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Urban Systems and Other Settlements

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Executive Summary

Although urbanisation is a global trend often associated with increased incomes and higher consumption, the growing concentration of people and activities is an opportunity to increase resource efficiency and decarbonise at scale (*very high confidence*). The same urbanisation level can have large variations in per capita urban carbon emissions. For most regions, per capita urban emissions are lower than per capita national emissions. {8.1.4, 8.3.3, 8.4, Box 8.1}

Most future urban population growth will occur in developing countries, where per capita emissions are currently low but expected to increase with the construction and use of new infrastructure and the built environment, and changes in incomes and lifestyles (*very high confidence*). The drivers of urban greenhouse gas (GHG) emissions are complex and include an interplay of population size, income, state of urbanisation, and how cities are laid out (i.e. urban form). How new cities and towns are designed, constructed, managed, and powered will lock-in behaviour, lifestyles, and future urban GHG emissions. Low-emission urbanisation can improve well-being while minimising impact on GHG emissions, but there is risk that urbanisation can lead to increased global GHG emissions through increased emissions outside the city's boundaries. {8.1.4, 8.3, Box 8.1, 8.4, 8.6}

The urban share of global GHG emissions (including carbon dioxide (CO_2) and methane (CH_4)) is substantive and continues to increase (*high confidence*). In 2015, urban emissions were estimated to be 25 $GtCO_2$-eq (about 62% of the global share) and in 2020, 29 $GtCO_2$-eq (67–72% of the global share).[1] About 100 of the highest emitting urban areas account for approximately 18% of the global carbon footprint. {8.1.6, 8.3.3}

The urban share of regional GHG emissions increased between 2000 and 2015, with much inter-region variation in the magnitude of the increase (*high confidence*). Globally, the urban share of national emissions increased 6 percentage points, from 56% in 2000 to 62% in 2015. For 2000 to 2015, the urban emissions share across AR6 WGIII regions increased from 28% to 38% in Africa, from 46% to 54% in Asia and Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West-Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East. {8.1.6, 8.3.3}

Per capita urban GHG emissions increased between 2000 and 2015, with cities in the Developed Countries region producing nearly seven times more per capita than the lowest emitting region (*medium confidence*). From 2000 to 2015, global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq per person (an increase of 11.8%); Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); Asia and Pacific increased from 3.0 to 5.1 tCO_2-eq per person (71.7%); Eastern Europe and West-Central Asia increased from 6.9 to 9.8 tCO_2-eq per person (40.9%); Latin America and Caribbean increased from 2.7 to 3.7 tCO_2-eq per person (40.4%); and Middle East increased from 7.4 to 9.6 tCO_2-eq per person (30.1%). Albeit starting from the highest level, Developed Countries had a decline of 11.4 to 10.7 tCO_2-eq per person (–6.5%). {8.3.3}

The global share of future urban GHG emissions is expected to increase through 2050, with moderate to low mitigation efforts, due to growth trends in population, urban land expansion, and infrastructure and service demands, but the extent of the increase depends on the scenario and the scale and timing of urban mitigation action (*medium confidence*). In modelled scenarios, global consumption-based urban CO_2 and CH_4 emissions are projected to rise from 29 $GtCO_2$-eq in 2020 to 34 $GtCO_2$-eq in 2050 with moderate mitigation efforts (intermediate GHG emissions, SSP2–4.5), and up to 40 $GtCO_2$-eq in 2050 with low mitigation efforts (high GHG emissions, SSP3–7.0). With aggressive and immediate mitigation policies to limit global warming to 1.5°C (>50%) with no or limited overshoot by the end of the century (very low emissions, SSP1–1.9), including high levels of electrification, energy and material efficiency, renewable energy preferences, and socio-behavioural responses, urban GHG emissions could approach net-zero and reach a maximum of 3 $GtCO_2$-eq in 2050. Under a scenario with aggressive but not immediate urban mitigation policies to limit global warming to 2°C (>67%) (low emissions, SSP1–2.6), urban emissions could reach 17 $GtCO_2$-eq in 2050.[2] (Figure TS.13) {8.3.4}

Urban land areas could triple between 2015 and 2050, with significant implications for future carbon lock-in. There is a large range in the forecasts of urban land expansion across scenarios and models, which highlights an opportunity to shape future urban development towards low- or net-zero GHG emissions and minimise the loss of carbon stocks and sequestration in the agriculture, forestry and other land use (AFOLU) sector due to urban land conversion (*medium confidence*). By 2050, urban areas could increase up to 211% over the 2015 global urban extent, with the median projected increase ranging from 43% to 106%. While the largest absolute amount of new urban land is forecasted to occur in Asia and Pacific, and in Developed Countries, the highest rate of urban land growth is projected to occur in Africa, Eastern Europe and West-Central Asia, and in the Middle East. The infrastructure that will be constructed concomitant with urban land expansion will lock-in patterns of energy consumption that will persist for decades if not generations. Furthermore, given past trends, the expansion of urban areas is likely to take place on agricultural lands and forests, with implications for the loss of carbon stocks and sequestration. {8.3.1, 8.3.4, 8.4.1, 8.6}

The construction of new, and upgrading of, existing urban infrastructure through 2030 will result in significant emissions (*very high confidence*). The construction of new and upgrading

1 These estimates are based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods, and services consumed in cities. Estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry, and agriculture. {8.1, Annex I: Glossary}

2 These scenarios have been assessed by WGI to correspond to intermediate, high, and very low GHG emissions.

of existing urban infrastructure using conventional practices and technologies can result in significant committed CO_2 emissions, ranging from 8.5 $GtCO_2$ to 14 $GtCO_2$ annually up to 2030 and more than double annual resource requirements for raw materials to about 90 billion tonnes per year by 2050, up from 40 billion tonnes in 2010 (*medium evidence*, *high agreement*). {8.4.1, 8.6}

Given the dual challenges of rising urban GHG emissions and future projections of more frequent extreme climate events, there is an urgent need to integrate urban mitigation and adaptation strategies for cities to address climate change and withstand its effects (*very high confidence*). Mitigation strategies can enhance resilience against climate change impacts while contributing to social equity, public health, and human well-being. Urban mitigation actions that facilitate economic decoupling can have positive impacts on employment and local economic competitiveness. {8.2, Cross-Working Group Box 2, 8.4}

Cities can only achieve net-zero GHG emissions through deep decarbonisation and systemic transformation (*very high confidence*). Three broad mitigation strategies have been found to be effective in reducing emissions when implemented concurrently: (i) reducing or changing urban energy and material use towards more sustainable production and consumption across all sectors, including through compact and efficient urban forms and supporting infrastructure; (ii) electrification and switching to net-zero-emissions resources; and (iii) enhancing carbon uptake and storage in the urban environment (*high evidence*, *high agreement*). Given the regional and global reach of urban supply chains, cities can achieve net-zero emissions only if emissions are reduced within and outside of their administrative boundaries. {8.1.6, 8.3.4, 8.4, 8.6}

Packages of mitigation policies that implement multiple urban-scale interventions can have cascading effects across sectors, reduce GHG emissions outside of a city's administrative boundaries, and reduce more emissions than the net sum of individual interventions, particularly if multiple scales of governance are included (*high confidence*). Cities have the ability to implement policy packages across sectors using an urban systems approach, especially those that affect key infrastructure based on spatial planning, electrification of the urban energy system, and urban green and blue infrastructure. The institutional capacity of cities to develop, coordinate, and integrate sectoral mitigation strategies within their jurisdiction varies by context, particularly those related to governance, the regulatory system, and budgetary control. {8.4, 8.5, 8.6}

Integrated spatial planning to achieve compact and resource-efficient urban growth through co-location of higher residential and job densities, mixed land use, and transit-oriented development (TOD) could reduce GHG emissions between 23% and 26% by 2050 compared to the business-as-usual scenario (*robust evidence*, *high agreement*, *very high confidence*). Compact cities with shortened distances between housing and jobs, and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emissions shared and public transportation, passive energy comfort in buildings, and urban green infrastructure can deliver significant public health benefits and have lower GHG emissions. {8.2, 8.3.4, 8.4, 8.6}

Urban green and blue infrastructure can mitigate climate change through carbon sequestration, avoided emissions, and reduced energy use while offering multiple co-benefits (*robust evidence*, *high agreement*). Urban green and blue infrastructure, including urban forests and street trees, permeable surfaces, and green roofs[3] offer potential to mitigate climate change directly through sequestering and storing carbon, and indirectly by inducing a cooling effect that reduces energy demand and reducing energy use for water treatment. Global urban trees store approximately 7.4 billion tonnes of carbon, and sequester approximately 217 million tonnes of carbon annually, although urban tree carbon storage and sequestration are highly dependent on biome. Among the multiple co-benefits of green and blue infrastructure are reducing the urban heat island (UHI) effect and heat stress, reducing stormwater runoff, improving air quality, and improving mental and physical health of urban dwellers. {8.2, 8.4.4}

The potential and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use, spatial form, development level, and state of urbanisation (i.e., whether it is an established city with existing infrastructure, a rapidly growing city with new infrastructure, or an emerging city with infrastructure buildup (*high confidence*). New and emerging cities will have significant infrastructure development needs to achieve high quality of life, which can be met through energy-efficient infrastructures and services, and people-centred urban design (*high confidence*). The long lifespan of urban infrastructures locks in behaviour and committed emissions. Urban infrastructures and urban form can enable socio-cultural and lifestyle changes that can significantly reduce carbon footprints. Rapidly growing cities can avoid higher future emissions through urban planning to co-locate jobs and housing to achieve compact urban form, and by leapfrogging to low-carbon technologies. Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, targeted infilling and densifying, as well as through modal shift and the electrification of the urban energy system. New and emerging cities have unparalleled potential to become low or net-zero GHG emissions while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and transit-oriented design, that also preserve existing green and blue assets. {8.2, 8.4, 8.6}

With over 880 million people living in informal settlements, there are opportunities to harness and enable informal practices and institutions in cities related to housing, waste, energy, water, and sanitation to reduce resource use and mitigate climate change (*low evidence*, *medium agreement*). The upgrading of informal settlements and inadequate housing to improve resilience and well-being offers a chance to create a low-carbon transition. However, there is limited quantifiable data on

[3] These examples are considered to be a subset of nature-based solutions or ecosystem-based approaches.

these practices and their cumulative impacts on GHG emissions. {8.1.4, 8.2.2, Cross-Working Group Box 2, 8.3.2, 8.4, 8.6, 8.7}

Achieving transformational changes in cities for climate change mitigation and adaptation will require engaging multiple scales of governance, including governments and non-state actors, and in connection with substantive financing beyond sectoral approaches (*very high confidence*). Large and complex infrastructure projects for urban mitigation are often beyond the capacity of local municipality budgets, jurisdictions, and institutions. Partnerships between cities and international institutions, national and regional governments, transnational networks, and local stakeholders play a pivotal role in mobilising global climate finance resources for a range of infrastructure projects with low-carbon emissions and related spatial planning programmes across key sectors. {8.4, 8.5}

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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 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 of climate change. A main finding in AR5 was that urban form shapes urban energy consumption and GHG emissions.

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 Working Group III (WGIII) Chapter 12 on Human Settlements, Infrastructure, and Spatial Planning, urban areas generate between 71% and 76% of carbon dioxide (CO_2) emissions from global final energy use and between 67% and 76% of global energy (Seto et al. 2014). Thus, focusing on 'urban systems' (see Annex I: Glossary and Figure 8.15) addresses one of the key drivers of emissions. Second, more than half of the world population lives 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 (SR1.5 Chapter 4) 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) (see 'infrastructure' in Glossary). The IPCC Special Report on Climate Change and Land (SRCCL) identified cities not only 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 while at the same time contain spatial units where the concentration of biodiversity compares favourably with some landscapes (IPBES 2019a). Cities are also featured as a key element in the transformational governance to tackle both climate change and biodiversity and ecosystem challenges in the first-ever IPCC-IPBES co-sponsored workshop report (Pörtner et al. 2021) (Section 8.5 and see 'governance' in Glossary).

The UN Sustainable Development Goals (SDGs) further underscore the importance of cities in the international arena with the inclusion of SDG 11 on Sustainable Cities and Communities for 'inclusive, safe, resilient and sustainable' cities and human settlements (United Nations 2015; Queiroz et al. 2017; United Nations 2019). Additionally, UN-Habitat's New Urban Agenda (NUA) calls for various measures, including 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).

Since AR5, there has also been an increase in scientific literature on urban mitigation of climate change, including more diversity of mitigation strategies than were covered during AR5 (Lamb et al. 2018), as well as a growing focus on how strategies at the urban scale can have compounding or additive effects beyond urban areas (e.g., in rural areas, land-use planning, and the energy sector).

There is more literature on using a systems approach to understand the interlinkages between mitigation and adaptation, and situating GHG emissions reduction targets within broader social, economic, and human well-being contexts and goals (Bai et al. 2018; Ürge-Vorsatz et al. 2018; Lin et al. 2021). 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 urban and national administrative 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.

8.1.1.1 City Climate Action

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

- Climate leadership at the local scale is growing with commitment from city decision-makers and policymakers to implement local-scale mitigation strategies (GCoM 2018, 2019; ICLEI 2019a; C40 Cities 2020a).
- More than 360 cities announced at the Paris Climate Conference that the collective impact of their commitments will lead to a reduction of up to 3.7 $GtCO_2$-eq (CO_2-equivalent) of urban emissions annually by 2030 (Cities for Climate 2015).
- The Global Covenant of Mayors (GCoM), a transnational network of more than 10,000 cities, has made commitments to reduce urban GHG emissions by up to 1.4–2.3 $GtCO_2$-eq annually by 2030 and 2.8–4.2 $GtCO_2$-eq annually by 2050, compared to business-as-usual (GCoM 2018, 2019).
- More than 800 cities have made commitments to achieve net-zero GHG emissions, either economy-wide or in a particular sector (NewClimate Institute and Data-Driven EnviroLab 2020).

Although most cities and other subnational actors are yet to meet their net-zero GHG or CO_2 emissions commitments, the growing numbers of those commitments, alongside organisations enabled to facilitate reaching those targets, underscore the growing support for climate action by city and other subnational leaders.

8.1.1.2 Historical and Future Urban Emissions

One major innovation in this Assessment Report is the inclusion of historical and future urban GHG emissions. Urban emissions based on consumption-based accounting by regions has been put forth for the time frame 1990–2100 using multiple datasets with projections given in the framework of the Shared Socio-economic Pathway (SSP)–Representative Concentration Pathway (RCP) scenarios. This advance has provided a time dimension to urban footprints considering different climate scenarios with implications for urban mitigation, allowing a comparison of the way urban emissions and their reduction can evolve given different scenario contexts (see Glossary for definitions of various 'pathways' and 'scenarios' in the context of climate change mitigation, including 'SSPs' and 'RCPs').

8.1.1.3 Sustainable Development Linkages and Feasibility Assessment

Special emphasis is placed on the co-benefits of urban mitigation options, including an evaluation of linkages with the SDGs based on synergies and/or trade-offs. Urban mitigation options are further evaluated based on multiple dimensions according to the feasibility assessment (see Section 8.5.5 and Figure 8.19, and Section 8.SM.2) indicating the enablers and barriers of implementation. These advances provide additional guidance for urban mitigation.

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 approved a Special Report on Climate Change and Cities during the Seventh Assessment Cycle of the IPCC (AR7). To stimulate scientific research knowledge exchange, the IPCC and nine global partners co-sponsored the IPCC Cities and Climate Change Science Conference, which brought together over 700 researchers, policymakers, and practitioners from 80 countries.

The conference identified key research priorities including the need for an overarching systems approach to understanding how sectors interact in cities as drivers for GHG emissions and the relationship between climate and other urban processes, as well as achieving transformation towards low-carbon and resilient futures (Bai et al. 2018). The subsequent report on the global research and action agenda identifies scale, informality, green and blue infrastructure, governance and transformation, as well as financing climate action, as areas for scientific research during the AR6 cycle and beyond (WCRP 2019).

8.1.3 The Scope of the Chapter: A 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' (Figure 8.15), 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 (Bai et al. 2016).

The notion of a system of cities has been around for nearly 100 years and recognises that cities are interdependent, in 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; Ramaswami et al. 2017b; Xu et al. 2018c). 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; Scholvin et al. 2019; Knoll 2021).

Moreover, there is a hierarchy of cities (Taylor 1997; Liu et al. 2014), with very large cities at the top of the hierarchy concentrating political power and financial resources, but of which there are very few. Rather, 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 but are also connected to their hinterlands for resources.

The second key component of the urban systems lens identifies the activities and sectors within a city as being inter-connected – that cities are ecosystems (Rees 1997; Grimm et al. 2000; Newman and Jennings 2008; Acuto et al. 2019; Abdullah and Garcia-Chueca 2020; Acuto and Leffel 2021). This urban systems 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 assesses 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 (Section 8.4). An urban systems perspective presents both challenges and opportunities for urban mitigation strategies. It shows that any mitigation option potentially has positive or negative consequences in other sectors, other settlements, cities, or other parts of the world, and requires more careful and comprehensive considerations on the broader impacts, including equity and social justice (see Glossary for a comprehensive definition of 'equity' in the context of mitigation and adaptation). This chapter focuses on cities, city regions, metropolitan regions, megalopolitans, mega-urban regions, towns, and other types of urban configurations because they are the primary sources of urban GHG emissions and tend to be where mitigation action can be most impactful.

There is no internationally agreed upon definition of 'urban', 'urban population', or 'urban area'. Countries develop their own definitions of urban, often based on 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 to Chapter 6 of AR6 WGII, referring to cities and urban settlements as 'concentrated human habitation centres that exist along a continuum' (Dodman et al. 2022) (for further definitions of 'urban', 'cities', 'settlements' and related terms, see Glossary, and WGII Chapter 6).

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 new urban infrastructure stock 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. As of 2018, approximately 55% of the global population lives in urban areas (about 4.3 billion people) (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, with considerable variation and complexity in the relationship between the two (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). In general, there is a clear positive correlation between the level of urbanisation and income levels (Figure 8.1 and Box 8.1).

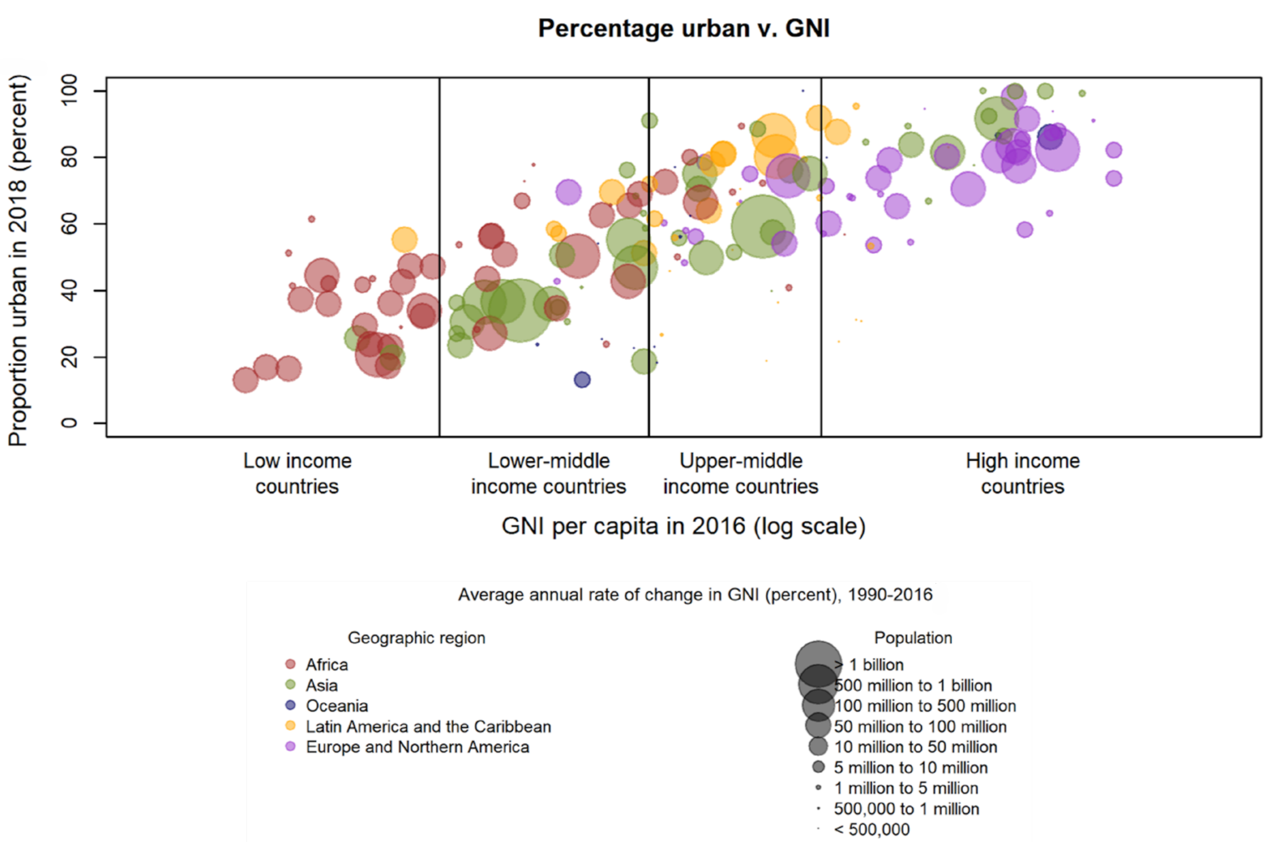

Figure 8.1[4]: Relationship between urbanisation level and gross national income (GNI). There is a positive and strong correlation between the urbanisation level and gross national income. High-income countries have high levels of urbanisation, on average 80%. Low-income countries have low levels of urbanisation, on average 30%. Source: UN DESA 2019, p. 42.

[4] The countries and areas classification in the underlying report for this figure deviates from the standard classification scheme adopted by WGIII as set out in Annex II, Section 1.

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 developing countries and least-developed countries (LDCs). About half of the world's urban population in 2018 lived in just seven countries, and about half of the increase in urban population through 2050 is projected to be concentrated in eight countries (UN DESA 2019) (Figure 8.2). 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 (Sections 8.3.4 and 8.4). Thus, it is essential that urban climate change mitigation strategies include solutions appropriate for cities of varying sizes and typologies (Section 8.6 and Figure 8.21).

