also increased in all regions except for the urban per capita CO_2-eq value which declined slightly for the Developing Countries region. Regional urban per capita CO_2-eq emissions are less than the regional national CO_2-eq emissions in all regions except for the Asia and Developing Pacific. Most regions, however, show convergence of the urban and national per capita CO_2-eq, not surprising as the urban share of national emissions increases. There is one exception for Africa and Middle East since the urban share increases from 38.5% to 51.9% while the per capita emissions do not converge as others.

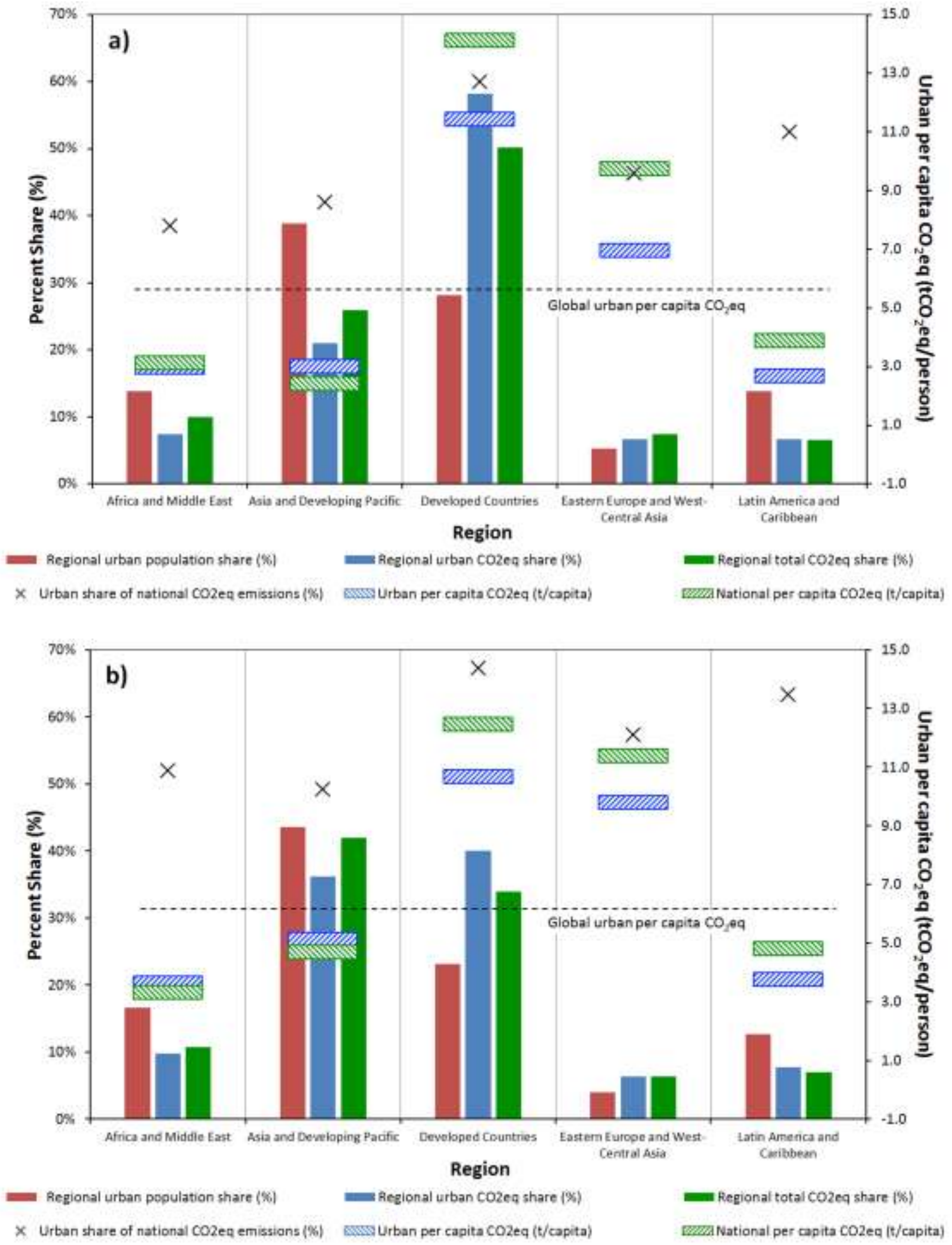


Figure 8.10. Changes in six metrics associated with urban and national-scale emissions represented in the 5-region aggregation, with a) 2000; b) 2015. The trends in Luqman et al. (2020, *submitted*) were combined with the work of Moran et al. (2018a) to estimate the regional urban CO$_2$-eq share in global urban emissions, the urban share of national CO$_2$-eq emissions, and the urban per capita CO$_2$-eq emissions by region. The dashed grey line represents the global average urban per capita CO$_2$-eq emissions. The regional urban population share, regional CO$_2$-eq share in total emissions, and national per capita CO$_2$-eq emissions are given for comparison. Figures adapted from Gurney et al. (2020a, *submitted*). *Permission pending.*

8.3.2.1 *The built environment, infrastructure, and resource demand*

The growth urban global populations that are anticipated over the next several decades will create significant demand for buildings and infrastructure. As cities expand in size and density, the production of mineral-based structural materials conventionally associated with mid- and high-rise urban construction morphologies will create a significant spike in GHG emissions and a discharge of CO_2 that takes place at the beginning of each building lifecycle.

Even in the most sustainable buildings, this production stage carbon debt could take decades to offset through operational energy efficiencies. Significantly more reductions in the energy demands and GHG emissions associated with the manufacture of mineral-based construction materials will be challenging, as these industries have already optimised their production processes. It is estimated that final energy demand for steel production can be reduced by nearly 30% compared to 2010 levels and 12% efficiency improvement for cement (Lechtenböhmer et al. 2016).

Steel and concrete, the most commonly used structural materials in urban buildings, have high production stage emissions and little or no capacity to store carbon. The parallel-to-grain strength of timber is similar to that of reinforced concrete (Ramage et al. 2017). New and emerging structural assemblies in engineered timber rival the structural capacity of steel and reinforced concrete while offering the benefit of storing significant quantities of atmospheric carbon. As much as half the weight of a given volume wood is carbon, sequestered during forest growth as a by-product of photosynthesis (Martin et al. 2018).

The broad-based substitution of engineered timber for steel and concrete in mid-rise urban buildings offers the opportunity to transform cityscapes from their current status as net sources of GHG emissions into large scale, human-made carbon sinks. The sheer volume of urban buildings projected for the remainder of the first half of the 21st century suggests that such a scenario could become a powerful tool to mitigate climate change. The construction of timber buildings for 2.3 billion new urban dwellers from 2020 to 2050 could store between 0.01–0.68 $GtCO_2$ per year depending on the scenario and the average floor area per capita. Over a period of thirty years, wood-based construction can accumulate 0.25–20 $GtCO_2$ and reduce cumulative emissions of carbon from 4 (7–20) to 2 (0.3–10) $GtCO_2$[1] (Churkina et al. 2020) (Figure 8.11).

Such a transition to biomass-based building materials, implemented through the adoption of engineered structural timber products and assemblies by the urban building sector, will succeed as a climate mitigation strategy only if working forests are managed and harvested sustainably and the wood from dismantled timber buildings is preserved through reuse as a material source for consumer product manufacture and future building or stored as biochar (Churkina et al. 2020).

Such a massive transition to biomass-based urban construction materials and techniques will demand more robust forest and urban land management policies, forest restoration, afforestation, and sustainable silviculture. Potential synergies between the carbon sequestration capacity of forests and the associated carbon storage capacity of dense mid-rise cities built from engineered timber offer the opportunity to construct carbon sinks deployed at the scale of landscapes and at least as durable as the lifecycle of the buildings we will inevitably build (Churkina et al. 2020).

FOOTNOTE [1] The numbers in the brackets indicate the uncertainty in the future floor areas per capita and CO_2 emission coefficients for steel, concrete, and timber.

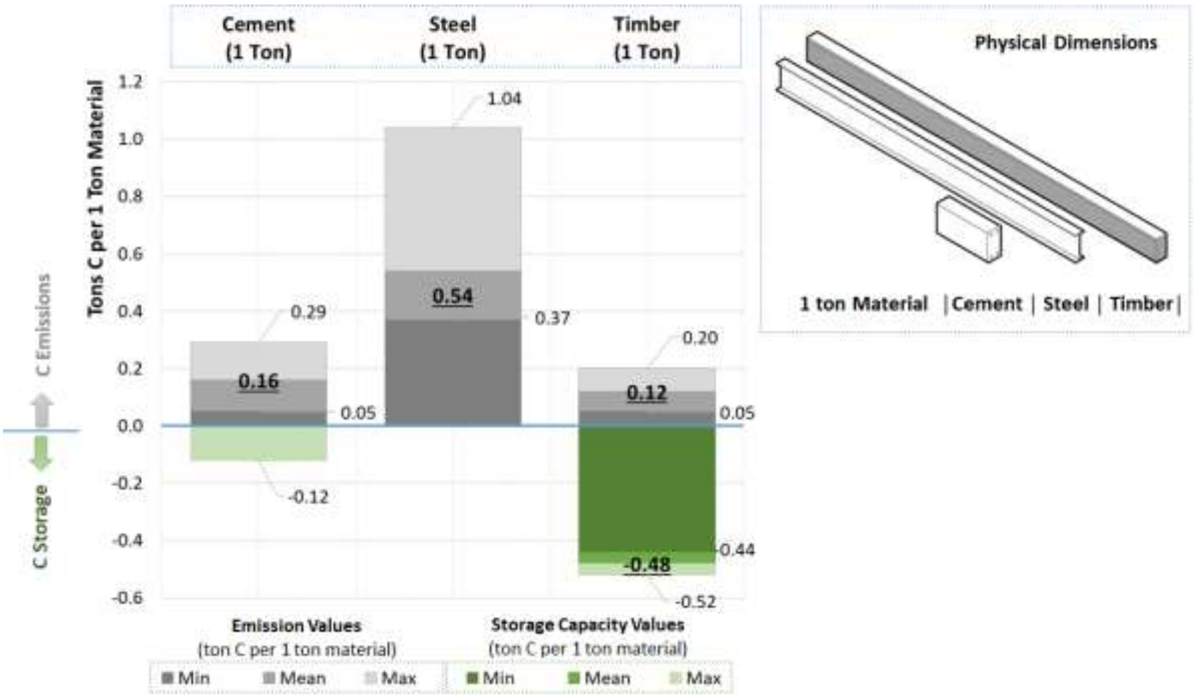


Figure 8.11 Physical dimensions, carbon emissions, and carbon storage capacity of one tonne of cement, steel, and timber materials. Mineral-based materials have substantial embodied carbon emissions with minimal carbon storage capacities, while timber stores a considerable quantity of carbon with a relatively small ratio of carbon emissions to material volume. The displayed carbon storage of cement is the theoretical maximum value, which may be achieved after hundreds of years. Carbon storage of steel is not displayed as its only 0.004 tonne C per tonne of steel. The mean carbon emission or mean carbon storage values are underlined and represented by the middle stacked bars. The darker and lighter coloured stacked bars depict the minimum and maximum values. Grey tones are given for carbon emissions and green tones are given for storage capacity values.

Adapted from Churkina et al. (2020). *Permission pending.*

8.3.3 Behavioural aspects

Urban emissions, as well as emissions from the supply chain of cities, are driven by the behaviour of residents, with households accounting for over 60% of carbon emissions globally (Ivanova et al. 2016). Overall, changes in behaviour across all areas (transport, buildings, food) could reduce an individual's emissions by 10–36%. Also, (Moran et al. 2018b) finds overall reduction potential of 25% of individual footprint from behaviour options.

Cities can play a role in influencing lifestyle choices through hard infrastructures such as the built environment, and potentially also via soft infrastructure interventions such as fostering pro-environmental cultural norms. Growing consumption from the urban middle class and rich is expected to greatly increase carbon footprints of households in developing nations such as China, where the total household carbon footprint for the country has increased by 19% between 2007 and 2012 associated with increased wealth and urbanisation (Wiedenhofer et al. 2017).

Energy using behaviours including lifestyle choices are driven by a combination of "hard infrastructure" like city form, technological options, and economic drivers, and "soft infrastructure" including psychological, social, cultural, and organisational factors (Stern et al. 2016).

8.3.4 Scenarios of future urbanisation and urban emissions

There remained little globally comprehensive literature on projections of future baseline GHG emissions from urban areas or relative scenarios deploying mitigation actions. This dearth of research rests on limited urban emissions data that are consistent and comparable across the globe and challenges synthesising the research that has been accomplished (Creutzig et al. 2016b). Existing studies estimated urban energy use in 2050 (Creutzig et al. 2015), energy savings for low-carbon development (Creutzig et al. 2016b), emission savings from existing and new infrastructure (Creutzig et al. 2016a - Figure 8.13), and urban emissions from buildings, transport, industry and agriculture (IEA 2016a).

Another analysis by the Coalition for Urban Transitions (CUT) attempts to quantify the urban portion of global GHG emissions within the residential and commercial building, transport, waste, and material production (focusing on cement, aluminium, and steel) sectors along with mitigation wedges aimed at staying below a 2°C level of atmospheric warming (Figure 8.12, Coalition for Urban Transitions 2019). Starting in 2015 with a global total urban emissions of almost 14 $GtCO_2$-eq, projections based on International Energy Agency (IEA) projections show an increase to 17.3 $GtCO_2$-eq by 2050 (IEA 2017a). Similar analysis by the urban networks C40 and GCoM examine the current and future GHG emissions on smaller subsets of global cities offering further insight on urban mitigation options but only for a sample of the global urban landscape (GCoM 2018, 2019; C40 Cities et al. 2019) with approaches still emerging (Kovac et al. 2020).

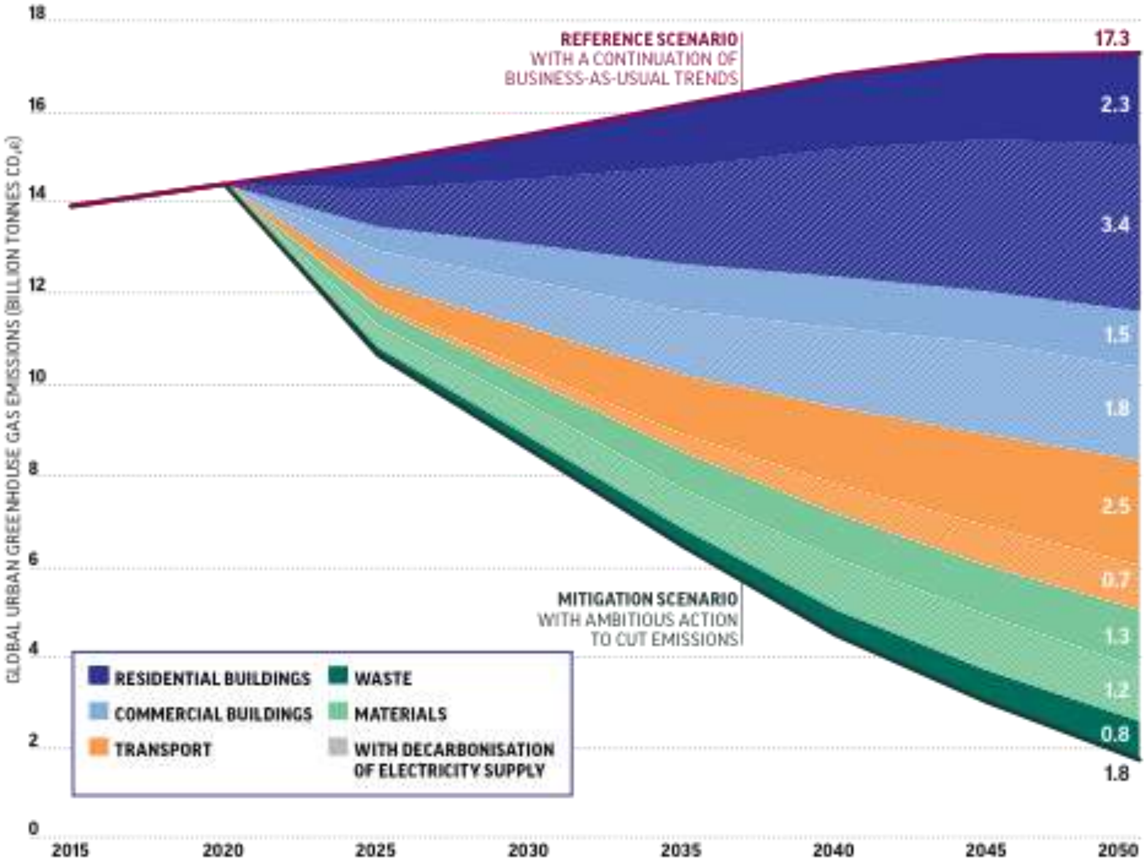


Figure 8.12 Reference and mitigation potential for global urban areas in the residential and commercial building, transport, waste and material production sectors.

Figure from Coalition for Urban Transitions (2019, p. 13). *Permission pending*.

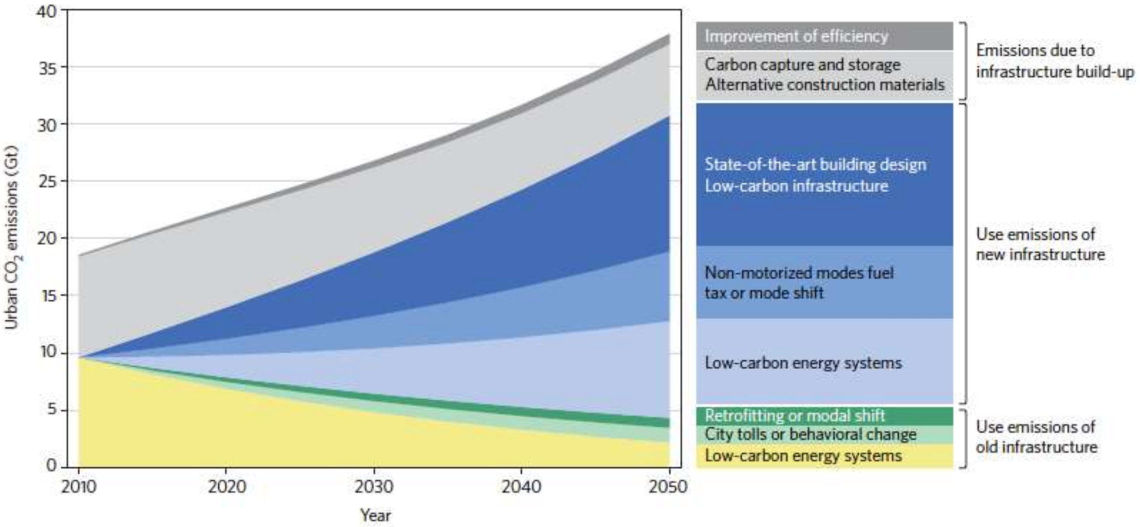


Figure 8.13 Urban infrastructure-based CO_2-eq emission mitigation wedges. Urban infrastructure-based CO_2-eq emission mitigation wedges across categories of existing (yellow/green), new (blue) and construction (grey) of urban infrastructure.

Figure from Creutzig et al. (2016a, p. 1056), *Permission pending.*

Gurney et al. (2020a, *submitted*) took a more comprehensive approach to quantifying urban emissions within the global context. The analysis combined the per capita carbon footprint estimates for 13,000 cities from Moran et al. (2018a) with projections of the share of urban population (Jiang and O'Neill 2017) within the IPCCs Shared Socioeconomic Pathway (SSP)-Representative Concentration Pathway (RCP) framework (van Vuuren et al. 2014, 2017a; Riahi et al. 2017). Urban emissions in seven SSP-RCP scenarios are shown in Figure 8.14 (a-g) along with an estimate of the global total CO_2-eq for context.

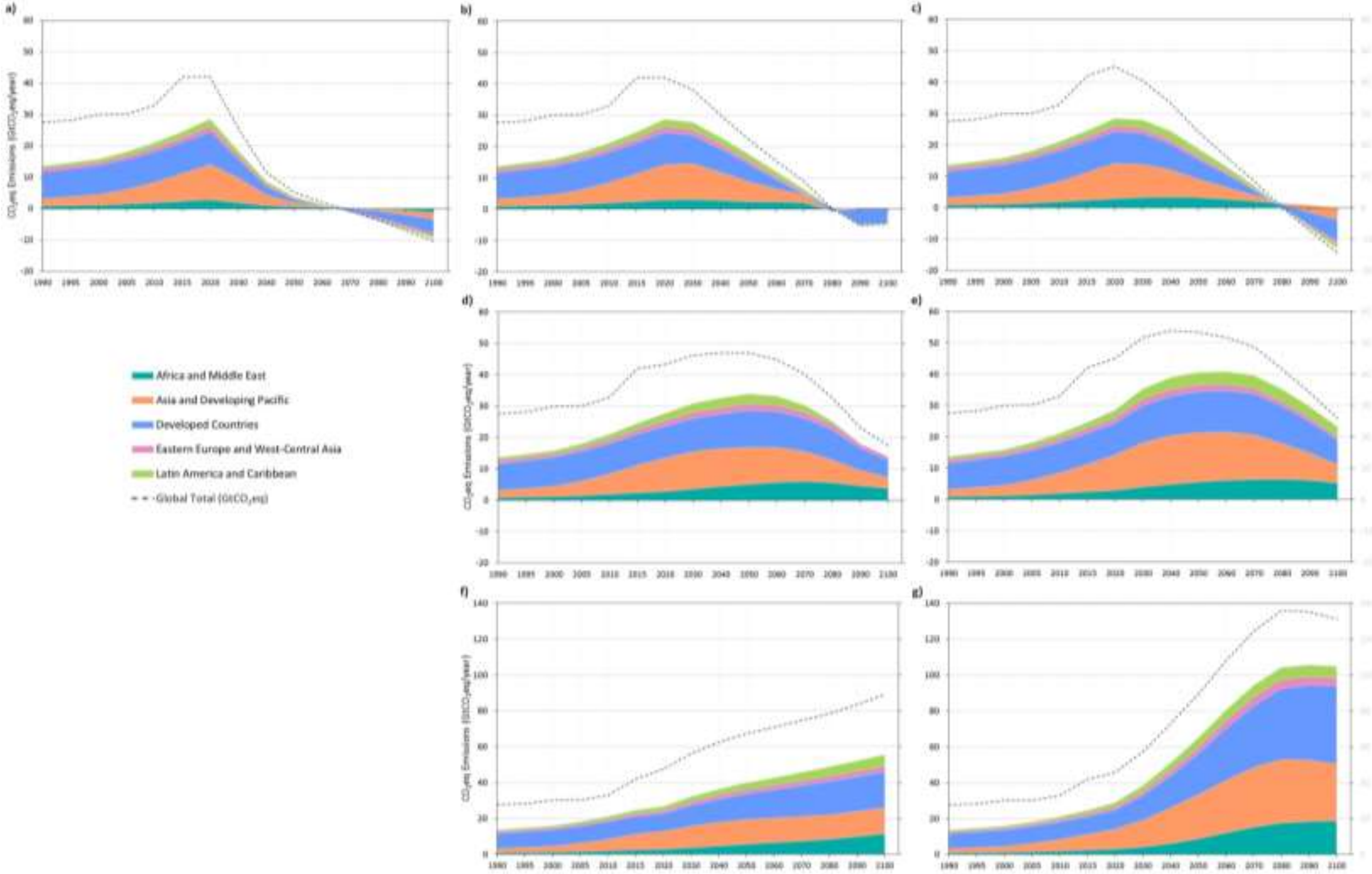


Figure 8.14. Carbon dioxide equivalent emissions from global urban areas in seven Model/SSP/RCP variations spanning the 1990 to 2100 time period. Urban areas are aggregated to 5 regional domains. Global total CO_2-eq emissions are also shown as marked by the dashed line. Future urban emissions in the context of SSP/RCP/SPA

variations correspond to (a) SSP1/RCP1.9/SPA1, (b) SSP1/RCP2.6/SPA1, (c) SSP4/RCP3.4/SPA4, (d) SSP2/RCP4.5/SPA2, (e) SSP4/RCP6.0/SPA4, (f) SSP3/RCP7.0/SPA0 and (g) SSP5/RCP8.5 based on the marker scenario implementations. Note that the scale of the panels (f) and (g) are different from the other panels (Gurney et al. 2020a, *submitted*). In the first three scenarios (a-c) with more stringent reduction pathways, the share of urban CO_2-eq emissions rises to values ranging from 90% to 100% of the global total CO_2-eq emissions by 2100. These scenarios represent contexts where urban per capita emissions decline rapidly against various increases in urban population and are oriented to reach net-zero emissions within this century at different radiative forcing levels. The two SSP1 scenarios (a) and (b) take place in contexts where urbanisation is foreseen to take place rapidly while providing environmentally-friendly accommodation and resource efficiency based on compact urban form (Jiang and O'Neill 2017). For the remaining four scenarios (a-g) that are not oriented towards net-zero GHG emissions, the urban share remains at about 65% and above by the end of the century at higher emission levels. The urbanisation and scenario contexts of the urban emissions scenarios are synthesised in Table 8.2. The scenario context of SSP1/RCP1.9 represents a pathway in which there is a transformative shift towards sustainability with climate mitigation and co-benefits for the SDGs.[2]

Figures adapted from Gurney et al. (2020a, *submitted*). *Permission pending.*

FOOTNOTE [2] The context of SSP1/RCP1.9 is the same as the illustrative pathway now named "SP" based on "shifting pathways."

In the first four scenarios (Figures 8.14a–14d) with more stringent reduction pathways, the share of urban CO_2-eq emissions rises to values ranging from 90% to 100% of the global total CO_2-eq emissions by 2100. For the remaining 3 scenarios the urban share exceeds 65% by the end of the century.

Table 8.2. Synthesis of the urbanisation and scenario contexts of the urban emissions scenarios. Descriptions for urbanisation are adapted based on Jiang and O'Neill (2017) while high-, medium-, low- or mixed-levels in the scenario context are drawn from the marker model implementations of SSP1-SSP5 for IMAGE (van Vuuren et al. 2017b; Rogelj et al. 2018), MESSAGE-GLOBIOM (Fricko et al. 2017), AIM/CGE (Fujimori et al. 2017), GCAM (Calvin et al. 2017), and REMIND-MAgPIE (Kriegler et al. 2017). The letters in parentheses refer to the panels in Figure 8.14. Energy and material efficiency relate to energy efficiency improvement and decrease in the intermediate input of materials, including steel and cement. Dietary responses include less meat-intensive diets. Implications for urban areas are relevant for the mitigation response options in Section 8.4.

Adapted from Gurney et al. (2020a, *submitted*). *Permission pending.*

SSP/RCP Framework	**Urbanisation Context**	**Scenario Context**					
		Electrification	Energy and material efficiency	Technology development / innovation	Renewable energy preferences	Behavioural, lifestyle and dietary responses	Afforestation and re-forestation
SSP1 RCP1.9 (a) RCP2.6 (b)	Resource efficient, compact and sustainable	High	High	High	High	High	High
		Implications for urban climate mitigation include: → Electrification across the urban energy system while supporting flexibility in end-use → Resource efficiency from a consumption-based perspective with cross-sector integration → Knowledge and financial resources to promote urban experimentation and innovation → Empowerment of urban inhabitants for reinforcing positive lock-in for decarbonisation → Integration of sectors, strategies and innovations across different typologies and regions					
SSP2 RCP4.5 (d)	Moderate progress	Medium	Medium	Medium	Medium	Medium	Medium
SSP3 RCP7.0 (f)	Slow urbanisation, poor urban planning	Medium	Low	Low	Medium	Low	Low
SSP4 RCP 3.4 (c) RCP6.0 (e)	Pace of urbanisation differs with inequalities	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed
SSP5 RCP8.5 (g)	Rapid urbanisation with carbon lock-in (*)	High (*)	Low	High (*)	Low	Low	-

8.3.4.1 Urban population and GDP projections

Downscaled climate projections need to be linked to downscaled projections of population and economic growth to fully develop implications for land, natural resources, and ecosystems for future scenarios (Wear and Prestemon 2019). While Grübler et al. (2004), McKee et al. (2015), Jones and O'Neill (2016), among others, have downscaled populations, research on GDP downscaling is still limited. Given that, the county-level scenarios of SSPs 1–3 on the population and GDP are downscaled into 0.5-degree grids (see Figure 8.15, Murakami and Yamagata 2019). To downscale the scenarios, the spatial econometric approaches have been often used to consider interactions among cities and to utilise auxiliary variables including land use and road network.

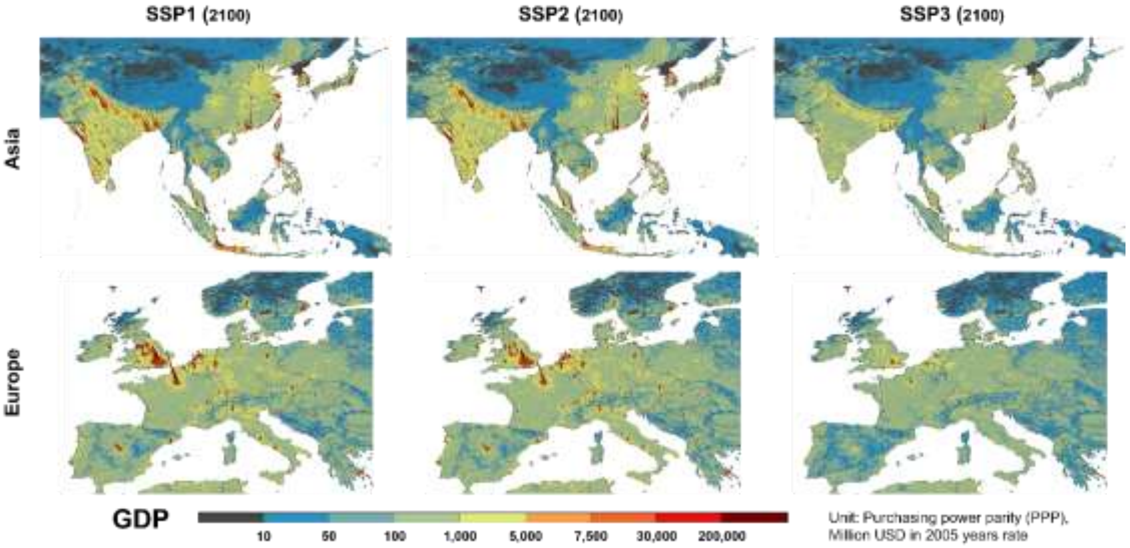


Figure 8.15 Downscaled gross productivities in 2100. Gridded GDP estimates in 2100 under SSP 1-3 of Europe and Eastern Asia are displayed. SSPs 1 and 2 indicated a higher level of urban growth within the existing major cities. Still, growth in non-urban areas are as slow as SSP 3, which is a less urbanised scenario. SSP 3 has an especially small GDP growth near major cities (e.g., London, Paris, Shanghai), whereas the GDPs in areas far from the existing major cities remain low similar to those in other scenarios.
Figure from Murakami et al. 2020, *submitted*. *Permission pending.*

8.3.4.2 Urban expansion forecasts since AR5

Six global-scale spatial forecasts of urban land expansion have been published since the AR5 (Figures 8.16 and 8.17). Four of the six that presented forecasts for each of the five SSPs are considered here. All four have forecasts to 2050 but only three to 2100. One of the two not included here (van Vliet et al. 2017) is also the first study that forecasts land displacement due to urban land expansion.

There are significant differences in forecasted urban expansion among these studies (Figures 8.16 and 8.17) but they all report that Africa and Asia would be the regions that will undergo significant urban growth in the coming years. However, these studies also reported that Developed Countries would continue to see increased urban growth, albeit at a slower rate in comparison to those in Asia and Africa. Both Huang et al. (2019) and Li et al. (2019) mentioned that the USA, China, and India will face continued urban growth, at least until 2050. However, Li et al. (2019) reported that after 2050, China would face a decrease in urban growth, while growth will continue for India.

Huang et al. (2019) forecasted an increase of 78–171% over the urban footprint in 2015 (Figure 8.16), which will result in average summer daytime and night-time warming in air temperature of 0.5°C-0.7°C, even up to about 3°C in certain locations. This warming is on average about half, and in certain locations nearly twice, as strong as that caused by GHG emissions based on the multi-model ensemble average forecasts in RCP 4.5.

There are three sets of spatial forecasts of urban expansion out to 2100 and four to 2050. Across all four sets of forecasts, current urban land (circa 2015) is the largest in Developed Countries followed by Asia and Developing Pacific (Figures 8.16 and 8.17). The largest increases in urban land by 2050 are expected in Asia and Developing Pacific and Developed Countries across all the SSPs. On the other hand, the smallest increase in urban extent is expected in Eastern Europe and East-Central Asia.

In spite of these general trends, there are differences in forecasted urban expansion in each region across the SSPs. Comparing across the averages of the forecasts, we expect the most urban expansion in Developed Countries (on average about 350, 000 km^2) and then in Asia and Developing Pacific (on average about 300,000 km^2). These two regions are followed by Africa and the Middle East with about 150,000 km^2. By 2100, however, we expect Developed Countries to have the most urban expansion only in SSP5. In SSP2 and SSP4, Developed Countries and Asia and Developing Pacific have about equal amounts of new urban land; in SSP1 and SSP3, the latter has more new urban land forecasted than the former. Moreover, there is more urban land expansion forecasted for Africa and Middle East than for either of the two regions in SSP1.

Overall, the largest urban extents are forecasted under SSP5 for both 2050 and 2100 whereas the smallest forecasted urban extents are under SSP3. Forecasted global urban extents reach between 1–2.2 million km^2 (with an average of 1.5 million km^2) in 2050 under SSP5 and between 0.8–1.5 million km^2 (with an average of 1.1 million km^2) in 2050 under SSP3. By 2100, the forecasted urban extents reach between 1.4–3.6 million km^2 (average 2.6 million km^2) under SSP5 and between 1–1.5 million km^2 (average 1.3 million km^2) under SSP3. Across the board, substantially larger amounts of urban land expansion are expected after 2050 under SSP5 compared to other SSPs.

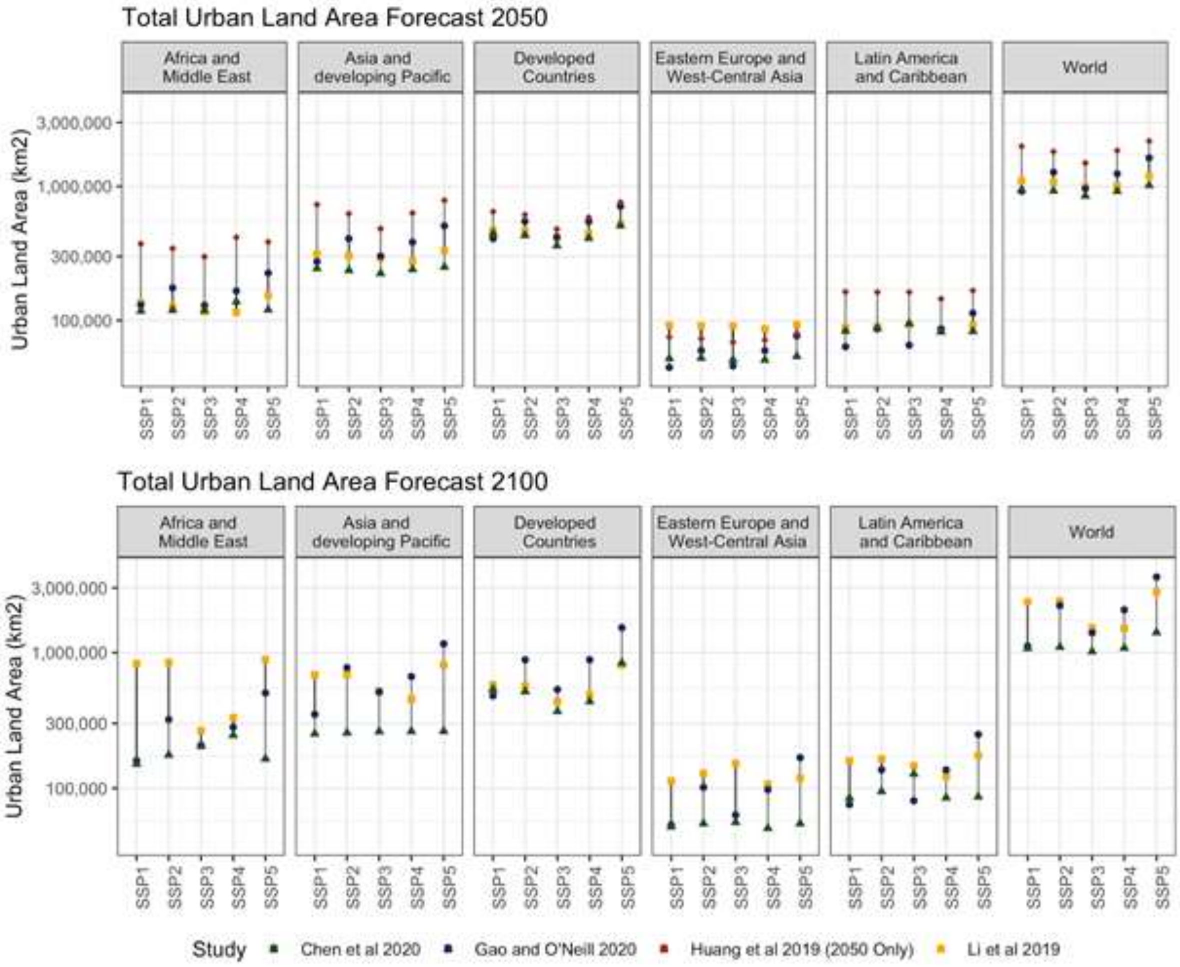


Figure 8.16 Four sets of forecasts of urban land expansion. Forecasts of urban land expansion to 2050 and 2100 according to each SSP. Three studies (Li et al. 2019; Chen et al. 2020a; Gao and O'Neill 2020) report forecasts of urban land expansion to both 2050 and 2100. One study (Huang et al. 2019) reports the forecast to 2050. Current urban extents and the respective initial years vary slightly among the four studies.

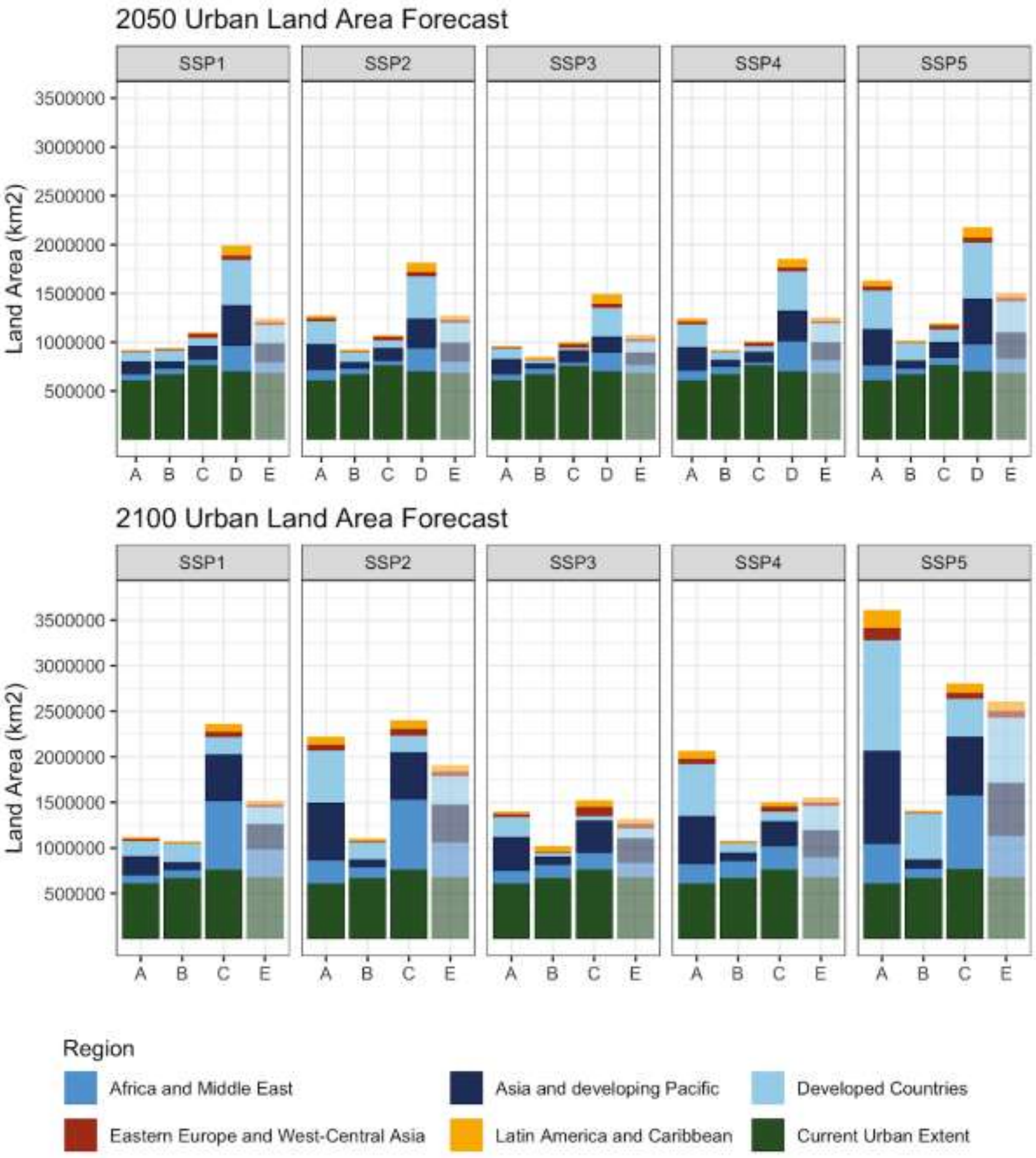


Figure 8.17 Forecasts of urban land expansion in 2050 and 2100 according to each SSP, by study, where A: Gao and O'Neill (2020), B: Chen et al. (2020a), C: Li et al. (2019), D: Huang et al. (2019), and E: Mean across studies. Three studies (Li et al. 2019; Chen et al. 2020a; Gao and O'Neill 2020) report forecasts of urban land expansion to both 2050 and 2100. One study (Huang et al. 2019) reports the forecast to 2050. Current urban extents and the respective initial years vary slightly among the four studies.

8.4 Urban mitigation options

Urban mitigation options will necessarily vary and differ based on many factors, including type of governance, development level, institutional capacity, urban form, economic structure, and geography. There is growing literature showing how certain mitigation actions in urban areas reduce emissions and enhance emission sinks (Figure 8.20). Various mitigation actions occur at multiple urban scales from households and blocks to districts and urban regions. Urban mitigation options can be implemented as standalones sectoral strategies such as increasing energy efficiency for appliances, but they can also be implemented as systemwide actions. Urban mitigation options and strategies that are effective, efficient, fair, can also support broader sustainability goals of the city and beyond (Güneralp et al. 2017b; Kona et al. 2018; Pasimeni et al. 2019).

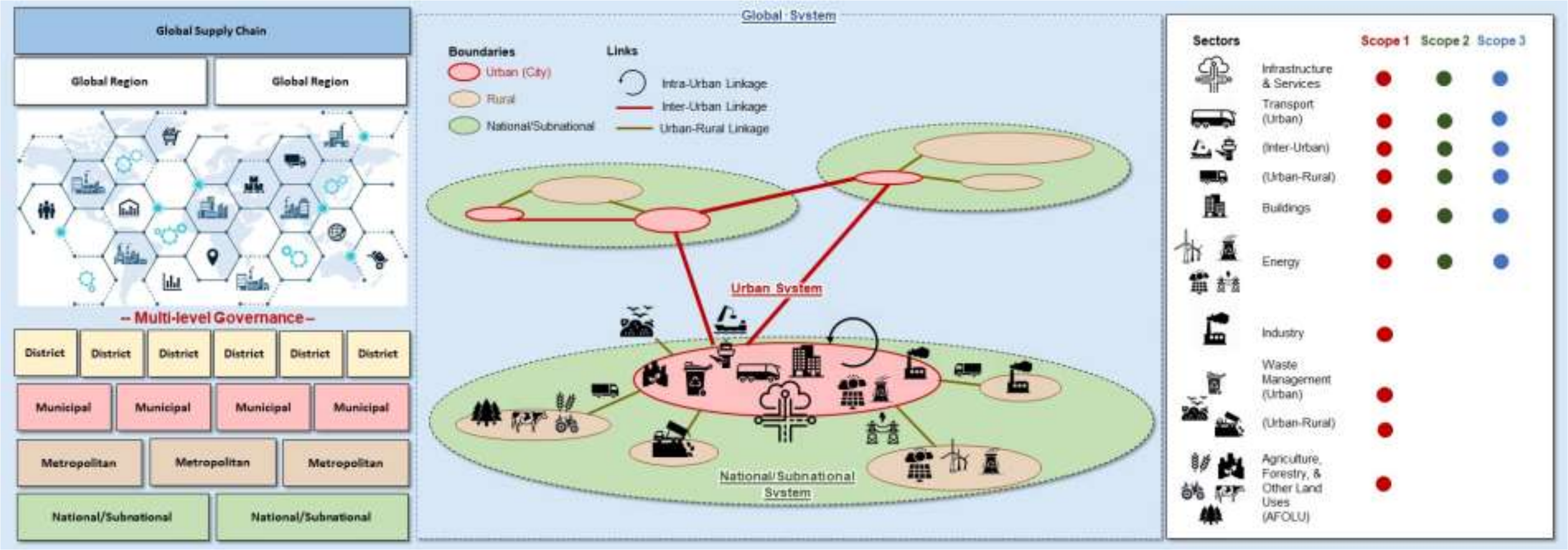


Figure 8.18. Urban Systems. Scope 1 = GHG emissions from sources located within the urban (city) boundary; Scope 2 = GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the urban (city) boundary; Scope 3 = All other GHG emissions that occur outside the urban (city) boundary as a result of activities taking place within the urban (city) boundary.

Due to the complex and intensive interactions in urban systems (Figure 8.18) and the interlinked nature among the SDGs, cities can be important intervention points to harness synergies and co-benefits for achieving emissions reduction but also other SDGs (Nilsson et al. 2016; Corbett and Mellouli 2017).

8.4.1 Mitigation potential of urban subnational actors

A significant research question that has been paid more attention in both the scientific and policy communities is related to subnational actors' role in and contribution to global climate mitigation. The 2018 UN Environment Programme's annual Emissions Gap report in 2018 included for the first time a special chapter on subnational and non-state (i.e., businesses and private actors) and assessed the landscape of studies aiming to quantify their contributions to global climate mitigation. There has been an increase in the number of studies aiming to quantify the overall aggregate mitigation impact of subnational climate action globally. Estimates for the significance of their impact vary widely, from up to 30 $MtCO_2$-eq from 25 US cities in 2030 (Roelfsema 2017); to a 2.3 $GtCO_2$-eq reduction in 2030, compared to a current policy scenario, from over 10,239 cities participating in GCoM (Hsu et al. 2018; GCoM 2019). For regional governments, the Under 2 Coalition, which includes more than 200 governments pledging goals to keep global temperature rise below 2°C, is estimated to reduce emissions by 4.2 $GtCO_2$-eq in 2030, compared to a current policy scenario (Kuramochi et al. 2020). Forty-nine state and regional governments disclosing to CDP are estimated to reduce emissions beyond national government NDCs by 0.69 $GtCO_2$-eq in 2030 (The Climate Group 2019). Erickson and Tempest (2014) estimate that the total mitigation contribution of all cities' climate policies addressing major urban emission sources (e.g., buildings, transport, and waste) is around 3.7 $GtCO_2$-eq in 2030, with a potential of 8 $GtCO_2$-eq in 2050.

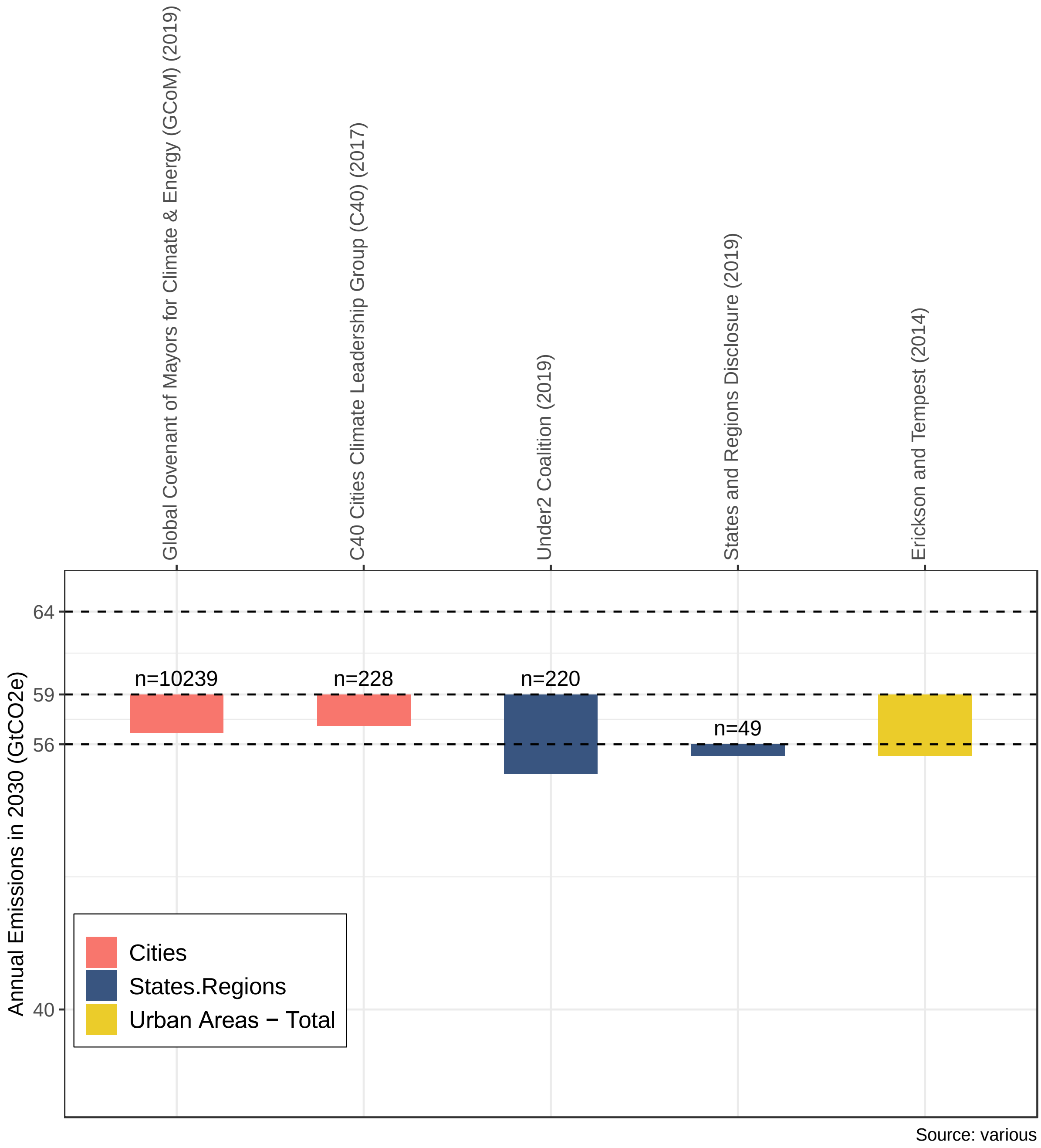


Figure 8.19 Mitigation potential of subnational actors in 2030.
Permission pending.

These estimated ranges (as illustrated in the Figure 8.19) reflect different selections of and number of actors, along with varying methodological approaches, including assumptions of overlap (e.g., between actions occurring on emissions in similar geographies or sectors) and baseline scenario definitions (Hsu et al. 2019). Some studies suggest that these subnational mitigation actions (Roelfsema 2017; Kuramochi et al. 2020) are in addition to national government mitigation efforts and can therefore reduce emissions even beyond current national policies, helping to "bridge the gap" (Blok et al., 2012) between emissions trajectories consistent with least-cost scenarios for limiting temperature rise below 1.5 or 2 C. In some countries, such as the United States, where national climate policies have been curtailed, the potential for cities and regions' emission reduction pledges to make up the country's Paris NDC is assessed to be significant (Kuramochi et al. 2020).

These estimates are also often contingent on assumptions that subnational actors fulfil their pledges and that these actions and do not result in rollbacks in climate action (i.e., weakening of national climate legislation) from other actors or rebound in emissions growth elsewhere, but data tracking or quantifying the likelihood of their implementation remains rare (Chan et al. 2018; Hsu et al. 2019; Hale et al. 2020; Kuramochi et al. 2020) On one hand, reporting networks may attract high-performing cities, suggesting an artificially high level of cities interested in taking climate action or piloting solutions that may not be effective elsewhere (van der Heijden 2018). On the other hand, these studies could also present a conservative view of potential mitigation impact because they draw upon publicly reported mitigation actions and inventory data, excluding subnational actors that may be taking actions but not reporting them (Kuramochi et al. 2020). The nuances of likelihood, and the drivers and obstacles of climate action across different contexts is a key source of uncertainty around subnational actors' mitigation impacts.

8.4.2 Integration, innovation, and urban carbon lock-in

Urban energy demand patterns are locked-in through incremental urban design and planning decisions, coupled with investments in long-lasting infrastructure, such as roads and buildings (Seto et al. 2016). The fundamental building blocks of cities are the layout of the street network, the size of city blocks and the density of street intersections. These three factors shape and lock-in energy demand for decades after their initial construction.

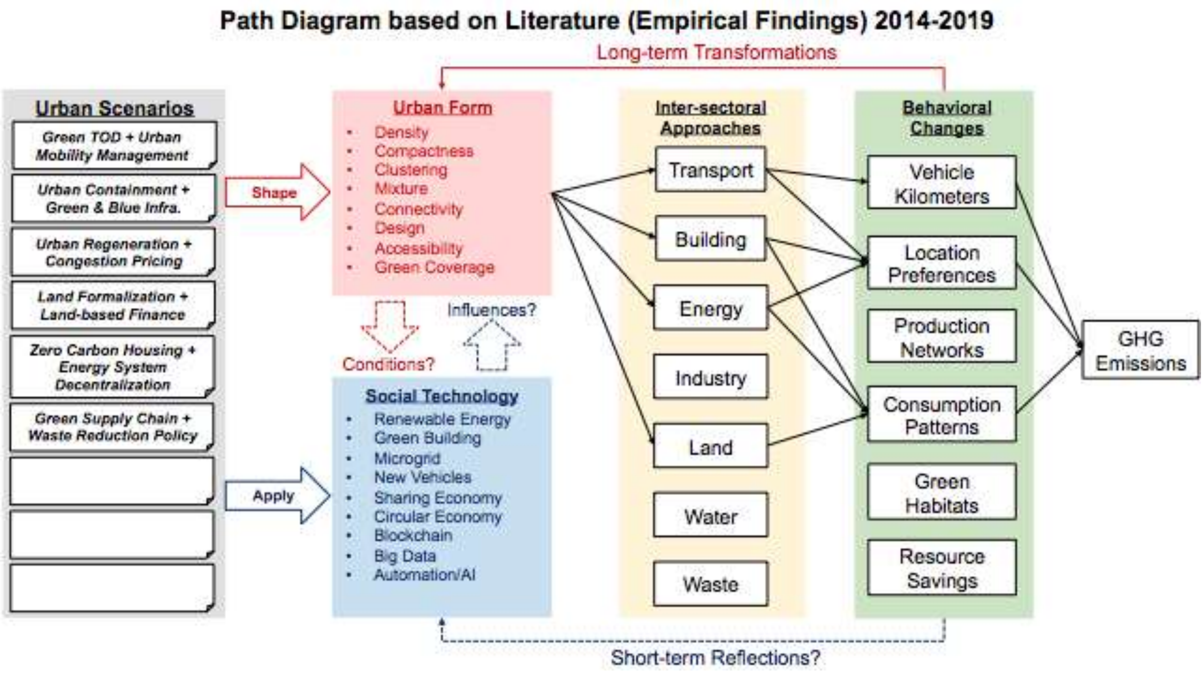


Figure 8.20 Path diagram based on literature (empirical findings) 2014–2019. This figure was produced based on the empirical findings on the linkage between urban form attributes and GHG emissions via different sectors reviewed. The objective of this path diagram is to present the urban systems structure based on evidence (neither conceptual nor hypothetical) in a collective (inter-sectoral) way so that we can identify what we have already reviewed/proved and have not yet known (knowledge gaps).

Urban carbon lock-in occurs on different levels: through institutions, technology and behaviour (Figure 8.21). Each of these types of lock-in are mutually reinforcing. For cities to break out of the existing carbon lock-in they will require systemic change, integration of strategies and rapid uptake of innovations.