Third, small and medium-sized cities and towns are a dominant type of urban settlement. In 2018, more than half (58%) of the urban population lived in cities and towns with fewer than 1 million inhabitants and almost half of the world's urban population (48%) lived 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 lived in a megacity – an urban area with at least 10 million inhabitants (UN DESA 2019). Thus, there is a need for a wide range of strategies for urban mitigation of climate change that are appropriate for cities of varying levels of development

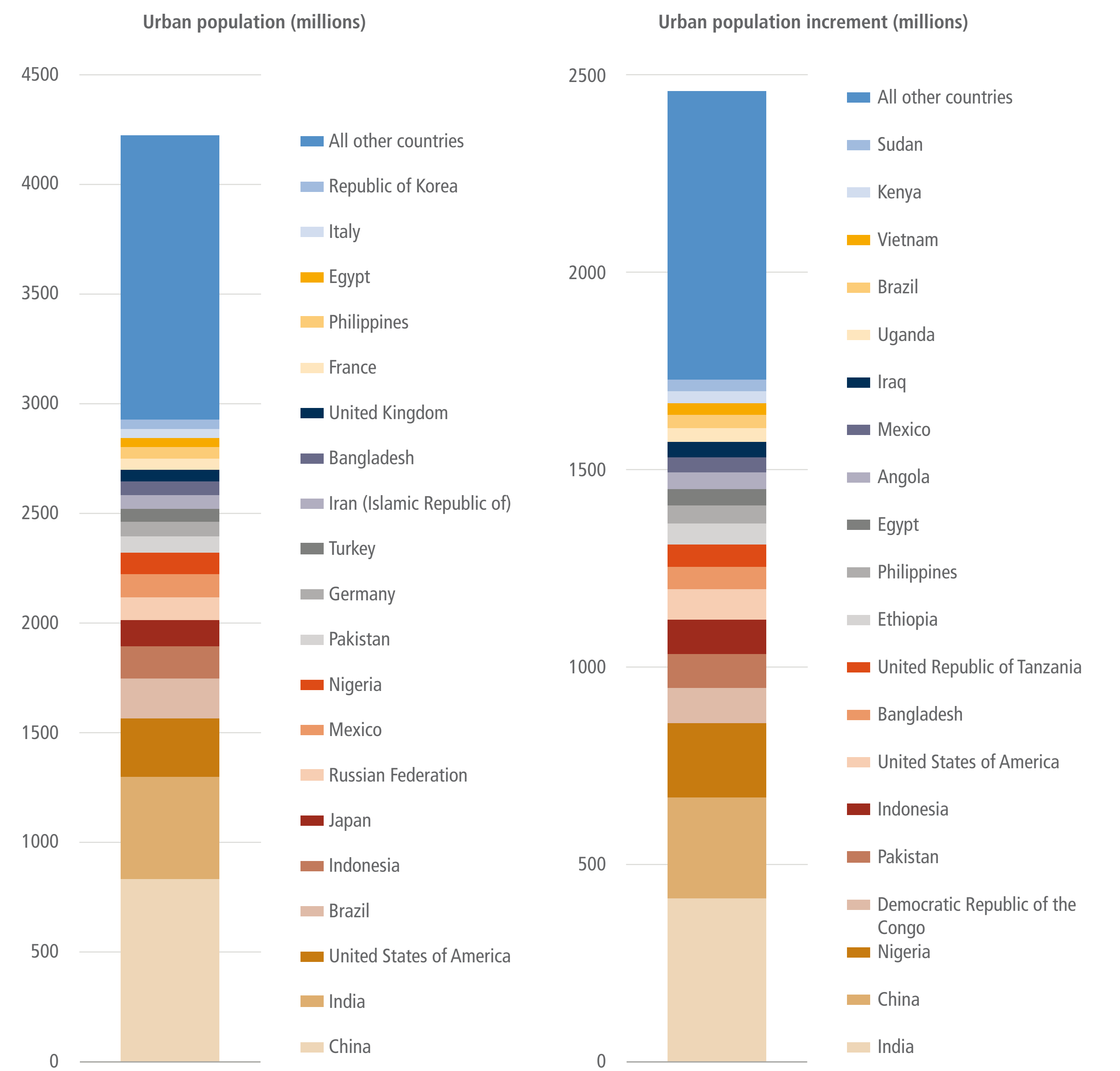

Figure 8.2: Urban population size in 2018 and increase in the projected urban population. In 2018, about half of the world's urban population lived in seven countries, and about half of the increase in urban population through 2050 is forecasted to concentrate in eight countries. Source: UN DESA 2019, p. 44.

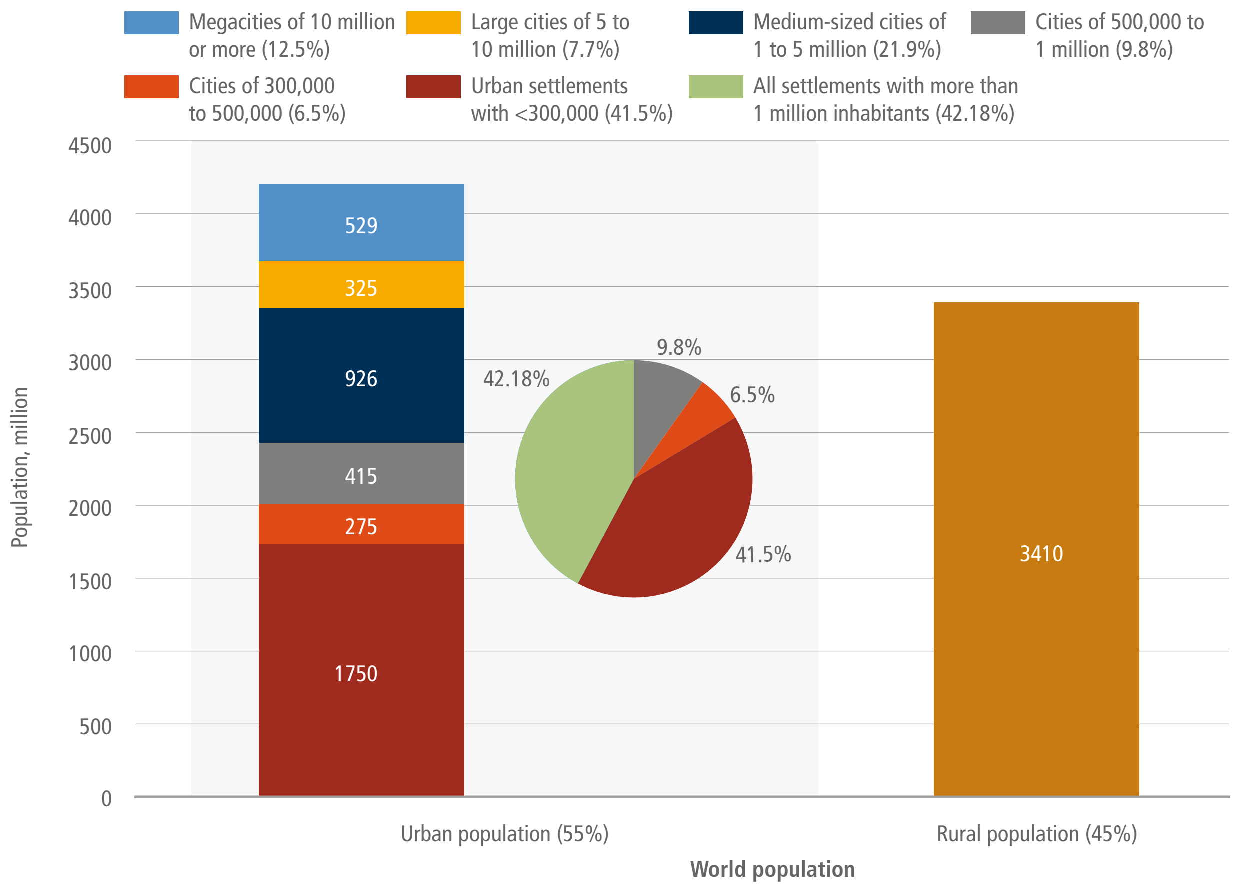

Figure 8.3: Population of the world, by area of residence and size class of urban settlement for 2018. As of 2018, 4.2 billion people or 55% of the world population reside in urban settlements while 45% reside in rural areas. The coloured stacked column for the urban population represents the total number of inhabitants for a given size class of urban settlements. Megacities of 10 million or more inhabitants have a total of only 529 million inhabitants, corresponding to 12.5% of the urban population. In contrast, about 1.8 billion inhabitants reside in urban settlements with fewer than 300,000 inhabitants, corresponding to 41.5% of the urban population. The pie chart represents the respective shares for 2018, with 42% of the urban population residing in settlements with more than 1 million inhabitants, and 58% of the urban population residing in settlements with fewer than 1 million inhabitants. Almost half of the world's urban population (48%) live in settlements with fewer than 500,000 inhabitants. Source: adapted from UN DESA 2019, p. 56.

and size, especially smaller cities which often have lower levels of financial capacities than large cities.

Fourth, another trend is the rise of megacities 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 the national population and economy.

Fifth, population declines have been observed for cities and towns across the world, including in Poland, Republic of Korea, Japan, United States, Germany, and 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, declining fertility, and outmigration to larger cities. Shrinking urban populations could offer retrofitting opportunities (UNEP 2019) and increasing greenspaces (Jarzebski et al. 2021), 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, and 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 the 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, it is important for urban climate change mitigation strategies to account for informality, especially in emerging and developing countries (Section 8.3.2).

8.1.5 Urbanisation in Developing Countries

Urbanisation in the 21st century will be dominated by population and infrastructure growth in developing countries, and as such it is important to highlight three aspects that are unique and especially relevant for climate change mitigation. First, urbanisation will increase in speed and magnitude. Given their significant impact on emissions, mitigation action in Asian cities, especially the large and rapidly growing cities, will have significant implications on global ambitions (Section 8.3.4).

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).

Third, there are sizable 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).

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). In some cases, these private interests are tied up with international flows of capital. In India, adaptation plans involving networks of private actors and related 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. 2019).

When planning and implementing low-carbon transitions, it is important to consider the socio-economic context. An inclusive approach emphasises the need to engage non-state actors, including businesses, research organisations, non-profit organisations and citizens (Lee and Painter 2015; Hale et al. 2020). For example, 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 a large economic corridor in Malaysia led to the development and implementation of a low-carbon blueprint for the region (Ho et al. 2013). Many cities in LDCs and developing countries lack adequate urban infrastructure and housing. An equitable transformation in these cities entails prioritising energy access and basic services, including safe drinking water and sanitation, to meet basic needs of their populations.

8.1.6 Urban Carbon Footprint

Urban areas concentrate GHG fluxes because of the size of the urban population, the size and nature of the urban economy, the energy and GHGs embodied in the infrastructure (see 'embodied emissions' in Glossary), and the goods and services imported and exported to and from cities (USGCRP 2018).

8.1.6.1 Urban Carbon Cycle

In cities, carbon cycles through natural (e.g., vegetation and soils) and managed (e.g., reservoirs and anthropogenic – buildings, transportation) pools. The accumulation of carbon in urban pools, such as buildings or landfills, results from the local or global transfer of carbon-containing energy and raw materials used in the city (Churkina 2008; Pichler et al. 2017; Chen et al. 2020b). Quantitative understanding of these transfers and the resulting emissions and uptake within an urban area is essential for accurate urban carbon accounting (USGCRP 2018). Currently, urban areas are a net source of carbon because they emit more carbon than they uptake. Thus, urban mitigation strategies require a twofold strategy: reducing urban emissions of carbon into the atmosphere, and enhancing uptake of carbon in urban pools (Churkina 2012) (for a broader definition of 'carbon cycle' and related terms such as 'carbon sink,' 'carbon stock,' 'carbon neutrality,' 'GHG neutrality,' and others, see Glossary).

Burning fossil fuels to generate energy for buildings, transportation, industry, and other sectors is a major source of urban GHG emissions (Gurney et al. 2015). At the same time, most cities do not generate within their boundaries all of the resources they use, such as electricity, gasoline, cement, water, and food needed for local homes and businesses to function (Jacobs 1969), requiring consideration of GHG emissions embodied in supply chains serving cities. Furthermore, urban vegetation, soils, and aquatic systems can both emit or remove carbon from the urban atmosphere and are often heavily managed. For example, urban parks, forests, and street trees actively remove carbon from the atmosphere through growing season photosynthesis. They can become a net source of carbon most often during the dormant season or heat waves. Some of the sequestered carbon can be stored in the biomass of urban trees, soils, and aquatic systems. Urban 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 (Churkina 2012) (Section 8.4.4 and Figures 8.17 and 8.18).

8.1.6.2 Urban Emissions Accounting

Urban GHG emissions accounting can determine critical conceptual and quantitative aspects of urban GHG emissions. The accounting framework chosen can therefore predetermine the emissions responsibility, the mitigation options available, and the level of effort required to correctly account for emissions (Afionis et al. 2017).

Two main urban carbon accounting advances have occurred since AR5. The first includes efforts to better understand and clarify how the different urban GHG accounting frameworks that have emerged over the past 15 years are interrelated, require different methodological tools, and reflect differing perspectives on emissions responsibility and quantification effort. The second main advance lies in a series of methodological innovations facilitating practical implementation, emissions verification, and scaling-up of the different GHG accounting approaches. This section provides an overview of the most used GHG urban accounting frameworks followed by a review of the advances since AR5.

Numerous studies have reviewed urban GHG accounting frameworks and methods with somewhat different nomenclatures and categorical divisions (Lin et al. 2015; Lombardi et al. 2017; Chen et al. 2019b; Arioli et al. 2020; Heinonen et al. 2020; Hachaichi and Baouni 2021; Ramaswami et al. 2021). Furthermore, accounting frameworks are reflected in multiple protocols used by urban practitioners (BSI 2013; Fong et al. 2014; ICLEI 2019b). Synthesis of these reviews and protocols, as well as the many individual methodological studies available, point to four general frameworks of urban GHG accounting: (i) territorial accounting (TA); (ii) community-wide infrastructure supply chain footprinting (CIF); and (iii and iv) consumption-based carbon footprint accounting (CBCF; Wiedmann and Minx 2008). The last, CBCF, can be further divided into accounting with a focus on household or personal consumption (iii: the personal carbon footprint, or PCF); and an approach in which one includes final consumption in an area by all consumers (iv: the areal carbon footprint, or ACF) (Heinonen et al. 2020). A number of small variations to these general categories are found in the literature (Lin et al. 2015; Chen et al. 2020a), but these four general frameworks capture the important distinctive (i.e., policy-relevant) features of urban GHG accounting.

All these approaches are foundationally rooted in the concept of urban metabolism, that is, the tracking of material and energy flows into, within, and out of cities (Wolman 1965). These frameworks all aim to quantify urban GHG emissions but reflect different perspectives on where the emission responsibility is allocated in addition to how much and which components of the GHG emissions associated with the import and export of goods and services to and from a city ('transboundary embedded/embodied GHG emissions') are included in a given urban emissions account. The four frameworks share some common, overlapping GHG emission quantities and their interrelationships have been defined mathematically (Chavez and Ramaswami 2013).

A key advance since AR5 lies in understanding the different GHG accounting frameworks in terms of what they imply for responsibility – shared or otherwise – and what they imply for the depth and breadth of GHG emission reductions. TA focuses on in-city direct emission of GHGs to the atmosphere (e.g., combustion, net ecosystem exchange, methane (CH_4) leakage) within a chosen geographic area (Sovacool and Brown 2010; Gurney et al. 2019). CIF connects essential infrastructure use and demand activities in cities with their production, by combining TA emissions with the transboundary supply chain emissions associated with imported electricity, fuels, food, water, building materials, and waste management services used in cities (Ramaswami et al. 2008; Kennedy et al. 2009; Chavez and Ramaswami 2013).

CBCF considers not only the supply-chain-related GHG emissions of key infrastructure, but also emissions associated with all goods and services across a city, often removing emissions associated with goods and services exported from a city (Wiedmann et al. 2016, 2021). The distinction between the PCF and ACF variants of the CBCF is primarily associated with whether the agents responsible for the final demand are confined to only city residents (PCF) or all consumers in a city (ACF), which can include government consumers, capital formation, and other final demand categories (Heinonen et al. 2020).

A recent synthesis of these frameworks in the context of a net-zero GHG emissions target suggests that the four frameworks contribute to different aspects of decarbonisation policy and can work together to inform the overall process of decarbonisation (Ramaswami et al. 2021). Furthermore, the relative magnitude of GHG emissions for a given city resulting from the different frameworks is often a reflection of the city's economic structure as a 'consumer' or 'producer' city (Chavez and Ramaswami 2013; Sudmant et al. 2018).

The TA framework is unique in that it can be independently verified through direct measurement of GHGs in the atmosphere, offering a check on the integrity of emission estimates (Lauvaux et al. 2020; Mueller et al. 2021). It is traditionally simpler to estimate by urban practitioners given the lower data requirements, and it can be relevant to policies aimed specifically at energy consumption and mobility activities within city boundaries. However, it will not reflect electricity imported for use in cities or lifecycle emissions associated with in-city consumption of goods and services.

The CIF framework adds to the TA framework by including GHG emissions associated with electricity imports and the lifecycle GHG emissions associated with key infrastructure provisioning activities in cities, serving all homes, businesses, and industries. This widens both the number of emitting categories and the responsibility for those emissions by including infrastructure-related supply chain emissions. The CIF framework enables individual cities to connect community-wide demand for infrastructure and food with their transboundary production, strategically aligning their net-zero emissions plans with larger-scale net-zero efforts (Ramaswami and Chavez 2013; Ramaswami et al. 2021; Seto et al. 2021).

The PCF version of the CBCF shifts the focus of the consumption and associated supply chain emissions to only household consumption of goods and services (Jones and Kammen 2014). This both reduces the TA emissions considered and the supply chain emissions, excluding all emissions associated with government, capital formation, and exports. The ACF, by contrast, widens the perspective considerably, including the TA and supply chain emissions of all consumers in a city, but often removing emissions associated with exports.

An additional distinction is the ability to sum up accounts from individual cities in a region or country, for example, directly to arrive at a regional or national total. This can only be done for the TA and PCF frameworks. The ACF and CIF frameworks would require adjustment to avoid double-counting emissions (Chen et al. 2020a).

A second major area of advance since AR5 has been in methods to implement, verify and scale up the different GHG footprinting approaches. Advances have been made in six key areas: (i) advancing urban metabolism accounts integrating stocks and flows, and considering biogenic and fossil-fuel-based emissions (Chen et al. 2020b); (ii) improving fine-scale and near-real-time urban use-activity data through new urban data science (Gately et al. 2017; Gurney et al. 2019; Turner et al. 2020; Yadav et al. 2021); (iii) using atmospheric monitoring from the ground, aircraft, and satellites combined with inverse modelling to independently quantify TA emissions (Lamb et al. 2016; Lauvaux et al. 2016, 2020; Davis et al. 2017; Mitchell et al. 2018; Sargent et al. 2018; Turnbull et al. 2019; Wu et al. 2020a); (iv) improving supply chain and input-output modelling, including the use of physically based input-output models (Wachs and Singh 2018); (v) establishing the global multi-region input-output models (Lenzen et al. 2017; Wiedmann et al. 2021); and (vi) generating multi-sector use and supply activity data across all cities in a nation, in a manner where data aggregate consistently across city, province, and national scales (Tong et al. 2021) (Section 8.3).

8.2 Co-benefits and Trade-offs of Urban Mitigation Strategies

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). AR5 WGIII Chapter 12 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 mount on the co-benefits of urban mitigation. Highlighting co-benefits could make a strong case for driving impactful mitigation action (Bain et al. 2016), especially in developing countries, where development benefits can be the argument for faster implementation (Sethi and Puppim de Oliveira 2018). Through co-benefits, urban areas can couple mitigation, adaptation, and sustainable development while closing infrastructure gaps (Thacker et al. 2019; Kamiya et al. 2020).

The urgency of coupling mitigation and adaptation is emphasised through a special Cross-Working Group Box on 'Cities and Climate Change' (Section 8.2.3 and Cross-Working Group Box 2 in this chapter). This section further addresses synergies and trade-offs for sustainable development with a focus on linkages with the SDGs and perspectives for economic development, competitiveness, and equity.

8.2.1 Sustainable Development

Sustainable development is a broad concept, encompassing socio-economic and environmental dimensions, envisaging long-term permanence and improvement. While long-term effects are more related to resilience – and hence carry 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 one on making cities inclusive, safe, resilient and sustainable (SDG 11) (United Nations 2015). The SDGs and related indicators can be an opportunity to improve cities by using science-based decision-making and engaging a diverse set of stakeholders (Simon et al. 2016; Klopp and Petretta 2017; Kutty et al. 2020).

There are multiple ways that development pathways can be shifted towards sustainability (Section 4.3.3, Cross-Chapter Box 5 in Chapter 4, Chapter 17 and Figure 17.1). Urban areas can work to redirect development pathways towards sustainability while increasing co-benefits for urban inhabitants. Figure 8.4 indicates that mitigation options for urban systems can provide synergistic linkages across a wide range of SDGs, and some cases where linkages can produce both synergies and trade-offs. While linkages are based on context and the scale of implementation, synergies can be most significant when urban areas pursue integrated approaches where one mitigation option supports the other (Sections 8.4 and 8.6).

Figure 8.4 summarises an evaluation of the synergies and/or trade-offs with the SDGs for the mitigation options for urban systems based on Supplementary Material 8.SM.1. The evaluations depend on the specific urban context, with synergies and/or trade-offs being more significant in certain contexts than others. Urban mitigation with a view of the SDGs can support shifting pathways of urbanisation towards greater sustainability. The feasibility of urban mitigation options is also malleable and can increase with more 'enabling conditions' (see Glossary), provided, perhaps, through institutional (i.e., financial or governmental) support (Section 8.5). Strengthened institutional capacity that supports the coordination of mitigation options can increase linkages with the SDGs and their synergies. For example, urban land use and spatial planning for walkable and co-located densities, together with electrification of the urban energy system, can hold more benefits for the SDGs than any one of the mitigation options alone (Sections 8.4.2.3, 8.4.3.1 and 8.6).

Evidence on the co-benefits of urban mitigation measures for 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 (PM_{10}) emissions (Diallo et al. 2016). Some measures, especially those related to land-use planning and transportation, have also 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). Mixed-use compact development with sufficient land-use diversity can have a positive influence on urban productivity (Section 8.4.2). Conversely, 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).

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

Figure 8.4: Co-benefits of urban mitigation actions. The first column lists urban mitigation options. The second column indicates synergies with the SDGs. The third column indicates both synergies and/or trade-offs. The dots represent confidence levels with the number of dots representing levels from low to high. In the last column, confidence levels for synergies and/or trade-offs are provided separately. A plus sign (+) represents synergy and a minus sign (–) represents a trade-off. Supplementary Material 8.SM.1 provides 64 references and extends the SDG mappings that are provided in Thacker et al. (2019) and Fuso Nerini et al. (2018). Please see Table 17.SM.1 for details and Annex II for the methodology of the SDG assessment.

pollution, but also enhance indoor air quality by 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 improved 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). Across 74 metropolitan areas around the world, an estimated 408,270 lives per year are saved due to air quality improvements that stem from a move to 100% renewable energy (Jacobson et al. 2020). Other studies indicate that there is potential to reduce premature mortality by up to 7000 people in 53 towns and cities, to create 93,000 new jobs, and to lower global climate costs and personal energy costs, through renewable energy transformations (Jacobson et al. 2018).

Across 146 signatories of a city climate network, local energy-saving measures led to 6596 avoided premature deaths and 68,476 years of life saved due to improved air quality (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) (Section 8.4.4 and Figure 8.18).

Cities in India, Indonesia, Vietnam, 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 $PM_{2.5}$ (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 associated with compact development include the marginal health costs of transport air pollution (Lohrey and Creutzig 2016) and stress from traffic noise (Gruebner et al. 2017) (Section 8.4.2.3).

Urban green and blue infrastructure – a subset of nature-based solutions (NBS) – acts as both climate mitigation and adaptation measures by reducing heat stress (Kim and Coseo 2018; Privitera and La Rosa 2018; Herath et al. 2021), improving air quality, reducing noise (Scholz et al. 2018; De la Sota et al. 2019), improving urban biodiversity (Hall et al. 2017b), and enhancing well-being, 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; Al-Kindi et al. 2020; Sharifi et al. 2021), raised birth weight (Dzhambov et al. 2014), and increased life expectancy (Jonker et al. 2014). Urban agriculture, including urban orchards, rooftop 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) (Section 8.4.4, Figure 8.18 and Box 8.2).

8.2.2 Economic Development, Competitiveness, and Equity

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

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 (TOD), and promotion of active transport modes provide economic co-benefits through, for example, reducing health care costs linked with pollution and cardiovascular diseases, improving labour productivity, and decreasing congestion costs (including waste of time and money) (Sharifi et al. 2021). 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 gross domestic product (GDP), ranging from 0.7% to 15.0% (Dulal 2017) (Section 8.4.2).

Since policy interventions can result in negative impacts or trade-offs with other objectives, fostering accessibility, equity, and inclusivity for disadvantaged groups is essential (Viguié and Hallegatte 2012; Sharifi 2020; Pörtner et al. 2021). Anti-sprawl policies that aim to increase density, or the introduction of large green areas in cities could increase property prices, resulting in trade-offs with affordable housing and pushing urban poor further away from cities (Reckien et al. 2017; Alves et al. 2019). Deliberate strategies 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).

Low-carbon urban development that triggers economic decoupling and involves capacity-building measures could 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).

Depending on the context, green and blue infrastructure can also offer considerable economic co-benefits. For example, green roofs and facades and other urban greening efforts such as urban agriculture and greening streets can improve microclimatic conditions and enhance thermal comfort, thereby reducing utility and health care costs. The presence of green and blue infrastructure may also increase the economic values of nearby properties (Votsis 2017; Alves et al. 2019) (Section 8.4.4 and Figure 8.18).

Studies in the UK show that beneficiaries are willing to pay (WTP) an additional fee (up to 2% more in monthly rent) for proximity to green and blue infrastructure, with the WTP varying depending on the size and nature of the green space (Mell et al. 2013, 2016). Urban agriculture can not only reduce household food expenditure, but also provide additional sources of revenue for the city (Ayerakwa 2017; Alves et al. 2019). Based on the assessed literature, there is *high agreement* on the economic co-benefits of green and blue infrastructure, but supporting evidence is still limited (Section 8.7).