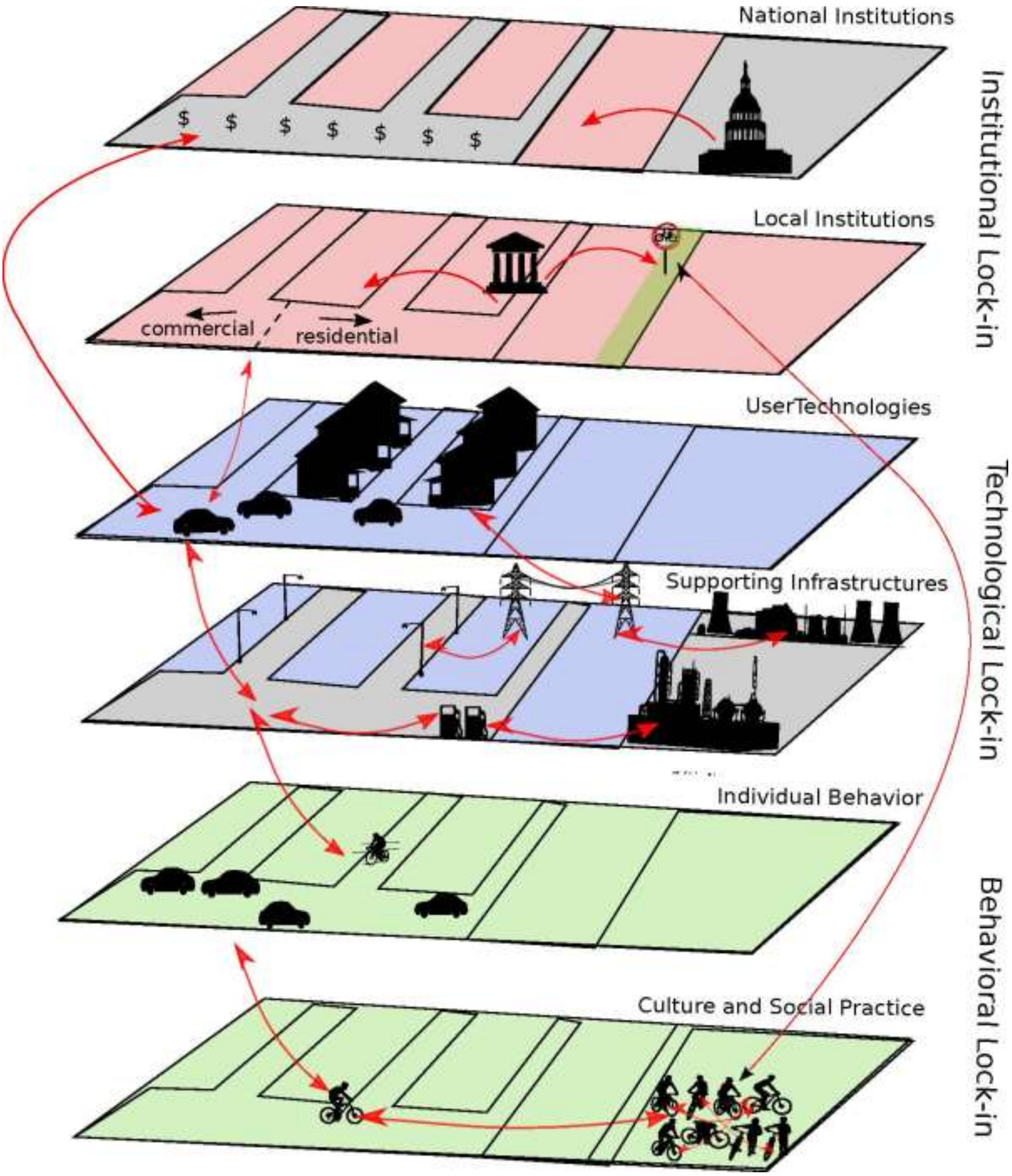
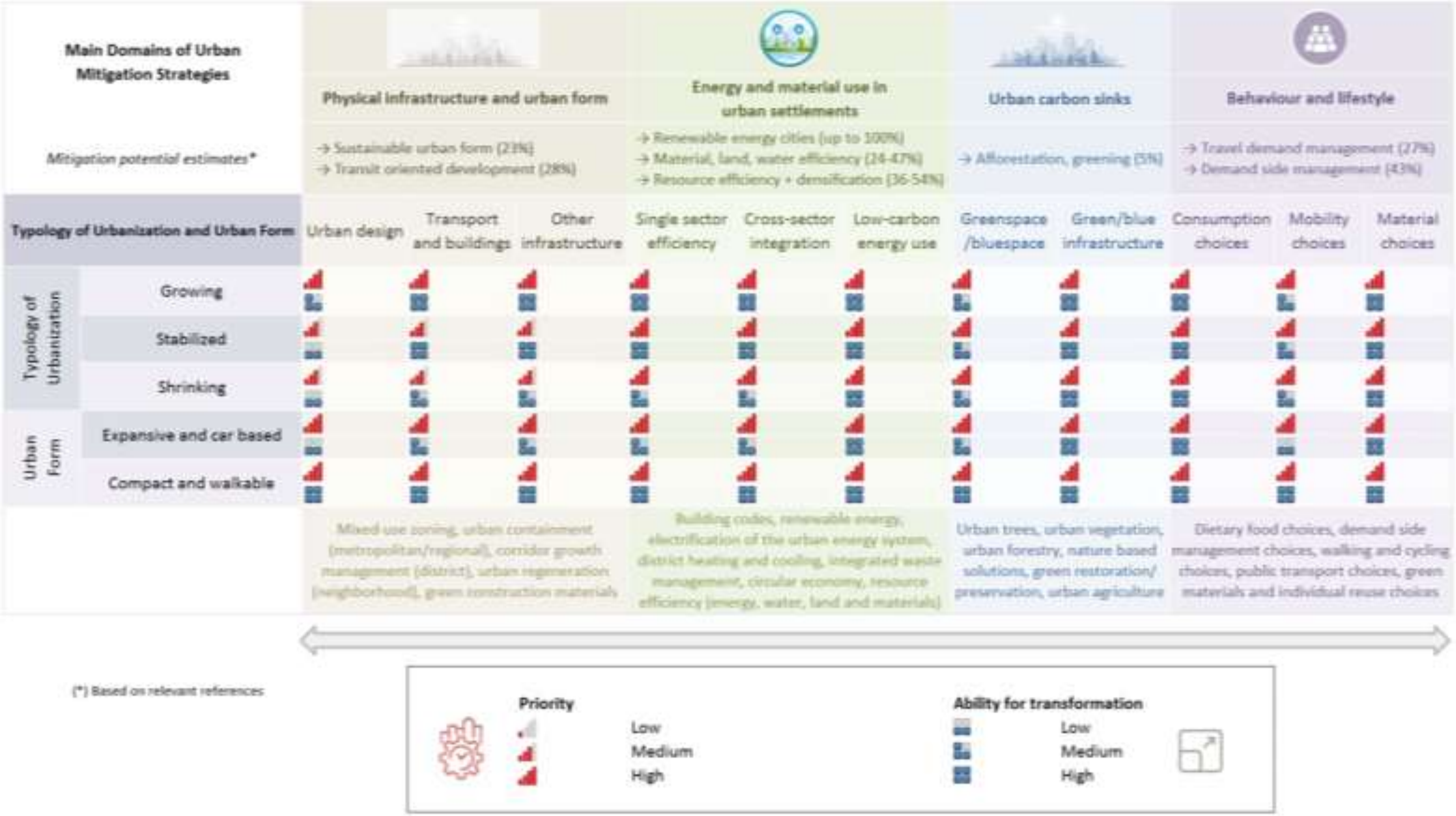


Figure 8.21. Multiple levels of urban carbon lock-in. Interconnections among technological, institutional and behavioural lock-in that exist in cities. Carbon lock-in exists in multiple dimensions (institutional, technological, behavioural), and at multiple spatial and administrative scales (from individual to national), with multidirectional causation between and among the levels.
Figure from Seto et al. (2016), *Permission pending*.

Moreover, in order for cities to achieve net-zero, they will require quite different strategies from the more conventional actions cities have pursued for low-carbon development, such as promoting increased efficiency, incorporating renewable energy, and increasing transit and non-motorised options to reduce motorised travel demand (Seto et al. 2021, *submitted)*. While these strategies will still be part of an urban net-zero portfolio, achieving net-zero will require systemic changes in urban areas and their key infrastructure. We posit that a sequence of three interconnected pathways illustrated in Figure 8.21, with a cascade of levers within each pathway. Urban areas can also prioritise land-based sequestration of carbon, since land management is within the purview of a city.

The way in which urban areas implement these opportunities will also determine their ability to provide co-benefits to their urban inhabitants through improved air quality, reducing the urban heat island effect, and contributing to local livelihoods while achieving climate targets and shifting pathways for sustainable development. Different typologies of urbanisation and urban form can provide different opportunities across the main domains of urban climate mitigation (Cross-chapter box 6 in Chapter 10). Pursuing these opportunities can increase the collective action of urban areas towards net-zero targets. Figure 8.22 summarises these main domains of urban climate mitigation based on priority and ability for transformation. Low-carbon energy supply has high priority and ability for transformation across all typologies of urbanisation and urban form that is further supported by the feasibility assessment of electrification of the urban energy system. Estimates of mitigation potential that are included in Figure 8.22 are based on (Swilling et al. 2018; Sethi et al. 2020) while the typologies of urbanisation and urban form are adapted from (Mahtta et al. 2019).



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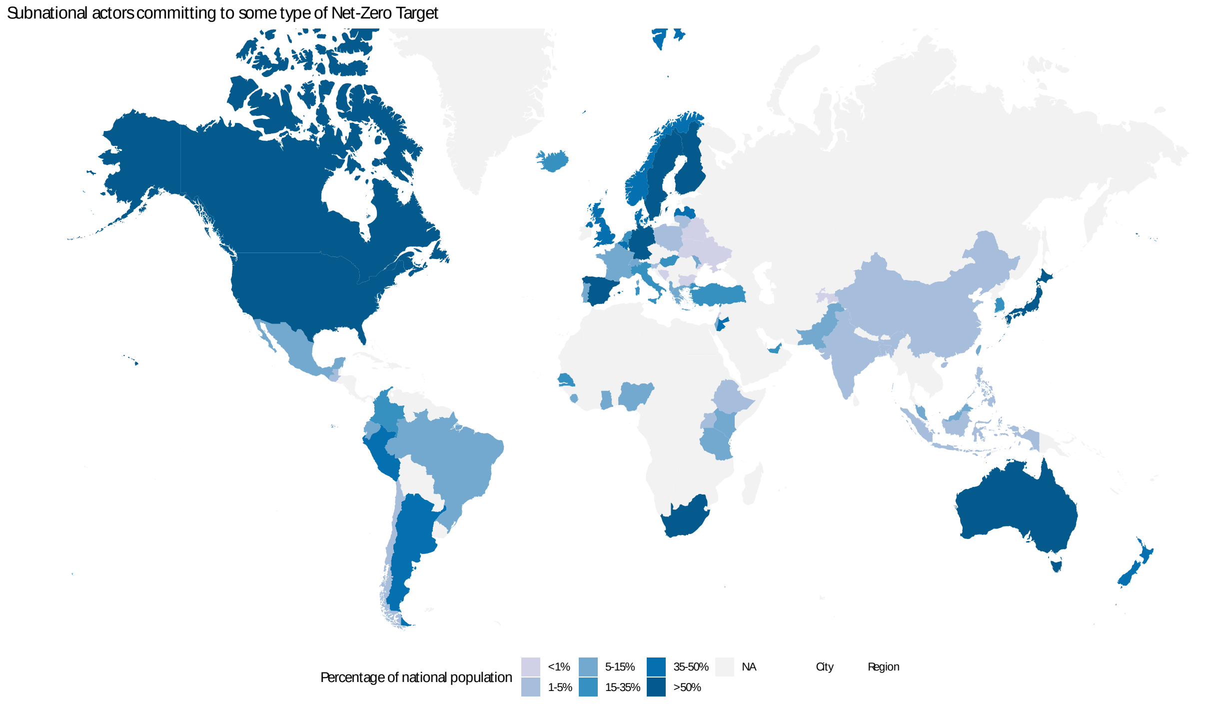
2 **Figure 8.22. Priority and ability for transformation across typologies of urbanisation and urban form for the main domains of urban mitigation strategies.** The main domains of urban mitigation strategies are physical infrastructure and urban form, energy and material use in urban settlements, urban carbon sinks as well as behaviour and lifestyle. Mitigation potential estimates are given for relevant measures based on Swilling et al. (2018) and Sethi et al. (2020). Each domain is further organised into constituent strategies that are evaluated for each cell according to priority and ability for transformation. Growing, stabilised and shrinking urban growth typologies are adapted from Mahtta et al. (2019). In the context of scenarios for resource-efficient urbanisation towards net-zero targets, priority is designated by red coloured bars with ascending order while the ability for transformation is marked by blue shaded areas within the square. All red bars or blue shaded areas represent high levels. Certain strategies have both high priority and high ability for transformation when considered for a given type of urbanisation and urban form that can be used to determine opportunities for policy sequencing. Additional examples for the scope of each domain are given in the last row.

Box 8.1. Net-Zero Targets and Urban Settlements

Around the world, net-zero targets, whether economy-wide or targeting a specific sector (e.g., transport, buildings) or emissions scope (e.g., direct scope 1 or scope 1 and 2), have been adopted by at least 823 cities and 101 regions that represent 11% of the global population with 846 million people across 6 continents (NewClimate Institute and Data-Driven EnviroLab 2020). In some countries, the share of such cities and regions have reached a critical mass by representing more than 70% of their total populations with or without net-zero targets at the national level (Data-Driven EnviroLab and NewClimate Institute 2020). In some cases, the scope of these targets extends beyond net-zero emissions from any given sector based on direct emissions and encompass downstream emissions from a consumption-based perspective with 195 targets that are found to represent economy-wide targets. Currently, 43% of the urban areas with net-zero targets have also put into place related action plans while about 24% have integrated net-zero targets into formal policies and legislation (Data-Driven EnviroLab and NewClimate Institute 2020). Moreover, thousands of urban areas have adopted renewable energy-specific targets for power, heating/cooling and transport and about 250 cities are pursuing 100% renewable energy targets (REN21 2020a).

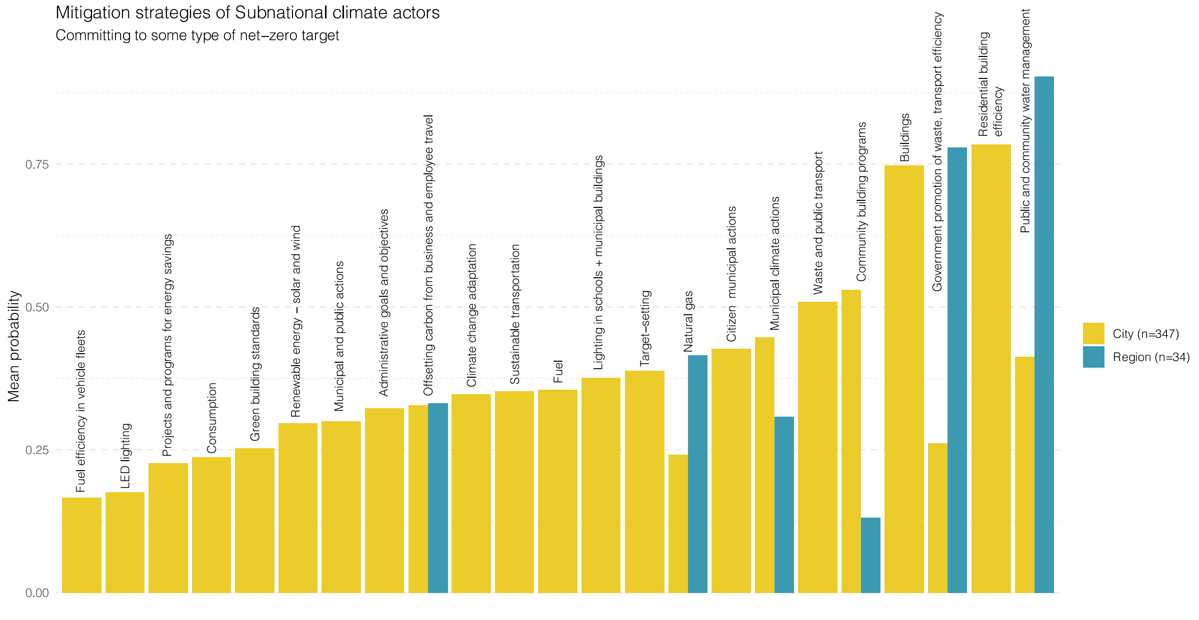
The number of cities, regional governments (i.e., states and provinces) pledging some form of commitment to decarbonise has accelerated in the last two years since SR15. These commitments range from carbon neutrality or net-zero targets, which entail near elimination of city’s own direct or electricity-based emissions but could involve some type of carbon offsetting, to more stringent zero emissions goals. As of October 2020, 826 cities and 103 regional governments had made net-zero commitments, whether economy-wide or focused on a specific sector (i.e., electricity or buildings) (NewClimate Institute and Data-Driven EnviroLab 2020). Some have joined initiatives like the UNFCCC’s Race to Zero campaign or the Carbon Neutral Cities Alliance (CNCA), which sets an emissions reduction target for its members of at least 80% or greater (CNCA 2015). The population living in these cities and regions equals around 880 million people or around 11% of the global population. As these maps show, the greatest density of city and regional governments making these pledges are located in North America, Europe, and East Asia and the Pacific, where Japan’s government has initiated a 2050 Zero Carbon Cities effort that includes 201 local governments that represent more than 70% of the country’s population and 4 trillion USD in GDP (Japan Ministry of the Environment 2020). In Australia, although the national government as of 2020 had not set its own net-zero target, all of its eight state-level governments have pledged to decarbonise by mid-century, which means that more than 95% of the country’s population is covered by net-zero targets.



*Includes sector-specific net-zero targets. Data source: Data-Driven EnviroLab & NewClimate Institute (2020). Accelerating Net Zero: Exploring Cities, Regions, and Companies' Pledges to Decarbonise.

Box 8.1, Figure 1. Subnational actors committing to some type of net-zero target.
Adapted from Hsu et al. (2020a). *Permission pending.*

The extent of realising and implementing these targets with the collective contribution of urban areas to net-zero scenarios with sufficient timing and pace of emission reductions will require a coordinated integration of sectors, strategies, and innovations (Swilling et al. 2018; Hsu et al. 2020b; Sethi et al. 2020; UNEP and IRP 2020). In turn, the transformation of urban systems can significantly impact net-zero emission trajectories within mitigation pathways. Institutional capacity, governance, and cross-sector coordination is crucial for enabling and accelerating urban actions for climate neutrality.



Source:Hsu, A., and R. Rauber (2021); Data–Driven Lab and NewClimate Institute (2020)

Box 8.1, Figure 2. Mitigation strategies of subnational climate actors committing to some type of net-zero target.
Adapted from Hsu and Rauber (2021, *submitted*)**.**

Machine learning algorithms and natural language processing applied to climate action plans from 347 cities and 34 regional governments that have pledged some type of net-zero target (i.e., whether economy-wide or targeting a particular sector like buildings or electricity) provides a systematic analysis of major themes in strategies to address climate change. Box 8.1, Figure 2 shows the likelihood (i.e., mean probability) that these city or regional actors' climate strategies refer to one of 30-topics (Hsu and Rauber 2021, *submitted*) initially derived by analysing more than 9,000 city, company, regional government, and country climate strategy documents. These climate action documents are self-reported to one of several voluntary climate action networks, such as the EU Covenant of Mayors for Climate and Energy, CDP, US Climate Alliance, or ICLEI Local Leaders for Sustainability. While some of these networks and registries have some reporting requirements, cities and regions can also choose to upload their own climate action plans or strategy documents.

The majority of topics revealed through the content analysis focus on climate mitigation activities – mentions of target-setting, renewable energy, fuel-efficiency, building efficiency, sustainable transportation are primarily referred to as ways to reduce greenhouse gas emissions. Reported climate actions reflect two broad approaches to climate mitigation: technological/engineering solutions and "soft" or policy management approaches. Cities and regions appear to focus on citizen engagement and community-building programs as common strategies. Education and awareness building campaigns that engage citizens to change consumption patterns are key strategies, including "soft mobility" campaigns to encourage citizens to increase usage of public transportation. Because the primary data source for regional climate actions was CDP, which provide a reporting template for these governments, there appears to be a lot less diversity in terms of topics reflected in their strategies. Their actions appear to be quite broad, with attention on government promotion of waste and transport efficiency as well as water management. Actions relating to climate adaptation is also another topic that appears with regularity. Some notable gaps in action include the relative lack of actions that address consumption or supply chain emissions.

The integration of sectors, strategies and innovations are necessary to accelerate the realisation of opportunities for climate mitigation in urban areas. The comparison of the outcomes of two urban scenarios that represent resource-efficient and compact urban settlements versus moderate action for sustainable urban settlements also suggest that urban areas need to use their complete urban advantage to initiate rapid reductions in GHG emissions by 2030 towards reaching net-zero targets. Table 8.3 and Figure 8.23 compares the results of these scenarios for the year 2030 across the world regions based on the ratio of 2020 levels for each world region and the resulting GHG emissions.

Table 8.3. Comparison of urban emissions as a ratio to estimated 2020 levels in 2030 (dimensionless). Urban emissions are compared to 2020 levels in 2030 for each region where 2020 levels = 1.00. In the context of urban emissions that are consistent with the IMAGE SSP1-RCP1.9-SPA1 scenario, 2030 urban emissions are between 0.57-0.71 of their 2020 levels towards the path of reaching net-zero emissions. The total urban emissions worldwide would be 0.65 times 2020 levels in 2030 based on resource efficient and compact urbanisation. In the scenario that represents moderate progress and a delayed net-zero response that corresponds to the scenario context of MESSAGE GLOBIOM SSP2-RCP4.5-SPA2, urban emissions would exceed their 2020 levels by ratios between 1.02-1.25 and by 1.08 worldwide in 2030. The values are based on urban scenario analyses as given in Gurney et al. (2020a,*submitted*). *Permission pending.*

Ratio to 2020 Levels in 2030 (2020 Levels = 1.00)	**Urban Scenario Context**	
	Resource efficient and compact	Moderate progress
Africa and Middle East	0.67	1.25
Asia and Developing Pacific	0.71	1.06
Developed Countries	0.57	1.02
E. Europe and West-Central Asia	0.65	1.02
Latin America and Caribbean	0.67	1.24
Total Urban Emissions (World)	0.65	1.08

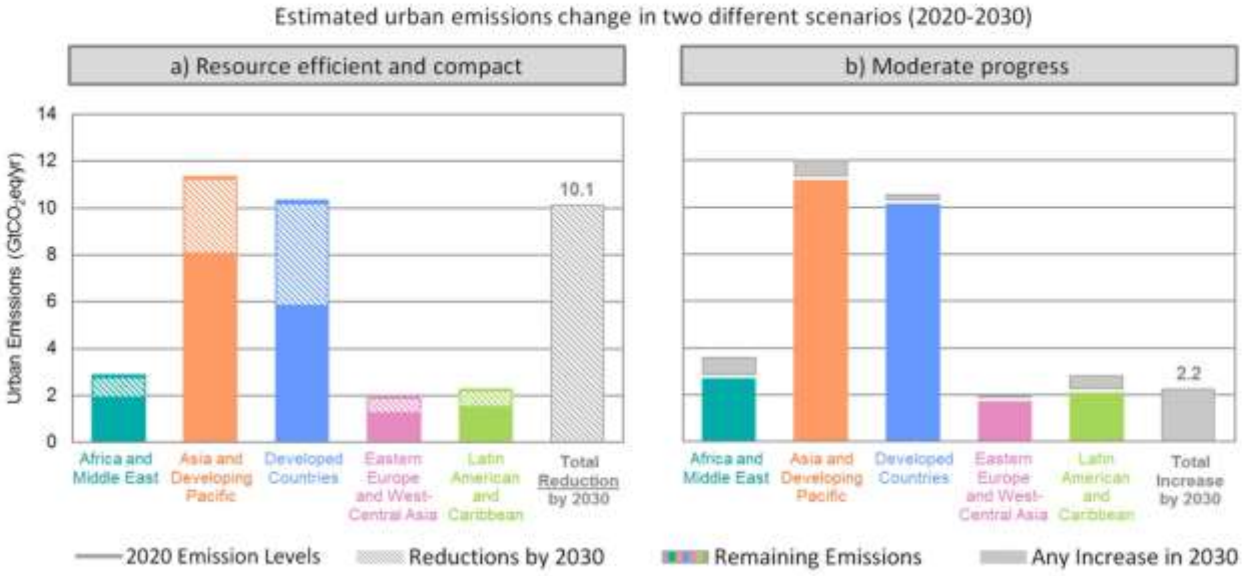


Figure 8.23. Comparison of urban emissions under different urbanisation scenarios (GtCO$_2$-eq yr^{-1}). The panels represent the estimated urban emissions change in two different scenarios for the time period 2020-2030.

Panel (a) represents resource efficient and compact urbanisation while panel (b) represents urbanisation with moderate progress. The two scenarios are consistent with estimated urban emissions under the IMAGE SSP1-RCP1.9-SPA1 and MESSAGE GLOBIOM SSP2-RCP4.5-SPA2 scenarios, respectively (see Figure 8.14). In both panels, urban emissions estimates for the year 2020 are marked by the lines for each region. In the resource efficient and compact scenario, various reductions in urban emissions take place by 2030 that are represented by the dashed areas within the bars. The remaining solid shaded areas represent the remaining urban emissions in 2030 for each region on the path towards net-zero emissions. The total reductions in urban emissions worldwide from 2020 levels by 2030 that are given by the last dashed grey bar in panel (a) is estimated to be 10.1 $GtCO_2$-eq yr^{-1} in this scenario. In the scenario with moderate progress, the white line for each region represents urban emissions in 2020 for each region. There are no regions with reductions in urban emissions in this scenario. The grey shaded areas are the estimated increases for each region so that the total urban emissions would increase by 2.2 $GtCO_2$-eq yr^{-1} from 2020 levels in 2030 under this scenario. The values are based on urban scenario analyses as given in Gurney et al. (2020a, *submitted*). *Permission pending.*

8.4.2.1 Avoiding Carbon lock-in

Urban infrastructures and the built environment are long-lived assets, embodying triple carbon lock-ins in terms of their construction, operations, and demolition (Creutzig et al. 2016b; Seto et al. 2016; Ürge-Vorsatz et al. 2018). In order to meet the Paris Agreement goals, urban infrastructures and the built environment will require fundamental changes, changes that cities alone cannot undertake, and will require provincial and national leadership and legislation, third-sector leadership, transformative actions, and supporting financing.

A major difficulty in confronting carbon lock-in in cities is that some of the issues underlying lock-in are often beyond the ability of cities to control (i.e., the development or pricing of low-emissions technology or materials; e.g. electric battery or hydrogen fuel technology for automobiles or buses) that will be necessary for urban transitions to low-carbon or carbon-free urban environments. In addition, the increasing financialisation of urban infrastructures makes it more difficult for local governments to determine infrastructure choices (O'Brien et al. 2019). However, urban governments in most parts of the world do have powers to set building codes that regulate materials and construction standards for buildings, including heating and cooling technologies, and major appliances; zoning that determines the location of buildings, land uses, and sets standards for densities; and public works, including streets, parks and open spaces (Blanco et al. 2011; Raven et al. 2018).

Urban governments often obtain their powers from provincial/state governments and/or national governments, and their powers to regulate development and implement infrastructure systems may be subject to provincial/national laws and regulations. Because of their importance, the sources of revenue for local governments are often set at the provincial, and, in some countries, the national level (see Section 8.5). Many urban governments rely on state/provincial and federal government funds for infrastructure improvements, especially for road and transit infrastructure. Urban transit system operations, in particular, are heavily subsidised in many countries, not only by local, but also by higher level governments. As a result of this interplay of policy and legal powers among various levels of government, the lock-in nature of urban infrastructures and built environments will require a multi-governmental response to ensure meeting decarbonisation targets. This urban reliance on state and national policy and/or funding can accelerate or impede the decarbonisation of urban environments (McCarney et al. 2011; McCarney 2019).

8.4.3 Reducing urban energy use

Chapter 6 of WGIII summarises the high-level strategy for achieving carbon neutral energy systems by describing the climate-neutral energy systems of; (1) electricity systems that produce zero CO_2 or that remove CO_2 from the atmosphere; (2) widespread electrification of end uses, taking advantage of the opportunities to decarbonise electricity; (3) limited and targeted use of fossil fuels, (4) alternative fuels (e.g., hydrogen, bioenergy, ammonia) to substitute for fossil fuels; (5) more efficient use of energy than today; (6) greater integration across components of the energy system along with greater reliance on integrated management of these systems.

8.4.3.1 Electrification

Most national studies of deep decarbonisation rely strongly on electrification (i.e., the shift from fossil-fuel-combusting devices to electrical ones) (DDPP 2015; Steinberg et al. 2017; Hultman et al. 2020). Electrification of the urban energy system across energy services from transport to heating and cooling represents one of the main domains of urban climate mitigation action. The realisation of the available physical potential depends on the ability to electrify the urban energy system across sectors while supporting flexibility options for deep decarbonisation (Hsieh et al. 2017; Wang et al. 2018; Aghahosseini et al. 2019, 2020; Bogdanov et al. 2019; Child et al. 2019; Hansen et al. 2019; Ram et al. 2020). Urban areas also have the advantage of using urban density to increase the penetration of renewable power and electric public transport, including benefits of mixed-use neighbourhoods for grid balancing (Hsieh et al. 2017; Tong et al. 2017; Fichera et al. 2018).

In this context, low-carbon, zero-carbon, and 100% renewable energy policies for urban development increasingly address multiple aspects of the urban system (Lwasa 2017; Zhao et al. 2017a; van den Dobbelsteen et al. 2018). Options for low-carbon development can involve decentralised systems for water, wastewater and energy, energy efficiency in buildings and transport, spatial configurations of land, and green infrastructure based on urban agriculture and forestry for sequestering GHG emissions (Lwasa 2017).