Implementing waste management and wastewater recycling measures can provide additional sources of income for citizens and local authorities. Wastewater recycling can minimise the costs associated with the renewal of centralised wastewater treatment plants (Bernstad Saraiva Schott and Cánovas 2015; Gharfalkar et al. 2015; Gonzalez-Valencia et al. 2016; Herrero and Vilella 2018; Matsuda et al. 2018; Nisbet et al. 2019). 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* (Sharifi 2021). 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 the promotion of behavioural measures such as dietary changes that can decrease the demand for costly food sources and reduce health care costs through promoting healthy diets (Hoppe et al. 2016) (Sections 8.4.5 and 8.4.6).

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 and blue 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). To achieve such benefits, however, the costs of integrating green and blue infrastructure and passive design measures into building design would need to be minimised. 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. Carefully designed measures that reduce such disproportionate impacts by involving experts, authorities and citizens would enhance social equity (Pandey et al. 2018; He et al. 2019; Mulligan et al. 2020).

8.2.3 Coupling Mitigation and Adaptation

There are numerous synergies that come from coupling urban adaptation and mitigation. A number of studies have developed methods to assess the synergies between mitigation and adaptation strategies, as well as their co-benefits (Solecki et al. 2015; Buonocore et al. 2016; Chang et al. 2017; Helgenberger and Jänicke 2017). Co-benefits occur when implementing mitigation (or adaptation) measures that have positive effects on adaptation (or 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. A systematic review of over 50 climate change articles provides evidence that mitigation can contribute to resilience – especially to temperature changes and flooding – with varying magnitudes, depending on factors such as the type of mitigation measure and the scale of implementation (Sharifi 2019).

Measures from different sectors that can provide both mitigation and adaptation benefits involve urban planning (Section 8.4.2), buildings (Sections 8.4.3.2 and 8.4.4), energy (Section 8.4.3), green and blue infrastructure (Section 8.4.4), transportation (Section 8.4.2), socio-behavioural aspects (Section 8.4.5), urban governance (Section 8.5), waste (Section 8.4.5.2), and water (Section 8.4.6). 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). Existing evidence is mainly related to urban green infrastructure, urban planning, transportation, and buildings. 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. Renewable-based distributed and decentralised energy systems improve resilience to energy shocks and can enhance adaptation to water stress considering the water-energy nexus. By further investment on these measures, planners and decision makers can ensure enhancing achievement of mitigation/adaptation co-benefits at the urban level (Sharifi 2021).

As for trade-offs, some mitigation efforts may increase exposure to stressors such as flooding and the urban heat island (UHI) effect (see Glossary), thereby reducing the adaptive capacity of citizens. For instance, in some contexts, 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. 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 corporate interests resulting in adverse effects on the urban poor (Chu et al. 2018; Mehta et al. 2019).

Urban green and blue infrastructure such as urban trees, greenspaces, and urban waterways can sequester carbon and reduce energy demand, and provide adaptation co-benefits by mitigating the UHI effect (Berry et al. 2015; Wamsler and Pauleit 2016; WCRP 2019) (Section 8.4.4, Figure 8.18 and Box 8.2).

Cross-Working Group Box 2: Cities and Climate Change

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Introduction

This Cross-Working Group Box on Cities and Climate Change responds to the critical role of urbanisation as a megatrend impacting climate adaptation and mitigation. Issues associated with cities and urbanisation are covered in substantial depth within all three Working Groups (including WGI Box TS.14, WGII Chapter 6 'Cities, Settlements and Key Infrastructure', WGII regional chapters, WGII Cross-Chapter Paper 'Cities and Settlements by the Sea', and WGIII Chapter 8 'Urban Systems and Other Settlements'). This Box highlights key findings from WGII and III and substantial gaps in literature where more research is urgently needed relating to policy action in cities. It describes methods of addressing mitigation and adaptation in an integrated way across sectors and cities to advance sustainable development and equity outcomes and assesses the governance and finance solutions required to support climate-resilient responses.

Urbanisation: A megatrend driving global climate risk and potential for low-carbon and resilient futures

Severe weather events, exacerbated by anthropogenic emissions, are already having devastating impacts on people who live in urban areas, on the infrastructure that supports these communities, as well as people living in distant places (*high confidence*) (Cai et al. 2019; Folke et al. 2021). Between 2000 and 2015, the global population in locations that were affected by floods grew by 58–86 million (Tellman et al. 2021). The direct economic costs of all extreme events reached USD210–268 billion in 2020 (Aon 2021; Munich RE 2021; WMO 2021) or about USD0.7 billion per day; this figure does not include knock-on costs in supply chains (Kii 2020) or lost days of work, implying that the actual economic costs could be far higher. Depending on RCP, between half (RCP2.6) and three-quarters (RCP8.5) of the global population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (Mora et al. 2017; Huang et al. 2019) (see WGII Section 6.2.2.1, WGII Figure 6.3, and WGIII Sections 8.2 and 8.3.4).

Urban systems are now global, as evidenced by the interdependencies between infrastructure, services, and networks driven by urban production and consumption; remittance flows and investments reach into rural places, shaping natural resource use far from the city and bring risk to the city when these places are impacted by climate change (WGIII Section 8.4 and Figure 8.15). This megatrend (Kourtit et al. 2015) amplifies as well as shapes the potential impacts of climate events and integrates the aims and approaches for delivering mitigation, adaptation, and sustainable development (*medium evidence*, *high agreement*) (Dawson et al. 2018; Tsavdaroglou et al. 2018; Zscheischler et al. 2018). For cities facing flood damage, wide-ranging impacts have been recorded on other urban areas near and far (Carter et al. 2021; Simpson et al. 2021) as production and trade is disrupted (Shughrue et al. 2020). In the absence of integrated mitigation and adaptation across and between infrastructure systems and local places, impacts that bring urban economies to a standstill can extend into supply chains and across energy networks causing power outages.

Urban settlements contribute to climate change, generating about 70% of global CO_2-eq emissions (*high confidence*) (see WGI Box TS.14, WGII Sections 6.1 and 6.2, and WGIII Section 8.3). This global impact feeds back to cities through the exposure of infrastructure, people, and business to the impacts of climate-related hazards. Particularly in larger cities, this climate feedback is exacerbated by local choices in urban design, land use, building design, and human behaviour (Viguié et al. 2020) that shape local environmental conditions. Both the local and global combine to increase hazardousness. Certain configurations of urban form and their elements can add up to 2°C to warming; concretisation of open space can increase run-off, and building height and orientation influences wind direction and strength (see WGII Section 6.3 and WGIII Section 8.4.2).

Cross-Working Group Box 2 (continued)

Designing for resilient and low-carbon cities today is far easier than retrofitting for risk reduction tomorrow. As urbanisation unfolds, its legacy continues to be the locking-in of emissions and vulnerabilities (*high confidence*) (Seto et al. 2016; Ürge-Vorsatz et al. 2018) (see WGIII Section 8.4 and Figure 8.15). Retrofitting, disaster reconstruction, and urban regeneration programmes offer scope for strategic direction changes to low-carbon and high-resilience urban form and function, so long as they are inclusive in design and implementation. Rapid urban growth means new investment, new buildings and infrastructure, new demands for energy and transport and new questions about what a healthy and fulfilling urban life can be. The USD90 trillion expected to be invested in new urban development by 2030 (NCE 2018) is a global opportunity to place adaptation and mitigation directly into urban infrastructure and planning, as well as to consider social policy including education, health care, and environmental management (Ürge-Vorsatz et al. 2018). If this opportunity is missed, and business-as-usual urbanisation persists, social and physical vulnerability will become much more challenging to address.

The benefits of actions taken to reduce GHG emissions and climate stressors diminish with delayed action, indicating the necessity for rapid responses. Delaying the same actions for increasing the resilience of infrastructure from 2020 to 2030 is estimated to have a median cost of at least USD1 trillion (Hallegatte et al. 2019) while also missing the carbon emissions reductions required in the narrowing window of opportunity to limit global warming to 1.5°C (WGI). In contrast, taking integrated actions towards mitigation, adaptation, and sustainable development will provide multiple benefits for the health and well-being of urban inhabitants and avoid stranded assets (see WGII Section 6.3, WGII Chapter 17, Cross-Chapter Box on 'Feasibility' in WGII Chapter 18, WGIII Chapter 5, and WGIII Section 8.2).

The policy-action gap: urban low-carbon and climate-resilient development

Cities are critical places to realise both adaptation and mitigation actions simultaneously with potential co-benefits that extend far beyond cities (*medium evidence*, *high agreement*) (Göpfert et al. 2019; Grafakos et al. 2020). Given rapid changes in the built environment, transforming the use of materials and the land intensiveness of urban development, including in many parts of the Global South, will be critical in the next decades, as well as mainstreaming low-carbon development principles in new urban development in all regions. Much of this development will be self-built and 'informal' – and new modes of governance and planning will be required to engage with this. Integrating mitigation and adaptation now rather than later, through reshaping patterns of urban development and associated decision-making processes, is a prerequisite for attaining resilient and zero-carbon cities (see WGIII Sections 8.4 and 8.6, and WGIII Figure 8.21).

While more cities have developed plans for climate adaptation and mitigation since AR5, many remain to be implemented (*limited evidence*, *high agreement*) (Araos et al. 2017; Aguiar et al. 2018; Olazabal and Ruiz De Gopegui 2021). A review of local climate mitigation and adaptation plans across 885 urban areas of the European Union suggests mitigation plans are more common than adaptation plans – and that city size, national legislation, and international networks can influence the development of local climate and adaptation plans with an estimated 80% of those cities with above 500,000 inhabitants having a mitigation and/or an adaptation plan (Reckien et al. 2018).

Integrated approaches to tackle common drivers of emissions and cascading risks provide the basis for strengthening synergies across mitigation and adaptation, and help manage possible trade-offs with sustainable development (*limited evidence*, *medium agreement*) (Grafakos et al. 2019; Landauer et al. 2019; Pierer and Creutzig 2019). An analysis of 315 local authority emission-reduction plans reveals that the most common policies cover municipal assets and structures (Palermo et al. 2020a). Estimates of emission reductions by non-state and sub-state actors in 10 high-emitting economies projected GHG emissions in 2030 would be 1.2–2.0 $GtCO_2$-eq yr^{-1} or 3.8–5.5% lower compared to scenario projections for current national policies (31.6–36.8 $GtCO_2$-eq yr^{-1}) if the policies are fully implemented and do not change the pace of action elsewhere (Kuramochi et al. 2020). The value of integrating mitigation and adaptation is underscored in the opportunities for decarbonising existing urban areas, and investing in social, ecological, and technological infrastructure resilience (WGII Section 6.4). Integrating mitigation and adaption is challenging (Landauer et al. 2019) but can provide multiple benefits for the health and well-being of urban inhabitants (Sharifi 2021) (See WGIII Section 8.2.3).

Effective climate strategies combine mitigation and adaptation responses, including through linking adaptive urban land use with GHG emission reductions (*medium evidence*, *high agreement*) (Xu et al. 2019; Patterson 2021). For example, urban green and blue infrastructure can provide co-benefits for mitigation and adaptation (Ürge-Vorsatz et al. 2018) and is an important entry point for integrating adaptation and mitigation at the urban level (Frantzeskaki et al. 2019) (see WGIII Section 8.4.4 and WGIII Figure 8.18). Grey and physical infrastructure, such as sea defences, can immediately reduce risk, but also transfer risk and limit future options. Social policy interventions including social safety nets provide financial security for the most at-risk and can manage vulnerability determined by specific hazards or independently.

Cross-Working Group Box 2 (continued)

Hazard-independent mechanisms for vulnerability reduction – such as population-wide social security – provide resilience in the face of unanticipated cascading impacts or surprise and novel climate-related hazard exposure. Social interventions can also support or be led by ambitions to reach the SDGs (Archer 2016). Climate-resilient development invites planners to develop interventions and monitor the effectiveness of outcomes beyond individual projects and across wider remits that consider sustainable development. Curbing the emission impacts of urban activities to reach net-zero emissions in the next decades, while improving the resilience of urban areas, necessitates an integrated response now.

Key gaps in knowledge include: urban-enabling environments; the role of smaller settlements, low-income communities, and informal settlements, as well as those in rental housing spread across the city; and the ways in which actions to reduce supply chain risk can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al. 2016; Shi et al. 2016; Rosenzweig et al. 2018; Dulal 2019).

Enabling action

Innovative governance and finance solutions are required to manage complex and interconnected risks across essential key infrastructures, networks, and services, as well as to meet basic human needs in urban areas (*medium confidence*) (Colenbrander et al. 2018a; Moser et al. 2019). There are many examples of 'ready-to-use' policy tools, technologies, and practical interventions for policymakers seeking to act on adaptation and mitigation (Bisaro and Hinkel 2018; Keenan et al. 2019; Chirambo 2021) (see WGIII Section 8.5.4). Tax and fiscal incentives for businesses and individuals can help support city-wide behaviour change towards low-carbon and risk-reducing choices. Change can start where governments have most control – often in public sector institutions and investment – but the challenge ahead requires partnership with private sector and community actors acting at scale and with accountability. Urban climate governance and finance needs to address urban inequalities at the forefront if the urban opportunity is to realise the ambition of the SDGs.

Increasing the pace of investments will put pressure on governance capability, transparency, and accountability of decision-making (*medium confidence*) (see WGII Section 6.4.5). Urban climate action that actively includes local actors is more likely to avoid unintended, negative maladaptive impacts and mobilise a wide range of local capacities. In the long run, this is also more likely to carry public support, even if some experiments and investments do not deliver the intended social benefits. Legislation, technical capacity, and governance capability are required to be able to absorb additional finance.

In recent years, about USD384 billion of climate finance has been invested in urban areas per year. This remains at about 10% of the annual climate finance that would be necessary for low-carbon and resilient urban development at a global scale (Negreiros et al. 2021). Rapid deployment of funds to stimulate economies in the recovery from COVID-19 has highlighted the pitfalls of funding expansion ahead of policy innovation and capacity building. The result can be an intensification of existing carbon-intensive urban forms – exactly the kinds of 'carbon lock-in' (see WGIII Glossary and WGIII Section 8.4.1) that have contributed to risk creation and its concentration amongst those with little public voice or economic power.

Iterative and experimental approaches to climate adaptation and mitigation decision-making grounded in data and co-generated in partnership with communities can advance low-carbon climate resilience (*medium evidence*, *high confidence*) (Culwick et al. 2019; Caldarice et al. 2021; van der Heijden and Hong 2021). Conditions of complexity, uncertainty, and constrained resources require innovative solutions that are both adaptive and anticipatory. Complex interactions among multiple agents in times of uncertainty makes decision-making about social, economic, governance, and infrastructure choices challenging and can lead decision-makers to postpone action. This is the case for those balancing household budgets, residential investment portfolios, and city-wide policy responsibilities. Living with climate change requires changes to business-as-usual design-making. Co-design and collaboration with communities through iterative policy experimentation can point the way towards climate-resilient development pathways (Ataöv and Peker 2021). Key to successful learning is transparency in policymaking, inclusive policy processes, and robust local modelling, monitoring, and evaluation, which are not yet widely undertaken (Sanchez Rodriguez et al. 2018; Ford et al. 2019).

The diversity of cities' experiences of climate mitigation and adaptation strategies brings an advantage for those city governments and other actors willing to 'learn together' (*limited evidence*, *high confidence*) (Bellinson and Chu 2019; Haupt and Coppola 2019). While contexts are varied, policy options are often similar enough for the sharing of experiments and policy champions. Sharing expertise can build on existing regional and global networks, many of which have already placed knowledge, learning, and capacity building at the centre of their agendas. Learning from innovative forms of governance and financial investment, as well as strengthening co-production of policy through inclusive access to knowledge and resources, can help address mismatches in local capacities and strengthen wider SDGs and COVID-19 recovery agendas (*limited evidence*, *medium agreement*). Perceptions of risk can greatly

Cross-Working Group Box 2 (continued)

influence the reallocation of capital and shift financial resources (Battiston et al. 2021). Coupling mitigation and adaptation in an integrated approach offers opportunities to enhance efficiency, increases the coherence of urban climate action, generates cost savings, and provides opportunities to reinvest the savings into new climate action projects to make all urban areas and regions more resilient.

Local governments play an important role in driving climate action across mitigation and adaptation as managers of assets, regulators, mobilisers, and catalysts of action, but few cities are undertaking transformative climate adaptation or mitigation actions (*limited evidence*, *medium confidence*) (Heikkinen et al. 2019). Local actors are providers of infrastructure and services, regulators of zoning, and can be conveners and champions of an integrated approach for mitigation and adaptation at multiple levels (*limited evidence*, *high confidence*). New opportunities in governance and finance can enable cities to pool resources together and aggregate interventions to innovate ways of mobilising urban climate finance at scale (Colenbrander et al. 2019; Simpson et al. 2019; White and Wahba 2019). However, research increasingly points towards the difficulties faced during the implementation of climate financing in situ, such as the fragmentation of structures of governance capable of managing large investments effectively (Mohammed et al. 2019) (see WGIII Section 8.5 and WGIII Chapter 13).

Scaling up transformative place-based action for both adaptation and mitigation requires enabling conditions, including land-based financing, intermediaries, and local partnerships (*medium evidence*, *high agreement*) (Chu et al. 2019; Chaudhuri, 2020) supported by a new generation of big data approaches. Governance structures that combine actors working at different levels with a different mix of tools are effective in addressing challenges related to implementation of integrated action while cross-sectoral coordination is necessary (Singh et al. 2020). Joint institutionalisation of mitigation and adaptation in local governance structures can also enable integrated action (Göpfert et al. 2020; Hurlimann et al. 2021). However, the proportion of international finance that reaches local recipients remains low, despite the repeated focus of climate policy on place-based adaptation and mitigation (Manuamorn et al. 2020). Green financing instruments that enable local climate action without exacerbating current forms of inequality can jointly address mitigation, adaptation, and sustainable development. Climate finance that also reaches beyond larger non-state enterprises (e.g., small and medium-sized enterprises, local communities, or non-governmental organisations (NGOs)), and is inclusive in responding to the needs of all urban inhabitants (e.g., disabled individuals, or citizens of different races or ethnicities) is essential for inclusive and resilient urban development (Colenbrander et al. 2019; Gabaldón-Estevan et al. 2019; Frenova 2021). Developing networks that can exert climate action at scale is another priority for climate finance.

The urban megatrend is an opportunity to transition global society. Enabling urban governance to avert cascading risk and achieve low-carbon, resilient development will involve the co-production of policy and planning, rapid implementation and greater cross-sector coordination, and monitoring and evaluation (*limited evidence*, *medium agreement*) (Di Giulio et al. 2018; Grafakos et al. 2019). New constellations of responsible actors are required to manage hybrid local-city or cross-city risk management and decarbonisation initiatives (*limited evidence*, *medium agreement*). These may increasingly benefit from linkages across more urban and more rural space as recognition of cascading and systemic risk brings recognition of supply chains, remittance flows, and migration trends as vectors of risk and resilience. Urban governance will be better prepared in planning, prioritising, and financing the kind of measures that can reduce GHG emissions and improve resilience at scale when they consider a view of cascading risks and carbon lock-ins globally, while also acting locally to address local limitations and capacities, including the needs and priorities of urban citizens (Colenbrander et al. 2018a; Rodrigues 2019).

8.3 Urban Systems and Greenhouse Gas Emissions

This section assesses trends in urban land use, the built environment, and urban GHG emissions, as well as forecasts for urban land use and emissions under certain scenarios to 2050 or 2100. These trends and scenarios hold implications for optimising the approaches to urban climate change mitigation discussed in Sections 8.4 and 8.6.

8.3.1 Trends in Urban Land Use and the Built Environment

Urban land use is one of the most intensive human impacts on the planet (Pouyat et al. 2007; Grimm et al. 2008). Urban land expansion to accommodate a growing urban population has resulted in the conversion of agricultural land (Pandey et al. 2018; Liu et al. 2019), deforestation (van Vliet 2019), habitat fragmentation (Liu et al. 2016b), biodiversity loss (McDonald et al. 2018, 2020), and the modification of urban temperatures and regional precipitation patterns (Li et al. 2017; Krayenhoff et al. 2018; Liu and Niyogi 2019; Zhang et al. 2019).

Urban land use and the associated built environment and infrastructure shape urban GHG emissions through the demand for materials and the ensuing energy-consuming behaviours. In particular, the structure of the built environment (i.e., its density, form, and extent) have long-lasting influence on urban GHG emissions, especially those from transport and building energy use, as well as the embodied emissions of the urban infrastructure (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 is essential for assessing energy behaviour in cities as well as long-term mitigation potential (Sections 8.4 and 8.6, and Figure 8.21).

This section draws on the literature to discuss three key trends in urban land expansion, and how those relate to GHG emissions.

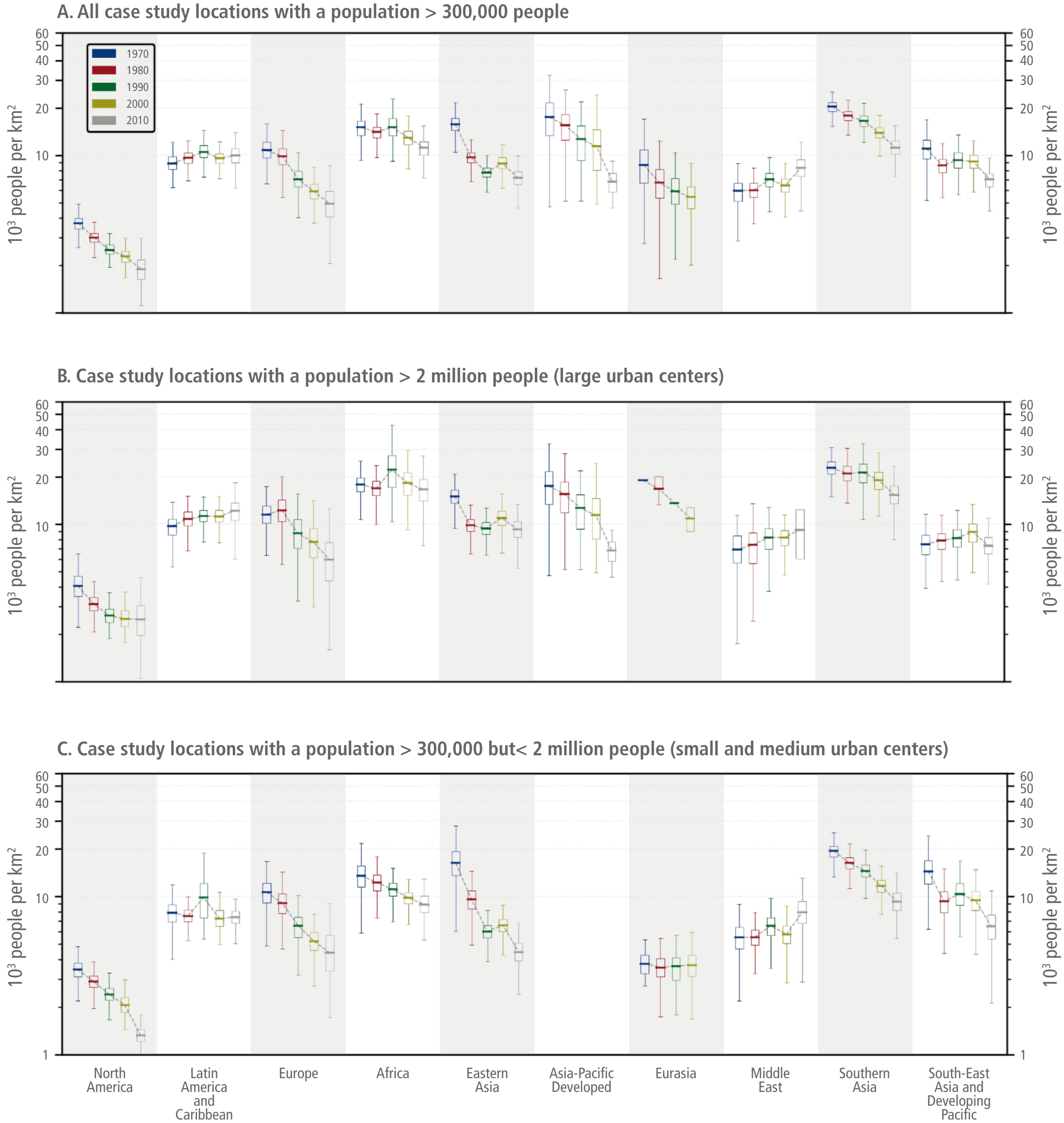

Figure 8.5: Urban population density by decade (1970–2010) grouped by the AR6 WGIII 10-region aggregation. Panel **(a)** displays the results from all case study locations with a population >300,000. Panels (b) and (c) show results grouped by city size: **(b)** cities with a population >2 million (large urban centres), and **(c)** those with a population >300,000 but <2 million (small and medium urban centres). Box plots show the median, first and third quartiles, and lower and upper mild outlier thresholds of bootstrapped average urban population densities at the turn of each decade. The estimates are shown on a logarithmic scale. The data shows an overall trend of declining urban population densities among all but one region in the last four decades, at varying rates – although the Latin America and Caribbean region indicates relatively constant urban population density over time. The Middle East region is the only region to present with an increase in urban population density across all city sizes. Source: adapted from Güneralp et al. (2020).