There is increasing evidence that sustainable urban regeneration can enable low-energy districts and greater quality of life (García-Fuentes and de Torre 2017) with co-benefits for climate mitigation and livelihoods (Thomson and Newman 2016), air quality, and energy security (Shakya 2016). The inclusion of these co-benefits at the societal level can change the results of cost-benefit analyses (Saujot and Lefèvre 2016) while net-zero targets at the local level may already be viable, such as those that involved only a 2.7% increase in net present power and transportation costs (Brozynski and Leibowicz 2018).

In addition, the level of integration among urban sectors can support the ability of increasing flexibility in energy systems with high penetration of variable renewable energy (Kennedy et al. 2017, 2018; Drysdale et al. 2019; Thellufsen et al. 2020) The technological scalability of electrifying the urban energy system depends on the level of support from such flexibility options as demand response, power-to-heat, smart charging and electric mobility, including electrified urban rail (Lund et al. 2015; Salpakari et al. 2016; Calvillo et al. 2016; Newman 2017; Sangiuliano 2017; Zenginis et al. 2017; Bartłomiejczyk 2018; Sharma 2018; Yuan et al. 2018; De Luca et al. 2018; McPherson et al. 2018; Narayanan et al. 2019; Drysdale et al. 2019; Bellocchi et al. 2020; Thellufsen et al. 2020; You and Kim 2020; Calise et al. 2020; Gjorgievski et al. 2020; Meha et al. 2020).

There is increasing evidence that sustainable urban regeneration can enable low-energy districts and greater quality of life (García-Fuentes and de Torre 2017) with co-benefits for climate mitigation and livelihoods (Thomson and Newman 2016) air quality and energy security (Shakya 2016). The inclusion of these co-benefits at the societal level can change the results of cost-benefit analyses (Saujot and Lefèvre 2016) while net-zero targets at the local level may already be viable, such as those that involved only a 2.7% increase in net present power and transportation costs (Brozynski and Leibowicz 2018).

Across global 1.5°C pathways with no or limited overshoot, electricity supplies an increasing share of final energy, reaching 34-71% in 2050 from 20% in 2020. Transportation and buildings made up about 67% of final energy consumption globally in 2018 (IEA 2020a), and while estimates vary widely based on the definition of “urban,” a large fraction of energy consumption in these sectors (between 37% and 86% in buildings and industry, and between 37% and 77% in on-road transportation) occurs in urban areas (Parshall et al. 2010). Thus, electrification of urban buildings and transport could address a significant source of CO_2 emissions in cities, and is one of the major pillars of creating 'net-negative electric cities' along with decarbonisation of the power supply and energy efficiency (Kennedy et al. 2018).

The International Renewable Energy Agency (IRENA) estimates that electrification of buildings and transport globally could provide 8.2 $GtCO_2$ (6.1 $GtCO_2$ for transport alone) in emissions reduction in 2050 (36% of the total potential) when combined with renewable energy (IRENA 2019; UNEP 2019b). In a study of 700 urban areas globally, building and transport electrification and efficiency represent about 20% of the estimated urban abatement potential (3.1 $GtCO_2$) in 2050 (Coalition for Urban Transitions 2019).

At the city-level, most of the exploration of the impact of electric vehicle (EV) deployment and programs, including on GHG emissions, have been in China, the US, and Europe (IEA 2012, 2014, 2016b, 2020b; Cazzola et al. 2019), where more than 83% of the electric cars worldwide are on the roads (IEA 2020b). In the global South, there have been recent studies exploring the conversion of public transport to electric, especially municipal buses (e.g., Bengaluru, India; Jakarta, Indonesia; Medellín, Colombia; Rio de Janeiro, Brazil; Quito, Ecuador) and micro-mobility (e.g., e-trikes in Manila, Philippines), and quantifying attendant benefits in terms of GHG emissions, PM2.5 emissions, avoided premature deaths, and increases in life expectancies (IEA 2014; C40 Cities 2018, 2019, 2020b,c,d). For example, electrification of 100% of the bus fleet in Rio de Janeiro could reduce bus GHG emissions by 93% (0.6 $MtCO_2\ yr^{-1}$) (C40 Cities 2019). In one study of 22 Latin American cities, converting 100% of buses and taxis in 2030 to electric was estimated to result in a reduction of 300 $MtCO_2$-eq compared to 2017 (ONU Medio Ambiente 2017).

While electric stoves are often the most expensive cooking option in developing countries (World Bank Group 2014), in some countries, such as Ecuador, their use is growing, especially in urban areas (Gould et al. 2018). One building electrification measure that has accelerated globally, including developing countries has been the installation of solar water heating (REN21 2020b). By 2015, an installation of 46,000 solar water heating units in Cape Town, South Africa, had reduced emissions by 132,000 tCO_2 per year (IRENA 2018).

The mitigation potential of electrification is highly dependent on the carbon intensity of the electricity grid (Kennedy 2015; Hofmann et al. 2016; Peng et al. 2018; Zhang and Fujimori 2020). Below a threshold of approximately 600 tCO_2-eq /GWh, electrification results in emissions reductions (Kennedy 2015).

Electrification technologies present potential trade-offs, which can be minimised through governance strategies such as international cooperation and circular economy practices. Trade-offs include the materials sourcing of these technologies, which is resource intensive and environmental and socially disruptive, especially if it includes so-called "critical" or "conflict" minerals that are linked to poor labour conditions, political instability, and violence (Church and Crawford 2018; Sovacool et al. 2020) (see also Chapter 10 Box 10.3 'Critical Minerals and The Future of Electro-Mobility and Renewables'). These materials are also subject to potential resource constraints due to high demand and/or conflict in their geographic sourcing (Gaustad et al. 2018).

Further, electrification technologies carry their own carbon footprint; this is particularly a concern for data centres, which generate significant direct emissions (Shehabi et al. 2011; Song et al. 2015; Bilal et al. 2018) as well as indirect climate impacts and other trade-offs through the space and water required for operation (Ristic et al. 2015). International cooperation, public-private partnerships, effective management, energy efficiency technology (for technology development and smart grid operation), and materials recycling are key to minimising potential environmental and social costs (Church and Crawford 2018; Gaustad et al. 2018; Sovacool et al. 2020) and can ensure electrification reaches its full mitigation potential (Chapters 5, 10). Circular economy strategies are particularly valuable to this goal by created closed-loop supply chains for these technologies through recycling, material recovery, repair, and reuse. In Europe, for example, the PV Cycle program has prevented more than 30,000 metric tonnes of renewable technology from reaching the waste stream (Sovacool et al. 2020).

Electrification requires a layering of policies at the national, state, and local levels. Cities have a particular role to play as a policy architect (e.g., transit planning), implementer (e.g., building codes and compliance checking), and complementary partner to national and state policymaking (e.g. permitting or installation of charging infrastructure) (Broekhoff et al. 2015). For electrification to realise its mitigation potential, it will require fiscal and regulatory policies and public investment (Hall et al. 2017b; Deason and Borgeson 2019; Wappelhorst et al. 2020). Where EVs have seen the most rapid deployment, there has generally been a suite of policies, including deployment targets, regulations and use incentives (e.g., zero-emission zone mandates, fuel economy standards, building codes), financial incentives (e.g., vehicles, chargers), industrial policies (e.g., subsidies), and fleet procurement (IEA 2016b, 2017b, 2018, 2019, 2020b). There is usually a mix of policies, such as mandates for bus deployment, purchase subsidies, or split ownership of buses and chargers (IEA 2020b). Subsidies are often critical to address the often higher upfront costs of electric devices. Ecuador has incentivised the uptake of electric induction stoves through the use of government credit and an allotment of free electricity (Martínez et al. 2017; Gould et al. 2018).

Smart Grids

Smart grids are "intelligent electricity grids" that use digital communications technology, information systems, and automation to detect and react to local changes in electricity demand, improve system operating efficiency, and reduce operating costs while maintaining high system reliability (US DOE 2017; Campbell 2018). They are characterised by bi-directional flows of electricity and information between generators and consumers. While smart grid technologies vary, they would include automated control devices, distributed resources, micro-grids, storage systems, power converters, reliable data communication system, sensors, and advanced meter technologies (Kempener et al. 2013; Al-Badi et al. 2020). The deployment of smart grids has been most notable in the US, Europe, Japan, and South Korea, but emerging economies have also invested significantly in smart grids, including China, India, and Brazil (Ngar-yin Mah et al. 2017; Ponce-Jara et al. 2017; Kappagantu and Daniel 2018; Farmanbar et al. 2019; Dranka and Ferreira 2020).

Smart grids are an integral component for cities to reduce emissions. Smart grids have been identified as important technologies for reducing GHG emissions through: (1) peak demand reductions, (2) overall conservation, (3) line loss reductions, and (4) enabling greater penetration of renewables (Hledik 2009). They are particularly beneficial for developing countries, where power outages are costly to the local economies (Westphal et al. 2017). However, in many developing countries, including Sub-Saharan Africa, adoption has been slow due to a number of factors, such as weak and unreliable existing infrastructure, lack of electricity access in urban areas, upfront cost, financial barriers, inefficient pricing of electricity, and lack of consumer education and engagement (Venkatachary et al. 2018; Acakpovi et al. 2019).

One study has estimated that full deployment of smart grids in the United States could reduce GHG emissions and energy consumption by 12–18% in 2030 (Pratt et al. 2010). The IEA has estimated that smart grids could directly and indirectly achieve global net CO_2 emissions reductions of 0.7 Gt to 2.1. Gt by 2050, with the largest reductions in the United States and China (IEA 2011). Moretti et al. (2017) reviewed smart grid studies and found that GHG emission reductions ranges from 10 to 180 gCO_2/kWh (median 89 gCO_2/kWh), depending on the electricity grid mix, penetration of renewables, and system boundary. The GHG emission reductions due to energy losses on the grid were three times smaller than the emission reductions due to the penetration of renewables, underscoring the importance of decarbonising the electricity supply.

However, the transition to a solar future has led to some self-sufficient housing but mostly it has created two-way consumers and producers (called "prosumers") who are able to not just save money by needing less power from the grid but can make money by sending excess power into the grid (Sproul 2019). This interdependence needs a smart grid which can enable the two-way power flows to instantaneously help the householder/business and the grid, creating peer-to-peer trading (P2P) (Hansen et al. 2020). It became more complicated when rooftop solar became part of shared roofs on medium and high-density dwellings but demonstrations have now shown that solar can be shared on a precinct or on a wider neighbourhood basis using smart technology such as blockchain, creating energy management opportunities through local Citizen Utilities (Green and Newman 2017; Green et al. 2020; Syed et al. 2020) and through community batteries (Mey and Hicks 2019; Green et al. 2020). EV's can recharge at such precincts and are now being found to provide grid services through their batteries when needed (Dia 2019) all managed through the smart grid. The vision being developed by this is of a 'distributed city' covered in solar, community batteries and EV's with a much bigger proportion of localised employment and recreation, even industrial estates, with multiple units being joined into a grid that ensures equity as well as a decarbonised future (Galloway and Newman 2014; Byrne and Taminiau 2016; Newman 2020).

8.4.3.2 Urban land use and spatial planning

AR5 WGIII Chapter 12 assessed the GHG emission impact of changes in urban form and urban spatial structure based on literature that was dominated by case studies of cities in North America, and those in other developed countries, emerging economies, and developing countries were highly limited.

Since AR5, a range of empirical findings on the relationships between urban form/urban spatial structure and GHG (CO_2-eq) emissions have increasingly been reported from cities in developed countries and emerging economies (predominantly China). The body of the literature can be divided up into two geographic approaches: inter-city case and intra-city unit comparison studies. Key findings are summarised by geographic approach, country category, spatial matrix, and source sector.

Integrated spatial planning, policies and systemic approaches are widely identified with development that is characterised by the 5Ds or Transit Oriented Development (TODs), which include density, diversity (mixed uses), design (street connectivity), destination accessibility, and distance to transit. Research indicates that spatial strategies to increase the 5Ds reduce vehicle miles travelled (VMT), and thereby GHG emissions, although research syntheses indicate that the impact of each factor alone on VMT is small. A major research synthesis has been published (Stevens 2017) on the effect of urban form/built environment strategies on VMT. The new synthesis goes beyond providing elasticity values by accounting for self-selection and reporting bias. The Table 8.4 below compares weighted average elasticities of VMT per capita with respect to D-variables from the earlier Ewing and Cervero (2010) synthesis to Stevens (2017).

Table 8.4. Comparison of US Major Studies on the Effects of Urban Form Strategies on VMT. Elasticity is a measure of the change in a variable to the associated change in VMT. For example, if the elasticity is -0.04, as the density is increased 100% or doubled, VMT would decrease by 4%.
Table from Blanco and Wikstrom (2018, p. 5). *Permission pending.*

Urban Form Strategies	Impacts of Strategies on VMT in terms of Elasticities			
	Transportation Research Board and National Research Council (2009): Driving and the Built Environment	Ewing and Cervero (2010) Meta-analysis		Stevens (2017) Meta-regression (First number controls for self-selection/second does not)
Density	-.05 to -.12	-0.04		-0.22/-0.10
Mixed Uses (Diversity)		-0.09		0.11/-0.03
Intersection/street density (Design)		-0.12		-0.14
Job Accessibility by auto (Destination Accessibility)		-0.20		-0.20
Job Accessibility by transit (Destination Accessibility)		-0.05		0.00
Distance to Transit		-0.05		-0.05

Meta-analyses of the reduction in VMT (and thereby of GHG emissions) as discussed above, given the existing and still dominant carbon-emitting transportation technology, transportation fleets, and urban form characteristics, assume, but do not take into account the varied historical legacies of transportation and the built environment.

Urban land use and spatial planning can significantly reduce pressures on physical land resources while changes in population density and different dynamics of stable, outward and/or upward growth are taking place in urban settlements (Mahtta et al. 2019; Güneralp et al. 2020), Related impacts on geophysical resources also depends on the ability to limit demands on materials for urban construction (Müller et al. 2013; Bai et al. 2018; Swilling et al. 2018; Magnusson et al. 2019; UNEP and IRP 2020) In contrast to existing trends, however, scenarios with more ambitious temperature goals involve lower urban land use (Gao and O’Neill 2020; Güneralp et al. 2020).

From an environmental and ecological perspective, the impact of urban land use and spatial planning on improving air quality depends on the energy mix that is involved in the urban infrastructure while compact urban form reduces energy use due to vehicle transport (Burgalassi and Luzzati 2015; Zhang et al. 2018a,b; Pierer and Creutzig 2019). Impacts on ecotoxicity depends on urban land use, permeable versus impermeable urban surfaces and the ability to limit urban storm water runoff with better urban land use and spatial planning (Phillips et al. 2018; Regier et al. 2020; Charters et al. 2021).

Impacts on water quantity and quality depends on the urban water system, including supply, purification, distribution and drainage, the magnitude, source and location of water supply, and the level of integration between urban land-use and water planning that requires policy integration and innovation (Serrao-Neumann et al. 2017; James et al. 2018; Rodríguez-Sinobas et al. 2018; Xu et al. 2018; Ahmad et al. 2020; Lei et al. 2021). Limiting the growth in urban extent, integrating ecosystem service information into spatial planning, reducing the demands of urban areas on resources and materials and increasing urban nature based solutions can further ensure that urbanisation reduces impacts on biodiversity (Huang et al. 2018a; McDonald et al. 2018, 2020; IPBES 2019b; Cortinovis and Geneletti 2020; Güneralp et al. 2020). At the same time, the geographical coverage of harmonised algorithms to monitor land use change is currently limited (Reba and Seto 2020).

Urban land use and spatial planning for sustainable urban form is a system-wide intervention (Sethi et al. 2020) and has potential to be combined with sustainable development objectives while pursuing climate mitigation for urban systems (Große et al. 2016; Cheshmehzangi and Butters 2017; Facchini et al. 2017; Lwasa 2017; Stokes and Seto 2019) Compact urban form can also enable positive impacts on employment and green growth given that the local economy is decoupled from emissions, vehicle km travelled and related parameters while the concentration of people and activity can increase productivity based on proximity and efficiency (Lee and Erickson 2017; Salat et al. 2017; Gao and Newman 2018; Han et al. 2018; Li and Liu 2018).

Public acceptance can have a positive impact on the feasibility of urban land use and spatial planning especially through a process of co-design (Grandin et al. 2018; Webb et al. 2018) The quality of spatial planning can also increase co-benefits for health and wellbeing, including decisions to balance urban green areas with density (Li et al. 2016; Sorkin 2018; Pierer and Creutzig 2019). The distributional effects of urban land use and spatial planning can have a positive or negative impact that depends on such aspects as the policy tools that shape the influence of urban densification on affordable housing while evidence for transit-induced gentrification is found to be partial and inconclusive (Chava and Newman 2016; Jagarnath and Thambiran 2018; Padeiro et al. 2019; Debrunner and Hartmann 2020).

From an institutional standpoint, aspects of political acceptance depends on the ability to integrate opportunities for climate mitigation with co-benefits for health and wellbeing (Grandin et al. 2018). At the same time, requirements for institutional capacity and governance for cross-sector coordination for integrated urban planning is high given the complex relations between urban mobility, buildings, energy systems, water systems, ecosystem services, other urban sectors and climate adaptation (Große et al. 2016; Castán Broto 2017a; Endo et al. 2017; Geneletti et al. 2017). In addition, the capacity for implementing land use zoning and regulations in a way that is consistent with urban land use and spatial planning is not equal across urban areas and depends on different contexts as well as institutional capacities (Deng et al. 2018; Yılmaz Bakır et al. 2018; Shen et al. 2019).

In addition, the physical potential of district heating and/or cooling networks depends on the thermal energy demands in comparison to the spatial characteristics of urban areas (Swilling et al. 2018; Möller et al. 2019; Persson et al. 2019; UNEP and IRP 2020). The heat demand density that is a function of both population density and heat demand per capita can be equally present in urban areas with high population density or high heat demand per capita (Möller et al. 2019; Persson et al. 2019). The piping layout and the implementation of eco-design principles can further optimise such networks (Wang et al. 2016; UNEP and IRP 2020).

District heating and cooling networks benefit from compact urban form and urban design parameters, including density, block area, and elongation that represent the influence of urban density on energy density (Fonseca and Schlueter 2015; Shi et al. 2020). The environmental and ecological benefits of the response options depends on the energy resource and the interaction of urban energy planning with urban land use and spatial planning (Tuomisto et al. 2015; Bartolozzi et al. 2017; Dénarié et al. 2018; Swilling et al. 2018; Zhai et al. 2020). Currently, the annual GHG emissions reduction potential of renewable energy based district heating and related measures is estimated to be 1.9 $GtCO_2$ by 2050 (UNEP 2019b).

From a technological perspective, urban areas provide economies of scope for district heating and/or cooling networks, including access to existing excess heat, power-to-heat options with large-scale heat pumps, urban infrastructure, support from GIS for urban planning and climate ambition for climate neutrality (UNEP 2015; Persson et al. 2019; REN21 2020a). This further supports the technological scalability of such networks that depends on the geographic heat demand density of the urban area in different contexts while also capable of supporting flexibility in the energy system by acting as low-cost energy storage options (Borelli et al. 2015; Webb 2015; Xiong et al. 2015; Zhang et al. 2016; Felipe Andreu et al. 2016; Liu et al. 2017b; Loibl et al. 2017; Lund et al. 2017; Pavičević et al. 2017; Popovski et al. 2018; Bünning et al. 2018; Yeo et al. 2018; Chaer et al. 2018; Dominković et al. 2018; Hast et al. 2018; Köfinger et al. 2018; Bozhikaliev et al. 2019; Möller et al. 2019; Persson et al. 2019; Pieper et al. 2019; Dominković and Krajačić 2019; Dorotić et al. 2019; Sorknæs et al. 2020).

8.4.4 Urban nature-based solutions for climate change mitigation

The European Commission (EC) defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience" (EC 2016). NBS may be regarded as a comprehensive umbrella concept that integrates established ecosystem-based approaches, such as green-blue infrastructure, that provide multiple ecosystem services, and which are of particular importance in the context of societal challenges related to urbanisation and climate change (Raymond et al. 2017). NBS are further linked to the ecosystem services approach in the context of climate change mitigation: "In nature-based climate change mitigation, ecosystem services are used to reduce greenhouse gas emissions and to conserve and expand carbon sinks" (Naumann et al. 2014, p. 4).

NBS may be related to built-up building infrastructure such as green roofs or green facades (e.g., green walls) or non-building related strategies such as trees (see Section 8.4.4.1) or sustainable urban drainage systems (SUDS). Integrated NBS strategies may also relate to urban planning that aims at providing a connected system of green infrastructure to promote active transportation. Figure 8.24 provides an overview on ecosystem services/benefits provided by NBS types as introduced in the literature.

In recent studies, green roofs and green walls were illustrated for their potential to mitigate air and surface temperature, improve thermal comfort, and mitigate UHI effects, while also lowering the energy demand of buildings. Bevilacqua et al. (2016) showed that temperature reduction potential was shown for green roofs compared to conventional roofs to be about 4°C in winter, and about 12°C during summer conditions. For green walls/facades, Perini et al. (2017) found a temperature difference between air temperature outside and behind a green wall of up to 10°C with an average difference of 5°C in a Mediterranean European case study. These authors also showed the potential of saving energy for air conditioning by green facades of around 26% for the summer months.

Concerning the potential of reduction of energy demand by green roofs, studies identified that energy demand was 60–70% and 45–60% lower with the green roof compared to black and white roofs, respectively (Silva et al. 2016). In addition, heating demand of buildings may be reduced by 10–30% through green roofs (Besir and Cuce 2018). Specific green roof configurations were shown to also store carbon by 18.28 kg C m^{-2} and sequester carbon by average on of 6.47 kg C m^{-2} yr^{-1} (combined biomass and substrate organic matter) (Luo et al. 2015).

In terms of stormwater management, specific NBS constructions are used as a sustainable solution to mitigate water runoff and urban floods. Here, measured quantified evidence is still low but some studies model water runoff processes and rainfall events to identify potential impacts of surface character and type of NBS. Using green was shown to significantly delay time to runoff while in addition porous pavement can significantly reduce the peak flow and runoff discharge. In terms of location, a study in Malmö, Sweden, concluded that implementing blue-green stormwater retrofit systems in downstream catchments are particularly useful at the most upstream areas in the network and then move towards downstream areas with implementation actions to reduce the peak flows by around 80% (Haghighatafshar et al. 2018).

SUDS as part of stormwater management systems provide a sustainable solution to stormwater flooding because rather than relying on piped engineered system, SUDS use nature based elements and processes (i.e., infiltration, evapotranspiration, filtration, retention and reuse) for water runoff attenuation and mitigation, reduction of flow rates, controlling pollution transport and capacity increase to store water (Srishantha and Rathnayake 2017). Still, implementing SUDS is challenging because of existing difficulties in quantifying the hydraulic performance, measuring water quality improvement, the requirement for high maintenance costs and, the need for coordination between stakeholders (Mguni et al. 2016). Green roofs have also been shown to have beneficial effects in storm water reduction (Andrés-Doménech et al. (2018)).

Providing a connected system of greenways throughout the city may promote active transportation, thereby reducing GHG emissions. Soft solutions such as NBS planning schemes for improving GI-connectivity for cycling can also be regarded as an NBS mitigation measure. Evidence is, however, low so far in terms of a (potential) reduction of emissions. In the city of Lisbon, Portugal, improvements in cycling infrastructure and bike-sharing system resulted in 3.5 more cyclists (Félix et al. 2020). Another study in Copenhagen, Denmark, compared the cost of cars and bicycles and showed that the cost of car driving is more than six times higher (Euro 0.50/km) than cycling (Euro 0.08/km) and the cost of cycling appears to be declining (Vedel et al. 2017). In a related survey, participants stated that they are willing to cycle 1.84 km longer if the route has a designated cycle track, and 0.8 km more if there are green surroundings too. Although no quantified results are available yet, supporting the transition from private motorised transportation to public and active transportation with and through changes in urban landscapes (i.e., through implementing NBS in sustainable urban and transport planning) is regarded as a major strategy to carbon-neutral, more liveable, healthier cities (Nieuwenhuijsen and Khreis 2016) (Nieuwenhuijsen 2020). One example is the implementation of the Superblock model in Barcelona’s neighbourhoods in which car infrastructure was transferred into public open and green space (Rueda 2019). Health impact assessment models estimated that 681 premature deaths may be prevented annually with this implementation (Mueller et al. 2020b). Another example is the creation of greenways in Maanshwahan, China, which have stimulated interests in walking or cycling (stated by 84.2% survey participants) (Zhang et al. 2020). The potential for the NBS in emerging urban areas of developing countries is yet to be assessed but the opportunities exist in these urban areas through spatial planning with existing built environment (Kavonic and Bulkeley, *submitted*; Tozer et al. 2021, *submitted*).

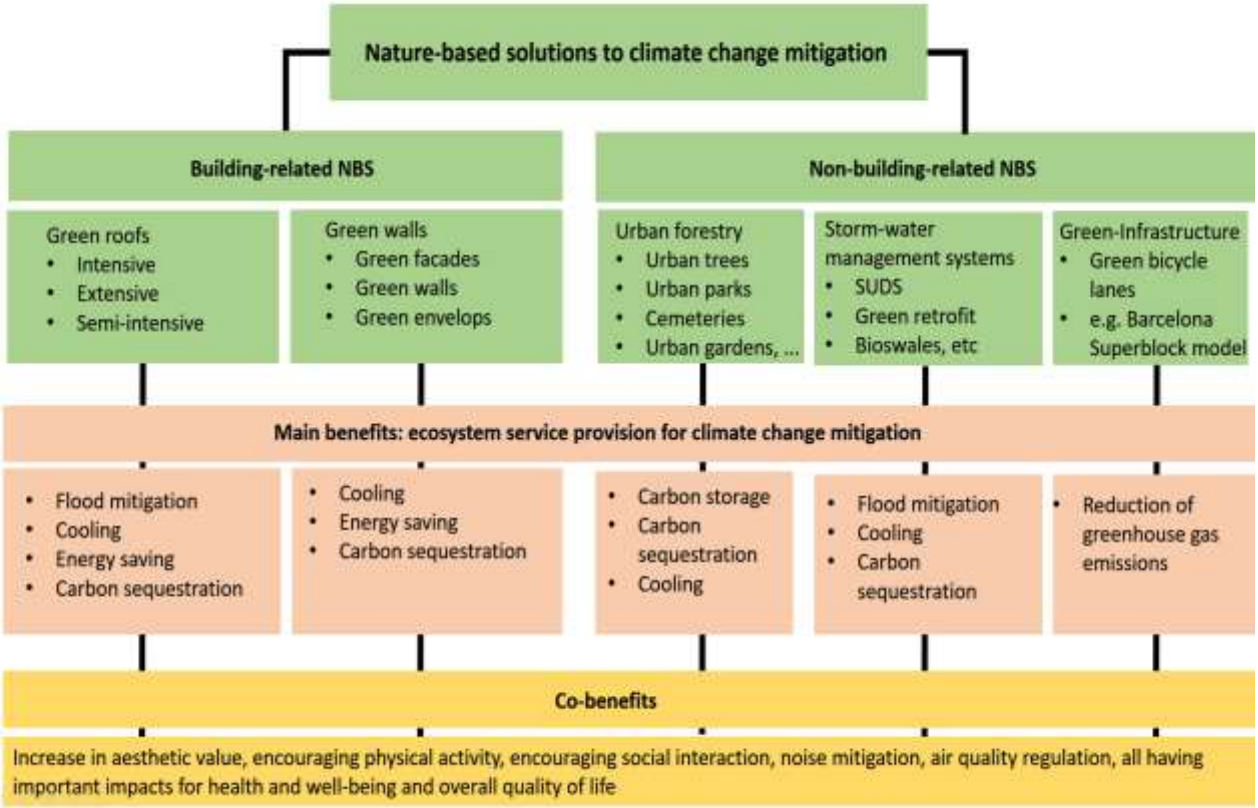


Figure 8.24. Selected types of NBS for climate change mitigation. This figure outlines selected types of NBS effective for climate change mitigation with main ecosystem services, as illustrated in the literature.

8.4.4.1 The potential of urban trees for climate change mitigation

Vegetation within urban areas, particularly trees, can play an important role in mitigating emissions and climate change impacts. Globally, urban tree cover averages 26.5%, but varies from an average of 12% in deserts to 30.4% in forested regions (Nowak and Greenfield 2020). Assuming 363 million hectares of urban land (World Bank et al. 2013) and an average carbon storage density of 7.69 kgC/m^2 of urban tree cover (Nowak et al. 2013), global urban tree carbon storage is on the order of 7.4 billion tonnes. Given an average plantable (non-tree and non-impervious) space of 48% (Nowak and Greenfield 2020), the carbon storage value could nearly triple if all this space is converted to tree cover. However, land use, water, and other environmental restrictions will limit the expansion of tree cover in urban areas. Assuming an average annual carbon sequestration rate of 0.226 kgC/m^2 of urban tree cover (Nowak et al. 2013), annual global urban tree carbon sequestration is on the order of 217 million tonnes.

The global estimates of urban tree carbon storage and sequestration are based on carbon density values from the US. As carbon sequestered by vegetation in Amazonian forests is two to five times higher compared to boreal and temperate forests (these global estimates are likely conservative) (Blais et al. 2005). Carbon storage density rates in the US vary from 3.14 to 14.1 kgC/m^2 of tree cover and are comparable to urban tree values from other countries: South Korea (3.85–5.58 kgC/m^2), Leipzig, Germany (6.82 kgC/m^2), Barcelona, Spain (4.45 kgC/m^2; range among land uses: 1.53-9.67 kgC/m^2), Hangzhou, China (4.28 kgC/m^2) and Leicester, England (28.1-28.9 kgC/m^2) (Nowak et al. 2013). More research is needed to develop better global estimates.

More importantly, trees in urban areas reduce air temperatures, shade surfaces, consequently alter building energy use and can be economically productive. On a per-tree basis, urban trees offer the greatest potential to reduce climate change as not only do they sequester carbon, but they also can provide a permanent reduction in GHG emissions through reduced energy use. Urban trees can also help mitigate some of the impacts of climate change by reducing UHIs and heat stress, reducing stormwater runoff, improving air quality, and improving health and wellbeing in areas where the majority of the world's population resides. In the US, urban forests reduce building energy use by 7.2%, equating to an emissions reduction of 43.8 million tonnes of CO_2 annually (Nowak et al. 2017). Urban trees in forested regions likely have similar percent reductions in energy use, but the actual reductions are unknown globally. Maximum possible street tree-planting among 245 cities from across the world could reduce residential electrical use by 0.9–4.8% annually (McDonald et al. 2016). However, depending upon tree locations around buildings, trees can increase winter energy use by shading buildings. In heating-dominated cities, landscape designs should consider tree locations near buildings to avoid increasing winter energy use and emissions. In developing countries, urban and peri-urban agriculture can have economic benefits with fruit, ornamental and medicinal trees (Gopal and Nagendra 2014; Lwasa 2017; Lwasa et al. 2018).

Box 8.2. Urban carbon storage: An example from New York City

The structure, composition, extant, and growing conditions of vegetation influences the potential they have for mitigating climate change in cities (Pregitzer et al. 2020, *under review*). Urban natural areas, particularly forested natural areas, grow in patches and contain many of the same components as non-urban forests, such as high tree density, down woody material, and regenerating trees (Box 8.2, Figure 1).

Urban forested natural areas have unique benefits as they can provide habitat for native plants and animals, protecting local biodiversity in a fragmented landscape (Di Giulio et al. 2009). Forests can have a greater cooling effect on cities than designed greenspaces, and the bigger the forest the greater the effect (Jaganmohan et al. 2015). In New York City, urban forested natural areas have been found to account for the majority of trees estimated in the city (69%), but are a minority of the total tree canopy (25%, or 5.5% of the total city land area) (Figure 1, Pregitzer et al. 2019a). In New York City, natural areas are estimated to store a mean of 263.5 Mg C ha-1, adding up to 1.84 Tg C across the city, with the majority of carbon (86%) being stored in the trees and soils (Figure 1, Pregitzer et al. 2020, *under review*). These estimates are similar to per-hectare estimates of carbon storage across different pools in non-urban forest types (Box 8.2, Table 1), and 1.5 times greater than estimates for carbon stored in just trees across the entire city (Pregitzer et al. 2020, *under review*).

Within urban natural areas, the amount of carbon stored varies widely based on vegetation type, tree density, and the species composition (Box 8.2, Figure 1). The oak-hardwood forest type is one of the most abundant in New York City's natural areas and is characterised by large and long-lived native hardwood tree species, with relatively dense wood. These forests store an estimated 311.5 Mg C ha-1. However, non-native exotic invasive species can be prevalent in the understory in cities, and account for about 50% of cover in New York City (Pregitzer et al. 2019b).

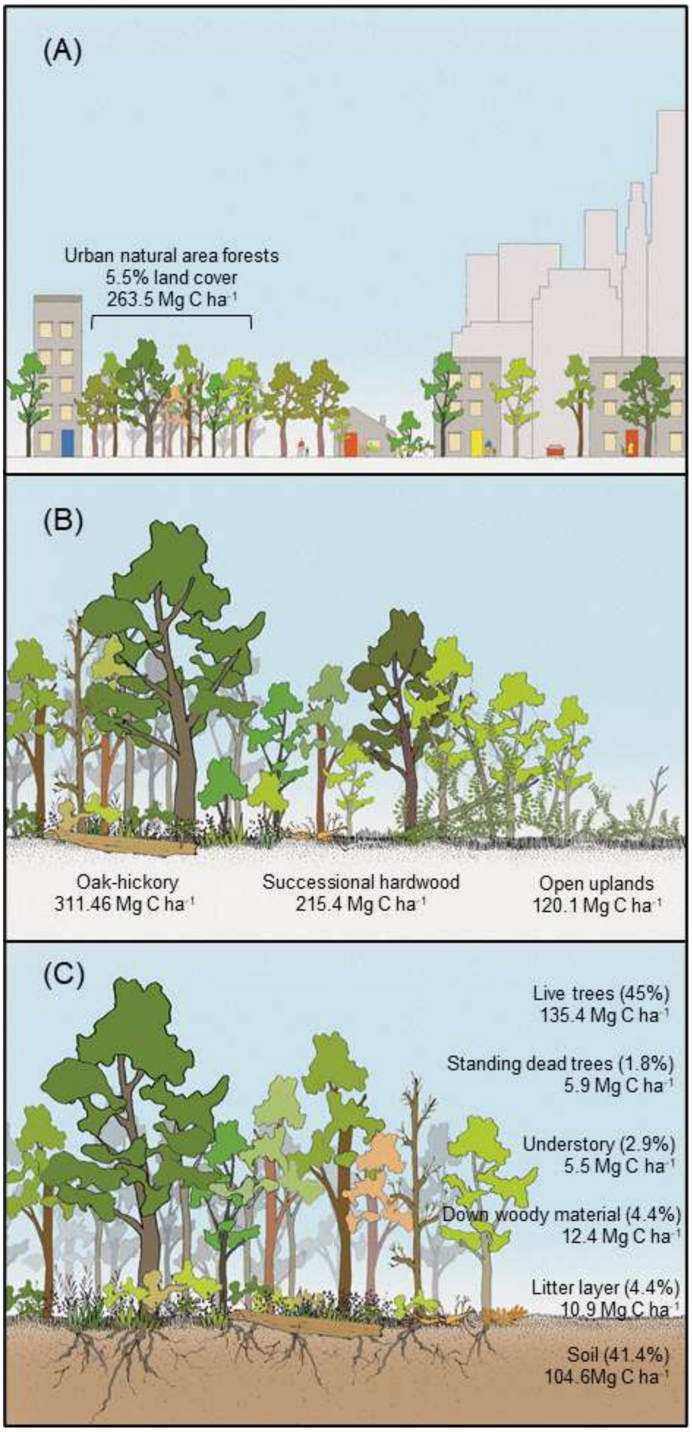
This could lead to a trajectory where exotic understory species out compete regenerating trees in the understory layer, alter the soil (Ward et al. 2020, Box 8.2, Figure 1) and alter the forest canopy (Matthews et al. 2016). A change in New York City's vegetation structure and composition to a more open vegetation type could reduce the carbon storage by over half (open grassland 120.1 Mg C ha-1, see Box 8.2, Figure 1). Due to their potential to store relatively high amounts of carbon compared to other types of urban vegetation as well as provide many climate mitigation co-benefits, natural area protection and natural forest management in cities should be an important priority in cities looking to mitigate climate change.

When compared to estimates of carbon storage to other studies, the components (pools) of the natural area forests in New York City store carbon in similar proportions to other non-urban forests (Box 8.2,

Table 1). This might suggest that in other geographies, similar adjacent non-urban forest types may store similar carbon stocks per unit area. However, despite similarities to non-urban forests, the urban context can lead to altered forest function and carbon cycling that should be considered. For example, trees growing in urban areas have been observed to grow at much higher rates due higher access to light, nutrients, and increased temperatures (Gregg et al. 2003; Reinmann et al. 2020).

Higher growth rates coupled with the urban heat island have also been suggested to yield greater evaporative cooling by urban canopies relative to rural forests (Winbourne et al. 2020). Based on estimates in New York City it is likely that the majority of tree biomass, and carbon in cities, could be found in urban natural area forest patches. More research is needed to map urban natural areas, assess vegetation, and differentiate tree canopy types (natural vs. non-natural) at fine scales within many cities and geographies. Accurate maps, and understanding of definitions of urban canopies and vegetation could lead to better accounts for carbon stocks and the many other unique benefits they provide (Raciti et al. 2012; Pregitzer et al. 2019a).

Despite this potential, natural areas are inherently a minority land use type in cities and should be viewed along with other types of urban tree canopy that occur in more designed environments that might out-perform natural areas in other ecosystem services. The mosaic of vegetation characteristics and growing conditions will yield different ecosystem services across cities (Pataki et al. 2011) and should be an important consideration in planning, management and policy in the future.



Box 8.2, Figure 1. Estimates for carbon storage in natural area forests in New York City. (A) Mean estimated carbon stock per hectare in natural area forests (Pregitzer et al. 2019a, 2020, *under review*); (B) Estimates for carbon stocks vary based on vegetation types; and (C) Estimates of the amount of carbon stock in different forest pools per hectare. The proportion of the total estimated carbon stock per pool is out of the total estimated for the entire city (1.84 Tg of C).

Figure from Pregitzer et al. (2020, *under review*)

Box 8.2, Table 1. Benchmark reference estimates for carbon stock and atmosphere exchange estimates for other studies in comparison to New York City natural area forests. Estimates for NYC stock and stock change are based off of Pregitzer et al. (2020, *under review*).

Pool	**Published Estimates Carbon Stock (Mg C ha-1)**	**NYC Natural Area Stock Estimates Mg C ha-1 (mean +/- standard deviation) - from Pregitzer et al. (2020, *under review*).**	**Published Atmosphere Exchange Estimates (Mg C ha-1 y-1)**	**NYC Natural Area Stock change* estimates Mg C ha-1 y-1 (mean +/- standard deviation) - from Pregitzer et al. (2020, *under review*).**
Live Trees	87.1 - Northeastern US (Smith et al. 2013) 73.3 - NYC assuming 100% cover (Nowak et al. 2013)	135.4 (+/- 106.6)	1.24 sequestered, NYC assuming 100% cover (Nowak et al. 2013)	8.98 (+/- 4.7) sequestered
Groundcover	1.8 - Northeastern US (Smith et al. 2013)	5.5 (+/- 3.68)	Negligible	not estimated
Standing Dead Trees	5.1 - Northeastern US (Smith et al. 2013) 2.59 - Massachusetts (Liu et al. 2006)	5.8 (+/- 16.2)	0.08 emitted, Massachusetts (Liu et al. 2006) 1.52 emitted, Japan (Jomura et al. 2007)	0.14 (+/-0.38) emitted

Down Woody Material	9.18 - Coarse woody material-NY state (Woodall et al. 2013) 2.52 - Coarse woody material - Massachusetts (Liu et al. 2006) 6.37 - Fine woody material - NY (Woodall et al. 2013) 3.67- Fine woody material Northern hardwood; 0 to 227.94, Northern US (Domke et al. 2016)	12.14 (+/-41.23) Coarse and fine woody material combined	0.53 emitted, Wisconsin (Forrester et al. 2012) 0.21 Michigan (Gough et al. 2007) and Massachusetts (Liu et al. 2006)	0.96 (+/-3.34) emitted
Litter and Duff	12 - NYC (Pouyat et al. 2002) 9.36 - Northern hardwood; 0.04 to 86.1, Northern US (Domke et al. 2016)	10.9 (+/- 7.4)	0.6 to 1.3 emitted, Massachusetts (Gaudinski et al. 2000) 2.3 to 2.6 Mg/ha/yr emitted, Rhode Island (Davis et al. 2010)	1.65 (+/- 0.96) emitted
Mineral Soil (Organic)	104 - to 30 cm depth, NYC (Cambou et al. 2018) 50 - to 10 cm depth, NYC (Pouyat et al. 2002)	104.6 (+/- 68.14)	6.83 emitted (A & Ap layers), Massachusetts (Gaudinski et al. 2000) – heterotrophic respiration only, excludes root respiration and sequestration	1.34 (+/-1.03) sequestered

8.4.5 Urban-rural linkages

Cities are open systems that depend on their hinterlands in terms of imports (e.g., resources, products for industrial production or final use) and exports (e.g., emissions, manufactured products). As supply chains are becoming increasingly global in nature, so do the hinterlands of cities. Since cities only have legislative power within their jurisdictional boundaries, the territorial approach may often be seen as the only enforceable strategy. However, cities can influence the large upstream emissions through their supply chains and through activities in cities that rely on resources outside the city. Cities can play an important and constructive role in climate change mitigation if they do not limit their efforts to reducing their own emissions, but if they engage in efforts to lower global emissions, which involves a dual strategy of implementing local actions and taking responsibility for the entire supply chains of imported and exported goods. The following sections discuss some of the key linkages between urban and rural emissions, namely through waste, food, and water.

8.4.5.1 Waste prevention, minimisation, and management

The waste sector remains the largest contributor to urban emissions after the energy sector, even in low-carbon cities (Lu and Li 2019). Integrated policymaking can increase both energy and material benefits in the waste sector (Hjalmarsson 2015), accelerating the peaking of emissions (Fang et al. 2017) and providing back-up capacity to solar and wind energy based renewable energy systems (Jiang et al. 2017).

Integrated municipal solid waste management can allow cities to maximise the mitigation potential of the waste sector while reducing pressures on land and the environment. This strategy reduces emissions due to (i) avoided emissions upstream in the supply chain of materials based on measures for recycling and the reuse of materials, and (ii) avoided emissions due to land use changes as well as emissions that are released into the atmosphere from waste disposal, and (iii) avoided primary energy spending based on waste-to-energy (WtE) measures.

Waste prevention, minimisation, and management thus provides the potential of alleviating resource usage and upstream emissions from urban settlements (Swilling et al. 2018; Chen et al. 2020b; Harris et al. 2020). From a technological perspective, the simplicity of waste management depends on the context of implementing the waste hierarchy from prevention onward and the effectiveness of waste separation at source (Sun et al. 2018a; Hunter et al. 2019). The technological scalability depends on the waste management system as well as the stage of urban development, including materials from urban construction (Eriksson et al. 2015; Kabir et al. 2015; Boyer and Ramaswami 2017; Soares and Martins 2017; Tomić and Schneider 2017, 2018; Jiang et al. 2017; Lwasa 2017; Pérez et al. 2020; Huang et al. 2018b; Islam 2018; Paul et al. 2018; Pérez et al. 2018; D'Adamo et al. 2021). The costs of waste management options depends on the choice of technology as well as the strategy and awareness of system users that can represent time-dependent costs and revenue changes (Khan et al. 2016; Chifari et al. 2017; Medick et al. 2018; Ranieri et al. 2018; Tomić and Schneider 2020). The positive impacts of waste management on employment and economic growth depends on the labour efficiency, ability to stimulate employment opportunities for value added products through circular economy and innovation activities with an estimate for 45 million jobs in the waste management sector by 2030 (Alzate-Arias et al. 2018; Coalition for Urban Transitions 2020; Soukiazis and Proença 2020).

Socio-culturally, there is growing public acceptance for waste management that depends on the pathways for circular economy while reducing system costs for citizens, greater awareness of primary waste separation at source, and possible positive behavioural spill-over across environmental policies (Milutinović et al. 2016; Boyer and Ramaswami 2017; Díaz-Villavicencio et al. 2017; Newman 2017; Tomić and Schneider 2017, 2020; Ek and Miliute-Plepiene 2018; Romano et al. 2019; Coalition for Urban Transitions 2020; Slorach et al. 2020). The distributional effects of waste management can be mixed based on sharing of the costs and benefits and the ability to transform informality of waste recycling activities into programs while supporting urban sustainability (Conke 2018; Grové et al. 2018).

Waste prevention, minimisation, and management measures and efficient waste management infrastructure are the most widely adopted strategies among circular economy actions in urban areas (Yu and Zhang 2016; Affolderbach and Schulz 2017; Dong et al. 2018; Grandin et al. 2018; Hulgaard and MSc 2018; Matsuda et al. 2018; Petit-Boix and Leipold 2018; Starostina et al. 2018). At the same time, the organisational structure for promoting integrated waste management and capabilities related to program administration can be complex, increasing the need for sufficient institutional capacity and governance as well as cross-sectoral coordination for maximum benefit (Hjalmarsson 2015; Kalmykova et al. 2016; Conke 2018; Marino et al. 2018; Yang et al. 2018b). The ease of administration depends on local legislation and policies, choices within municipal waste management strategies to reduce investment costs, and compliance with broader targets for circular economy (Potdar et al. 2016; Agyepong and Nhamo 2017; Tomić et al. 2017; Conke 2018; Tomić and Schneider 2020).

The climate mitigation potential of WtE depends on the technological choices that are undertaken (e.g., anaerobic digestion of the organic fraction, landfill methane recovery, and waste incineration), the emissions factor of the energy mix that it replaces, and its broader role within integrated municipal solid management practices (Eriksson et al. 2015; Potdar et al. 2016; Yu and Zhang 2016; Soares and Martins 2017; Alzate-Arias et al. 2018; Islam 2018). The climate mitigation potential of WtE plants can also increase when power, heat and/or cold is produced (Thanopoulos et al. 2020), including integration with district heating networks in cities such as in Seoul (Yeo et al. 2018), and other products. In Copenhagen, the new WtE plant supplies 70 MWh of electricity, 71 MWh for district heating, 150 kg of bottom ash for road construction, 10-15 kg metal for recycling, and 400 kg of water for recycling per each tonne of municipal solid waste (Hulgaard and MSc 2018).

The avoided emissions of waste prevention activities in Kyoto were at least 200,000 tonnes of CO_2 per year between the years 2008 and 2013 (Matsuda et al. 2018). The current carbon footprint of the waste sector in Madrid with current levels of recycling and energy recovery was 88% less when compared to a case in which all waste is landfilled (Pérez et al. 2018). Urban symbiosis with and without separation at source was found to be the most climate beneficial and profitable option in Tokyo (Sun et al. 2018a). Empirical data from Palermo suggests that an ecological footprint of 6331 hectares from collecting, transporting and disposing waste can be transformed into a net savings of 36,336 hectares based on material recycling, composting, and landfill methane recovery as included in an integrated waste management plan (Peri et al. 2018). Distributed waste treatment facilities, home composting, compact urban form, and alternative fuels can also reduce emissions from waste transport (Oliveira et al. 2017).

8.4.5.2 Food

Urban food systems and city-regional production and distribution of food factor into supply chains. Reducing food demand from urban hinterlands can have positive impact on energy and water demand for food production (Eigenbrod and Gruda 2015). Managing food waste in urban areas through recycling or reduction of food waste at source of consumption would require behavioural change (Gu et al. 2019). Strategies for managing food demand in urban areas would depend on the integration of food systems in urban planning. Urban and Peri-Urban Agriculture and Forestry is pursed both developing and some developed country cities. Strategies for to promote food production in cities have been implemented through enterprises which rely on recycling nutrients from urban waste and utilisation of harvested rainwater or wastewater. These strategies have created economic opportunities or enhance food security while reducing the emissions associated with waste and transportation of food. In a systematic review of literature, evidence is identified in respect to an evolution of economically feasible, socially acceptable and environmentally supportive enterprises through multiple pathways that contextual to the urban area (Brown 2015; Eigenbrod and Gruda 2015; De la Sota et al. 2019; Blay-

Palmer et al. 2020). The pathways include Integrated crop-livestock systems, Urban agroforestry systems, Aquaculture-livestock-crop systems and Crop systems (Lwasa et al. 2015).

8.4.5.3 Water

Systems for water reallocation between rural areas and urban areas will require change by leveraging technological innovations for water capture in urban areas, water purification, and reducing water wastage either by plugging leakages or changing behaviour in regard to water use, which can be utilised for urban food production (Eigenbrod and Gruda 2015; Prior et al. 2018). For example, encouraging short baths of 5 minutes combined with high pressure taps for hand washing reduced water demand in Cape Town by 30-40% depending on locality within the western cape (Fisher-Jeffes et al. 2017).

8.5 Governance, institution, and finance

SR15 identified a number of enabling conditions that promote the “systems transformation” necessary to achieve climate change mitigation and adaptation consistent with 1.5C targets, including “strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilisation of finance, and changes in human behaviour and lifestyles” – some of which have been addressed in previous sections (IPCC 2018a, pp. 18-19 and Section 8.4.3.1 and 8.4.5.1, for example). Both SR15 and AR6 WGIII Chapter 13 identify governance and institutions as a vehicle through which to accomplish this systems transformation (Chapter 13, IPCC 2018a). Figure 8.14 demonstrates the potential transformative global impact of including the urban level in climate mitigation plans.

As such, governance frameworks that encompass multiple levels of authority from the local to the global, as well as subnational and nonstate actors (Castán Broto 2017b; Fuhr et al. 2018), provide an optimal lens through which to identify pathways to transformation, and promote enabling through efficient cooperation. A multilevel, multi-player framework highlights the opportunities and constraints on local autonomy to engage in urban mitigation efforts (Kern 2019). This multifaceted framework demonstrates that when multiple actors—national, regional, and urban policymakers, as well as nonstate actors and civil society—work together to offer and exploit these enabling conditions, it leads to the most impactful mitigation gains (Melica et al. 2018; Estrada et al. 2021, *submitted*). This framework also highlights the multiple paths and potential synergies available to actors who wish to pursue mitigation policies despite not having a full slate of enabling conditions (Castán Broto 2017b; Keller 2017; Fuhr et al. 2018; Hsu et al. 2020a,c; Seto et al. 2021, *submitted*).

Like the mitigation strategies they promote, enabling conditions are most effective when integrated across multiple sectors. Governance provides a valuable means for managing these cross-sectoral linkages. For example, as discussed in Section 8.4.3.1 and 8.4.5.1 circular economy efforts can be synergised with low-carbon technologies (e.g., renewables, retrofits, EVs) to maximise the mitigation potential of electrification and waste reduction (Pan et al. 2015; Gaustad et al. 2018; Sovacool et al. 2020). Local governments can enable waste prevention, minimisation, and management through circular economy approaches that include public-private partnerships between consumers and producers, financial and institutional support, and networking for stakeholders like entrepreneurs (Pan et al. 2015; Prendeville et al. 2018; Fratini et al. 2019).These partnerships increase the accessibility and efficiency of recycling for consumers by providing a clear path from consumer waste back to the producer.

Still, there are constraints on urban autonomy that might limit urban mitigation influence. The capacity of subnational governments to autonomously pursue emissions reductions on their own depends on different political systems and other aspects of multilevel governance, such as innovation, legitimacy and institutional fit (Widerberg and Pattberg 2015; Valente de Macedo et al. 2016; Green 2017; Roger et al. 2017). Michaelowa and Michaelowa (2017) show that to date most subnational mitigation initiatives do not have features that would lead to effective mitigation. A key enabling condition, financing is considered one of the most crucial facets of urban climate change mitigation. It is also considered one of the biggest barriers given the limited financial capacities of local and regional governments (see Section 8.5.3).

This section explores the complex nature of urban climate governance and institutions, discusses some of the opportunities and pathways available within a multilevel governance context alongside recent trends, and offers an overview of financing options available to urban areas to fund mitigation efforts.

8.5.1 Multi-level governance

SR15 identified multilevel governance as an enabling condition that facilitates system transformation consistent with the 1.5°C objectives. Indeed, it is well-recognised that effective governance is necessary to enable cities to undertake low carbon actions or aspire to be net-zero. Further, regional, national, and international climate goals are most effective when the local level governments are involved, rendering urban areas key foci of climate governance at all levels (Kern 2019; Hsu et al. 2020a). Discussions of urban climate governance include the interaction of actors who bear the responsibility to implement climate change actions alongside the motivation and actions of those actors, and how decisions are ultimately made. This encompasses multiple levels of authority from the local to the global, as well as subnational and nonstate actors (Castán Broto 2017b; Fuhr et al. 2018).

Since AR5, multilevel governance has grown in influence within the literature and has been defined as a framework to understanding the complex interaction of the many players involved in GHG generation and mitigation across geographic scales—the vertical layers of governance from neighbourhoods to the national and international levels, and those ‘horizontal’ networks of non-state and subnational actors at various scales (Corfee-Morlot et al. 2009; Seto et al. 2014; Castán Broto 2017b; Keller 2017; Fuhr et al. 2018; Kern 2019). This more inclusive understanding of climate governance provides multiple pathways through which urban actors can engage in climate policy.

When sufficient local autonomy is present, local policies have the ability to upscale to higher levels of authority imparting influence at higher geographic scales. Chan et al. (2015), Keller (2017), and Kern (2019) provide examples of this type of ‘upscaling’ influence in a European context, asserting that established urban climate leaders with large institutional capacity (e.g. Paris, Copenhagen, Bristol, etc.) can influence small and mid-sized cities – or urban areas with less institutional capacity-to enact effective climate policies by engaging with those cities through transnational networks and by adopting a public presence of climate leadership. These cases underscore the importance of relative local autonomy in urban GHG mitigation policy. They also highlight the growing recognition of subnational authorities’ role in climate change mitigation by national and international authorities.

The confluence of political will and policy action at the local level, and growing resources offered through municipal and regional networks and agreements, have provided a platform for urban actors to engage in international climate policy (see Section 8.5.2). This phenomena is recognised in The Paris Agreement, which, for the first time in a multilateral climate treaty, referenced the crucial role subnational and nonstate actors like local communities have in meeting the goals set forth in the agreement (UNFCCC 2015). The Durban Platform for Enhanced Action (Widerberg and Pattberg 2015) as well as UN Habitat’s New Urban Agenda and the 2030 Development Agenda are other examples of the international sphere elevating the local level to global influence (Fuhr et al. 2018). Another facet of local-to-global action is the emergence of International Cooperative Initiatives (ICIs) (Widerberg and Pattberg 2015). One such ICI, the City Hall Declaration, was signed alongside the Paris Agreement during the first Climate Summit for Local Leaders. Signatories included hundreds of local government leaders, private sector representatives, and NGOs, who pledged to enact the goals of the Paris Agreement through their own spheres of influence (UNFCCC Newsroom 2015). A similar Summit has been held at each subsequent UNFCCC COP. Like transnational networks, these platforms provide key opportunities to local governments to further their own mitigation goals, engage in knowledge transfer with other cities and regions, and shape policies at higher levels of authority (UNFCCC Newsroom 2015; Castán Broto 2017b).

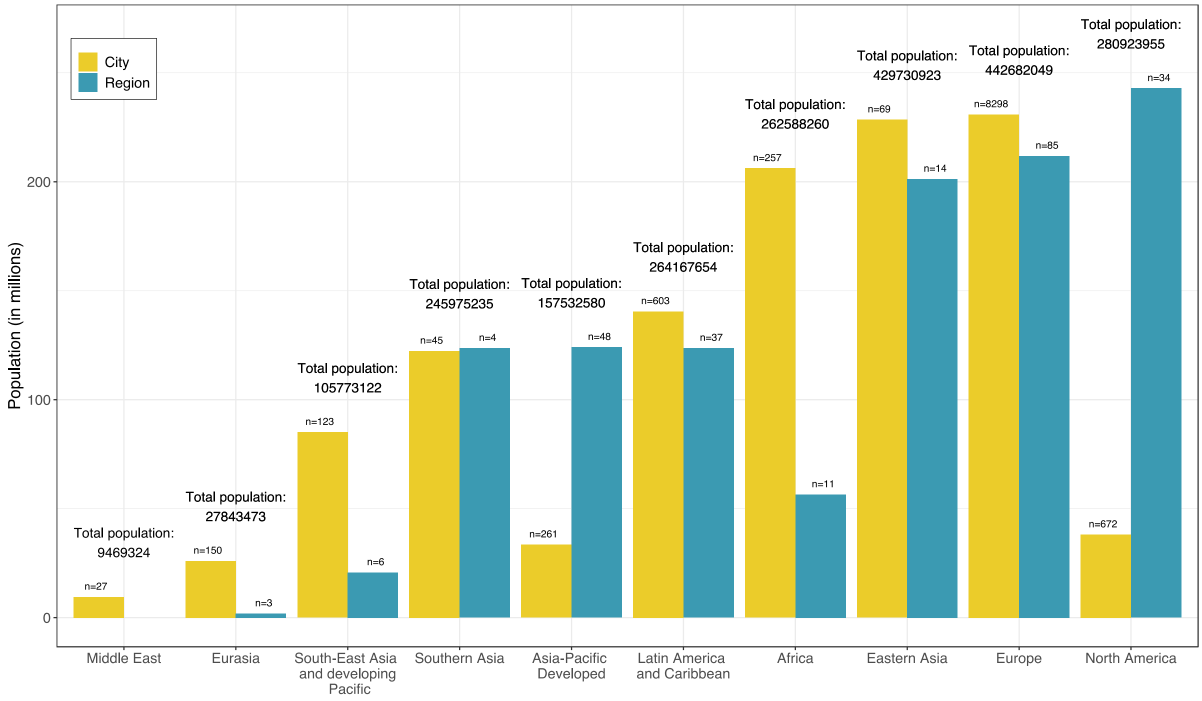
8.5.2 Urban climate networks

More than 10,000 cities (Hsu et al. 2020c) have recorded participation in a transnational or cooperative climate action network, which are voluntary membership networks of subnational governments, often operating across and between national boundaries, that entail some type of action on climate change. These networks include the GCoM, which includes more than 10,000 cities and asks its members to adopt emission reduction commitments, develop climate action plans, and regularly report on emissions inventories. Regional governments, which are larger in geographic scope than cities and typically encompass several cities, similarly participate in these transnational climate action networks and initiatives, such as the Under 2 Coalition, which had 220 members as of 2020 representing 1.3 billion people and nearly 43% of the global economy (The Climate Group 2020). For example, US states are primary actors on climate change and have adopted voluntary emissions reduction targets in the absence of national legislation or policy mandates.