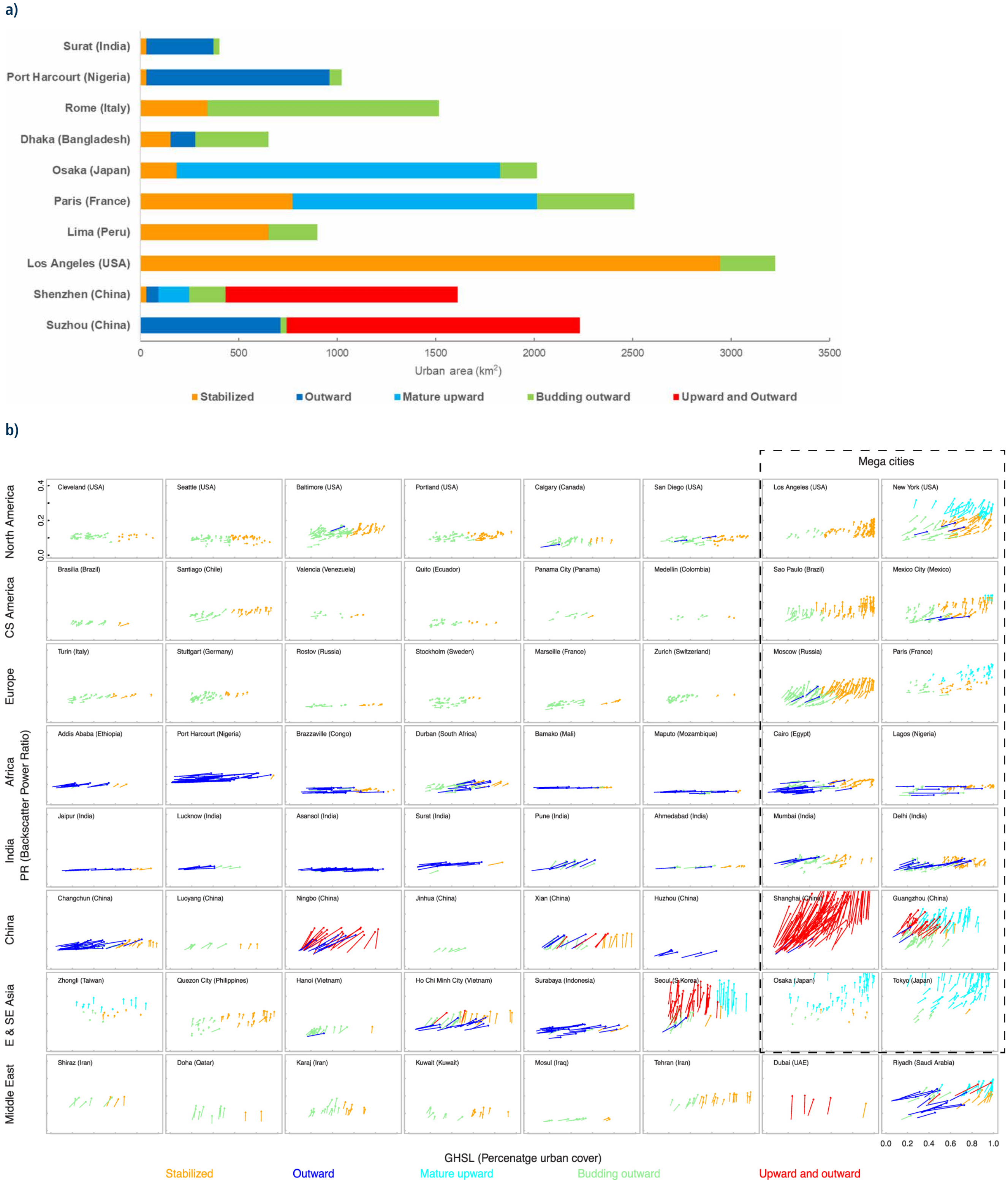

Figure 8.6: (a) Distribution of growth typologies across 10 cities, and (b) sample of 64 cities by region with different patterns of urban growth. The empirical data is based on the Global Human Settlement Layer and backscatter power ratio for different patterns of urban growth across the sample of cities. In (b), the blue arrows indicate outward urban growth. Other urban patterns indicate stabilised (orange), mature upward (light blue), budding outward (green), and upward and outward (red). Note that with few exceptions, each city is comprised of multiple typologies of urban growth. Source: Mahtta et al. (2019).

First, urban land areas are growing rapidly all around the world. 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). Nearly 70% of the total urban expansion between 1992 and 2015 occurred in Asia and North America (Liu et al. 2020a). By 2015, the extent of urban and built-up lands was between 0.5% and 0.6% of the total 130 Mkm^2 global ice-free land use, taking up other uses such as fertile cropland and natural ecosystems.

Second, as Figure 8.5 shows, urban population densities are declining, with significant implications for GHG emissions. From 1970 to 2010, while the global urban settlement extent doubled in size (Pesaresi et al. 2016), most regions (grouped by the AR6 WGIII 10-region aggregation) exhibited a trend of decreasing urban population densities, suggesting expansive urban growth patterns. Urban population densities have consistently declined in Australia, Japan and New Zealand, and Europe, North America, and Southern Asia regions, across all city sizes. North America consistently had the lowest urban population densities. Notably, the Middle East region appears to be the only region exhibiting an overall increasing trend across all city-size groups, while Latin America and Caribbean appears to be relatively stable for all city sizes. While the larger cities in Africa and South-East Asia and Pacific exhibit slightly stable urban population densities, the small and medium-sized cities in those regions trend toward lower urban population densities. In large urban centres of Eastern Asia and North America, rapid decreases in earlier decades seem to have tapered. Compared to larger cities, small-medium urban areas with populations of less than 2 million have more declines in urban population densities and higher rates of urban land expansion (Güneralp et al. 2020).

This decline in urban densities is paralleled by an increase in 'sprawl', or 'outward' urban development. Urban expansion occurs in either one of three dimensions: (i) outward in a horizontal manner; (ii) upward, by way of vertical growth; or (iii) infill development, where unused, abandoned, or underutilised lands within existing urban areas are developed or rehabilitated (Figure 8.20). Outward expansion results in more urban land area and occurs at the expense of other land uses (i.e., the conversion and loss of cropland or forests). Vertical expansion results in more multi-storey buildings and taller buildings, more floor space per area, and an increase in urban built-up density. Every city has some combination of outward and upward

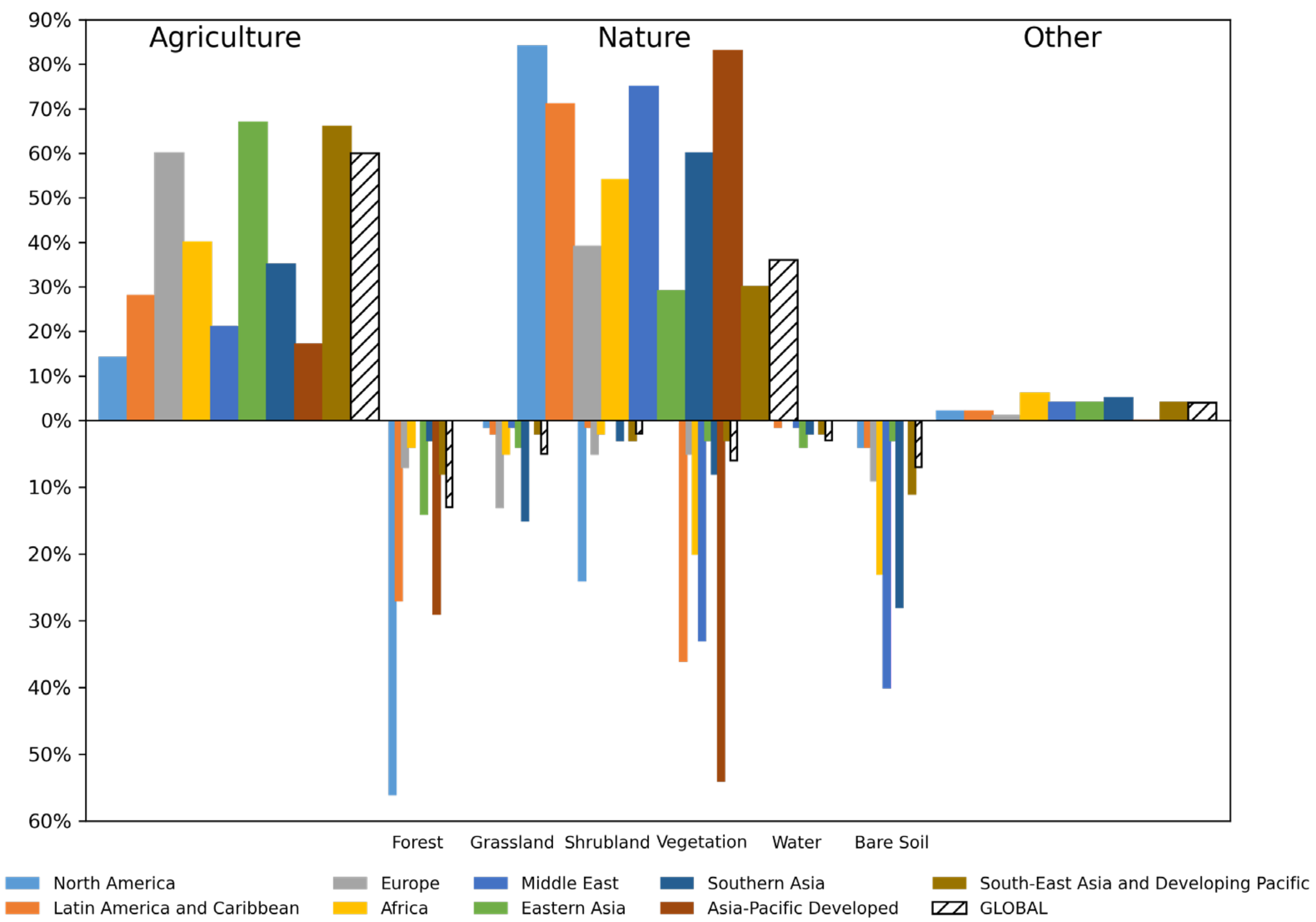

Figure 8.7: Percent of total urban land expansion from other land covers, sorted by the AR6 WGIII 10-region aggregation (1970–2010). As urban land has expanded outward, other forms of land cover, including agriculture, 'nature' (e.g., forest, grassland, shrubland, water, and bare soil, all of which are disaggregated to the bottom half of the plot), and other land covers, have been displaced. Globally, agriculture comprises the majority (about 60%) of the land displaced by urban expansion since 1970. Forests and shrubland vegetation – important carbon stocks – also make up a significant proportion of displacement. The loss of carbon-sequestering land like forests and shrubland independently impacts climate change by reducing global carbon stocks. Eurasia is omitted because there are no case studies from that region that report land conversion data. Source: adapted from Güneralp et al. (2020).

growth in varying degrees (Mahtta et al. 2019) (Figure 8.6). That each city is comprised of different and multiple urban growth typologies suggests the need for differentiated mitigation strategies for different parts of a single city (Section 8.6 and Figure 8.21). Recent research shows that the relative combination of outward versus upward growth is a reflection of its economic and urban development (Lall et al. 2021). That is, how a city grows – whether upward or outward – is a function of its economic development level. Upward growth, or more tall buildings, is a reflection of higher land prices (Ahlfeldt and McMillen 2018; Ahlfeldt and Barr 2020).

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) (Figure 8.6). The study also found that cities within a geographic region exhibit remarkably similar patterns of urban growth. Some studies have found a mix of urban forms emerging around the world; an analysis of 194 cities identified an overall trend (from 1990 to 2015) toward urban forms that are a mixture of fragmented and compact (Lemoine-Rodriguez et al. 2020). The exception to this trend is a group of large cities in Australia, New Zealand, and the United States that are still predominantly fragmented. The same study also identified small to medium-sized cities as the most dynamic in terms of their expansion and change in their forms.

A third trend in is urban land growth taking place on agricultural land, carbon stocks, and other land uses (see 'carbon stock' and 'AFOLU' – agriculture, forestry, and other land uses – in Glossary). As Figure 8.7 shows, over 60% of the reported urban expansion (nearly 40,000 km^2) from 1970 to 2010 was formerly agricultural land (Güneralp et al. 2020). This percentage increased to about 70% for global urban expansion that occurred between 1992 and 2015, followed by grasslands (about 12%) and forests (about 9%) (Liu et al. 2020a). In terms of percent of total urban land expansion, the largest conversion of agricultural lands to urban land uses from 1970 to 2010 took place in the Eastern Asia, and South-East Asia and Pacific regions; the largest proportional losses of natural land cover were reported for the North America and Australia, Japan and New Zealand regions (Güneralp et al. 2020). At a sub-regional level, agricultural land constituted the largest proportion of land converted to urban areas in China, India, Europe, Southeast Asian countries and the central United States between 1995 and 2015; in the eastern United States, most new urban land was converted from forests (Liu et al. 2020a). Urban expansion through 2040 may lead to the loss of almost 65 Mt of crop production – a scenario that underscores the ongoing relationship between urbanisation and AFOLU (van Vliet et al. 2017) (Chapter 7).

8.3.2 Informal Urban Settlements

About 880 million people currently live in informal settlements – defined as unplanned areas operating outside of legal and regulatory systems, where residents have no legal claim over their property and have inadequate basic services and infrastructure (United Nations 2018). Furthermore, upgrading informal settlements and inadequate housing is essential for improving resilience to climate change and well-being. Given the ubiquity of informal settlements in developing countries and LDCs, there is potential to harness informality to accelerate transitions to low-carbon urban development. There are several key reasons for their potential to mitigate GHG emissions. 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 an urban form that supports low- or carbon-neutral infrastructure for transportation, energy use in residential buildings, and other sectors (Baurzhan and Jenkins 2016; Henneman et al. 2016; Byrne et al. 2017; Oyewo et al. 2019).

Informal urban areas can avoid the conventional trajectory of urban development by utilising large-scale strategies, such as micro-scale technologies, modal shifts towards compact, walkable urban form, as well as decentralised or meso-scale utilities of water, sanitation, and service centres – thereby mitigating emissions associated with transport and treating wastes (Tongwane et al. 2015; Yang et al. 2018). Some specific mitigation options include spatial adjustments for walkability of neighbourhoods, low-energy-intensive mobility, low-energy-intensive residential areas, low-carbon energy sources at city scale, 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 and business start-ups, increased incomes, air quality improvement, and enhanced health and well-being (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) (Section 8.2).

Non-networked and non-centralised urban services and infrastructure in informal settlements, including sanitation, waste, water, and electricity, serve 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 at micro to meso scales have potential for low-emissions development in urban areas of developing countries (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 the short term as responses with long-term influence on emissions reduction. The cumulative impact of the disruptive technologies can reduce emissions by 15–25% through enhanced emissions sinks in 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).

8.3.3 Trends in Urban Greenhouse Gas Emissions

One major innovation presented in AR6 – particularly in this chapter – is the inclusion of trend data on urban GHG emissions. Using multiple datasets in conjunction with the SSP and RCP scenarios, this chapter provides an estimate of urban GHG emissions from 1990 through 2100, based on a consumption-based approach. This innovation provides, for the first time, a temporal dimension to urban footprints considering different climate scenarios with implications for urban mitigation. The new analysis presents a comparison of ways urban emissions can evolve given different scenario contexts (Section 8.3.4.2). Additionally, new research has quantified trends in urban CO_2 emissions and their key drivers across 91 global cities from 2000 to 2018 (Luqman et al. 2021).

Figures 8.8 and 8.9 present key urban emission metrics and trends for six regions (based on the AR6 WGIII regional breakdown) – the first for the year 2015, and the latter for both 2000 and 2015.

The key trends are as follows. First, the urban share of global GHG emissions (including CO_2 and CH_4) is substantive and continues to increase (Figure 8.9). Total urban CO_2-eq emissions based on consumption-based accounting were estimated to be 25 $GtCO_2$-eq, or 62% of the global total in 2015, and increased to an estimated 29 $GtCO_2$-eq in 2020, representing about 67–72% of global emissions. This estimate includes all CO_2 and CH_4 emissions except aviation, shipping, and biogenic sources (i.e., land-use change, forestry, and agriculture). About 100 of the highest-emitting urban areas account for approximately 18% of the global carbon footprint (Moran et al. 2018). Globally, the urban share of national CO_2-eq emissions increased 6 percentage points, from 56% in 2000 to 62% in 2015.

Second, while urban CO_2 emissions were increasing in all urban areas, the dominant drivers were dependent upon development level. Emissions growth in urban areas other than in Developed Countries was driven by increases in area and per capita emissions. Across all cities, higher population densities are correlated with lower per capita GHG emissions (Luqman et al. 2021).

Third, the urban share of regional GHG emissions increased between 2000 and 2015, with much inter-region variation in the magnitude of the increase (*high confidence*) (Figure 8.9). Between 2000 and 2015, the urban emissions share across AR6 WGIII regions (6-region aggregation) increased from 28% to 38% in Africa, from 46% to 54% in Asia and Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West-Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East.

Between 2000 and 2015, urban population, urban CO_2-eq emissions, and national CO_2-eq emissions increased as a share of the global total in the Asia and Pacific region while the share declined for Developed Countries. The urban share of total regional CO_2-eq emissions decreased in Developed Countries from 58.2% (2000) to 40.0% (2015). 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 in the Developed Countries region, which declined slightly.

Fourth, the global average per capita urban GHG emissions increased between 2000 and 2015, with cities in the Developed Countries region producing nearly seven times more per capita than the lowest emitting region (*medium confidence*). From 2000 to 2015, the global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq per person (an increase of 11.8%), with increases across five of the six regions: Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); Asia and Pacific increased from 3.0 to 5.1 tCO_2-eq per person (71.7%); Eastern Europe and West-Central Asia increased from 6.9 to 9.8 tCO_2-eq per person (40.9%); Latin America and Caribbean increased from 2.7 to 3.7 tCO_2-eq per person (40.4%); and the Middle East increased from 7.4 to 9.6 tCO_2-eq per person (30.1%). Albeit starting from the highest level, Developed Countries had a decline of 11.4 to 10.7 tCO_2-eq per person (–6.5%).

In 2015, regional urban per capita consumption-based CO_2-eq emissions were lower than regional consumption-based national per capita CO_2-eq emissions in five of the six regions. These regions in order of the difference are: Developed Countries (lower by 1.0 tCO_2-eq per capita); Latin America and Caribbean (lower by 0.8 tCO_2-eq per capita); Eastern Europe and West-Central Asia (lower by 0.7 tCO_2-eq per capita); Middle East (lower by 0.4 tCO_2-eq per capita); and Africa (lower by 0.2 tCO_2-eq per capita); while higher only in the Asia and Pacific region (higher by 0.9 tCO_2-eq per capita). All regions show convergence of the urban and national per capita CO_2-eq, as the urban share of national emissions increases and dominates the regional total.

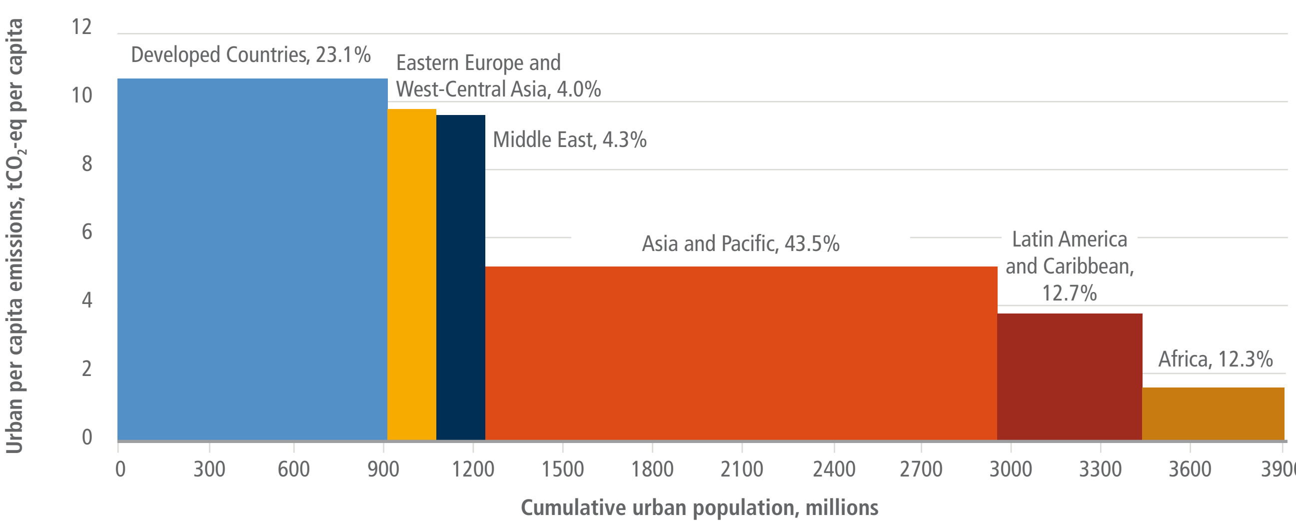

Figure 8.8: 2015 average urban greenhouse gas emissions per capita, considering carbon dioxide (CO_2) and methane (CH_4) emissions from a consumption-based perspective, alongside urban population, for regions represented in the AR6 WGIII 6-region aggregation. The average urban per capita emissions are given by the height of the bars while the width represents the urban population for a given region, based on 2015 values for both axes. Provided within the bars are the percentage shares of the urban population by region as a share of the total urban population. Source: synthesised based on data from UN DESA (2019) and Gurney et al. (2022).

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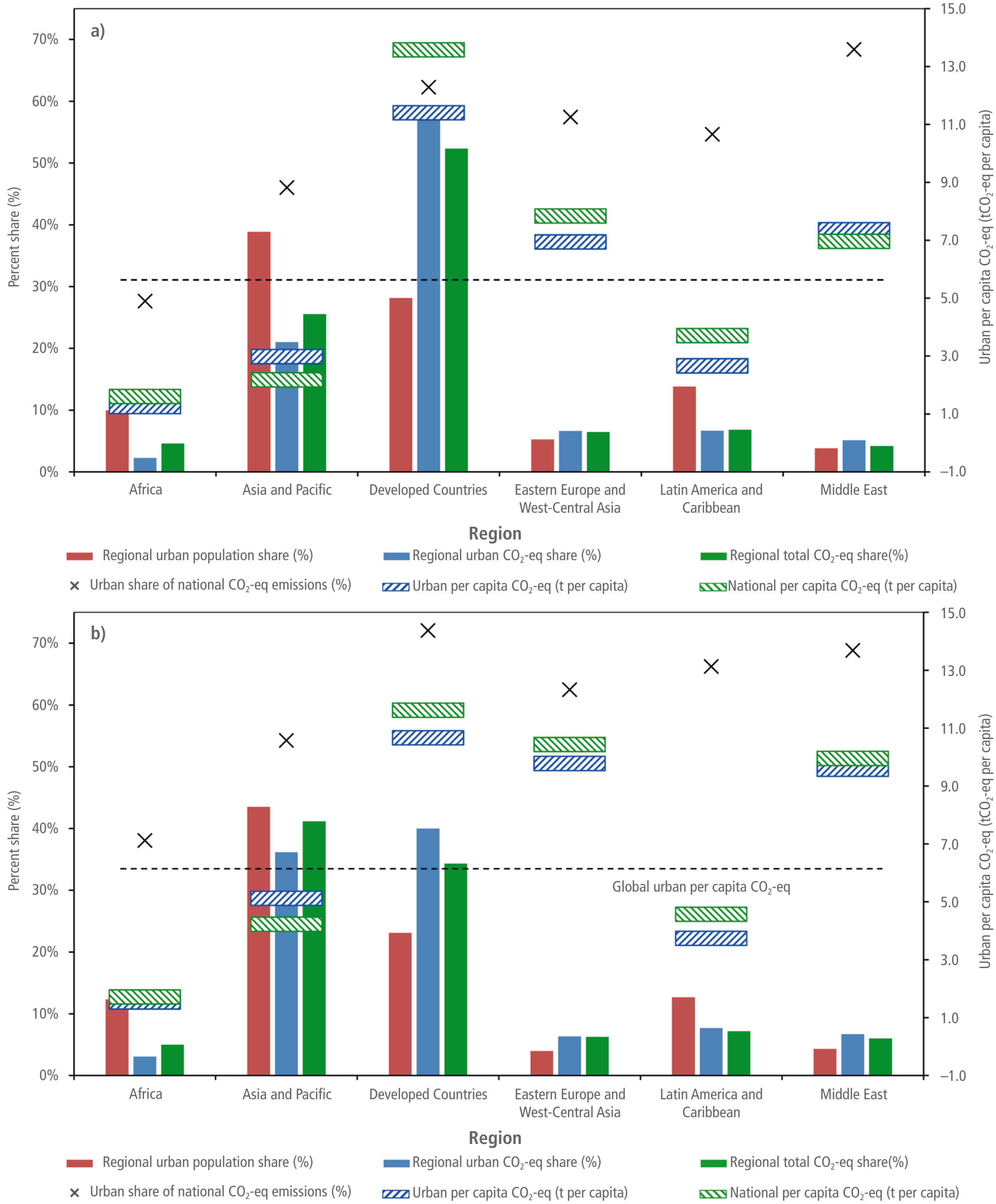


Figure 8.9*:* **Changes in six metrics associated with urban and national-scale carbon dioxide (CO_2) and methane (CH_4) emissions represented in the AR6 WGIII 6-region aggregation, with (a) 2000 and (b) 2015.** The trends in Luqman et al. (2021) were combined with the work of Moran et al. (2018) to estimate the regional urban CO_2-eq share of global urban emissions, the urban share of national CO_2-eq emissions, and the urban per capita CO_2-eq emissions by region. This estimate is derived from consumption-based accounting that includes both direct emissions from within urban areas and indirect emissions from outside urban areas related to the production of electricity, goods, and services consumed in cities. It incorporates all CO_2 and CH_4 emissions except aviation, shipping and biogenic sources (i.e., land-use change, forestry, and agriculture). 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 by region are given for comparison. Source: adapted from Gurney et al. (2022).[5]

5 Figure adapted from *Global Environmental Change*, Vol 73, Gurney et al., Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, ©2022 with permission from Elsevier.

Box 8.1: Does Urbanisation Drive Emissions?

Urbanisation can drive emissions if the process is accompanied by an income increase and higher levels of consumption (Sudmant et al. 2018). This is typically observed in countries with a large urban-rural disparity in income and basic services, and where urbanisation is accompanied by economic growth that is coupled to emissions. In addition, the outward expansion of urban land areas often results in the conversion and loss of agricultural land (Pandey et al. 2018; Liu et al. 2019), forests (Austin et al. 2019), and other vegetated areas, thereby reducing carbon uptake and storage (Quesada et al. 2018) (Section 8.3.1). Furthermore, the buildup and use of urban infrastructure (e.g., buildings, power, sanitation) requires large amounts of embodied energy and carbon (Figures 8.17 and 8.22). Building new and upgrading existing urban infrastructure could produce cumulative emissions of 226 $GtCO_2$ by 2050 (Bai et al. 2018).

However, for the same level of consumption and basic services, an average urban dweller often requires less energy than their rural counterparts, due to higher population densities that enable sharing of infrastructure and services, and economies of scale. Whether and to what extent such emission reduction potentials can be realised depends on how cities are designed and laid out (i.e., urban form – see Section 8.4.2) as well as how urban infrastructure is built and powered, such as the energy intensity of the city's transportation system, type and level of urban services, the share of renewable energy, as well as the broader national and international economic and energy structure that supports the function of the cities (Sections 8.4.3 and 8.6).

Although population-dense cities can be more efficient than rural areas in terms of per capita energy use, and cities contribute less GHG emissions per person than low-density suburbs (Jones and Kammen 2014), there is some, albeit *limited*, evidence that larger cities are not more efficient than smaller ones (Fragkias et al. 2013; Ribeiro et al. 2019). A number of studies comparing urban and rural residents in the same country have shown that urban residents have higher per capita energy consumption and CO_2 emissions (Chen et al. 2019a; Hachaichi and Baouni 2021). There is some evidence that the benefits of higher urban densities on reducing per capita urban GHG emissions may be offset by higher incomes, smaller household sizes, and, most importantly, higher consumption levels, thus creating a counter-effect that could increase GHG emissions with urbanisation (Gill and Moeller 2018).

Many studies have shown that the relationship between urbanisation and GHG emissions is dependent on the level and stage of urban development, and follows an inverted U-shaped relationship of the environmental Kuznets curve (Wang et al. 2016, 2022; Zhang et al. 2017; Xu et al. 2018a; Zhou et al. 2019) (Sections 8.3.1 and 8.6, and Figure 8.20). Considering existing trends, earlier phases of urbanisation accompanied by rapid industrialisation, development of secondary industries, and high levels of economic growth, are correlated with higher levels of energy consumption and GHG emissions. However, more mature phases of urbanisation, with higher levels of economic development and establishment of the service sector, are correlated with lower levels of energy consumption and GHG emissions (Khan and Su 2021).

8.3.4 Scenarios of Future Urbanisation and Greenhouse Gas Emissions

This section assesses scenarios of future urban land expansion and urban GHG emissions. These scenarios have implications for the urban climate change mitigation strategies discussed in Sections 8.4 and 8.6 – in particular, in the context of the potential mitigation and development pathways for urban areas under certain scenarios.

8.3.4.1 Urban Land Expansion and Greenhouse Gas Emissions

The uncertainties across urban land expansion forecasts, and associated SSPs, highlight an opportunity to pursue compact, low or net-zero GHG emissions development that minimises land-use competition, avoids carbon lock-in, and preserves carbon-sequestering areas like forests and grasslands (Sections 8.4. and 8.6, and Figure 8.21). Among the forecasts available are six global-scale spatially explicit studies of urban land expansion that have been published since AR5; four of the six, which present forecasts for each of the five SSPs, are considered in Table 8.1 and Figure 8.10 (Huang et al. 2019; Li et al. 2019b; Chen et al. 2020a; Gao and O'Neill 2020). All four have forecasts to 2050 but only three to 2100. One of the two not included here (van Vliet et al. 2017) also forecasts land displacement due to urban land expansion.

Four overarching findings can be gleaned from these studies.

First, urban land areas will expand significantly by 2050 – by as much as 211% (see SSP5 forecast in Huang et al. 2019), but likely within a large potential range of about 43–106% over the 2015 extent by 2050 – to accommodate the growing urban population (Table 8.1). Globally, there are large uncertainties and variations among the studies – and between the SSPs – about the rates and extent of future urban expansion, owing to uncertainties about economic development and population growth (ranges of estimates are provided in Table 8.1). Overall, the largest urban extents are forecasted under SSP5 (fossil fuel-intensive development) for both 2050 and 2100, whereas the smallest forecasted urban extents are under SSP3 ('regional rivalry'). Forecasted global urban extents could reach between 1 and 2.2 million km^2 (median of 1.4 million km^2, a 106% increase) in 2050 under SSP5, and between 0.85 and 1.5 million km^2 (median of 1 million km^2, a 43% increase) in 2050 under SSP3. Under SSP1, which is characterised by a focus on sustainability with more compact, low-emissions development, urban extents could reach

1 million km^2 (range of 0.9 to 2 million km^2, a 49% increase) in 2050. By 2100, the forecasted urban extents reach between 1.4 and 3.6 million km^2 (median 2.5 million km^2) under SSP5 and between 1 and 1.5 million km^2 (median 1.3 million km^2) under SSP3. Across the studies, substantially larger amounts of urban land expansion are expected after 2050 under SSP5 compared to other SSPs.

Second, there is a wide variation in estimates of urban land expansion across regions (using the AR6 WGIII 6-region aggregation). Across all four sets of forecasts, current urban land (circa 2015) is the largest in Developed Countries and in the Asia and Pacific region, with approximately two-thirds of the current urban extent occurring in those two regions (Table 8.1 and Figure 8.10). The largest increases in urban land by 2050 are expected in the Asia and Pacific and Developed Countries regions, across all the SSPs. However, the rate of increase in urban land in Eastern Europe and West-Central Asia, Latin America and Caribbean, and the Middle East is significant and urban land could more than double by 2050. One-third of the studies conclude that the United States, China, and India will experience continued urban land expansion at least until 2050 (Huang et al. 2019; Li et al. 2019b). However, Li et al. (2019) report that, after 2050, China could experience a decrease in the rate of urban land expansion, while growth will continue for India. This is not surprising since India's urban demographic transition will only get underway after the middle of the century, when the urban population is expected to exceed the rural population. In contrast, China's urban demographic transition could be nearly complete by 2050.

Third, in spite of these general trends, there are differences in forecasted urban expansion in each region across the SSPs and studies, with Huang et al. (2019) forecasting the most future urban land expansion between 2015 and 2050. The range across studies is significant. Under SSP1, urban land areas could increase by between 69,000 and 459,000 km^2 in Developed Countries, 77,000–417,000 km^2 in Asia and Pacific, and 28,000–216,000 km^2 in Africa. Under SSP3, where urban land expansion is forecasted to be the lowest, urban land areas could increase by between 23,000 and 291,000 km^2 in Developed Countries, 57,000–168,000 km^2 in Asia and Pacific, and 16,000–149,000 km^2 in Africa. Under SSP5, where urban land expansion is forecasted to be the highest, urban land area could increase by between 129,000 and 573,000 km^2 in Developed Countries, 83,000–472,000 km^2 in Asia and Pacific, and 40,000–222,000 km^2 in Africa (Huang et al. 2019; Li et al. 2019b; Chen et al. 2020a; Gao and O'Neill 2020). By 2100, however, the Developed Countries region is expected to have the most urban expansion only in SSP5. In SSP2 and SSP4, the Developed Countries and Asia and Pacific regions have about equal amounts of new urban land; in SSP3, Asia and Pacific has more new urban land forecasted.

Fourth, both the range of estimates and their implications on land-use competition and urban life point to an opportunity for urban areas to consider their urban form when developing. Under the current urbanisation trajectory, 50–63% of newly expanded urban areas are expected to occur on current croplands (Chen et al. 2020a). However, there is significant regional variation; between 2000 and 2040, 12.5% of cropland in China and 7.5% of cropland in the Middle East and North Africa could potentially be displaced due to urban expansion, compared to the world average of 3.7% (van Vliet et al. 2017). As urban clusters increase in size and greenspace is converted, future urban land expansion is expected to intensify UHIs and exacerbate night-time extreme temperatures. An urban footprint increase of 78–171% by 2050 over the urban footprint in 2015 is expected to 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 (Huang

Table 8.1: Forecasts of total urban land per AR6 WGIII region (6-region aggregation) in 2050 for each SSP, with the median and range of estimates from four studies: Huang et al. (2019), Li et al. (2019), Chen et al. (2020), and Gao and O'Neill (2020). Median estimates for the 2015 urban extent are based on the mean/median of estimates in Huang et al. (2019) and Chen et al. (2020). Median and range of estimates for each SSP in 2050 are based on values derived from the four studies: Huang et al. (2019), Li et al. (2019), Chen et al. (2020), and Gao and O'Neill (2020). While each study and SSP forecast increases in urban land in each region, the range and magnitude vary. Source: data compiled from Huang et al. (2019), Li et al. (2019), Chen et al. (2020), and Gao and O'Neill (2020).

	2015 median (km^2; range)	SSP1 median (km^2; range)	SSP2 median (km^2; range)	SSP3 median (km^2; range)	SSP4 median (km^2; range)	SSP5 median (km^2; range)
Africa	**64,423**	**97,718**	**116,486**	**96,571**	**119,971**	**138,604**
	(41,472–87,373)	(67,488–303,457)	(59,638–274,683)	(56,071–235,922)	(54,633–344,645)	(79,612–309,532)
Asia and Pacific	**241,430**	**293,647**	**355,445**	**296,431**	**329,485**	**419,781**
	(167,548–315,312)	(244,575–732,303)	(236,677–624,659)	(224,520–483,335)	(240,639–632,678)	(250,670–787,257)
Developed Countries	**260,167**	**459,624**	**506,301**	**414,661**	**496,526**	**616,847**
	(188,660–331,674)	(407,483–648,023)	(431,592–614,592)	(362,063–479,584)	(411,320–586,058)	(510,468–761,275)
Eastern Europe and West-Central Asia	**35,970**	**63,625**	**65,251**	**59,779**	**64,434**	**76,994**
	(27,121–44,819)	(42,990–91,612)	(52,397–91,108)	(44,129–90,794)	(50,806–86,546)	(54,039–93,008)
Latin America and Caribbean	**62,613**	**86,236**	**88,793**	**93,804**	**85,369**	**102,343**
	(60,511–64,716)	(63,507–163,329)	(86,411–162,526)	(65,286–162,669)	(82,148–144,940)	(82,961–167,102)
Middle East	**21,192**	**51,351**	**51,221**	**48,032**	**49,331**	**55,032**
	(19,017–23,366)	(187,68–69,266)	(25,486–69,716)	(19,412–63,236)	(25,415–71,720)	(33,033–75,757)
World	**685,795**	**1,023,220**	**1,174,742**	**980,719**	**1,123,900**	**1,412,390**
	(669,246–702,343)	(919,185– 1,991,579)	(927,820–1,819,174)	(850,681–1,493,454)	(922,539–1,851,438)	(1,018,321–2,180,816)

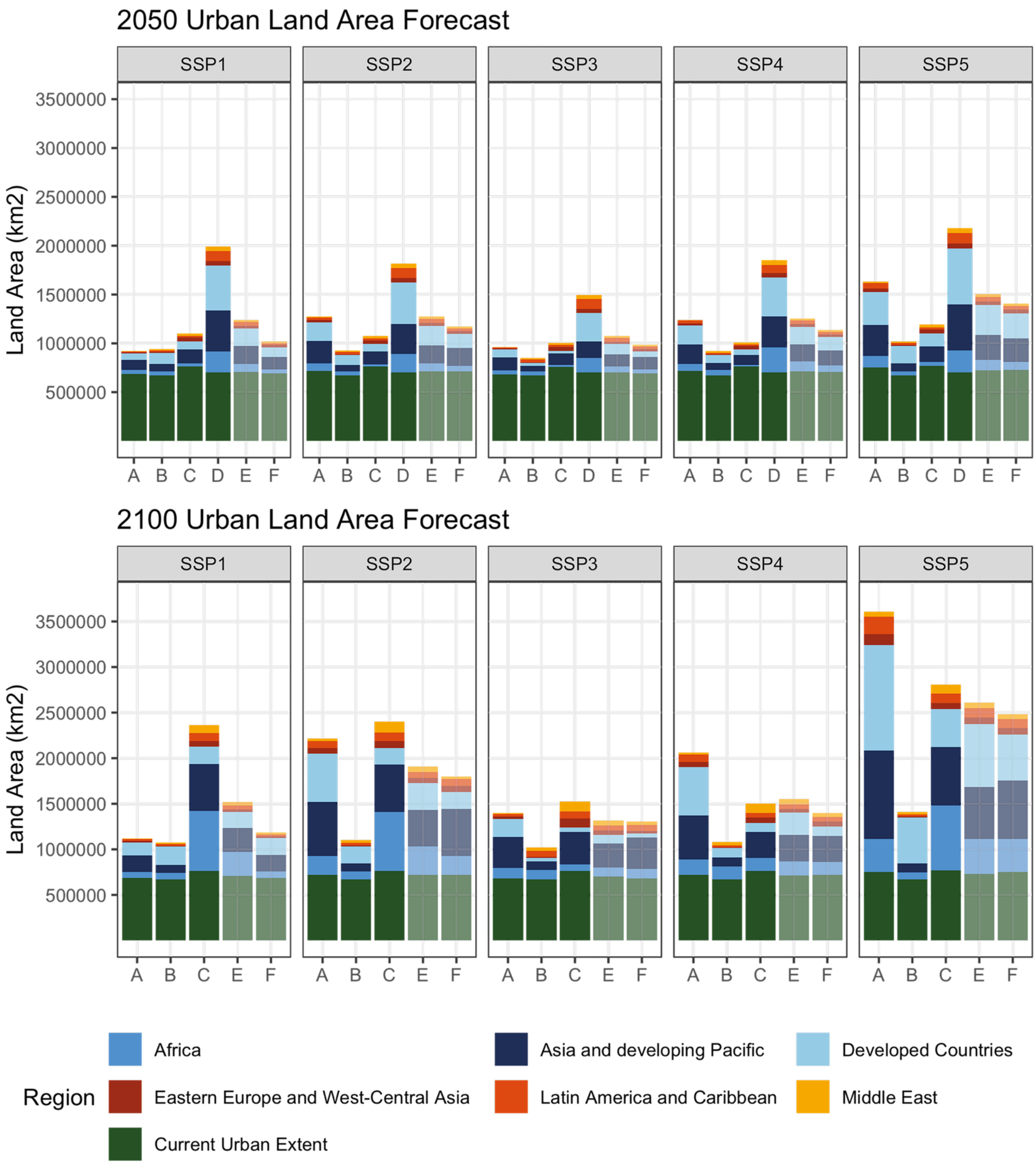


Figure 8.10: Forecasts of urban land expansion in 2050 and 2100 according to each SSP and AR6 WGIII 6-region aggregation, by study, where A: Gao and O'Neill (2020), B: Chen et al. (2020a), C: Li et al. (2019), D: Huang et al. (2019), E: mean across studies, and F: median across all studies. Three studies (Li et al. 2019b; 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 only to 2050. Global current urban extents and the respective initial years vary slightly among the four studies. Years for values of current urban extent range from 2010 to 2020. See Table 8.1 for the range of data across the four studies and across SSPs. Source: data compiled form Huang et al. (2019), Li et al. (2019), Chen et al. (2020), and Gao and O'Neill (2020).

et al. 2019). Furthermore, this urban expansion-induced warming is on average about half – and in certain locations nearly twice – as strong as warming that will be caused by GHG emissions based on the multi-model ensemble average forecasts in RCP4.5. In short, future urban expansion will amplify the background warming caused by GHG emissions, with extreme warming most pronounced during night-time (*very high confidence*) (Huang et al. 2019). These findings corroborate those in the Technical Summary of AR6 WGI (Arias et al. 2021).

The forecasted amounts and patterns of urban expansion presented here bear significant uncertainty due to underlying factors beyond mere methodological differences between the studies. These factors include potential changes in the social, economic, and institutional dynamics that drive urban land development across the world (Güneralp and Seto 2013). Some of these changes may come in the form of sudden shocks such as another global economic crisis or pandemic. The forecasts presented here do not take such factors into account.

8.3.4.2 Scenarios of Future Urban Greenhouse Gas Emissions

There remains little globally comprehensive literature on projections of future baseline GHG emissions from urban areas or scenarios deploying urban mitigation actions on the part of city or regional governments. This dearth of research rests on limited urban emissions data that are consistent and comparable across the globe, making review and synthesis challenging (Creutzig et al. 2016b). Some research has presented urban emissions forecasts and related projections, including 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 8.12), and urban emissions from buildings, transport, industry, and agriculture (IEA 2016a).

In its study of about 700 urban areas with a population of at least 750,000, the Coalition for Urban Transitions (2019), attempts to quantify the urban portion of global GHG emissions, including 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 8.11). Starting in 2015 with a global urban emissions total of almost 14 $GtCO_2$-eq, the study projects an increase to 17.3 $GtCO_2$-eq by 2050 – but this reduces to 1.8 $GtCO_2$-eq by 2050 with the inclusion of mitigation wedges: 58% from buildings, 21% from transport, 15% materials efficiency, and 5% waste, with decarbonisation of electricity supply as a cross-cutting strategy across the wedges.

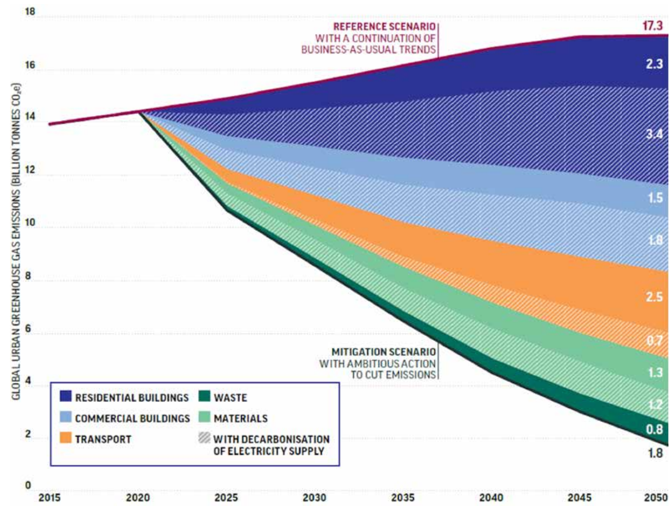


Figure 8.11: Reference scenario and mitigation potential for global urban areas in the residential and commercial building, transport, waste, and material production sectors. The top red line indicates the reference scenario where no further emissions reduction efforts are taken, while the bottom dark line indicates the combined potential of reducing emissions across the sectors displayed. Wedges are provided for potential emissions savings associated with decarbonising residential buildings, commercial buildings, transport, waste, and materials as indicated in the legend. The shaded areas that take place among the wedges with lines indicate contributions from decarbonisation of electricity supply. Source: Re-used with permission from Coalition for Urban Transitions (2019).

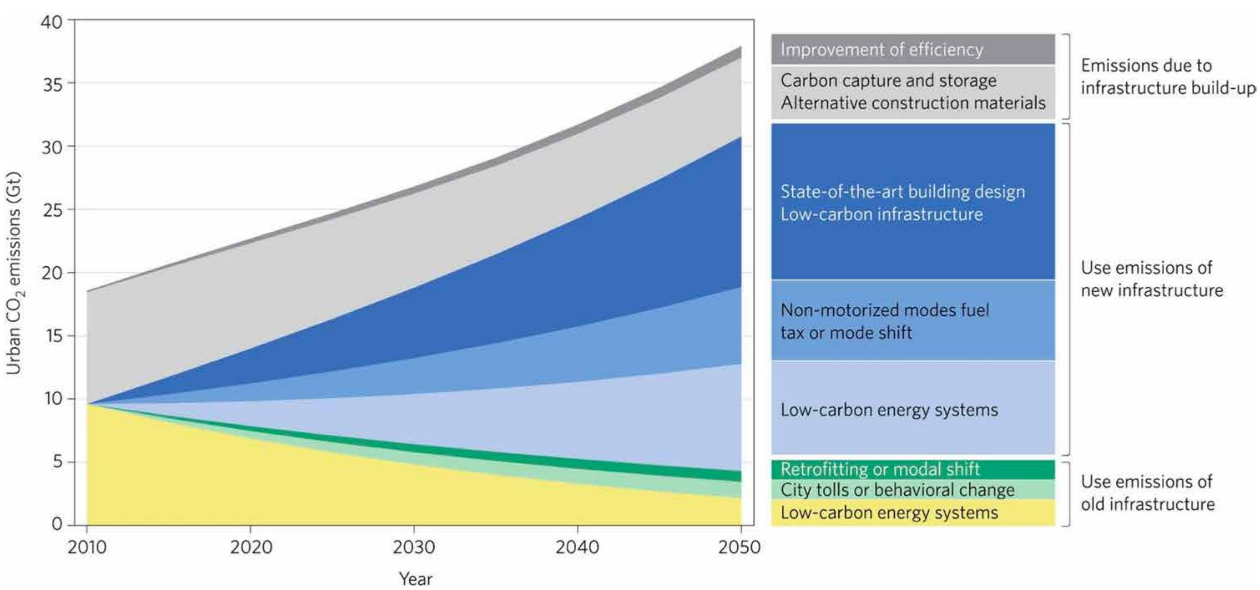


Figure 8.12: Urban infrastructure-based CO_2-eq emission mitigation wedges. Urban infrastructure-based CO_2-eq emission mitigation wedges across categories of existing (yellow/green), new (blue), and construction (grey) of urban infrastructure. The wedges include low-carbon energy systems and infrastructure, modal shift, tolls/tax, or behavioural change, and reductions from construction materials. Source: re-used with permission from Creutzig et al. (2016a).