As discussed in Section 8.5.1, municipal and regional networks and agreements have provided a platform for urban actors to engage in international climate policy (Fraundorfer 2017; Keller 2017; Fuhr et al. 2018; Hsu et al. 2018, 2020a; Westman and Broto 2018; Kern 2019). Their impact comes through (1) providing resources for cities and regions to reduce their carbon emissions and improve environmental quality more generally, independent of national policy; (2) encouraging knowledge transfer between member cities and regions; and (3) as platforms of national and international policy influence (Castán Broto 2017b; Fuhr et al. 2018).

Subnational governments that participate in transnational climate networks, however, are primarily located in developed countries, particularly Europe and North America, with far less representation in developing countries (Figure 8.25). In one of the largest studies of subnational climate mitigation action, more than 93% of just over 6,000 quantifiable subnational climate commitments come from cities and regions based in the EU (NewClimate Institute et al. 2019). Such gaps in geographic coverage have been attributed to factors such as the dominating role of Global North actors in the convening and diffusion of “best practices” related to climate action (Bouteligier 2013), or the more limited autonomy or ability of subnational or non-state actors in Global South countries to define boundaries and interests separately from national governments, particularly those that exercise top-down decision-making or have vertically-integrated governance structures (Bulkeley et al. 2012). Many of the participating subnational actors from under-represented regions are large mega-cities - of 10 million people or more - that will play a pivotal role in shaping emissions trajectories (Data Driven Yale et al. 2018; NewClimate Institute et al. 2019).

While these networks have proven to be an important resource in local-level mitigation, their long-term effects and impact at larger scales is less certain (Valente de Macedo et al. 2016; Fuhr et al. 2018). Their influence is most effective when multiple levels of governance are aligned in mitigation policy. Nevertheless, these groups have become essential resources to cities and regions with limited institutional capacity and support (Kern 2019).



*Population calculation considers overlap between City and Regions.
Data source: Hsu et al. (2020). ClimActor: a harmonized dataset of 10,000+ city and region transnational climate network participation. Nature Scientific Data

Figure 8.25 Subnational actors participating in transnational climate initiatives.
Adapted from Hsu et al. (2020a). *Permission pending*

8.5.3 Financing urban mitigation

The world's infrastructure is expected to more than double over the next 20 years (Bhattacharya et al. 2016). More than 70% of the low-carbon infrastructure will concentrate in urban areas. However, today's financing does not provide cities with enough capital flows into infrastructure for urban mitigation across key sectors. Low-carbon urban form (e.g. compact, high-density, mixed-use) is likely to economise spending in infrastructure along with the application of new technologies and renewable energies that would be able to recover the increasing upfront cost of low-carbon infrastructure from more efficient operating and energy savings (Global Commission on the Economy and Climate 2014; Foxon et al. 2015; Floater et al. 2017; Colenbrander et al. 2018).

Governments have traditionally financed a large proportion of infrastructure investment. When budget powers remain largely centralised, intergovernmental transfers will be needed to fund low-carbon infrastructure in cities (Granoff et al. 2016; Floater et al. 2017; Colenbrander et al. 2018).

However, larger and more complex infrastructure projects for decarbonisation are often beyond the capacity of both national government and local municipality budgets. To fill the funding gap in urban areas, cities increasingly play a pivotal role in debt financing for a range of low-carbon infrastructure projects and related spatial planning programs, whereas national governments together with domestic and international financial institutions are expected to create the environments for "urban climate finance" by articulating various goals and strategies, improving pricing, regulation and standards, and developing investment vehicles and risk sharing instruments (Qureshi 2015; Bielenberg et al. 2016; Granoff et al. 2016; Floater et al. 2017; Sudmant et al. 2017; Colenbrander et al. 2018; Zhan and de Jong 2018; Hadfield and Cook 2019).

Indeed, 75% of the global finance for both climate change mitigation and adaptation in 2013 took the form of commercial financing (e.g., balance sheets, commercial-rate loans, and equity), while 25% came from the form of concessionary financing (e.g., grants, below-market-rate loans). However, cities in developing countries are facing difficulty making use of commercial financing and getting access to international credit markets. Cities without international creditworthiness currently rely on local sources, including local commercial banks (Global Commission on the Economy and Climate 2014; CCFLA 2015; Floater et al. 2017).

Cities with creditworthiness have rapidly become issuers of "green bonds" eligible for renewable energy, energy efficiency, low-carbon transport, sustainable water, waste, and pollution, and various climate mitigation projects across the global regions since 2013. While green municipal bonds account for a very small share of the broader $3.7 trillion bond market, the scale is predicted to grow further in emerging economies over the coming years. Green municipal bonds have great potential for cities to expand and/or diversify their investor base. In addition, the process of issuing green municipal bonds is expected to promote cross-sector cooperation within a city by bringing together various agencies responsible for finance, climate change, infrastructure, and planning. Indeed, the demand for green bonds presently outstrips supply as being constantly over-subscripted (Global Commission on the Economy and Climate 2014; Saha and D'Almeida 2017).

On the other hand, cities without creditworthiness face difficulty making use of commercial financing and getting access to international credit markets (Global Commission on the Economy and Climate 2014; CCFLA 2015; Floater et al. 2017). The lack of creditworthiness is one of the main problems preventing cities from issuing green municipal bonds in developing countries. As a prerequisite for the application of municipal debt-financing, it is an essential condition for cities to ensure sufficient own revenues from low-carbon urbanisation, or the default risk becomes too high for potential investors. Indeed, many cities in developed countries and emerging economies have already accumulated substantial amounts of debts through bond insurances, and on-going debt payments prevent new investments in low-carbon infrastructure projects.

National governments and multilateral development banks might be able to provide support for debt financing by developing municipal creditworthiness programs and issuing sovereign bonds or providing national guarantees for investors (Floater et al. 2017). Another problem with green municipal bonds is the lack of aggregation mechanisms to support various small-scale projects in cities. Asset-backed securities not only reduce the default risk for investors through portfolio diversification but also create robust pipelines for a bundle of smalls-scale (re)development projects (Granoff et al. 2016; Floater et al. 2017; Saha and D'Almeida 2017).

The funding sources for various low-carbon infrastructure projects eventually come from users and other stakeholders in the forms of taxes, charges, fees, and other revenues. Nevertheless, small cities in developing countries are likely to have a small revenue base, most of which is committed to operating costs, associated with weak revenue collection and management systems. In recent years, there has been scope to apply not only user-based but also land-based funding instruments for the recovery of upfront capital costs (Braun and Hazelroth 2015; Kościelniak and Górka 2016; Floater et al. 2017) (Colenbrander et al., 2018; Zhan and de Jong, 2018; Zhan et al., 2018).

In practice, however, the application of land-based or "land value capture" funding requires cities to arrange various instruments, including property (both land and building taxes), betterment levies/special assessments, impact fees (exactions), tax increment financing, land readjustment/land pooling, sales of public land/development rights, recurring lease payments, and transfer taxes/stamp duties, across sectors in different urban development contexts (Suzuki et al. 2015; Chapman 2017; Walters and Gaunter 2017; Berrisford et al. 2018). Land value capture is expected not only for cities to generate additional revenue streams but also to prevent sprawl around city-fringe locations. Inversely, land value capture is supposed to perform well when accompanied by low-carbon urban form and private real estate investments along with green building technologies (Suzuki et al. 2015; Floater et al. 2017; Colenbrander et al. 2018).

For the implementation of land-based funding, property rights are essential. However, over 70% of the world's population still lacks access to formal land titles, and weak governance leads to corruption in land occupancy and administration, especially in developing countries with no land information system or less reliable paper-based land records under a centralised registration system. The lack of adequate property rights seriously discourages low-carbon infrastructure and real estate investments in growing cities.

The emerging application of blockchain technology for land registry and real estate investment can change the governance framework, administrative feasibility, allocative efficiency, public accountability, and political acceptability of land-based funding in cities across developed countries, emerging economies, and developing countries (Graglia and Mellon 2018; Kshetri and Voas 2018). Particularly, the concept of a transparent, decentralised public ledger is adapted to facilitate value-added property transactions on a peer-to-peer (P2P) basis without centralised intermediate parties and produce land-based funding opportunities for low-carbon infrastructure and real estate development districtwide and citywide in unconventional ways (Veuger 2017; Nasarre-Aznar 2018).

The consolidation of local transaction records into national or supranational registries would be even more valuable for large-scale land formalisation, but most pilot programs are not yet at the scale (Graglia and Mellon 2018). Moreover, the potential application of blockchain for land-based funding instruments is possibly associated with urban form attributes, such as density and compactness, to prevent sprawl for emission reductions around city-fringe locations (Allam and Jones 2019).

8.5.4 Barriers and opportunities

Irrespective of geography or development level, many cities face similar climate governance challenges such as lacking institutional, financial, and technical capacities (Gouldson et al. 2015; Hickmann and Stehle 2017; Sharifi et al. 2017; Fuhr et al. 2018). Large-scale system transformations are also deeply influenced by factors outside governance and institutions such as private interests and power dynamics (Jaglin 2014; Tyfield 2014). At the local level, a lack of empowerment, high upfront costs, inadequate and uncertain funding for mitigation, diverse and conflicting policy objectives, multiple agencies and actors with diverse interests, high levels of informality, and a siloed approach to climate action are constraining factors to mainstreaming climate action (Beermann et al. 2016; Gouldson et al. 2016; Pathak and Mahadevia 2018; Khosla and Bhardwaj 2019).

8.6 Integrating sectors, strategies, and innovations

Achieving carbon neutrality will not be possible at national and global levels without cities taking action (Gouldson et al. 2016). An effective low-carbon urban strategy requires actions from a variety of areas and a key approach to mitigation is embedded in city form and urban design (Mi et al. 2019). An illustrative case is the embedded need for urban transport under different planning modalities (Pan 2020). Under a functional zoning approach that sets apart business centres and industrial parks from residential quarters, transport emissions are unavoidable no matter how low the level of emissions. If all the urban functions are mixed or nearby spatially, zero-transport emissions would be the natural case as the demand for automobile transport can be zero.

In general, there are two categories of urban mitigation planning analyses in literature. One investigates the roles of key sectors, including energy use, sustainable transport, and construction (Rocha et al. 2017; Álvarez Fernández 2018; Magueta et al. 2018; Seo et al. 2018; Waheed et al. 2018). The other looks at the needs for emissions through a more systematic or fundamental understanding of urban design, urban form, and spatial urban planning (Wang et al. 2017; Privitera et al. 2018), and proposes synergistic scenarios for carbon-neutrality (Ravetz et al. 2020).

Single-sector analysis in low-carbon urban planning examines solutions in supply, demand, operations, and assets management either from technological efficiency or from a system approach. For example, the deployment of renewable energy technologies for urban mitigation can be evaluated in detail and the transition to zero-carbon energy in energy systems and EVs in the transport sector can bring about a broad picture for harvesting substantial low-carbon potentials through urban planning (Álvarez Fernández 2018; Tarigan and Sagala 2018).

Urban lock-in effects on land use, energy demand and carbon emissions varies by different national circumstances (Wang et al. 2017; Pan 2020). Systematic consideration of urban spatial planning and urban forms such as polycentric urban regions and rational urban population density is essential not only for liveability but also for climate neutrality as it aims to shorten commuting distances and is able to make use of NBS for energy and resilience.

However, crucial knowledge gaps remain in this field. There is a shortage of consistent and comparable GHG emissions data at the city level and a lack of in-depth understanding of how urban renewal and design can contribute to carbon neutrality (Mi et al. 2019).

An assessment of opportunities suggests that strategies for material efficiency that cross-cut sectors will have greater impact than those that focus one dimensionally on a single sector (UNEP and IRP 2020). In the urban context, this implies using less material by the design of physical infrastructure based on light-weighting and down-sizing, material substitution, prolonged use as well as enhanced recycling, recovery, remanufacturing, and reuse of materials and related components. For example, light-weight design in residential buildings and passenger vehicles can enable about 20% reductions in life-cycle material-related GHG emissions (UNEP and IRP 2020).

The context of urban areas as the nexus of both sectors underlines the role of urban planning and policies in contributing to reductions in material-related GHG emissions while enabling housing and mobility services for the benefit of inhabitants. In addition, combining resource efficiency measures with densification can increase the GHG reduction potential. While resource efficiency measures are estimated to reduce GHG emission impacts by 24–47% over a baseline, combining resource efficiency with densification can increase this range to about 36–54% over the baseline for a sample of 84 urban settlements worldwide (Swilling et al. 2018).

Evidence from a systematic scoping of urban solutions further indicate that the GHG abatement potential of integrating measures across urban sectors is greater than the net sum of individual interventions due to the potential of realising synergies when realised in tandem, such as urban energy infrastructure and renewable energy (Sethi et al. 2020). Similarly, system-wide interventions, such as sustainable urban form, are important for increasing the GHG abatement potential of interventions based on individual sectoral projects (Sethi et al. 2020). Overall, the pursuit of inter-linkages among urban interventions are important for accelerating GHG reductions in urban areas (Sethi et al. 2020); this also holds importance for reducing reliance on negative emission technologies at a global scale.

Currently, cross-sectoral integration is one of the main thematic areas of climate policy strategies among the actions that are adopted by signatories to an urban climate and energy network (Hsu et al. 2020b). Although not as prevalent as those for efficiency, municipal administration and urban planning measures (Hsu et al. 2020b), strategies that are cross-cutting in nature across sectors can provide important emission saving opportunities for accelerating the pace of climate mitigation in urban areas. Cross-sectoral integration also involves mobilising urban actors to increase innovation in energy services and markets beyond individual energy efficiency actions (Hsu et al. 2020b). Indeed, single-sector versus cross-sector strategies for 637 cities from a developing country was found to enable an additional 15–36% contribution to the national climate mitigation reduction potential (Ramaswami et al. 2017). The strategies at the urban level involved those for energy cascading and exchange of materials that connected waste, heat, and electricity strategies. The contribution of cross-sector integration for driving urban transformation is also relevant for ensuring co-benefits for health and wellbeing. For the same 637 cities, co-benefits in the aspect of health were quantified as saving approximately 25,500–57,500 lives annually due to better air quality (Ramaswami et al. 2017).The implementation of strategies that extend beyond sectors is thus an urban advantage, including strategies for limiting the urban extent, electrification of the urban energy system, urban NBS as well as circular economy. Empirical evidence further suggests that mixed-use compact development with sufficient land use diversity can have a positive influence on urban productivity (Salat et al. 2017). In contrast, urban spatial structures that increase walking distances and produce car dependency have negative impacts on urban productivity considering congestion as well as energy costs (Salat et al. 2017). Urban regeneration strategies have and can be used to purposefully alter this urban spatial structure in retrospect while there can be relatively more limited opportunities.

8.6.1 Mitigation opportunities for *established* urban settlements

Shifting pathways to low-carbon development in established urban settlements with stabilised urban growth underlines the importance of an intense shift across the urban system for supporting ongoing or new targets for climate neutrality. Urban settlements where urban infrastructure has already been built have opportunities to increase energy efficiency measures, prioritise compact and mixed-use neighbourhoods in urban regeneration, advance the urban energy system through electrification, undertake cross-sector synergies, integrate NBS, encourage behavioural and lifestyle change to reinforce climate mitigation, and put into place a wide range of enabling conditions as necessary to guide and coordinate actions in the urban system and its impacts in the global boundary.

System-wide energy savings and emission reductions for low-carbon urban development is widely recognised to require both behavioural and structural changes (Zhang and Li 2017). Synergies between social and ecological innovation can reinforce the sustainability of urban systems while decoupling energy usage and economic growth (Hu et al. 2018; Ma et al. 2018). In addition, an integrated sustainable development approach that enables cross-sector energy efficiency, sustainable transport, renewable energy and local development in urban neighbourhoods can address issues of energy poverty (Pukšec et al. 2018). In this context, cross-sectoral, multi-scale, and public-private collaborative action is crucial to steer societies and cities closer to low-carbon futures (Hölscher et al. 2019), including those for guiding residential living area per capita, limiting private vehicle growth, expanding public transport, improving the efficiency of urban infrastructure, enhancing urban carbon pools, and waste management (Lin et al. 2018). Through a coordinated approach, urban areas can be transformed into hubs for renewable and distributed energy, more circular metabolism for regeneration, sustainable mobility as well as inclusivity and health (Newman et al. 2020). In addition, the co-design of infill residential development through an inclusive and participatory process with citizen utilities and disruptive innovation can support net-zero carbon power while contributing to 1.5°C pathways, the SDGs, and affordable housing simultaneously (Wiktorowicz et al. 2018).

A shared understanding for urban transformation through a participatory approach can largely avoid maladaptation and contribute to equity (Moglia et al. 2018). Transformative urban futures that are radically different from the existing trajectories of urbanisation, including in developing countries, can support the ability to remain within planetary boundaries while ensuring inclusivity across the urban poor (Friend et al. 2016). At the urban policy level, an analysis of 12,000 thousand measures in urban level monitoring emission inventories according to the mode of governance further suggests that local authorities with lower population have mainly relied on municipal self-governing while local authorities with higher population more frequently adopted regulatory measures as well as financing and provision (Palermo et al. 2020). Policies that relate to education and enabling were uniformly adopted regardless of population size (Palermo et al. 2020).

8.6.2 Mitigation opportunities for *emerging* urban settlements

Emerging and growing cities have significant opportunities for integrating climate mitigation response options in earlier stages of ongoing urban development, which can provide even greater response options in avoiding carbon lock-in and shifting pathways towards climate neutrality. In growing cities that are expected to receive rapid increases in population, a significant share of urban development remains to be planned and built. The ability of shifting these investments towards low-carbon development earlier in the process represents an important opportunity for contributing to climate neutrality at the global scale. In particular, evidence suggests that investment in low-carbon development measures and re-investment based on the returns of the measures even without considering substantial co-benefits can provide tipping points for climate mitigation action and reaching peak emissions at lower levels while decoupling emissions from economic growth, even in fast-growing megacity contexts with well-established infrastructure (Colenbrander et al. 2017).

At the same time, some of the rapidly growing urban settlements of the Developing countries can have existing walkable urban design that can be maintained and supported with electrified urban rail plus renewable energy based solutions to avoid a shift to private vehicles (Sharma 2018). In addition, community-based distributed renewable electricity can be applicable for the regeneration of informal settlements rather than more expensive slum clearance (Teferi and Newman 2018). Scalable options for decentralised energy, water and wastewater systems, spatial planning as well as urban agriculture and forestry are applicable to urban settlements across multiple regions simultaneously (Lwasa 2017).

At the same time, rapidly urbanising areas can have challenges in confronting pressures for rapid growth in urban infrastructure to address growth in population. This challenge, however, can be achieved with coordinated urban planning and support from enabling conditions for pursuing effective climate mitigation. The ability to mobilise low-carbon development will also increase opportunities for capturing co-benefits for urban inhabitants while reducing embodied and operational emissions.

8.6.3 Mitigation opportunities for future urban settlements

The UN International Resource Panel estimates that building future cities under a BAU scenario will require a more than doubling of material consumption, from 40 billion tonnes annually in 2010 to about 90 billion tonnes annually by 2050 (Swilling et al. 2018). Thus, the demand that new urban settlements will place on natural resource use, materials, and emissions can be minimised and avoided only if urban settlements are planned and built much differently than today, including minimised impacts on land use based on compact urban form, lowered use of materials, and related cross-sector integration, including energy-driven urban design for sustainable urbanisation.

In low energy-driven urban design, urban design parameters are evaluated based on the energy performance of the urban area in the early design phase of future urban development (Shi et al. 2017b). Energy-driven urban design generates and optimises urban form according to the energy performance outcome (Shi et al. 2017b). Beyond the impact of urban form on building energy performance, the approach focuses on the interdependencies between urban form and energy infrastructure in urban energy systems. The process can provide opportunities for both passive options for energy-driven urban design as well as active options that involve the use of energy infrastructure and technologies while recognising interrelations of the system. Future urban settlements can also be planned and built with climate neutrality and renewable energy targets.

Integrated scenarios across sectors at the local level can decouple resource usage from economic growth (Hu et al. 2018) and enable 100% renewable energy scenarios (Zhao et al. 2017a; Bačeković and Østergaard 2018). Relative decoupling is obtained (Kalmykova et al. 2015) with increasing evidence for turning points in per capita emissions, total emissions, or urban metabolism (Chen et al. 2018b; Shen et al. 2018). The importance of integrating energy and resource efficiency in sustainable and low carbon city planning (Dienst et al. 2015), structural changes, as well as forms of disruptive social innovation, such as the sharing economy, is also evident based on analyses for multiple cities, including those that can be used to lower the carbon footprints of urban areas relative to sub-urban areas (Chen et al. 2018a).

The potential for change in established and emerging human settlements is constrained by the longevity and sunk costs of existing urban infrastructures and built environment. Future urban settlements, in contrast, can benefit from the less constrained utopian lens of emerging knowledge and values. What would be the major features and characteristics of ideal urban settlements? First, electrification for all urban services, transportation, cooling, heating, cooking, recycling, water extraction, wastewater recycling, etc., supplied by renewable sources of energy.

To minimise carbon footprints, future urban settlements will need not only to change energy sources and material processes, but also to engage in new intelligence functions. The new urban intelligence functions are holistic and pro-active rather than reactive. While today, for example, many cities use environmental impact reviews to identify potential negative consequences of individual development projects on environmental conditions in a piecemeal project basis, new cities institutionalise system-wide analyses, for example, of construction materials, or renewable power sources that minimise ecosystem disruption and energy use, through the use of life-cycle assessments for building types permitted in the new city (Ingrao et al. 2019); urban-scale metabolic impact assessments for neighbourhoods in the city (Pinho and Fernandes 2019); strategic environmental assessments (SEAs) that go beyond the individual project and assess plans for neighbourhoods (Noble and Nwanekezie 2017); or the modelling of the type and location of building masses, tree canopies and parks, and temperature (surface conditions) and prevailing winds profiles to reduce the combined effects of climate change and the heat island effect, thus minimising the need for air conditioning (Matsuo and Tanaka 2019).

Resource efficient, compact, sustainable and liveable urban areas can be enabled with an integrated approach across sectors, strategies, and innovations. From a geophysical perspective, the use of materials with lower life-cycle GHG impacts, including the use of timber in urban infrastructure, and the selection of urban development plans with lower material and land demand can lower the emission impacts of existing and future urban settlements (Müller et al. 2013; Carpio et al. 2016; Liu et al. 2016; Ramage et al. 2017; Shi et al. 2017a; Stocchero et al. 2017; Bai et al. 2018; Zhan et al. 2018; Swilling et al. 2018; Xu et al. 2018; UNEP and IRP 2020).

The integration of response options across urban land use and spatial planning, electrification of urban energy systems, renewable energy district heating and cooling networks, urban nature based solutions and circular economy can also have positive impacts on improving air and environmental quality with related co-benefits for health and wellbeing (Liu et al. 2017a)(Sun et al. 2018b) (Diallo et al. 2016; Shakya 2016; Ramaswami et al. 2017; Tayarani et al. 2018; Park and Sener 2019; González-García et al. 2021)(Nieuwenhuijsen and Khreis 2016). Low carbon development options can also be implemented in ways that reduce impacts on water use, including water use efficiency, demand management, and water recycling, while increasing water quality (Koop and van Leeuwen 2015; Topi et al. 2016; Drangert and Sharatchandra 2017; Lam et al. 2017, 2018; Vanham et al. 2017; Kim and Chen 2018). The ability for enhancing biodiversity while addressing climate change depends on improving urban metabolism and biophilic urbanism towards urban areas that are able to regenerate natural capital (Thomson and Newman 2018; IPBES 2019b).

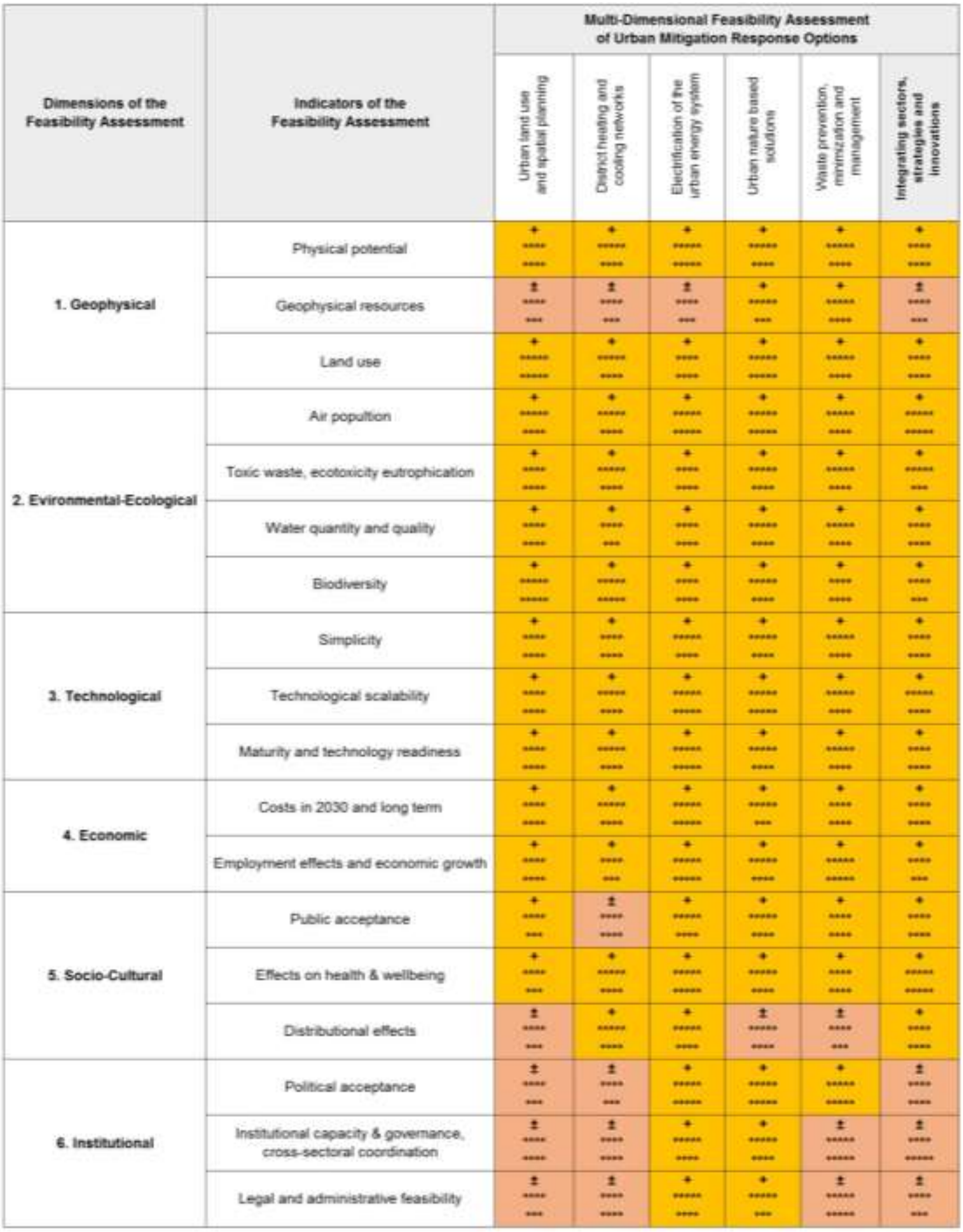
The feasibility of upscaling multiple response options depends on the urban context as well as the stage of urban development with certain stages providing additional opportunities over others (Yamagata and Seya 2013; Dienst et al. 2015; Maier 2016; Affolderbach and Schulz 2017; Pacheco-Torres et al. 2017; Ramaswami et al. 2017; Roldán-Fontana et al. 2017; Zhao et al. 2017a; Beygo and Yüzer 2017; Lwasa 2017; Alhamwi et al. 2018; Kang and Cho 2018; Lin et al. 2018; Collaço et al. 2019; Kılkış 2019; Kılkış and Kılkış 2019).

There are readily available solutions for low-carbon urban development that can be further supported by new emerging ones, such as energy-driven urban design for optimising the impact of urban form on energy infrastructure (Hu et al. 2015; Shi et al. 2017b; Xue et al. 2017; Dobler et al. 2018; Egusquiza et al. 2018; Pedro et al. 2018; Soilán et al. 2018). The costs of low-carbon urban development are manageable and enhanced with a portfolio approach for cost-effective, cost-neutral, and re-investment options with evidence across different urban typologies (Colenbrander et al. 2015, 2017; Gouldson et al. 2015; Nieuwenhuijsen and Khreis 2016; Saujot and Lefèvre 2016; Sudmant et al. 2016; Yazdanie et al. 2017; Brozynski and Leibowicz 2018).

Low-carbon urban development that triggers economic decoupling can also have a positive impact on employment and local competitiveness (Kalmykova et al. 2015; Chen et al. 2018b; García-Gusano et al. 2018; Hu et al. 2018; Shen et al. 2018). In addition, sustainable urban transformation can be supported with participatory approaches that provide a shared understanding of future opportunities and challenges where public acceptance increases with citizen engagement and citizen empowerment as well as an awareness of co-benefits (Blanchet 2015; Bjørkelund et al. 2016; Flacke and de Boer 2017; Gao et al. 2017; Neuvonen and Ache 2017; Sharp and Salter 2017; Wiktorowicz et al. 2018; Fastenrath and Braun 2018; Gorissen et al. 2018; Herrmann et al. 2018; Moglia et al. 2018). Sustainable and low-carbon urban development that integrates issues of equity, inclusivity, and affordability while safeguarding urban livelihoods, providing access to basic services, lowering energy bills, addressing energy poverty, and improving public health can also improve the distributional effects of existing and future urbanisation (Friend et al. 2016; Claude et al. 2017; Colenbrander et al. 2017; Ma et al. 2018; Mrówczyńska et al. 2018; Pukšec et al. 2018; Wiktorowicz et al. 2018; Ramaswami 2020).

The capacity to implement relevant policy instruments in an integrated and coordinated manner within a policy mix while leveraging multilevel support as relevant can increase the enabling conditions for urban system transformation (Agyepong and Nhamo 2017; Roppongi et al. 2017).

Multi-dimensional feasibility assessment enables an approach for considering multiple aspects and can be used as a tool for policy support (Singh et al. 2020). The feasibility assessment of land use and spatial planning in the SR15 Report along with references in the systematic assessment of urban case studies in Lamb et al. (2019) and additional searches according to the indicators of the feasibility assessment are used to provide the feasibility assessment of response options for urban systems. The feasibility assessment is summarised in Figure 8.26 with additional line of sight in the chapter supplementary material.



Dimensions of the Feasibility Assessment	Indicators of the Feasibility Assessment	Multi-Dimensional Feasibility Assessment of Urban Mitigation Response Options					
		Urban land use and spatial planning	District heating and cooling networks	Electrification of the urban energy system	Urban nature based solutions	Waste prevention, minimization and management	**Integrating sectors, strategies and innovations**
1. Geophysical	Physical potential	+ **** ****	+ ***** ****	+ ***** *****	+ ***** ****	+ ***** ****	+ **** ****
	Geophysical resources	± **** ***	± **** ***	± **** ***	+ ***** ***	+ ***** ****	± **** ***
	Land use	+ ***** *****	+ ***** ****	+ **** ****	+ ***** *****	+ ***** ****	+ **** ****
2. Evironmental-Ecological	Air popultion	+ ***** ****	+ ***** ****	+ ***** *****	+ ***** *****	+ ***** ****	+ ***** *****
	Toxic waste, ecotoxicity eutrophication	+ **** ****	+ ***** ****	+ **** ****	+ ***** ****	+ ***** ****	+ ***** ***
	Water quantity and quality	+ **** ****	+ **** ***	+ **** ****	+ ***** ****	+ ***** ****	+ **** ****
	Biodiversity	+ ***** *****	+ ***** *****	+ **** ****	+ ***** ****	+ **** ****	+ **** ***
3. Technological	Simplicity	+ **** ****	+ **** ****	+ ***** ****	+ ***** ****	+ ***** ****	+ **** ****
	Technological scalability	+ **** ****	+ ***** ****	+ ***** *****	+ ***** *****	+ ***** ****	+ ***** ****
	Maturity and technology readiness	+ **** ****	+ ***** ****	+ ***** *****	+ ***** ****	+ ***** ****	+ **** ****
4. Economic	Costs in 2030 and long term	+ **** ****	+ ***** ****	+ ***** *****	+ ***** ***	+ **** ****	+ **** ****
	Employment effects and economic growth	+ **** ****	+ **** ***	+ ***** *****	+ ***** ****	+ ***** *****	+ **** ***
5. Socio-Cultural	Public acceptance	+ **** ***	± **** ****	+ ***** ****	+ ***** ****	+ **** ****	+ **** ****
	Effects on health & wellbeing	+ **** ***	+ ***** ****	+ ***** *****	+ ***** ****	+ **** ****	+ ***** *****
	Distributional effects	± **** ***	+ ***** ****	+ ***** ****	± ***** ****	± **** ***	+ **** ****
6. Institutional	Political acceptance	± **** ***	± **** ***	+ ***** *****	+ ***** *****	+ ***** *****	± **** ****
	Institutional capacity & governance, cross-sectoral coordination	± **** ****	± **** ****	+ ***** ****	+ ***** ****	± ***** *****	± **** *****
	Legal and administrative feasibility	± **** ***	± **** ****	+ ***** ****	+ ***** ***	± ***** *****	± **** ***

Figure 8.26. Urban mitigation response options according to the dimensions and indicators of the feasibility assessment. In the figure, (+) indicates a positive impact and (±) indicates a positive or negative impact according to context [*Agreement and evidence are starred with (*****) full marks]*. The feasibility assessment is based on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional feasibility. A given indicator can have a positive and/or negative impact on the feasibility of the response option and can vary according to context. Indicators that provide a positive impact are marked with a plus sign (+) and shaded in orange while those that can have both a positive or negative impact depending on context are marked with (±). Institutional feasibility can have mixed evidence for certain indicators while coordinated action can accelerate urban mitigation, including those for integrating sectors, strategies and innovation for resource efficient and compact urbanisation. Line of sight is provided in the supplementary material and represented with asterisks on a scale of 1 (low) to 5 (very high) in the order of level of agreement and level of confidence.

8.7 Gaps in knowledge

While there is growing literature on NBS such as green and blue infrastructure in cities, there is still a huge knowledge gap in regard to how these climate mitigation actions can be integrated in urban planning and design as well as their mitigation potential (Kavonic and Harriet Bulkeley, *submitted*). In moving forward with the research agenda on cities and climate change science, transformation of urban systems will be critical but understanding this transformation and assessment of mitigation action remains another key knowledge gap (Estrada et al. 2021, *submitted*; Tozer et al. 2021, *submitted*).

There is a key knowledge gap in respect to the potential of informal sector in developing country cities. Informality extends beyond illegality of economic activities to include housing, locally developed off-grid infrastructure and alternative waste management strategies. Limited literature and understanding of the mitigation potential of enhanced informal sector is highlighted in the key research agenda on cities from the cities and climate change science conference (Prieur-Richard et al. 2018).

City-level models and data for understanding of urban systems is another knowledge gap. With increased availability of open data systems, Big data and computing capacities, there is an opportunity for analysis of urban systems (Frantzeskaki et al. 2019).

While there is much literature on urban climate governance, there is still limited understanding of the governance models and regimes that support multi-level decision making for mitigation and climate action in general. Transformative climate action will require changing relationships between actors to utilise the knowledge from data and models and deepen understanding of the urban system to support decision-making.

8.7.1 COVID-19 and cities

COVID-19 raises major questions about urban densities, transportation, public space, and other urban issues. The impact of COVID-19 on urban activity and urban GHG emissions may offer insights into urban emissions and their behavioural drivers and may include structural shifts in emissions that may last into the future. The science is unclear as to the links between urban characteristics and COVID. For example, some research shows higher COVID-19 infection rates with city size (e.g., Dalziel et al. 2018; Stier et al. 2020, *accepted, in review*), as well as challenges to epidemic preparedness due to high population density and high volume of public transportation (Layne et al. 2020; Lee et al. 2020). Other research from 913 metropolitan areas shows that density is unrelated to COVID-19 infection rates and in fact, has been inversely related to COVID-19 mortality rates when controlled by metropolitan population. Dense counties are found to have significantly lower mortality rates, possibly due to such advantages as better health care systems as well as greater adherence to social distancing measures (Hamidi et al. 2020). Sustainable urbanisation and urban infrastructure that addresses the SDGs can also improve preparedness and resilience against future pandemics. For example, long-term exposure to air pollution has been found to exacerbate the impacts of COVID-19 infections (Wu et al. 2020, *accepted, in review*) while urban areas with clean air based on clean energy and greenspace can provide advantages.

At the global scale COVID-related lock-down and travel restrictions reduced CO_2 emissions by 17% between January and early April 2020 compared to 2019 values (Le Quéré et al. 2020) Research in the U.S. found that emissions reached a maximum decline of 19.3% in early April and that projections for 2020 show a 10.8% decline relative 2019—roughly twice the equivalent estimated global annual reduction (Gurney et al. 2020d, *submitted*). Research in China estimates that the first quarter of 2020 saw an 11% decline in CO_2 emissions relative to 2019 (Zheng et al. 2020; Han et al. 2021).

Though preliminary, recent studies suggest that urban areas saw larger overall declines in emissions due to the fact that their emissions portfolio is more dominated by on-road emissions relative to the country scale. For example, researchers have explored the COVID-19 impact in the cities of Los

Angeles, Baltimore, Washington, DC, and San Francisco Bay Area, US. In the San Francisco region, a decline of 30% in anthropogenic CO_2 was observed, which was primarily due to changes in on-road traffic (Turner et al. 2020). Declines in the Washington, DC/Baltimore region and in the Los Angeles urban area were 33% and 34%, respectively, in the month of April compared to previous years (Yadav et al. 2020, *submitted*).

These shorter-term emission reductions suggest that 2020 can exhibit anomalously low emissions at the absence of rebound effects. However, sustaining such reduction rates is unlikely as relaxing travel restrictions and returning to pre-pandemic 'normal' can induce a rebound and even lead to increased emissions considering that some stimulus packages involve delaying actions aimed at green economic development and increased investment in renewable sources of energy. It remains unclear to what extent there has been any structural change in the underlying drivers of urban emissions.

Changes in transportation patterns have caused temporary air quality improvements in many cities around the world (Lian et al. 2020; Rodríguez-Urrego and Rodríguez-Urrego 2020; Sharifi and Khavarian-Garmsir 2020; Zangari et al. 2020). A promising transformation that has been observed in many cities is an increase in the share of active travel modes such as cycling and walking (Sharifi and Khavarian-Garmsir 2020). While this may be temporary, other trends such as increased rates of teleworking and/or increased reliance on smart solutions that allow remote provision of services provide an unprecedented opportunity to transform urban travel patterns (Belzunegui-Eraso and Erro-Garcés 2020; Sharifi and Khavarian-Garmsir 2020).

Some studies indicate that socio-economic factors, such as poverty, racial and ethnic disparities, and crowding are more significant than density in COVID-19 spread and associated mortality rate (Borjas 2020; Lamb et al. 2020; Maroko et al. 2020). The evidence for the connection between household crowding and the risk of contagion from infectious diseases is also strong. A 2018 WHO systematic review of the effect of household crowding on health concluded that a majority of studies of the risk of non-tuberculosis infectious diseases, including flu-related illnesses, were associated with household crowding (Shannon et al. 2018).

Related to the transport sector, the pandemic has resulted in concerns regarding the safety of public transport modes and this has resulted in significant reductions in public transport ridership in some cities (Bucsky 2020; de Haas et al. 2020). Considering the significance of public transportation for achieving low-carbon and inclusive urban development, appropriate response measures should be taken to enhance health safety of public transport modes to regain public trust (Sharifi and Khavarian-Garmsir 2020). There is public perception of higher densities as a risk factor that may contribute to the spread of the virus. However, while some evidence supports such concerns, there is also evidence showing that density is not a major risk factor and indeed cities that are more compact have more capacities to respond to and control the pandemic (Hamidi et al. 2020). Furthermore, the way density is distributed matters. It is argued that even distribution of density reduces the possibility of crowding that is found to contribute to the scale and length of the outbreak in cities. Overall, more research is needed to better understand the impacts of density on the outbreak dynamics. In the meantime, considering the multiple benefits of compact cities for climate mitigation, appropriate adaptive measures are needed to regain trust in compact cities by overcoming public health concerns.

Cities should seize this opportunity to provide better infrastructure to further foster active transportation. This could involve measures such as expanding cycling networks and restricting street networks, to make them more pedestrian- and cycling-friendly- that will also provide other health and adaptation co-benefits as discussed in Section 8.2 (Sharifi 2021).

The pandemic has proved the significance cost-saving benefits of early actions. Drawing parallels between climate actions and actions to contain the spread of the COVID-19 pandemic, Klenert et al. (2020) argue that timely action is essential and will significantly reduce costs. Significance of timely action for reducing mitigation costs is also emphasised in SR15. Despite this, there is a tendency among some policymakers to delay climate actions due to the short-term economic consequences. The pandemic clearly shows that delayed action can be significantly more costly in the long run (Klenert et al. 2020). Therefore, timely actions at the city level are also needed.

8.7.2 Future urbanisation scenarios

The urban share of global emissions is significant, drawing attention to the need to increase studies that place the urban share in the context of climate mitigation scenarios as has been recently initiated (Gurney et al. 2020a, *submitted*). In addition, a recent review of the applications of the SSP/RCP scenario framework across more than 700 studies places emphasis on recommending the downscaling of the global SSPs to improve the applicability of this framework to regional and local scales (O'Neill et al. 2020). Multi-disciplinary research efforts are increasingly important for quantifying the urban share of global emissions explicitly within climate mitigation scenarios. Knowledge generation that includes urban reduction potentials within the scenario framework also remains as a need while addressing this need can further underline the role of urban systems in accelerating GHG reductions for net-zero emissions.

8.7.3 Urban emissions data

Though there has been a rapid rise in quantification and analysis of urban emissions, there remain gaps in comprehensive global coverage of urban emissions and their role in future scenario trajectories (Mueller et al. 2020a, *submitted*). The development of protocols by which urban areas can organise emissions accounts has been an important step forward, but no single agreed-upon reporting framework exists (Lombardi et al. 2017; Chen et al. 2019). Additionally, there is no standardisation of emissions data and independent validation procedures. This is partly driven by the recognition that urban emissions can be conceptualised from multiple perspectives, each of which has a different meaning for different urban communities. The limited standardisation has also led to incomparability of the many individual or city cluster analyses that have been accomplished since AR5. Finally, comprehensive, global quantification of urban emissions remains incomplete.

Similarly, independent verification or evaluation of urban GHG emissions has seen a large number of research studies (Wu et al. 2016; Sargent et al. 2018; Whetstone 2018; Lauvaux et al. 2020). This has been driven by the recognition that self-reported approaches may not provide adequate accuracy to track emissions changes and provide confidence for mitigation investment. For example, a study in the US compared 48 self-reported urban emission inventories to a research-grade quantification system and found that the self-reported inventories under-reported emissions by an average of 18% with a range that varied from -145.5% to +63.5%) (Gurney et al. 2020c, *submitted*).

The most promising approach to independent verification of urban emissions has been the use of urban atmospheric monitoring (direct flux and/or concentration) as a means to assess and track urban GHG emissions (Davis et al. 2017). However, like the basic accounting approach itself, standardisation and practical deployment is an essential near-term need.

Frequently Asked Questions

FAQ 8.1 Why are urban areas important to global climate change mitigation?

The world is rapidly urbanising and this will likely lead to an increasing share of global GHG emissions. The trends and potentials associated with this phenomenon render urban emissions reduction crucial to global climate change mitigation. Indeed, over half of the world's population currently reside in urban areas—a number forecasted to increase to nearly 70% by 2050. Furthermore, urban areas take up a growing proportion of national and global emissions, estimated to be between 45–87% today, depending on emissions scope. This range is projected to grow in the coming decades; in 2100, some scenarios show urban share as high as 100%, with 65% being at the minimum for any scenario. One study of 84 cities found that urban areas that utilise energy-efficiency in transport, commercial buildings, and building heating/cooling could reduce urban emissions by 36–54%—significant considering the global urban emissions share. Furthermore, subnational governments (e.g., those governing cities, towns, villages) are uniquely situated to influence other levels of governance and stakeholders by upscaling effective mitigation efforts and promoting technology transfer through such means as urban mitigation experimentation, participation in transnational municipal networks and international organisations, and other enabling strategies. Urban areas can also act as points of intervention to amplify synergies and co-benefits for accomplishing the SDGs.

FAQ 8.2 What are the most impactful options cities can take to mitigate urban emissions, and how can these be best implemented?

There is a wide array of GHG mitigation options available to urban areas that help break—or prevent—the cycle of urban carbon lock-in. These options have the greatest mitigation impact when urban actors employ them across sectors, operate within an urban systems framework, offer “enabling conditions” (e.g., supportive policy instruments and institutions, financing, etc.), and continually innovate over time. Cross-sector integration might include updating building and zoning regulations while promoting renewable-energy based decentralisation of energy systems and promoting compact urban development that is coupled with land use mix and transit-oriented development.

The optimal mitigation options and their implementation will depend on the governance and developmental context of the urban area (e.g., new, emerging, or established urban areas). In emerging and yet-to-be-built urban areas, carbon lock-in in can be avoided by deploying low- and negative-carbon infrastructure and urban form. For existing cities, electrification of the grid and transport, and implementing energy efficiency across sectors, are highly transformative mitigation options. Figure 8.22 illustrates those strategies with the largest mitigation potential common to all cities, regardless of development status; these include low-carbon energy use, nature-based solutions, and enabling consumer behaviour change through incentivising/increasing accessibility to consumption and material choices with a smaller carbon footprint (e.g., through low-impact dietary choices, offering walking and cycling, expanding recycling and its accessibility, etc.). In general, electrification of urban services and ensuring that sources of electricity are from renewable energy are among the most impactful options that cities can take to reduce urban emissions. Without such urban-scale changes, pro-environmental behaviour can reduce individual footprints significantly.

FAQ 8.3 How do we estimate global emissions from cities, and how reliable are the estimates?

Broadly, there are two different approaches used to estimate emissions from cities globally: top-down and bottom-up. The top-down approach starts from atmospheric observations and attempts to allocate those to urban areas through atmospheric modelling. This approach estimates direct (scope 1) emissions only. The second approach estimates emissions from GHG emitting activities in a given urban area via a combination of local activity data or direct measurement such as stack monitoring, traffic data, energy consumption information, and building attributes. Activity data is combined with CO_2 emission factors to estimate emissions. These estimates can also be achieved via downscaling from national or regional estimates. The emissions may include solely direct emissions (scope 1), or also factor in indirect emissions (i.e., from purchased electricity consumption – or scope 2) or all remaining emissions, like those from the urban supply chain (scope 3). Some researchers also take a hybrid approach. No approach has systematically accounted for all cities worldwide. Rather, they have been applied to subsets of global cities and often include the largest cities globally. These continue to support the conclusion that cities account for an average share of about 70% of global CO_2 emissions and 60% of global GHG emissions, including CO_2 and CH_4—numbers that are projected to increase into 2050 and 2100. However, these estimates and the urban share depends upon how one defines the emissions (i.e., the scope and city boundary). Uncertainty remains for both the top-down and bottom-up approaches (10–20%). Individual self-reported inventories from cities have shown chronic underestimation when compared to atmospherically-calibrated estimates.

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Supplementary Material

Scope of the Multi-Dimensional Feasibility Assessment

Supplementary Material of Figure 8.26

Dimensions	**Indicators**
Geophysical (***D₁***)	**1.1.** Physical potential
	1.2. Geophysical resources (incl. geological storage capacity)
	1.3. Land use
Environmental-ecological (***D₂***)	**2.1.** Air pollution
	2.2. Toxic waste, ecotoxicity and eutrophication
	2.3. Water quantity and quality
	2.4. Biodiversity
Technological (***D₃***)	**3.1.** Simplicity
	3.2. Technology scalability
	3.3. Maturity and technology readiness
Economic (***D₄***)	**4.1.** Costs in 2030 and long term
	4.2. Employment effects and economic growth
Socio-cultural (***D₅***)	**5.1.** Public acceptance
	5.2. Effects on health and wellbeing
	5.3. Distributional effects
Institutional (***D₆***)	**6.1.** Political acceptance
	6.2. Institutional capacity and governance, cross-sectoral coordination
	6.3. Legal and administrative feasibility

Assessment of the impacts of a given indicator on the feasibility of the response option:

- Plus (+): The indicator has a positive impact
- Negative (−): The indicator has a negative impact
- Agreement (A): 1=low, 5= full
- Confidence (C): 1=low, 5= full

Response Options for Urban Systems

Response Option 1 → Urban land use and spatial planning
Response Option 2 → District heating and cooling networks
Response Option 3 → Electrification of the urban energy system
Response Option 4 → Urban nature-based solutions
Response Option 5 → Waste prevention, minimisation and management
Response Option 6 → Integrating sectors, strategies and innovations

Main Sources of References

- IPCC SR15 Feasibility Assessment “Land Use and Urban Planning”
- References in the Supplementary Material of (Lamb et al., 2019)
- Updated literature search based on keywords in the indicator

Response Option 1 → Urban land use and spatial planning

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D₁	**1.1.**	Plus (+)	4	4	Depends on the ability to reduce pressures on physical land resources, thereby having a positive impact on the feasibility of the option, e.g. a total of 125,000 km^2 of land could be saved between the years 1970 and 2020 if population density remained the same as 1970 levels while cities have had different dynamics of stable, outward and/or upward growth	(Güneralp et al., 2020), (Mahtta et al., 2019)
	1.2.	Plus/Minus (±)	4	3	Depends on the ability of the response option to limit demands on materials for urban construction needs, thereby avoiding and shifting pressures on geophysical resources, including scarce resources	(Magnusson et al., 2019), (UNEP IRP, 2020), (Swilling et al., 2018), (Bai et al., 2018), (Müller et al., 2013)
	1.3.	Plus (+)	5	5	Urban land use depends on the drivers in SSP scenarios; in SSP scenarios with more ambitious temperature goals, urban land use is much lower (e.g. 1.1 million km^2 in 2100 in SSP1 versus 3.6 million km^2 in SSP5)	(Gao and O'Neill, 2020), (Güneralp et al., 2020)
D₂	**2.1.**	Plus (+)	5	4	Depends on the energy mix that is involved in the urban infrastructure (energy use in buildings, private vehicles and public transport) while energy use due to vehicle transport is reduced with compact urban form	(Burgalassi and Luzzati, 2015), (Zhang et al., 2018a), (Pierer and Creutzig, 2019), (Zhang et al., 2018b)
	2.2.	Plus (+)	4	4	Depends on urban land use, urban surface (permeable versus impermeable) and ability to limit urban storm water runoff, i.e. better urban land use and spatial planning limits negative impacts)	(Regier et al., 2020), (Charters et al., 2021), (Phillips et al., 2018)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
	2.3.	Plus (+)	4	4	Depends on the urban water system (supply, purification, distribution, drainage, the magnitude, source and location of water supply) to more compact versus less compact areas, and the level of integration between urban land-use and water planning that requires both policy integration and innovation	(Lei et al., 2021), (Serrao-Neumann et al., 2017), (Ahmad et al., 2020), James et al. (2018), (Rodríguez-Sinobas et al., 2018), (Xu et al., 2018)
	2.4.	Plus (+)	5	5	Depends on the ability to limit urban growth, governance, and integrating ecosystem service information into spatial planning while land use change due to urbanization threatens biodiversity	(McDonald et al., 2020), (McDonald et al., 2018), (Güneralp et al., 2020), (Huang et al., 2018a), (Cortinovis and Geneletti, 2020), (IPBES, 2019)
D$_3$	**3.1.**	Plus (+)	4	4	Urban land use and spatial planning as a response option supports other response options as a fundamental necessity for climate mitigation while the geographical coverage of harmonized algorithms to monitor land use change remains to be one of the current gaps in knowledge	Related references for this indicator are given under Response Option 6, (Reba and Seto, 2020)
	3.2.	Plus (+)	4	4	Depends on combining urban land use and spatial planning practices with climate mitigation as well as sustainable development objectives	(Lwasa, 2017), (Stokes and Seto, 2019), (Facchini et al., 2017), (Cheshmehzangi and Butters, 2017), (Große et al., 2016)
	3.3.	Plus (+)	4	4	Depends on the level of integration, e.g. energy-driven urban design for optimizing the impact of urban form on energy infrastructure	Related references for this indicator are given under Response Option 6
D$_4$	**4.1.**	Plus (+)	4	4	Depends on the characteristics of urban development while limiting the growth in urban extent for climate mitigation has multiple benefits	Related references for this indicator are given under Response Option 6
	4.2.	Plus (+)	4	4	Depends on the ability to decouple urban economic growth from emissions and other parameters, e.g. vehicle kilometres travelled, although the concentration of people and activity	(Gao and Newman, 2018), (Han et al., 2018), (Li and Liu, 2018), (Lee and Erickson, 2017), (Salat et al., 2017)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
					in compact urban areas increases productivity based on proximity and efficiency	
D_5	**5.1.**	Plus (+)	4	3	Depends on processes that are involved in the planning and implementation of the urban mitigation option, i.e. co-design	(Webb et al., 2018), (Grandin et al., 2018)
	5.2.	Plus (+)	4	3	Depends on the quality of spatial planning to increase co-benefits for health and wellbeing, e.g. balancing urban green areas with density	(Pierer and Creutzig, 2019), P. P.-J. (Yang et al., 2018b), (Li et al., 2016a)
	5.3.	Plus/Minus (±)	4	3	Depends on the policy tools that shape the impacts or benefits of urban densification on affordable housing while evidence for transit-induced gentrification is partial and inconclusive	(Debrunner and Hartmann, 2020), (Padeiro et al., 2019), (Chava and Newman, 2016), (Jagarnath and Thambiran, 2018)
D_6	**6.1.**	Plus/Minus (±)	4	3	Depends on the ability to integrate opportunities for climate mitigation with co-benefits for health and wellbeing	(Grandin et al., 2018)
	6.2.	Plus/Minus (±)	4	4	Depends on the ability to implement integrated urban planning as well as relations between urban mobility, buildings, energy systems, water systems, ecosystem services, other urban sectors and climate adaptation	(Broto, 2017), (Endo et al., 2017), (Geneletti et al., 2017) (Große et al., 2016)
	6.3.	Plus/Minus (±)	4	3	Depends on the capacity for implementing land use zoning and regulations consistently with urban land use and spatial planning	(Shen et al., 2019), (Deng et al., 2018), (Yılmaz Bakır et al., 2018)

Response Option 2 → District heating and cooling networks

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D_1	**1.1.**	Plus (+)	5	4	Depends on district heating and cooling demands in comparison to the spatial characteristics of urban areas. For example, heat demand density is a function of both population density and heat demand per capita where physical suitability can be equally present in urban areas with high population density or high heat demand per capita	(Persson et al., 2019), (Möller et al., 2019), (UNEP IRP, 2020), (Swilling et al., 2018)
	1.2.	Plus/Minus (±)	4	3	Depends on optimization of the piping layout with metal use and the implementation of eco-design principles for resource efficiency	(Wang et al., 2016), (UNEP IRP, 2020)
	1.3.	Plus (+)	5	4	Depends on urban design parameters, including density, block area, and elongation with close impact of urban density on energy density	(Shi et al., 2020), (Fonseca and Schlueter, 2015)
D_2	**2.1.**	Plus (+)	5	4	Depends on the energy resource that is replaced with the response option, e.g. replacing coal use improves air and water pollution	(Zhai et al., 2020), (Tuomisto et al., 2015), (Dénarié et al., 2018)
	2.2.	Plus (+)	5	4	Depends on the energy resource that is replaced with the response option, e.g. replacing coal use improves air and water pollution	(Zhai et al., 2020), (Bartolozzi et al., 2017)
	2.3.	Plus (+)	4	3	Depends on the integration of the response option with other response options, e.g. options to improve urban metabolism and reduce impacts	(Swilling et al., 2018)
	2.4.	Plus (+)	5	5	Depends on the interaction of urban energy planning with urban land use and spatial planning such that limiting the growth in urban extent that poses a threat to biodiversity also supports this response option	Related references for this indicator are given under Response Option 1