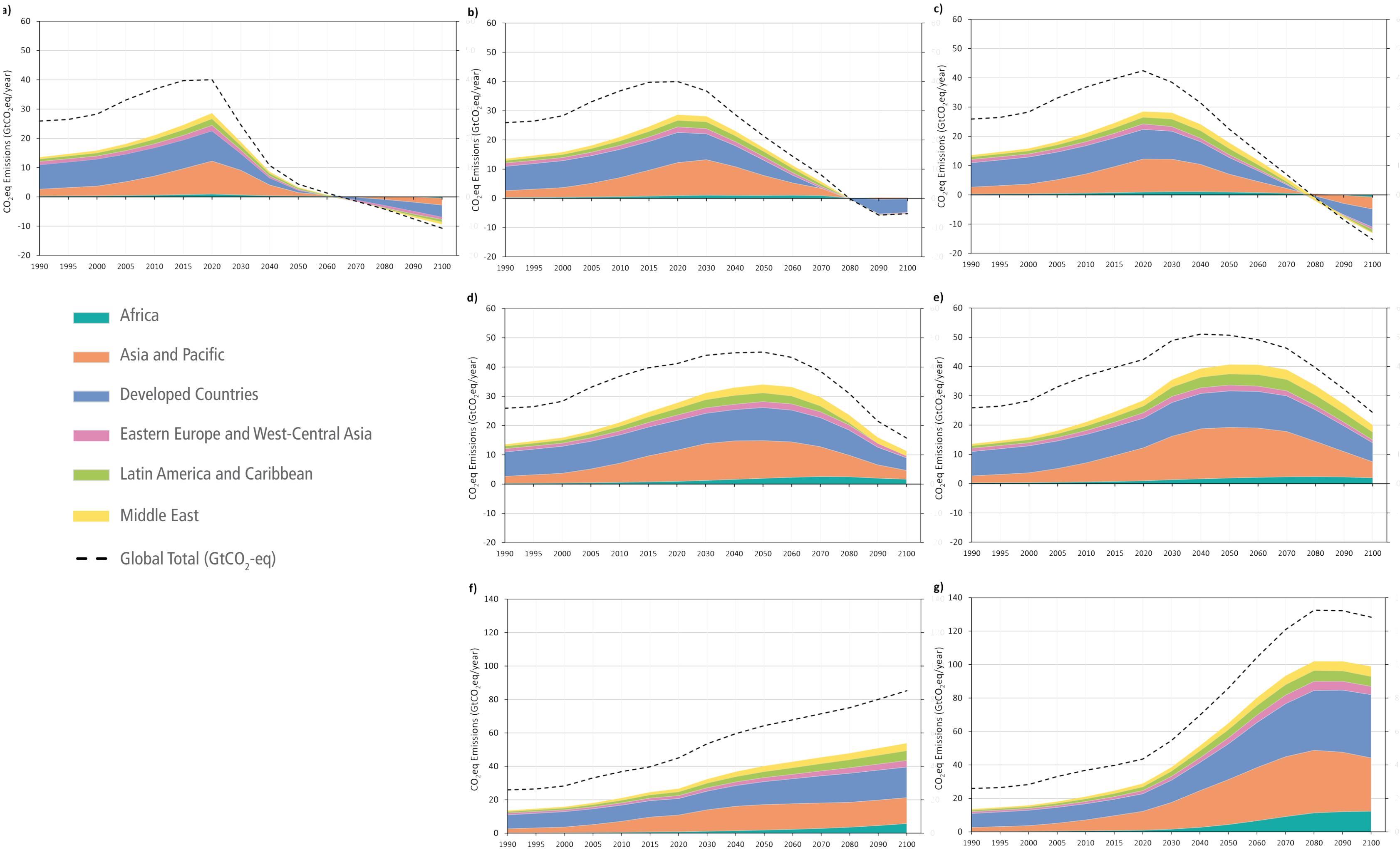


Figure 8.13: Carbon dioxide equivalent (CO_2-eq) emissions from global urban areas in seven SSP-RCP variations spanning the 1990 to 2100 time period. Urban areas are aggregated to six regional domains based on the AR6 WGIII 6-region aggregation. Global total CO_2-eq emissions (CO_2 and CH_4 (methane)) are also shown as marked by the dashed line. Future urban emissions in the context of SSP-RCP-Shared Policy Assumption (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.[6] The first three scenarios (a–c) with more stringent reduction pathways 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. SSP1 scenarios (a, b) represent contexts where urbanisation takes place rapidly while providing resource efficiency based on compact urban form (Jiang and O'Neill 2017), with high levels of electrification (van Vuuren et al. 2017b; Rogelj et al. 2018). The scenario context of SSP1-RCP1.9 represents a pathway in which there can be a transformative shift towards sustainability. Note that the scale of panels (f) and (g) is different from the other panels.[7] See Table 8.2 detailing the SSP-RCPs. Source: adapted from Gurney et al. (2022).[8]

6 These scenarios have been assessed by WGI to correspond to intermediate, high, and very low GHG emissions.

7 The SSP1-RCP1.9 scenario is aligned with the C1 category of the Illustrative Mitigation Pathways (IMPs) that include IMP-LD, IMP-Ren and IMP-SP. Implications are provided in Table 8.3.

8 Figure adapted from *Global Environmental Change*, Vol 73, Gurney et al., Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, ©2022 with permission from Elsevier.

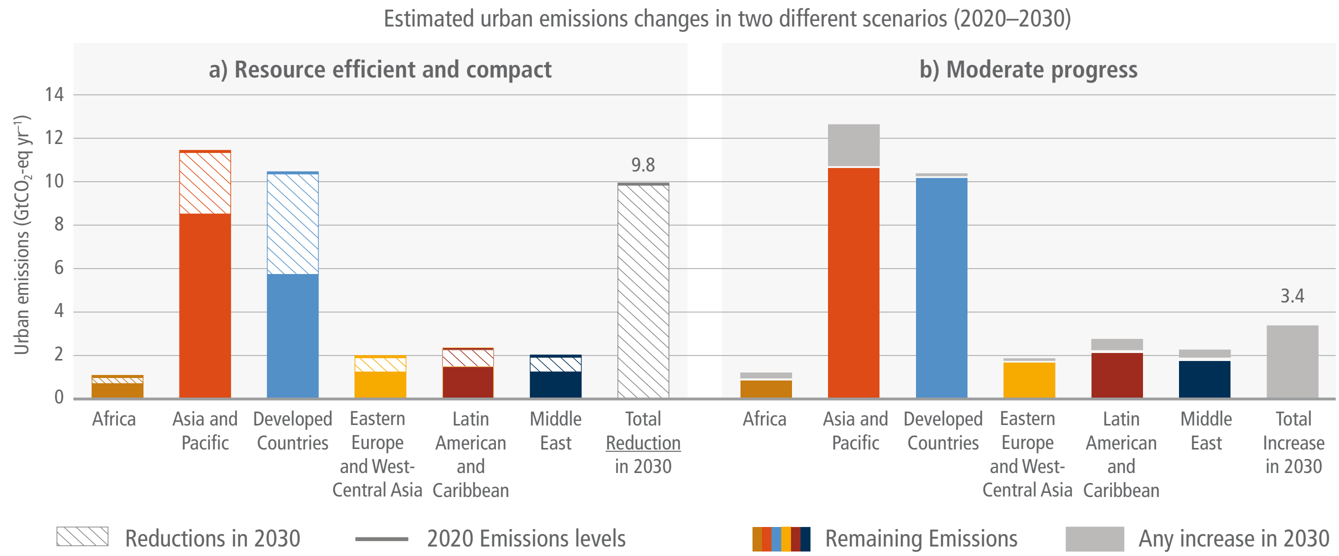


Figure 8.14: Comparison of urban emissions under different urbanisation scenarios ($GtCO_2$-eq yr^{-1}) for the AR6 WGIII 6-region aggregation. The panels represent the estimated urban emissions change in two different scenarios for the time period 2020–2030. Panel **(a)** represents resource efficient and compact urbanisation while panel **(b)** represents urbanisation with moderate progress. The two scenarios are consistent with estimated urban emissions under the SSP1-RCP1.9-SPA1 and SSP2-RCP4.5-SPA2 scenarios, respectively (Figure 8.13). 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 that take place by 2030 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 that are given by the last dashed grey bar in panel (a) is estimated to be 9.8 $GtCO_2$-eq yr^{-1} between 2020 and 2030 in this scenario. In the scenario with moderate progress, there are no regions with reductions in urban emissions. Above the white lines that represent urban emissions in 2020, the grey shaded areas are the estimated increases for each region so that the total urban emissions would increase by 3.4 $GtCO_2$-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. (2021, 2022). Source: synthesised based on data from Gurney et al. (2022).[9]

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 8.13. 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 relate to the mitigation options in Section 8.4. Source: adapted from Gurney et al. (2022).

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, walkable and sustainable rapid urbanisation	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, inadequate urban planning	Medium	Low	Low	Medium	Low	Low
SSP4 RCP3.4 (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	–

9 Figure adapted from *Global Environmental Change*, Vol 73, Gurney et al., Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, ©2022 with permission from Elsevier.

Similar analysis by the urban networks C40 and GCoM examine current and future GHG emissions on smaller subsets of global cities, offering further insight on the potential emissions impacts of urban mitigation options. However, this analysis is limited to just a sample of the global urban landscape and primarily focused on cities in the Global North (GCoM 2018, 2019; C40 Cities et al. 2019) with methods to project avoided emissions in development (Kovac et al. 2020). Different scopes of analysis between sectors, as well as limited knowledge of the impact of existing and new urban infrastructure, limit the possibility of direct comparisons in emissions. Still, the shares of urban mitigation potential ranges between 77.7% and 78.9% for combined strategies that involve decarbonised buildings and transport in urban infrastructure, and the wedges approach the remaining emissions reductions also considering construction materials and waste. This data supports urban areas pursuing a package of multiple, integrated mitigation strategies in planning for decarbonisation (Sections 8.4 and 8.6, and Figure 8.21).

The most comprehensive approach to-date for quantifying urban emissions within the global context (Gurney et al. 2021, 2022) combines the per capita carbon footprint estimates for 13,000 cities from Moran et al. (2018) with projections of the share of urban population (Jiang and O'Neill 2017) within the IPCC's SSP-RCP framework (van Vuuren et al. 2014, 2017a; Riahi et al. 2017). Urban emissions in seven SSP-RCP scenarios are shown in Figure 8.13 along with an estimate of the global total CO_2-eq for context.

In 2020, total urban emissions (including CO_2 and CH_4) derived from consumption-based accounting were estimated to be 29 $GtCO_2$-eq, representing between 67% and 72% of global CO_2 and CH_4 emissions, excluding aviation, shipping, and biogenic sources of emissions. By 2050, with moderate to low urban mitigation efforts, urban emissions are projected to rise to 34.0 $GtCO_2$-eq (SSP2-RCP4.5) or 40.2 $GtCO_2$-eq (SSP3-RCP7.0) – driven by growing urban population, infrastructure, and service demands. However, scenarios that involve rapid urbanisation can have different outcomes as seen in SSP1-RCP1.9 based on green growth, versus SSP5-RCP8.5 with the strongest carbon lock-in lacking any decarbonisation. Other scenarios involve mixed and/or low urbanisation, along with other differences, including the implementation of electrification, energy, and material efficiency, technology development and innovation, renewable energy preferences, and behavioural, lifestyle, and dietary responses (Table 8.2). With aggressive and immediate mitigation efforts to limit global warming to 1.5°C (>50%) with no or limited overshoot, urban GHG emissions could approach net-zero and reach a maximum of 3.3 $GtCO_2$-eq in 2050 (SSP1-RCP1.9). Under aggressive but not immediate urban mitigation efforts to limit global warming to 2°C (>67%), urban emissions could reach 17.2 $GtCO_2$-eq in 2050 (SSP1-RCP2.6).

When 2020 levels are compared to the values for the year 2030, urban areas that utilise multiple opportunities towards resource-efficient and walkable urbanisation are estimated to represent a savings potential of 9.8 $GtCO_2$-eq of urban emissions, under SSP1-RCP1.9 scenario conditions, on the path towards net-zero CO_2 and CH_4 emissions. In contrast, urban emissions would increase by 3.4 $GtCO_2$-eq from 2020 levels in 2030 under SSP2-RCP4.5 scenario conditions with moderate changes lacking ambitious mitigation action (Figure 8.14).

Table 8.3: Cross-cutting implications of the reference scenarios and Illustrative Mitigation Pathways (IMPs) for urban areas. The IMPs illustrate key themes of mitigation strategies throughout the WGIII report (Section 3.2.5). The implications of the key themes of the six IMPs (in addition to two pathways illustrative of higher emissions) for mitigation in urban areas are represented based on the main storyline elements that involve energy, land use, food biodiversity and lifestyle, as well as policy and innovation. The cross-cutting implications of these elements for urban areas, where multiple elements interact, are summarised for each reference scenario and the IMPs. IMP-Ren, IMP-LD and IMP-SP represent pathways in the C1 category that also includes SSP1–1.9. Source: adapted from the key themes of the IMPs for urban areas.

Reference scenarios and IMPs	Cross-cutting implications for urban areas
Current Policies (CurPol scenario)	– Urban mitigation is challenged by overcoming lock-in to fossil fuel consumption; also with car-based and low-density urban growth prevailing – Consumption patterns have land impacts, supply chains remain the same, urban inhabitants have limited participation in mitigation options – Progress in low-carbon urban development takes place at a relatively slower pace and there is limited policy learning within climate networks
Moderate Action (ModAct scenarios)	– Renewable energy continues to increase its share that is supported by urban areas to a more limited extent with ongoing lock-in effects – Changes in land use, consumption patterns, and lifestyles mostly continue as before with negligible changes taking place – if any – The fragmented policy landscape also prevails at the urban level with different levels of ambitions and without integration across the urban system
Gradual Strengthening (IMP-GS)	– Urban areas depend upon energy supply from distant power plants or those in rural areas without rapid progress in urban electrification – Afforestation/reforestation is supported with some delay while lower incentives for limiting growth in urban extent provide inconsistencies – The mobilisation of urban actors for GHG emission reductions is strengthened more gradually with stronger coordination taking place after 2030
Net Negative Emissions (IMP-Neg)	– Urban areas depend upon energy supply from distant power plants or those in rural areas with more limited electrification in urban energy systems – Afforestation/reforestation is supported to a certain extent while lower incentives for limiting growth in urban extent provide inconsistencies – Urban areas are less prominent in policy and innovation given emphasis on carbon capture and storage (CCS) options. Rural areas are more prominent considering BECCS
Renewable Energy (IMP-Ren)	– Urban areas support renewable energy penetration with electrification of urban infrastructure and sector coupling for increasing system flexibility – Consumption patterns and urban planning are able to reduce pressures on land use, demand response is increased to support renewables – Urban climate governance is enabling rapid deployment of renewable energy while fostering innovation for sustainable urban planning
Low Demand (IMP-LD)	– Walkable urban form is increased, active and public transport modes are encouraged, low-energy buildings and green-blue infrastructure is integrated – Changes in consumption patterns and urban planning reduce pressures on land use to lower levels while service provisioning is improved – Urban policymaking is used to accelerate solutions that foster innovation and increased efficiencies across all sectors, including material use
Shifting Pathways (IMP-SP)	– Urban areas are transformed to be resource efficient, low demand, and renewable energy supportive with an integrated approach in urban planning – Reinforcing measures enable GHG emission reductions from consumption patterns while also avoiding resource impacts across systems – Urban climate mitigation is best aligned with the SDGs to accelerate GHG emission reductions, increasing both scalability and acceptance

Among the 500 urban areas with the highest consumption-based urban emissions footprint in 2015 (Moran et al. 2018), urban-level emission scenarios under SSP1 conditions are constructed for 420 urban areas located across all regions of the world (Kılkış 2021a). These scenarios are based on urban-level population projections by SSP (Kii 2021), trends in relevant CMIP6 scenarios (Gidden et al. 2019), and a 100% renewable energy scenario (Bogdanov et al. 2021). In the year 2020, the 420 urban areas are responsible for about 10.7 ± 0.32 $GtCO_2$-eq, or 27% of the global total CO_2 and CH_4 emissions of about 40 $GtCO_2$-eq, excluding aviation, shipping, and biogenic sources. Under three SSP1-based scenarios, the urban emissions of the 420 urban areas in 2030 is projected to be about 7.0 $GtCO_2$-eq in SSP1-RCP1.9, 10.5 $GtCO_2$-eq in SSP1-RCP2.6, and 5.2 $GtCO_2$-eq in the SSP1 renewable energy scenario.

The Illustrative Mitigation Pathways (IMPs) represent different strategies for maintaining temperature goals that are compliant with the Paris Agreement, as well as their comparison with the continuation of current policies (Sections 1.5 and 3.2.5, and Table 8.3). The key characteristics that define the IMPs involve aspects of energy, land use, lifestyle, policy, and innovation. Urban areas provide cross-cutting contexts where each of these key characteristics can be enabled and have a particularly important role in the transformation pathways for renewable energy (IMP-Ren), low demand (IMP-LD), and shifting to sustainability (IMP-SP). Pathways that are compliant with the Paris Agreement include such urban implications as a reversal of decreasing land-use efficiency in urban areas to lower energy demand based on spatial planning for compact urban form (Section 8.4.2), changes in urban infrastructure for supporting demand flexibility to handle variable energy supply (Section 8.4.3), as well as policies and governance that are conducive to innovation in urban areas (Section 8.5). Spatial planning for compact urban form can enable reduced energy demand and changes in service provisioning, including through walkable neighbourhoods and mixed land use, providing venues for socio-behavioural change towards active transport (Section 8.4.5). Electrification and sector coupling in urban infrastructure can, for instance, be an important enabler of supporting higher penetrations of renewable energy in the energy system.

8.4 Urban Mitigation Options

Urban mitigation options can be categorised into three broad strategies: (i) reducing or changing urban energy and material use towards more sustainable production and consumption across all sectors, including through spatial planning and infrastructure; (ii) electrification and switching to net-zero-emissions resources; and (iii) enhancing carbon storage in the urban environment through urban green and blue infrastructure, which can also offer multiple co-benefits. A fourth, socio-behavioural aspects, can shift energy demand and emerge as the result of implementing the strategies. Urban mitigation options covered in this section are organised around these three strategies and can facilitate deep decarbonisation through systemic transformation (see Section 8.6 and Figure 8.21 for prioritising mitigation options based on urban form and urban growth typologies).

Urban areas are systems where multiple mitigation options – especially when integrated – have cascading effects across transport, energy, buildings, land use, and behaviour. These cascading effects take place both within and across urban systems (Figure 8.15). Mitigation actions also occur at multiple urban scales, from households and blocks to districts and city regions, and can be implemented as standalone sectoral strategies, such as increasing energy efficiency for appliances, and also as system-wide actions. In reducing emissions locally, urban areas can help lower emissions outside of their administrative boundaries through their use of materials and resources, and by increasing the efficiency of infrastructure and energy use beyond what is possible with individual sectoral strategies. Urban mitigation policies that implement multiple integrated interventions will provide more emissions savings than the sum of individual interventions (Sethi et al. 2020).

Integrated action also has a key role in providing benefits for human well-being. Urban mitigation options and strategies that are effective, efficient, and fair can also support broader sustainability goals (Güneralp et al. 2017; Kona et al. 2018; Pasimeni et al. 2019). Due to the complex and intensive interactions in urban systems and the interlinked nature of the SDGs, cities can be important intervention points to harness synergies and co-benefits for achieving emissions reductions along with other SDGs (Nilsson et al. 2016; Corbett and Mellouli 2017) (Section 8.2 and Figure 8.4).

8.4.1 Avoiding Carbon Lock-in

Carbon lock-in occurs as the result of interactions between different geographic and administrative scales (institutional lock-in) and across sectors (infrastructural and technological lock-in), which create the conditions for behavioural lock-in covering both individual and social structural behaviours (Seto et al. 2016) (see Glossary for a broader definition of 'lock-in'). The way that urban areas are designed, laid out, and built (i.e., urban form) affects and is affected by the interactions across the different forms of carbon lock-in (Figures 8.15 and 8.16). Cities are especially prone to carbon lock-in because of the multiple interactions of technological, institutional, and behavioural systems, which create inertia and path dependency that are difficult to break. For example, the lock-in of gasoline cars is reinforced by highway and energy infrastructures that are further locked-in by social and cultural preferences for individual mobility options. The dominance of cars and their supporting infrastructures in auto-centric urban forms is further reinforced by zoning and urban development patterns, such as dispersed and low-density housing distantly located from jobs, that create obstacles to creating alternative mobility options (Seto et al. 2016; Linton et al. 2021).

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). There is much focus in the climate change literature on the operational lifetimes of the energy sector, especially power plants and the electricity grid, which are between 30 and 60 years (Rode et al. 2017). Yet, in reality, the lifespans of urban

(a)

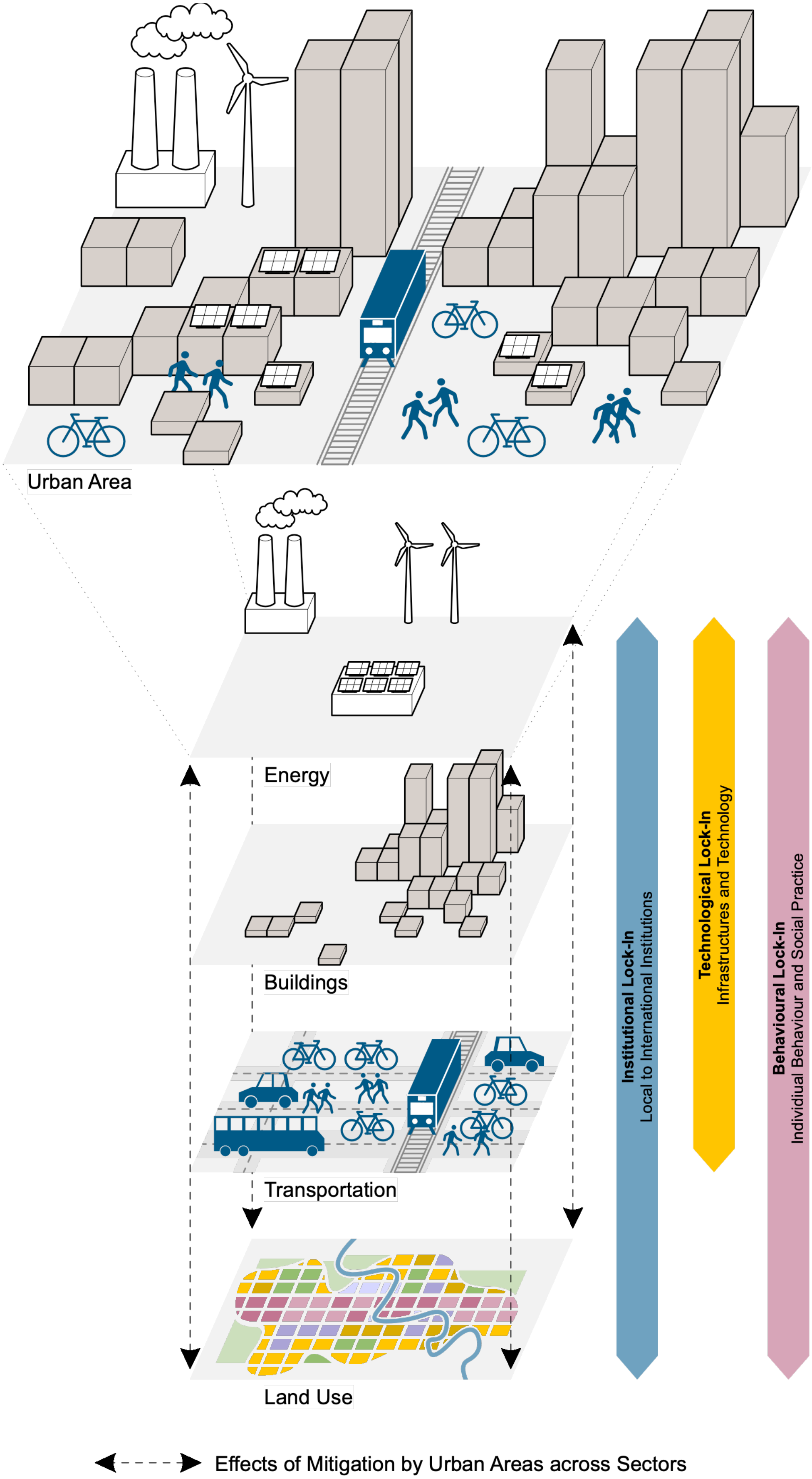


Figure 8.15: Urban systems, lock-in, and cascading effects of mitigation strategies.

8

(b)

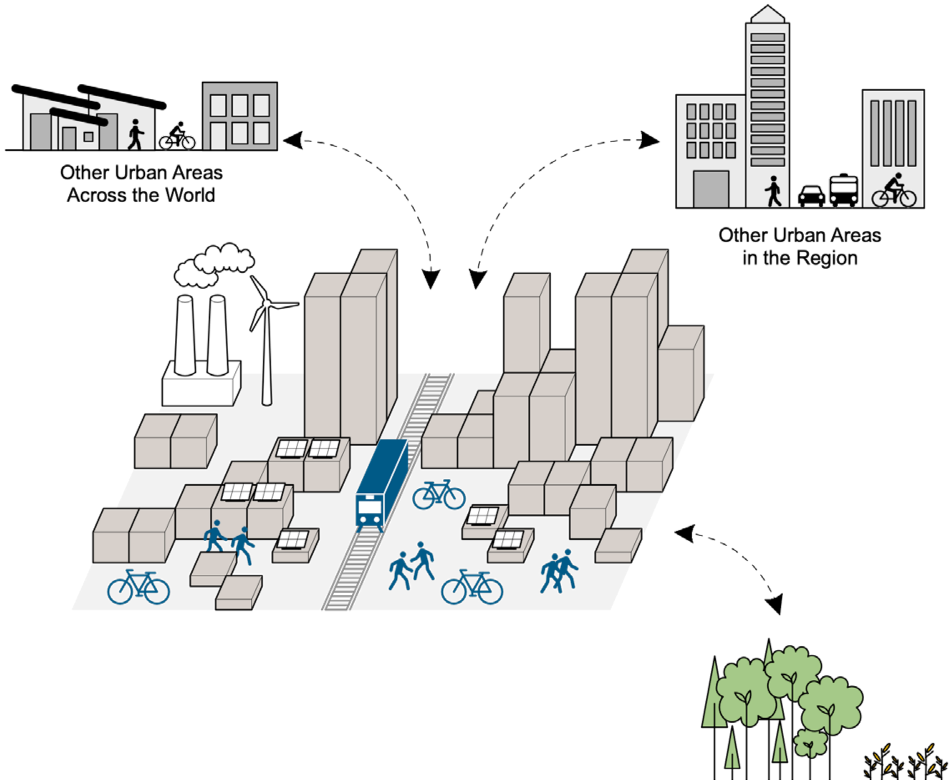


Figure 8.15 (continued): Urban systems, lock-in, and cascading effects of mitigation strategies. Cities are systems of interconnected sectors, activities, and governance structures. Urban-scale mitigation action can have cascading effects across multiple sectors, as shown in panel **(a)**, as well as regional, national, and global impacts through supply chains, resource flows, and institutions, as shown in panel **(b)**. Mitigation efforts implemented at larger scales of governance or in sectors that transcend urban boundaries, like energy and transportation, can also facilitate and amplify mitigation at the urban scale, as shown by the arrows extending in both directions across layers (a). Because urban areas are connected locally and globally, urban mitigation efforts can also impact other cities and surrounding areas (agriculture, forestry and other land use (AFOLU)). Cities are prone to carbon lock-in due to the numerous reinforcing interactions among urban infrastructures and technologies, institutions, and individual and collective behaviours; see the side arrows extending across the layers in panel (a): the yellow arrow represents the infrastructure and technological lock-in involving user technologies and supporting infrastructure, the blue arrow indicates lock-in of local to international institutions, and the pink arrow represents behavioural lock-in for individuals and society. Urban carbon lock-in is strongly determined by urban form, in particular the layout of streets and land-use mix. The different coloured spatial patterns represent varying levels of co-location of housing and jobs, and mobility options (Figure 8.16). Efforts to break urban carbon lock-in require meta-transformations to break inertia in and among infrastructures, institutions, and behaviours. Source: adapted in part from Seto et al. (2016).

infrastructures, especially the basic layout of roadways, are often much longer (Reyna and Chester 2015). A number of detailed case studies on the evolution of urban road networks for cities around the world reveal that the current layout of streets grew out of street networks that were established hundreds of years ago (Strano et al. 2012; Masucci et al. 2013; Mohajeri and Gudmundsson 2014). Furthermore, there is evidence that urban street layout, population growth, urban development, and automobile ownership co-evolve (Li et al. 2019a).

For cities to break out of mutually reinforcing carbon lock-in, it will require systematic transformation and systems-based planning that integrates mitigation strategies across sectors and geopolitical scales. Urban energy demand patterns are locked-in whenever incremental urban design and planning decisions, coupled with investments in long-lasting infrastructure, such as roads and buildings, take place (Seto et al. 2016). The fundamental building blocks of cities are based on the layout of the street network, the size of city blocks, and the density of street intersections. If not significantly altered, these three factors will continue to shape and lock-in energy demand for decades after their initial construction, influencing the mitigation potential of urban areas (Section 8.4.2 and Figure 8.22).

Avoiding carbon lock-in inherently involves decisions that extend beyond the administrative boundaries of cities. This includes pricing of low-emissions technology or materials, such as electric battery or hydrogen vehicles and buses, although cities can support their development and deployment (Cross-Chapter Box 12 in Chapter 16 on Transition Dynamics). In contrast, 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. Other examples include zoning that determines the location of buildings, land uses, standards for densities, and the inclusion of energy planning in their building standards and public works, including streets, parks, and open spaces (Blanco et al. 2011; Raven et al. 2018).

8.4.2 Spatial Planning, Urban Form, and Infrastructure

Urban form is the resultant pattern and spatial layout of land use, transportation networks, and urban design elements, including the physical urban extent, configuration of streets and building orientation, and the spatial figuration within and throughout cities and towns (Lynch 1981; Handy 1996). Infrastructure describes the physical structures, social and ecological systems, and corresponding institutional arrangements that provide services and enable urban activity (Dawson et al. 2018; Chester 2019) and comprises services and built-up structures that support urban functioning, including transportation infrastructure, water and wastewater systems, solid waste systems, telecommunications, and power generation and distribution (Seto et al. 2014).

8.4.2.1 Urban Form

The AR5 concluded that infrastructure and four dimensions of urban form are especially important for driving urban energy use: density, land-use mix, connectivity, and accessibility. Specifically, low-carbon cities have the following characteristics: (i) co-located medium to high densities of housing, jobs, and commerce; (ii) high mix of land uses; (iii) high connectivity of streets; and (iv) high levels of accessibility, distinguished by relatively low travel distances and travel times that are enabled by multiple modes of transportation. Urban areas with these features tend to have smaller dwelling units, smaller parcel sizes, walking opportunities, high density of intersections, and are highly accessible to shopping. For brevity, we will refer to these characteristics collectively as 'compact and walkable urban form' (Figure 8.16). Compact and walkable urban form has many co-benefits, including mental and physical health, lower resource demand, and saving land for AFOLU. In contrast, dispersed and auto-centric urban form is correlated with higher GHG emissions, and characterised by separated land uses, low population and job densities, large block size, and low intersection density.

Since AR5, a range of studies have been published on the relationships between urban spatial structures, urban form, and GHG emissions. Multiple lines of evidence reaffirm the key findings from AR5, especially regarding the mitigation benefits associated with reducing vehicle miles or kilometres travelled (VMT/VKT) through spatial planning. There are important cascading effects not only for transport but also other key sectors and consumption patterns, such as in buildings, households, and energy. However, these benefits can be attained only when the existing spatial structure of an urban area does not limit locational and mobility options, thereby avoiding carbon lock-in through the interaction of infrastructure and the resulting socio-behavioural aspects.

Modifying the layout of emerging urbanisation to be more compact, walkable, and co-located can reduce future urban energy use by 20–25% in 2050 while providing a corresponding mitigation potential of 23–26% (Creutzig et al. 2015, 2016b; Sethi et al. 2020), forming the basis for other urban mitigation options. Cross-Chapter Box 7 in Chapter 10 provides perspectives on simultaneously reducing urban transport emissions, avoiding infrastructure lock-in, and providing accessible services. The systemic nature of compact urban form and integrated spatial planning influences 'Avoid-Shift-Improve' (ASI, see Glossary) options across several sectors simultaneously, including for mobility and shelter (for an in-depth discussion on the integration of service provision solutions within the ASI framework, see Section 5.3).

8.4.2.2 Co-located Housing and Jobs, Mixed Land Use, and High Street Connectivity

Integrated spatial planning, co-location of higher residential and job densities, and systemic approaches are widely identified with development that is characterised by the 5Ds of transit-oriented development (TOD) based on density, diversity (mixed land uses), design (street connectivity), destination accessibility, and distance to transit. Spatial strategies that integrate the 5Ds are shown to reduce VMT/VKT, and thereby transport-related GHG emissions through energy savings. The effect of urban form and built environment strategies on VMT per capita varies by a number of factors (Ewing and Cervero 2010; Stevens 2017; Blanco and Wikstrom 2018). Density and destination accessibility have the highest elasticities, followed by design (Stevens 2017). Population-weighted densities for

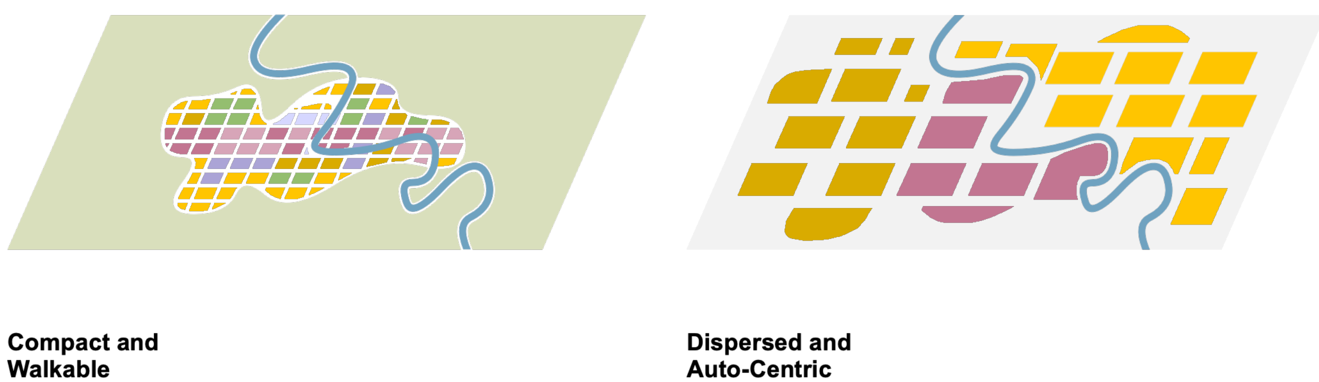


Figure 8.16: Urban form and implications for GHG emissions. Compact and walkable urban form is strongly correlated with low GHG emissions and characterised by co-located medium to high densities of housing and jobs, high street density, small block size, and mixed land use (Seto et al. 2014). Higher population densities at places of origin (e.g., home) and destination (e.g., employment, shopping) concentrate demand and are necessary for achieving the Avoid-Shift-Improve (ASI) approach for sustainable mobility (Chapters 5 and 10). Dispersed and auto-centric urban form is strongly correlated with high GHG emissions, and characterised by separated land uses, especially of housing and jobs, low street density, large block sizes, and low urban densities. Separated and low densities of employment, retail, and housing increase average travel distances for both work and leisure, and make active transport and modal shift a challenge. Since cities are systems, urban form has interacting implications across energy, buildings, transport, land use, and individual behaviour. Compact and walkable urban form enables effective mitigation while dispersed and auto-centric urban form locks-in higher levels of energy use. The colours represent different land uses and indicate varying levels of co-location and mobility options.

121 metropolitan areas have further found that the concentration of population and jobs along mass transit corridors decreases VMT/VKT significantly when compared to more dispersed metropolitan areas. In this sample, elasticity rates were twice as high for dense metropolitan areas located along mass transit lines (Lee and Lee 2020).

Meta-analyses of the reduction in VMT and the resulting GHG emissions consider the existing and still dominant use of emitting transportation technology, transportation fleets, and urban form characteristics. Varied historical legacies of transportation and the built environment, which can be utilised to develop more sustainable cities (Newman et al. 2016, 2017), are often not taken into account directly. Metropolitan policies and spatial planning, as evident in Copenhagen's Finger Plan, as well as strategic spatial planning in Stockholm and Seoul, have been major tools to restructure urban regions and energy patterns (Sung and Choi 2017). Road prices and congestion charges can provide the conditions for urban inhabitants to shift mobility demands and reduce vehicle use (Section 5.6.2). Surprisingly, even cities with higher population densities and a greater range of land uses can show declines in these important attributes, which can lead to emissions increases, such as found in a study of 323 East and South East Asian cities (Chen et al. 2020c). Conversely, the annual CO_2 emissions reduction of passenger cars in compact versus dispersed urban form scenarios can include at least a 10% reduction by 2030 (Matsuhashi and Ariga 2016). When combined with advances in transport technology, this share increases to 64–70% in 2050 based on compact urban form scenarios for 1727 municipalities (Kii 2020).

As a reaffirmation of AR5, population density reduces emissions per capita in the transport, building, and energy sectors (Baur et al. 2015; Gudipudi et al. 2016; Wang et al. 2017; Yi et al. 2017) (see also Sections 8.3.1 and 8.3.4 on past trends and forecasts of urban population density and land expansion). Urban compactness tends to reduce emissions per capita in the transport sector, especially for commuting (Matsuhashi and Ariga 2016; Lee and Lim 2018; Lee and Lee 2020). The relative accessibility of neighbourhoods to the rest of the region, in addition to the density of individual neighbourhoods, is important (Ewing et al. 2018). Creating higher residential and employment densities, developing smaller block sizes, and increasing housing opportunities in an employment area can significantly reduce household car ownership and car driving, and increase the share of transit, walk, and bicycle commuting (Ding et al. 2018). In addition to population density, land-use mix, rail transit accessibility, and street design reduce emissions from transport (Dou et al. 2016; Cao and Yang 2017; Choi 2018). The impact of population density and urban compactness on emissions per capita in the household or energy sector is also associated with socioeconomic characteristics or lifestyle preferences (Baiocchi et al. 2015; Miao 2017). Changes in the attributes of urban form and spatial structure have influences on overall energy demand across spatial scales, particularly street, block, neighbourhood, and city scales, as well as across the building (housing) and transport (mobility) sectors (Silva et al. 2017). Understanding the existing trade-offs (or synergetic links) between urban form variables across major emissions source sectors, and how they impact the size of energy flows within the urban system, is key to prioritising action for energy-efficient spatial planning strategies, which are likely to vary across urban areas.

8.4.2.3 Urban Form, Growth, and Sustainable Development

Spatial planning for compact 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 enable positive impacts on employment and green growth given that the local economy is decoupled from GHG emissions and related parameters while the concentration of people and activity can increase productivity based on both proximity and efficiency (Lee and Erickson 2017; Salat et al. 2017; Gao and Newman 2018; Han et al. 2018; Li and Liu 2018; Lall et al. 2021).

Public acceptance can have a positive impact on integrated spatial planning especially when there is 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 well-being, including decisions to balance urban green areas with density (Li et al. 2016; Sorkin 2018; Pierer and Creutzig 2019). The distributional effects of spatial planning can depend on 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) (Sections 8.2 and 8.4.4).

Reducing GHG emissions across different urban growth typologies (Figure 8.20) depends in part on the ability to integrate opportunities for climate mitigation with co-benefits for health and well-being (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). The capacity for implementing land-use zoning and regulations in a way that is consistent with supporting spatial planning for compact urban form is not equal across urban areas and depends on different contexts as well as institutional capacities (Bakır et al. 2018; Deng et al. 2018; Shen et al. 2019).

Currently, integrating spatial planning, urban form, and infrastructure in urban mitigation strategies remains limited in mainstream practices, including in urban areas targeting an emissions reduction of 36–80% in the next decades (Asarpota and Nadin 2020). Capacity building for integrated spatial planning for urban mitigation includes increasing collaboration among city departments and with civil society to develop robust mitigation strategies, bringing together civil engineers, architects, urban designers, public policy and spatial planners, and enhancing the education of urban professionals (Asarpota and Nadin 2020) (Section 8.5).

Spatial planning for compact urban form is a prerequisite for efficient urban infrastructure, including district heating and/or cooling networks (Swilling et al. 2018; Möller et al. 2019; Persson et al. 2019; UNEP IRP 2020). District heating and cooling networks benefit from 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). Heat-demand density is a function of both population density and heat demand per capita and 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). Low-temperature networks that utilise waste heat or renewable energy can provide an option to avoid carbon lock-in to fossil fuels while layout and eco-design principles can further optimise such networks (Gang et al. 2016; Buffa et al. 2019; Dominković and Krajačić 2019). Replacing gas-based heating and cooling with electrified district heating and cooling networks, for instance, provides 65% emissions reductions also involving carbon-aware scheduling for grid power (De Chalendar et al. 2019). The environmental and ecological benefits increase through the interaction of urban energy and spatial planning (Tuomisto et al. 2015; Bartolozzi et al. 2017; Dénarié et al. 2018; Zhai et al. 2020). These interactions include support for demand-side flexibility, spatial planning using geographic information systems, and access to renewable and urban waste heat sources (Möller et al. 2018; REN21 2020; Sorknæs et al. 2020; Dorotić et al. 2019) (see Table 8.SM.2 for other references).

8.4.3 Electrification and Switching to Net-Zero-Emissions Resources

Pursuing the electrification of mobility, heating, and cooling systems, while decarbonising electricity and energy carriers, and switching to net-zero materials and supply chains, represent important strategies for urban mitigation. Electrification of energy end uses in cities and efficient energy demand for heating, transport, and cooking through multiple options and urban infrastructure, has an estimated mitigation potential of at least 6.9 $GtCO_2$-eq by 2030 and 15.3 $GtCO_2$-eq by 2050 (Coalition for Urban Transitions 2019). Energy efficiency measures in urban areas can be enabled by urban form, building codes, retrofitting and renovation, modal shifts, and other options. Decarbonising electricity supply raises the mitigation potential of efficient buildings and transport in urban areas to about 75% of the total estimate (Coalition for Urban Transitions 2019). In addition, relatively higher-density urban areas enable more cost-effective infrastructure investments, including electric public transport and large-scale heat pumps in districts that support electrification. Urban policymakers can play a key role in supporting carbon-neutral energy systems by acting as target setters and planners, demand aggregators, regulators, operators, conveners, and facilitators for coordinated planning and implementation across sectors, urban form, and demand (IEA 2021a; IRENA 2021).

8.4.3.1 Electrification and Decarbonisation of the Urban Energy System

Urban energy infrastructures often operate as part of larger energy systems that can be electrified, decarbonised, and become enablers of urban system flexibility through demand-side options. With multiple end-use sectors (e.g., transport, buildings) and their interactions with land use drawing on the same urban energy system(s), increasing electrification is essential for rapid decarbonisation, renewable energy penetration, and demand flexibility (Kammen and Sunter 2016) (see IMPs in Sections 3.2.5 and 8.3.4). The mitigation potential of electrification is ultimately dependent on the carbon intensity of the electricity grid (Kennedy 2015; Hofmann et al. 2016; Peng et al. 2018; Zhang and Fujimori 2020) and starts providing lifecycle emission savings for carbon intensities below a threshold of 600 tCO_2-eq GWh^{-1} (Kennedy et al. 2019). Integrated systems of roof-top photovoltaics (PVs) and all-electric vehicles (EVs) alone could supply affordable carbon-free electricity to cities and reduce CO_2 emissions by 54–95% (Brenna et al. 2014; Kobashi et al. 2021). Furthermore, electrification and decarbonisation of the urban energy system holds widespread importance for climate change mitigation across different urban growth typologies and urban form (Section 8.6 and Figure 8.21) and leads to a multitude of public health co-benefits (see Section 8.2).

Strategies that can bring together electrification with reduced energy demand based on walkable and compact urban form can accelerate and amplify decarbonisation. Taking these considerations – across the energy system, sectors, and land use – contributes to avoiding, or breaking out of, carbon lock-in and allows continued emission savings as the energy supply is decarbonised (Kennedy et al. 2018; Teske et al. 2018; Seto et al. 2021). Indeed, electrification is already transforming urban areas and settlements and has the potential to continue transforming urban areas into net-negative electric cities that may sequester more carbon than emitted (Kennedy et al. 2018; Seto et al. 2021).

In its simplest form, electrification involves the process of replacing fossil fuel-based technologies with electrified innovations such as electric vehicles, buses, streetcars, and trains (Sections 10.3 and 10.4), heat pumps, PVs (Section 6.4.2.1), electric cook-stoves (Section 9.8.2.1), and other technologies (Stewart et al. 2018). Cost-effective decarbonisation of energy use can be supported by electrification in urban areas if there is also demand-side flexibility for power, heat, mobility, and water with sector coupling (Guelpa et al. 2019; Pfeifer et al. 2021). Overall, demand-side flexibility across sectors in urban areas is supported by smart charging, electric mobility, electrified urban rail, power-to-heat, demand side response, and water desalination (Lund et al. 2015; Calvillo et al. 2016; Salpakari et al. 2016; Newman 2017; Meschede 2019).

As an enabler, electrification supports integrating net-zero energy sources in urban infrastructure across sectors, especially when there is more flexible energy demand in mobility, heating, and cooling to absorb greater shares of variable renewable energy. In the transport sector, smart charging can reduce electric vehicle impacts on peak demand by 60% (IEA 2021a). Urban areas that connect efficient building clusters with the operation of smart thermal grids in district heating and cooling networks with large-scale heat pumps can support higher penetrations of variable renewable energy in smart energy systems (Lund et al. 2014, 2017). Higher urban densities provide the advantage of increasing the penetration of renewable power for deep decarbonisation, including mixed-use neighbourhoods for grid balancing and electric public transport (Hsieh et al. 2017; Tong et al. 2017; Fichera et al. 2018; Kobashi et al. 2020). Based on these opportunities, urban areas that provide low-cost options to energy storage for integrating the power sector with multiple demands reduce investment needs in grid electricity storage capacities (Mathiesen et al. 2015; Lund et al. 2018).

Electrification at the urban scale encompasses strategies to aggregate energy loads for demand response in the urban built environment to reduce the curtailment of variable renewable energy and shifting time-of-use based on smart charging for redistributing energy demands (O'Dwyer et al. 2019). Peak shaving or shifting takes place among frequent interventions at the urban level (Sethi et al. 2020). Business models and utility participation, including municipal level demonstrations, can allow for upscaling (Gjorgievski et al. 2020; Meha et al. 2020). The urban system can support increasing demand-side flexibility in energy systems, including in contexts of 100% renewable energy systems (Drysdale et al. 2019; Thellufsen et al. 2020).

Smart grids in the urban system

Smart electricity grids enable peak demand reductions, energy conservation, and renewable energy penetration, and are a subset of smart energy systems. GHG emission reductions from smart grids range from 10 to 180 $gCO_2\ kWh^{-1}$ (grams of CO_2 per kilowatt-hour) with a median value of 89 $gCO_2\ kWh^{-1}$, depending on the electricity mix, penetration of renewable energy, and the system boundary (Moretti et al. 2017). Smart electricity grids are characterised by bi-directional flows of electricity and information between generators and consumers, although some actors can be both as 'prosumer' (see Glossary). Two-way power flows can be used to establish peer-to-peer trading (P2P) (Hansen et al. 2020). Business models based on local citizen utilities (Green and Newman 2017; Green et al. 2020; Syed et al. 2020) and community batteries (Mey and Hicks 2019; Green et al. 2020) can support the realisation of distributed energy and solar energy cities (Galloway and Newman 2014; Byrne and Taminiau 2016; Stewart et al. 2018; Allan 2020).