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D_3	**3.1.**	Plus (+)	4	4	Depends on economies of scope in urban areas with access to already existing excess heat, the integration of power-to-heat technologies, level of climate ambition for climate neutrality, urban infrastructure and support from GIS for planning district heating and cooling networks that also provide an entry point for decarbonizing urban heating needs	(Persson et al., 2019), (UNEP, 2015), (REN21, 2020)
	3.2.	Plus (+)	5	4	Depends on the geographic heat demand density of the urban area while district heating and/or cooling networks are also able to support flexibility in the energy system and act as low-cost storage options	(Sorknæs et al., 2020), (Dorotić et al., 2019b), (Lund et al., 2017), (Yeo et al., 2018), (Borelli et al., 2015), (Felipe Andreu et al., 2016), (Zhang et al., 2016), (Hui et al., 2017), (Bünning et al., 2018), (Hast et al., 2018), (Popovski et al., 2018), (Loibl et al., 2017), (Köfinger et al., 2018), (Chaer et al., 2018), (Webb, 2015), (Möller et al., 2019), (Pieper et al., 2019), (Dominković and Krajačić, 2019), (Dominković et al., 2018), (Bozhikaliev et al., 2019), (Xiong et al., 2015), (Persson et al., 2019), (Pavičević et al., 2017)
	3.3.	Plus (+)	5	4	Depends on the generation with a role for low temperature, fourth generation DHC networks in emerging and future energy networks	(Lund et al., 2018a), (Lund et al., 2018b), (Baldvinsson and Nakata, 2017), (IEA, 2020), (UNEP IRP, 2020)
D_4	**4.1.**	Plus (+)	5	4	Depends on system optimization, the ability to integrate low-temperature renewable energy sources and excess electricity from renewables in upgrading existing or implementing new district heating and cooling networks and a modular approach across urban areas	(Bordin et al., 2016), (Petersen, 2016), (Djørup et al., 2020), (Dorotić et al., 2019a), (Doračić et al., 2020), (Aunedi et al., 2020), (Xiong et al., 2015), (Persson et al., 2019), (Möller et al., 2019), (Pavičević et al., 2017)
	4.2.	Plus (+)	4	3	Depends on the ability to stimulate a green economy as access to renewable energy based DHC networks reduces the operational GHG emissions of the local economy, increases	(Lee and Erickson, 2017), (UNEP, 2015)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
					competitiveness and supports jobs in design and implementation, equipment manufacturing, operation and maintenance	
D_5	**5.1.**	Plus/Minus (±)	4	4	Depends on role in climate neutrality targets, co-benefits for air quality, addressing energy poverty, citizen and consumer ownership models, technology perception as well as public and consumer awareness	(Robinson et al., 2018), (Karlsson et al., 2016), (Palermo et al., 2020a), (Palermo et al., 2020b), (Hvelplund and Djørup, 2017)
	5.2.	Plus (+)	5	4	Depends on improvement in both indoor and outdoor air quality, provision of thermal comfort, alleviation of the urban heat island effect, and improved safety with gas supply outside accommodation	(Zhai et al., 2020), (UNEP, 2015), (Meggers et al., 2016)
	5.3.	Plus (+)	5	4	Depends on the business model with local ownership of district heating and cooling networks having a positive impact on local benefits. The response option can also contribute to addressing energy poverty based on the provision of affordable energy for satisfying thermal comfort	(Hvelplund and Djørup, 2017), (Robinson et al., 2018), (UNEP, 2015)
D_6	**6.1.**	Plus/Minus (±)	4	3	Depends on the ability to plan and implement structural policies for climate neutrality as well as the population size of municipalities	(Grandin et al., 2018), (Palermo et al., 2020a), (Palermo et al., 2020b)
	6.2.	Plus/Minus (±)	4	4	Depends on coordination with urban planning, the scope of urban energy planning, forming of partnerships and local ownership	(Guo and Hendel, 2018), (Kim et al., 2018), (Delmastro et al., 2016), (Chambers et al., 2019), (Hvelplund and Djørup, 2017), (Tong et al., 2017)
	6.3.	Plus/Minus (±)	4	4	Depends on the ability to implement policy instruments to exploit and integrate local resources for supplying thermal energy cost effectively to urban areas while implementing climate neutrality targets. Bottom up and	(Doračić et al., 2020), (Moser et al., 2020), (Möller et al., 2019), (Hvelplund and Djørup, 2017)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
		🟩			interactive regulatory frameworks based on multilevel policies are suggested for facilitating coordination among energy sectors	

Response Option 3 → Electrification of the urban energy system

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D₁	**1.1.**	Plus (+)	5	5	The realization of the available physical potential depends on the ability to electrify the urban energy system while supporting flexibility and sector coupling options for deep decarbonization	(Hsieh et al., 2017), (Bogdanov et al., 2019), (Child et al., 2019), (Aghahosseini et al., 2019), (Aghahosseini et al., 2020), (Ram et al., 2020), (Hansen et al., 2019), (Wang et al., 2018)
	1.2.	Plus/Minus (±)	4	3	Depends on the demands on geophysical resources in comparison to other energy technologies with suitable levels given in scenarios	(Gibon et al., 2017), (IEA, 2020)
	1.3.	Plus (+)	4	4	Depends on the ability to use urban density to increase the penetration of renewable power and electric public transport, including benefits of mixed-use neighbourhoods for grid balancing	(Hsieh et al., 2017), (Tong et al., 2017), (Fichera et al., 2018)
D₂	**2.1.**	Plus (+)	5	5	Depends on the shift to non-polluting energy sources with a shift to 100% renewable energy saving about 408,270 lives per year due to air quality improvements in 74 metropolitan areas around the world	(M. Z. Jacobson et al. 2020), (Ajanovic and Haas, 2019), (Jacobson et al., 2018), (Bagheri et al., 2019), (Gai et al., 2020)
	2.2.	Plus (+)	4	4	Depends on the source of the electrification of urban energy systems that can displace water and soil pollution from conventional fuels	(Gibon et al., 2017)
	2.3.	Plus (+)	4	4	Depends on the source of the electrification of urban energy systems that can displace water and soil pollution from conventional fuels	(Gibon et al., 2017)
	2.4.	Plus (+)	4	4	Depends on the decarbonization pathway, e.g. deep decarbonization pathways require electrification including urban vehicle kilometres and reduction in land use, including for urban	(Bataille et al., 2020), other related references for this indicator are given under Response Option 1

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
					areas, that have a positive impact on biodiversity considering reduced land and climate impacts	
D₃	**3.1.**	Plus (+)	5	4	Depends on the level of integration among urban sectors to support flexibility in energy systems with high penetration of renewable energy	(Kennedy et al., 2017), (Kennedy et al., 2018), (Thellufsen et al., 2020), (Drysdale et al., 2019)
	3.2.	Plus (+)	5	5	Depends on the level of support from flexibility options, e.g. demand response, power-to-heat and electric mobility to increase the penetration of electrification in the urban system. The choice of options, e.g. electrified urban rail, can integrate with existing urban design based on walkable neighbourhoods in rapidly growing cities	(Calvillo et al., 2016), (Gjorgievski et al., 2020), (Calise et al., 2020), (Thellufsen et al., 2020), (Drysdale et al., 2019), (Newman, 2017), (De Luca et al., 2018), (You and Kim, 2020), (Yuan et al., 2018), (Meha et al., 2020), (Narayanan et al., 2019), (McPherson et al., 2018), (Sangiuliano, 2017), (Bartłomiejczyk, 2018), (Lund et al., 2015), (Salpakari et al., 2016), (Bellocchi et al., 2020), (Zenginis et al., 2017), (Sharma, 2018),
	3.3.	Plus (+)	5	5	Demand response based on power-to-heat in support of electrification is mature and has technical feasibility for providing flexibility in the energy system particularly based on municipal level demonstrations	(Gjorgievski et al., 2020), (Kennedy et al., 2017), (Kennedy et al., 2018), (Meha et al., 2020), (IEA, 2020), (Sethi et al., 2020)
D₄	**4.1.**	Plus (+)	5	5	Renewable electricity is also relevant for decarbonizing the heating sector through power-to-heat that is reviewed to be a cost-effective option, including large-scale heat pumps in district infrastructure	(Bloess et al., 2018), (Newman, 2017), (Jacobson et al., 2018)
	4.2.	Plus (+)	5	5	Depends on the ability to establish local jobs and use revenues locally. Access to renewable electricity reduces the operational GHG emissions of the local economy, thereby increasing competitiveness, while providing a net status of long-term, full-time jobs	(Lee and Erickson, 2017), (Jacobson et al., 2020), (Jacobson et al., 2018), (Kennedy et al., 2017), (Mikkola and Lund, 2016), (REN21, 2020), (Coalition for Urban Transitions, 2020)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D_5	**5.1.**	Plus (+)	5	4	Depends on the provision of clean and affordable energy services through electrification of the urban energy system	(Newman, 2017), (Coalition for Urban Transitions, 2019)
	5.2.	Plus (+)	5	5	Depends on the energy resources that are displaced with electrification of the urban energy system with positive influence on health and wellbeing based on improvements in air quality	(Jacobson et al., 2020), (Newman, 2017), (REN21, 2020), (Gai et al., 2020)
	5.3.	Plus (+)	5	4	Depends on the ability of addressing aspects of energy poverty as well as increasing energy access in informal settlements based on urban planning. Urbanization is also a driver of access to electricity, which if combined with renewable energy, can further support sustainable development. Business models and nature of ownership can increase intra-generational equity while shifting to inter-generational equity	(Teferi and Newman, 2018), (Aklin et al., 2018), (Brandoni et al., 2018), (Lekavičius et al., 2020), (Kennedy et al., 2017), (Hunter et al., 2018a)
D_6	**6.1.**	Plus (+)	5	5	Depends on the coordination ability of local authorities and the local level renewable energy target setting and implementation with 823 cities and 101 regions having adopted climate neutrality targets, including some that further extend into urban climate positive targets	(Grandin et al., 2018), (Takao, 2020), (Data-Driven EnviroLab & NewClimate Institute, 2020), (REN21, 2020), (Palermo et al., 2020a), (Palermo et al., 2020b), (Coalition for Urban Transitions, 2019), (Li et al., 2016b), (Havas et al., 2015)
	6.2.	Plus (+)	5	4	Depends on policy coherence to avoid policy fragmentation. High renewable energy targets, high climate ambition as well as high fuel and CO_2 prices further support the diffusion of related options	(Glazebrook and Newman, 2018), (Bloess et al., 2018), (Takao, 2020), (Alkhalidi et al., 2018), (Fenton and Kanda, 2017)
	6.3.	Plus (+)	5	4	Depends on the policy and financing instruments that are used to support and increase electrification of the urban energy system,	(Glazebrook and Newman, 2018), (Hadfield and Cook, 2019), (Byrne et al., 2017), (Suo et al., 2017), (Xie et al., 2018), (Lewandowska et al.,

Dimensions	**Indicators**	**Assessment**	**(A)**	**(C)**	**Role of Context, Scale, Time, Temperature Goal**	**References/Line of Sight**
		🟧			including green bonds and green procurement strategies	2020), (Data-Driven EnviroLab & NewClimate Institute, 2020), (Kennedy et al., 2017)

Response Option 4 → Urban nature-based solutions

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D₁	**1.1.**	Plus (+)	5	4	Depends on the physical space that is available for greenspace/bluespace as well as green and blue infrastructure especially to an extent that will support climate mitigation strategies	(Keeler et al., 2019), (Elmqvist et al., 2015)
	1.2.	Plus (+)	5	3	Nature-based solutions are based on ecomimicry and sustainability innovations and do not represent geophysical resource demands	(Collier et al., 2016)
	1.3.	Plus (+)	5	5	Depends on the scope of nature-based solution while restoration based nature-based solutions can also restore degraded urban land area	(Nastran and Regina, 2016), (Fan et al., 2017), (Raymond et al., 2017), (Elmqvist et al., 2015)
D₂	**2.1.**	Plus (+)	5	5	Depends on the design of urban ecological infrastructure and related parameters that influence better air quality, including leaf area index, foliage density and the impact on reducing urban energy usage	(Song et al., 2019), (Keeler et al., 2019), (Elmqvist et al., 2015), (Jandaghian and Akbari, 2018), (Scholz et al., 2018), (Kim and Coseo, 2018), (Santamouris et al., 2018a)
	2.2.	Plus (+)	5	4	Depends on the use of urban nature-based solutions for remediating brownfield sites, e.g. phytoremediation and bioremediation, and the use of green and blue infrastructure for limiting urban runoff	(Song et al., 2019), (Risch et al., 2018), (Keeler et al., 2019), (Elmqvist et al., 2015)
	2.3.	Plus (+)	5	4	Depends on the ability to reduce water runoff, increase permeable surfaces and increase the quality of waterways and wetlands	(Keeler et al., 2019), (Raymond et al., 2017), (Elmqvist et al., 2015), (Albert et al., 2019)
	2.4.	Plus (+)	5	4	Depends on the location, ecosystem and context of intervention as well as connectivity of natural habitats for increasing urban biodiversity	(Keeler et al., 2019), (McPhearson et al., 2018), (Elmqvist et al., 2015), (McDonald et al., 2018), (Nero et al., 2018), (Hale et al., 2019), (Schwarz et al., 2017)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D_3	**3.1.**	Plus (+)	5	4	Depends on the ability to harness local resources and available technologies in multi-actor and cross-scalar processes	(Keeler et al., 2019), (Elmqvist et al., 2015), (Sasaki et al., 2018)
	3.2.	Plus (+)	5	5	Depends on the ability to up-scale interventions, including for urban regeneration and restoration, and the utilization of available urban areas for multifunctional, place and location based ecological solutions	(Raymond et al., 2017), (Lwasa, 2017), (De Masi et al., 2019), (Grafakos et al., 2020), (Kabisch et al., 2015), (Chen, 2015), (Ferrari et al., 2017), (Cleveland et al., 2017), (Lee et al., 2015), (Kanniah and Siong, 2018), (Gargiulo et al., 2018), (De la Sota et al., 2019), (Albert et al., 2019), (Dorst et al., 2019), (Ruckelshaus et al., 2016)
	3.3.	Plus (+)	5	4	Depends on the ability to up-scale interventions and the role of nature-based solutions in urban sustainability, resilience and transformations	(Elmqvist et al., 2015), (Dorst et al., 2019), (Collier et al., 2016), (Elmqvist et al., 2019)
D_4	**4.1.**	Plus (+)	5	3	Depends on the ecosystem context with the benefit to cost ratio already favourable based on monetary costs excluding co-benefits	(Elmqvist et al., 2015)
	4.2.	Plus (+)	5	4	Depends on the upscaling of interventions to support local employment opportunities and sustainable growth, including urban forestry	(Thomson and Newman, 2016), (Raymond et al., 2017), (Kareem et al., 2020)
D_5	**5.1.**	Plus (+)	5	4	Public acceptance for urban nature-based solutions is commonly high and represents a positive lock-in with awareness and recreational use also given that potential concerns for green gentrification is addressed	(Song et al., 2019), (Ürge-Vorsatz et al., 2018), (Raymond et al., 2017)
	5.2.	Plus (+)	5	4	Depends on the ability of urban green/blue infrastructure to provide reductions in the urban heat island effect, cleaner air as well as cardiovascular and mental health benefits that is related to availability and accessibility	(Huang et al., 2017), (Song et al., 2019), (Jamei et al., 2020), (Andersson et al., 2019), (Keeler et al., 2019), (Grafakos et al., 2020), (van den Bosch and Sang, 2017), (Santamouris et al., 2018b), (Privitera and La Rosa, 2018)

Dimensions	**Indicators**	**Assessment**	**(A)**	**(C)**	**Role of Context, Scale, Time, Temperature Goal**	**References/Line of Sight**
	5.3.	Plus/Minus (±)	5	4	Depends on the availability (percentage of total area) and accessibility (proportion of the urban population living within an accessible distance) of urban green areas as well as public versus private ownership. Distributional effects in the flow of the benefits of green-blue infrastructure are important and may or may not represent inequalities that depends on inclusive policy design and empowerment	(Huang et al., 2017), (Andersson et al., 2019), (Khumalo and Sibanda, 2019), (Keeler et al., 2019), (Lwasa et al., 2015)
D_6	**6.1.**	Plus (+)	5	5	Political acceptance for urban nature-based solutions is commonly high with potential additional support from collaborative planning, co-creating solutions and mandate for urban greening in development	(Grandin et al., 2018), (Grafakos et al., 2020), (Linnenluecke et al., 2017), (Fan et al., 2017), (Collier et al., 2016)
	6.2.	Plus (+)	5	4	Depends on a transdisciplinary coordination for urban ecological infrastructure that encompasses terrestrial and/or aquatic ecosystems as well as institutional and community capacity for holistic design that is better connected with the ecological constraints of Earth systems	(Childers et al., 2019), (Keeler et al., 2019), (Raymond et al., 2017), (Linnenluecke et al., 2017), (Jahanfar et al., 2018), (He et al., 2015), (Albert et al., 2019), (Dorst et al., 2019)
	6.3.	Plus (+)	5	3	Depends on governance and new targets for restoring degraded ecosystems based on the Convention on Biological Diversity	(Elmqvist et al., 2015)

Response Option 5 → Waste prevention, minimization and management

Dimensions	**Indicators**	**Assessment**	**(A)**	**(C)**	**Role of Context, Scale, Time, Temperature Goal**	**References/Line of Sight**
D$_1$	**1.1.**	Plus (+)	5	4	Depends on the potential to alleviate resource usage and upstream emissions from urban settlements based on the response option	(Swilling et al., 2018), (Chen et al., 2020), (Harris et al., 2020)
	1.2.	Plus (+)	5	4	Depends on the scale of material recovery with an urban circular economy approach that can reduce demands for new virgin raw resources	(Russo, 2018), (Vaitkus et al., 2018), (López-Uceda et al., 2018)
	1.3.	Plus (+)	5	4	Depends on the reduction in the ecological footprint due to integrated waste management and possibly biochar to improve soil quality. Compact urban form can also reduce distances for waste collection	(Chiaramonti and Panoutsou, 2018), (Zhang et al., 2018a), (Medick et al., 2018), (Peri et al., 2018), (Oliveira et al., 2017)
D$_2$	**2.1.**	Plus (+)	5	4	Depends on adopted circular economy principles and the energy use of facilities for material and energy recovery in the urban vicinity if any	(Lima et al., 2018), (Zhang et al., 2020), (Ramaswami et al., 2017)
	2.2.	Plus (+)	5	4	Depends on the avoided environmental burden of local strategies for waste and wastewater management and avoided resource use	(Lima et al., 2018), (Ibáñez-Forés et al., 2018), (Zhang et al., 2020), (Zhou et al., 2018), (Roig et al., 2012)
	2.3.	Plus (+)	5	4	Depends on the ability of integrated waste management to avoid environmental contamination, including micropollutants, and the stringency of municipal wastewater treatment systems	(Lima et al., 2018), (Ibáñez-Forés et al., 2018), (Pesqueira et al., 2020), (Vergara-Araya et al., 2020), (Proctor et al., 2021)
	2.4.	Plus (+)	4	4	Depends on avoiding waste to landfill and landfill leachate as well as activities for land reclamation for biodiversity preservation	(Weng et al., 2015), (Hale et al., 2019), (IPBES, 2019)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D₃	**3.1.**	Plus (+)	5	4	Depends on the context of implementing the waste hierarchy from prevention onward and the effectiveness of waste separation at source	(Hunter et al., 2018b), (Sun et al., 2018a)
	3.2.	Plus (+)	5	4	Depends on the waste management system as well as the stage of urban development, including materials from urban construction	(Lwasa, 2017), (Tomić and Schneider, 2018), (Tomić and Schneider, 2017), (Eriksson et al., 2015), (Boyer and Ramaswami, 2017), (Paul et al., 2018), (Islam, 2018), (Huang et al., 2018b), (Jiang et al., 2017), (Pérez et al., 2018), (Pérez et al., 2020)
	3.3.	Plus (+)	5	4	Depends on the waste management pathway and opportunities for further reducing the embodied energy for material recovery	(Kabir et al., 2015), (Soares and Martins, 2017), (Tomić and Schneider, 2018), (D'Adamo et al., 2021)
D₄	**4.1.**	Plus (+)	4	4	Depends on the choice of technology, strategy and awareness of system users that can represent time-dependent costs and revenue changes	(Ranieri et al., 2018), (Medick et al., 2018), (Tomić and Schneider, 2020), (Chifari et al., 2017), (Khan et al., 2016)
	4.2.	Plus (+)	5	4	Depends on labour efficiency, ability to stimulate employment for value added products through circular economy and innovation activities with an estimate for 45 million jobs in the waste management sector by 2030	(Alzate-Arias et al., 2018), (Soukiazis and Proença, 2020), (Coalition for Urban Transitions, 2020)
D₅	**5.1.**	Plus (+)	4	4	Depends on the pathways for circular economy while reducing system costs for citizens, greater awareness of primary waste separation and possible positive behavioural spillover across environmental policies	(Tomić and Schneider, 2020), (Tomić and Schneider, 2017), (Milutinović et al., 2016), (Ek and Miliute-Plepiene, 2018), (Romano et al., 2019), (Díaz-Villavicencio et al., 2017)
	5.2.	Plus (+)	4	4	Depends on the ability to contribute to liveable cities, reduce human toxicity, particulate matter, photochemical oxidant and similar with possibilities of increasing the nutrition status of	(Slorach et al., 2020), (Newman, 2017), (Coalition for Urban Transitions, 2020), (Boyer and Ramaswami, 2017)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
					urban diets also considering food systems with less water, GHG emissions and land impacts	
	5.3.	Plus/Minus (±)	4	3	Depends on the sharing of costs and benefits and the ability to transform informality of waste recycling activities into programs	(Grové et al., 2018), (Conke, 2018)
D_6	**6.1.**	Plus (+)	5	5	Efficient waste management infrastructure is the most widely adopted strategy in a review of 210 circular economy strategies in urban areas	(Petit-Boix and Leipold, 2018), (Grandin et al., 2018), (Affolderbach and Schulz, 2017), (Yu and Zhang, 2016), (Hulgaard and Søndergaard, 2018), (Starostina et al., 2018), (Dong et al., 2018), (Matsuda et al., 2018)
	6.2.	Plus/Minus (±)	5	4	Depends on the organizational structure for promoting integrated waste management and capabilities related to program administration	(Hjalmarsson, 2015), (Yang et al., 2018a), (Kalmykova et al., 2016), (Conke, 2018), (Marino et al., 2018)
	6.3.	Plus/Minus (±)	5	4	Depends on local legislation and policies, choices within municipal waste management strategies to reduce investment costs, and compliance with broader targets for circular economy	(Agyepong and Nhamo, 2017), (Potdar et al., 2016), (Tomić and Schneider, 2020), (Tomić et al., 2017), (Conke, 2018)

Response Option 6 → Integrating sectors, strategies and innovations

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
D₁	**1.1.**	Plus (+)	4	4	Depends on the ability to reduce pressures on physical land resources, thereby having a positive impact on the feasibility of the option	(Güneralp et al., 2020), (Mahtta et al., 2019)
	1.2.	Plus/Minus (±)	4	3	Depends on the material demands for urban development with opportunities for considering materials with lower GHG impacts and the selection of urban development plans with lower material demand	(Carpio et al., 2016), (Ramage et al., 2017), (Liu et al., 2016), (Stocchero et al., 2017), (Zhan et al., 2018), (Shi et al., 2017a), (UNEP IRP, 2020), (Swilling et al., 2018), (Bai et al., 2018), (Müller et al., 2013)
	1.3.	Plus (+)	4	4	Depends on the role of urban land use and spatial planning in the low carbon development (see Response Option 1) and the relevance of brownfield urban development for the project	(Xu et al., 2018), (Gao and O'Neill, 2020), (Güneralp et al., 2020)
D₂	**2.1.**	Plus (+)	5	5	Depends on the integrated response options and climate ambition while urban land use and spatial planning, electrification of urban energy systems, district heating and cooling networks, urban nature based solutions and circular economy have positive impacts on improving air quality with related co-benefits as noted elsewhere	(Sun et al., 2018b), (Diallo et al., 2016), (Nieuwenhuijsen and Khreis, 2016), (Liu et al., 2017), (Tayarani et al., 2018), (Park and Sener, 2019), (Shakya, 2016), (Ramaswami et al., 2017)
	2.2.	Plus (+)	4	3	Depends on the demands of the low carbon development on materials and the performance of the urban metabolism case by case	(González-García et al., 2021)
	2.3.	Plus (+)	4	4	Depends on the interaction and inclusion of low carbon development options that reduce impacts on water use and increases quality, including water use efficiency, demand management and recycling	(Vanham et al., 2017), (Lam et al., 2017), (Lam et al., 2018), (Kim and Chen, 2018), (Topi et al., 2016), (Drangert and Sharatchandra, 2017), (Koop and van Leeuwen, 2015)

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
	2.4.	Plus (+)	4	4	Depends on improving urban metabolism and biophilic urbanism towards urban areas that regenerate natural capital	(Thomson and Newman, 2018), (IPBES, 2019)
D_3	**3.1.**	Plus (+)	4	4	Depends on the ability to initiate and learn from experimentation and the ability to support GHG emission reductions based on both structural, behavioural and lifestyle changes	(Aziz et al., 2018), (Matschoss and Heiskanen, 2017), (McLean et al., 2016), (Williams, 2017), (Chen et al., 2018a), (Zhang and Li, 2017)
	3.2.	Plus (+)	5	4	Depends on the response options and stage of urban development with certain stages providing additional opportunities over others	(Lwasa, 2017), (Roldán-Fontana et al., 2017), (Pacheco-Torres et al., 2017), (Alhamwi et al., 2018), (Beygo and Yüzer, 2017), (Maier, 2016), (Kang and Cho, 2018), (Dienst et al., 2015), (Zhao et al., 2017), (Lin et al., 2018), (Affolderbach and Schulz, 2017), (Ramaswami et al., 2017), (Collaço et al., 2019), (Kılkış, 2019), (Kılkış and Kılkış, 2019), (Yamagata and Seya, 2013)
	3.3.	Plus (+)	4	4	Depends on the level of integration, e.g. energy-driven urban design for optimizing the impact of urban form on energy infrastructure	(Shi et al., 2017b), (Egusquiza et al., 2018), (Pedro et al., 2018), (Soilán et al., 2018), (Dobler et al., 2018), (Xue et al., 2017), (Hu et al., 2015)
D_4	**4.1.**	Plus (+)	4	4	Depends on a portfolio approach for cost-effective, cost-neutral and re-investment options with evidence across different urban typologies	(Colenbrander et al., 2015), (Saujot and Lefèvre, 2016), (Nieuwenhuijsen and Khreis, 2016), (Yazdanie et al., 2017), (Brozynski and Leibowicz, 2018), (Colenbrander et al., 2016) (Sudmant et al., 2016), (Gouldson et al., 2015)
	4.2.	Plus (+)	4	3	Depends on the speed that the response option triggers economic decoupling with a positive impact on employment and local competitiveness	(García-Gusano et al., 2018), (Hu et al., 2018), (Kalmykova et al., 2015), (Chen et al., 2018b), (Shen et al., 2018)
D_5	**5.1.**	Plus (+)	4	4	Depends on a participatory approach towards urban transformation with a shared understanding of future opportunities and challenges. Public acceptance increases with citizen engagement and	(Moglia et al., 2018), (Wiktorowicz et al., 2018), (Gao et al., 2017), (Bjørkelund et al., 2016), (Herrmann et al., 2017), (Blanchet, 2015), (Neuvonen and Ache, 2017), (Sharp and Salter,

Dimensions	Indicators	Assessment	(A)	(C)	Role of Context, Scale, Time, Temperature Goal	References/Line of Sight
					citizen empowerment as well as an awareness of the co-benefits	2017) (Flacke and De Boer, 2017), (Gorissen et al., 2018), (Fastenrath and Braun, 2018)
	5.2.	Plus (+)	5	5	Depends on the scope of low carbon urban development measures with significant potential for co-benefits for public health and wellbeing	(Newman, 2017), (Diallo et al., 2016), (Liu et al., 2017), (Li et al., 2018), (Laeremans et al., 2018), (García-Fuentes and de Torre, 2017), (Dodman, 2009)
	5.3.	Plus (+)	4	4	Depends on integrating issues of equity, inclusivity and affordability, safeguarding urban livelihoods, access to basic services, lowering the energy bill, addressing energy poverty, and improving public health	(Colenbrander et al., 2016) (Wiktorowicz et al., 2018), (Ma et al., 2018), (Colenbrander et al., 2017), (Pukšec et al., 2018), (Claude et al., 2017), (Mrówczyńska et al., 2018), (Friend et al., 2016), (Ramaswami, 2020)
D_6	**6.1.**	Plus/Minus (±)	4	4	Depends on the GHG reduction or climate neutrality target that has been officially set as well as support from participatory processes	(Grandin et al., 2018), (Salvia et al., 2021), (Lu et al., 2017), (Fang et al., 2017), (Powell et al., 2018), (Van Den Dobbelsteen et al., 2018), (Larondelle et al., 2016)
	6.2.	Plus/Minus (±)	4	5	Depends on the ability to form partnerships to overcome barriers, including technology development, rule-setting and demonstration, capacity to manage transitions, establishing integrated departments and funding schemes for low carbon urban development, implementing system innovations and aligning system actors, engaging in policy learning among cities and implementing supportive policy mix	(Petit-Boix et al., 2017), (Broto, 2017), (Westman and Broto, 2018), (Tayarani et al., 2018), (Valek et al., 2017), (Engström et al., 2017), (Tillie et al., 2018), (Olsson et al., 2015), (Dong and Fujita, 2015), (McGuirk et al., 2016), (Peng and Bai, 2018), (den Hartog et al., 2018), (Engels and Walz, 2018), (Lee and Painter, 2015), (Niemeier et al., 2015), (Kilkiş, 2015), (Delmastro et al., 2016), (Große et al., 2016), (Hölscher et al., 2019), (Leck and Simon, 2018), (Peng and Bai, 2020)
	6.3.	Plus/Minus (±)	4	3	Depends on the capacity to implement relevant policy instruments in an integrated way and leverage multilevel policies as relevant	(Agyepong and Nhamo, 2017), (Roppongi et al., 2017)

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