Currently, despite power outages that are costly to local economies, the adoption of smart electricity grids or smart energy systems has been slow in many developing regions, including in Sub-Saharan Africa (Westphal et al. 2017; Kennedy et al. 2019). This is due to a number of different factors, such as unreliable existing infrastructure, fractured fiscal authority, lack of electricity access in urban areas, upfront cost, financial barriers, inefficient pricing of electricity, and low consumer education and engagement (Venkatachary et al. 2018; Acakpovi et al. 2019; Cirolia 2020).

Pathways and trade-offs of electrification in urban systems

Urbanisation and population density are one of the key drivers for enabling access to electricity across the world, with benefits for sustainable development (Aklin et al. 2018). Grid-connected PV systems for urban locations that currently lack electricity access can allow urban areas to leapfrog based on green electrification (Abid et al. 2021). In the Global South, the conversion of public transport to electric transport, 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) have been quantified based on reductions in GHG and $PM_{2.5}$ emissions, avoided premature deaths, and increases in life expectancies (IEA 2014; C40 Cities 2018, 2020b,c,d,e). In 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). Yet the scaling up of electric vehicles in cities can be examined within a larger set of possible social objectives, such as reducing congestion and the prioritisation of other forms of mobility.

Electrification requires a layering of policies at the national, state, and local levels. Cities have roles as policy architects, including transit planning (e.g., EV targets and low-emission zones, restrictions on the types of energy use in new buildings), implementers (e.g., building codes and compliance checking, financial incentives to encourage consumer uptake of EVs and heat pumps), and complementary partners to national and state policymaking (e.g., permitting or installation of charging infrastructure) (Broekhoff et al. 2015). The number of cities that have instituted e-mobility targets that aim for a certain percentage of EVs sold, in circulation or registered, is increasing (REN21 2021). Realising the mitigation potential of electrification will require fiscal and regulatory policies and public investment (Hall et al. 2017a; Deason and Borgeson 2019; Wappelhorst et al. 2020) (Section 8.5).

EVs are most rapidly deployed when there has 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, 2017, 2018, 2020a; Cazzola et al. 2019). The policy mix has included mandates for bus deployment, purchase subsidies, or split ownership of buses and chargers (IEA 2021b) (Chapter 10). Subsidies are often critical to address the often-higher upfront costs of electric devices. In other instances, the uptake of electric induction stoves was increased through government credit and allotment of free electricity (Martínez et al. 2017; Gould et al. 2018).

Bringing multiple stakeholders together in local decision-making for smart energy systems requires effort beyond usual levels while multi-actor settings can be increased to enable institutional conditions (Lammers and Hoppe 2019). Public participation and community involvement in the planning, design and operation of urban energy projects can be an enabler of decarbonising local energy demands (Corsini et al. 2019). Cooperation across institutions is important for municipalities that are engaged in strategic energy planning and implementation for smart energy systems (Krog 2019) (Section 8.5).

Electrification technologies can present potential trade-offs that can be minimised through governance strategies, smart grid technologies, circular economy practices, and international cooperation. One consideration is the increase in electricity demand (Section 5.3.1.1). Across 23 megacities in the world (population greater than 10 million people), electrification of the entire gasoline vehicle fleet could increase electricity demand on average by 18% (Kennedy et al. 2018). How grid capacity will be impacted is dependent on the match between daily electricity loads and supply (Tarroja et al. 2018). Materials recycling of electrification technologies is also 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 complete mitigation potential. Circular economy strategies are particularly valuable to this goal by creating closed-loop supply chains through recycling, material recovery, repair, and reuse. For instance, the PV CYCLE programme in Europe prevented more than 30,000 metric tonnes of renewable technology from reaching the waste stream (Sovacool et al. 2020) (Box 10.6 and 'circular economy' in Glossary).

8.4.3.2 Switching to Net-zero-emissions Materials and Supply Chains

For the carbon embodied in supply chains to become net-zero, all key infrastructure and provisioning systems will need to be decarbonised, including electricity, mobility, food, water supply, and construction (Seto et al. 2021). The growth of global urban populations that is anticipated over the next several decades will create significant demand for buildings and infrastructure. As cities expand in size and density, there is an increase in the production of mineral-based structural materials

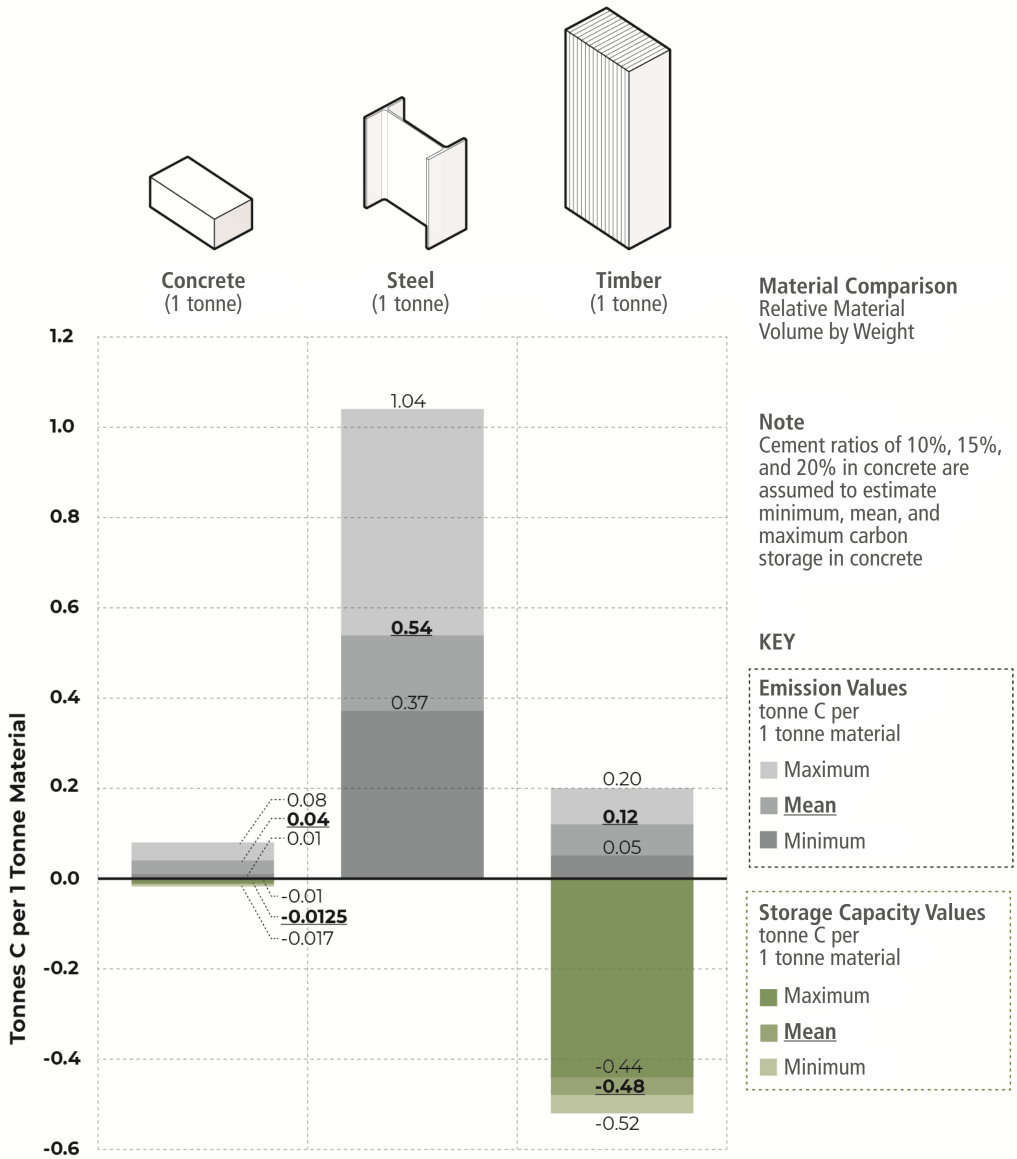


Figure 8.17: Relative volume of a given weight, its carbon emissions, and carbon storage capacity of primary structural materials comparing one tonne of concrete, steel, and timber. Concrete and steel have substantial embodied carbon emissions with minimal carbon storage capacities, while timber stores a considerable quantity of carbon with a relatively small ratio of carbon emissions-to-material volume. The displayed carbon storage of concrete is the theoretical maximum value, which may be achieved after hundreds of years. Cement ratios of 10%, 15%, and 20% are assumed to estimate minimum, mean, and maximum carbon storage in concrete. Carbon storage of steel is not displayed as it is negligible (0.004 tonne C per tonne of steel). The middle-stacked bars represent the mean carbon emission or mean carbon storage values displayed in bold font and underlined. The darker and lighter coloured stacked bars depict the minimum and maximum values. Grey tones represent carbon emissions and green tones are given for storage capacity values. Construction materials have radically different volume-to-weight ratios, as well as material intensity (see representations of structural columns in the upper panel. These differences should be accounted for in the estimations of their carbon storage and emissions (see also Figure 8.22). Source: adapted with permission from Churkina et al. (2020).

and enclosure systems that are conventionally associated with mid- and high-rise urban construction morphologies, including concrete, steel, aluminium, and glass. This will create a significant spike in GHG emissions and discharge of CO_2 at the beginning of each building lifecycle, necessitating alternatives (Churkina et al. 2020).

The initial carbon debt incurred in the production stage, even in sustainable buildings, can take decades to offset through operational stage energy efficiencies alone. Increased reduction 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. Among the category of primary structural materials, it is estimated that final energy demand for steel production can be reduced by nearly 30% compared to 2010 levels, with 12% efficiency improvement for cement (Lechtenböhmer et al. 2016). Even when industries are decarbonised, residual CO_2 emissions will remain from associated chemical reactions that take place in calcination and use of coke from coking coal to reduce iron oxide (Davis et al. 2018). Additionally, carbon sequestration by cement occurs over the course of the building lifecycle in quantities that would offset only a fraction of their production stage carbon spike (Xi et al. 2016; Davis et al. 2018). Moreover, there are collateral effects on the carbon cycle related to modern construction and associated resource extraction. The production of cement, asphalt, and glass requires large amounts of sand extracted from beaches, rivers, and seafloors, disturbing aquatic ecosystems and reducing their capacity to absorb atmospheric carbon. The mining of ore can lead to extensive local deforestation and soil degradation (Sonter et al. 2017). Deforestation significantly weakens the converted land as a carbon sink and in severe cases may even create a net emissions source.

A broad-based substitution of monolithic engineered timber systems 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 storage of photosynthetic forest carbon through the substitution of biomass-based structural materials for emissions-intensive steel and concrete is an opportunity for urban infrastructure. The construction of timber buildings for 2.3 billion new urban dwellers from 2020 to 2050 could store between 0.01 and 0.68 $GtCO_2$ per year depending on the scenario and the average floor area per capita. Over 30 years, wood-based construction can accumulate between 0.25 and 20 $GtCO_2$ and reduce cumulative emissions from 4 $GtCO_2$ (range of 7–20 $GtCO_2$) to 2 $GtCO_2$ (range of 0.3–10 $GtCO_2$) (*high confidence*) (Churkina et al. 2020).

Figure 8.17 indicates that 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 (see also Figure 8.22). 'Mass timber' refers to engineered wood products that are laminated from smaller boards or lamella into larger structural components such as glue-laminated (glulam) beams or cross-laminated timber (CLT) panels. Methods of mass-timber production that include finger-jointing, longitudinal and transverse lamination with both liquid adhesive and mechanical fasteners, have allowed for the reformulation of large structural timbers. The parallel-to-grain strength of mass (engineered) timber is similar to that of reinforced concrete (Ramage et al. 2017). As much as half the weight of a given volume of wood is carbon, sequestered during forest growth as a by-product of photosynthesis (Martin et al. 2018). Mass timber is inflammable, but in large sections forms a self-protective charring layer when exposed to fire that will protect the remaining 'cold wood' core. This property, formed as massive structural sections, is recognised in the fire safety regulations of building codes in several countries, which allow mid- and high-rise buildings in timber. Ongoing studies have addressed associated concerns about the vulnerability of wood to decay and the capacity of structural timber systems to withstand seismic and storm-related stresses.

Transitioning to biomass-based building materials, implemented through the adoption of engineered structural timber products and assemblies, will succeed as a mitigation strategy only if working forests are managed and harvested sustainably (Churkina et al. 2020). Since future urban growth and the construction of timber cities may lead to increased timber demand in regions with low forest cover, it is necessary to systematically analyse timber demand, supply, trade, and potential competition for agricultural land in different regions (Pomponi et al. 2020). The widespread adoption of biomass-based urban construction materials and techniques will demand more robust forest and urban land governance and management policies, as well as internationally standardised carbon accounting methods to properly value and incentivise forest restoration, afforestation, and sustainable silviculture.

Expansion of agroforestry practices may help to reduce land-use conflicts between forestry and agriculture. Harvesting pressures on forests can be reduced through the reuse and recycling of wooden components from dismantled timber buildings. 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, sinks that are at least as durable as other buildings (Churkina et al. 2020). Policies and practices promoting design for disassembly and material reuse will increase their durability.

8.4.4 Urban Green and Blue Infrastructure

The findings of AR6 WGI and WGII have underscored the importance of urban green and blue infrastructure for reducing the total warming in urban areas due to its local cooling effect on temperature and its benefits for climate adaptation (IPCC 2021; Cross-Working Group Box 2 in this chapter). Urban green and blue infrastructure in the context of nature-based solutions (NBS) involves the protection, sustainable management, and restoration of natural or modified ecosystems while simultaneously providing benefits for human well-being and biodiversity (IUCN 2021) (see Glossary for additional definitions). As an umbrella concept, urban NBS integrates established ecosystem-based approaches that provide multiple ecosystem services and are important in the context of societal challenges related to urbanisation, climate change, and reducing GHG emissions through the conservation and expansion of carbon sinks (Naumann et al. 2014; Raymond et al. 2017) (Section 8.1.6.1).

Urban green and blue infrastructure includes a wide variety of options, from street trees, parks, and sustainable urban drainage systems (Davis and Naumann 2017), to building-related green roofs or green facades, including green walls and vertical forests (Enzi et al. 2017). Figure 8.18 synthesises urban green and blue infrastructure based on urban forests, street trees, green roofs, green walls, blue spaces, greenways, and urban agriculture. Key mitigation benefits, adaptation co-benefits, and SDG linkages are represented by types of green and blue infrastructure. Local implementations of urban green and blue infrastructure can pursue these linkages while progressing toward inclusive sustainable urban planning (SDG 11.3) and the provision of safe, inclusive and accessible green and public spaces for all (SDG 11.7) (Butcher-Gollach 2018; Pathak and Mahadevia 2018; Rigolon et al. 2018; Anguelovski et al. 2019; Buyana et al. 2019; Azunre et al. 2021) (Section 8.2).

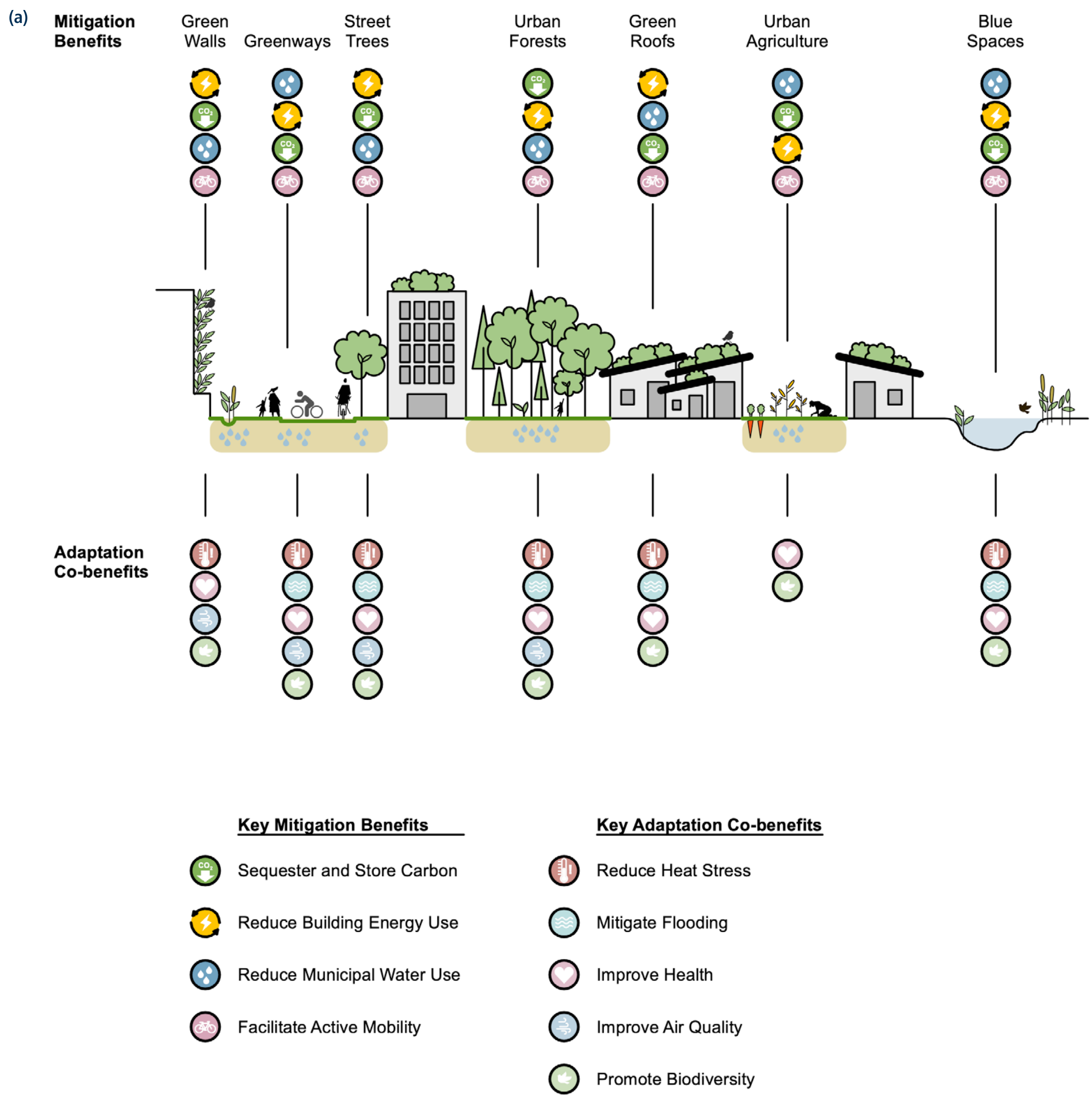


Figure 8.18: Key mitigation benefits, adaptation co-benefits, and SDG linkages of urban green and blue infrastructure. Panel **(a)** illustrates the potential integration of various green and blue infrastructure strategies within an urban system.

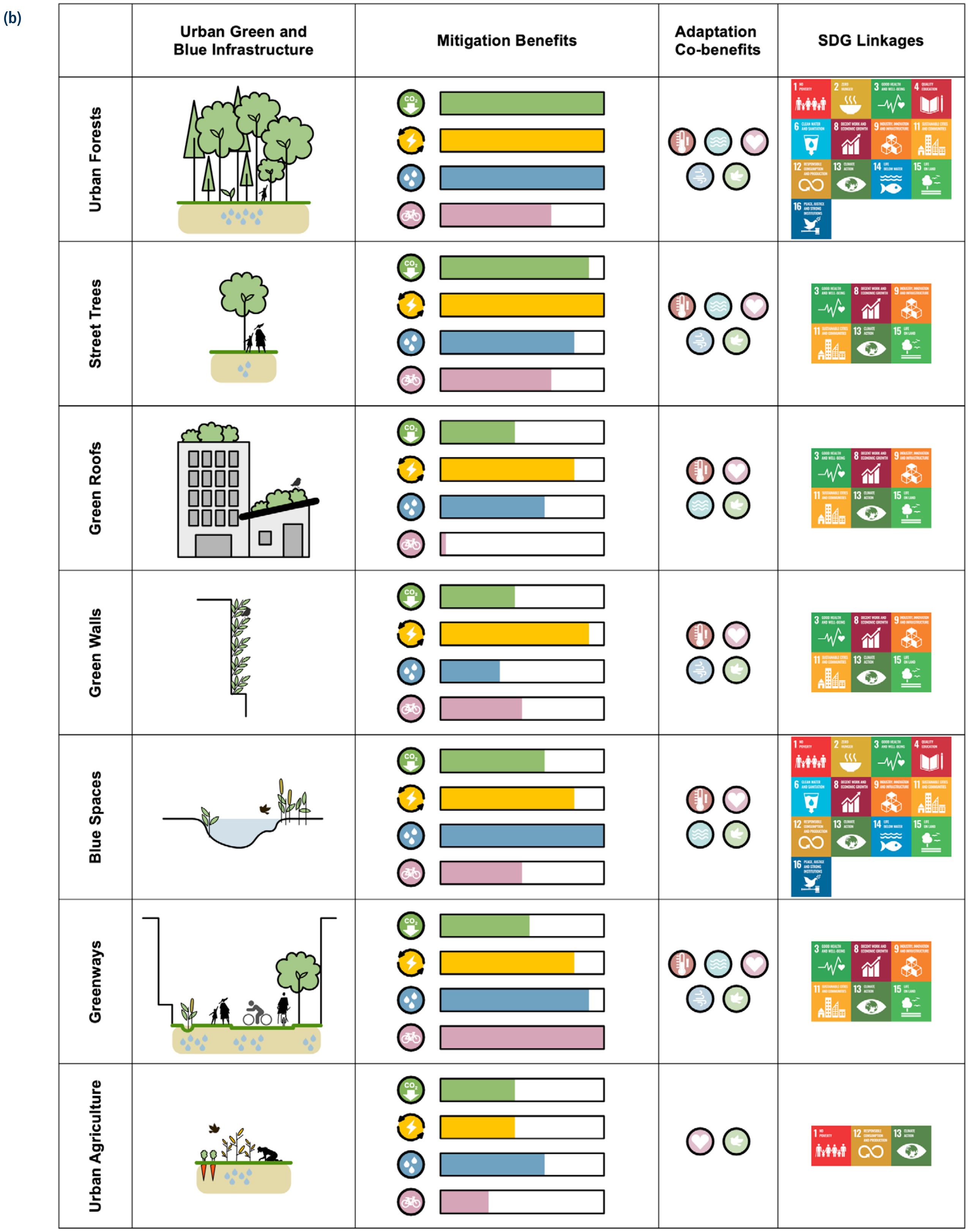


Figure 8.18: Key mitigation benefits, adaptation co-benefits, and SDG linkages of urban green and blue infrastructure. Panel **(b)** evaluates those strategies in the context of their mitigation benefits, adaptation co-benefits, and linkages to the SDGs. Urban forests and street trees provide the greatest mitigation benefit because of their ability to sequester and store carbon while simultaneously reducing building energy demand. Moreover, they provide multiple adaptation co-benefits and synergies based on the linkages to the SDGs (Figure 8.4). The assessments of mitigation benefits are dependent on context, scale, and spatial arrangement of each green and blue infrastructure type and their proximity to buildings. Mitigation benefits due to reducing municipal water use are based on reducing wastewater loads that reduce energy use in wastewater treatment plants. The sizes of the bars are illustrative and their relative size is based on the authors' best understanding and assessment of the literature.

8.4.4.1 The Mitigation Potential of Urban Trees and Associated Co-benefits

Due to their potential to store relatively high amounts of carbon compared to other types of urban vegetation, as well as their ability to provide many climate mitigation co-benefits (*high agreement, robust evidence*), natural area protection and natural forest management in urban areas is an important priority for cities looking to mitigate climate change. 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).

Global urban tree carbon storage is approximately 7.4 billion tonnes (GtC) given 363 million hectares of urban land, 26.5% tree cover, and an average carbon storage density of urban tree cover of 7.69 kgC m^{-2} (kilograms carbon per square metre) (Nowak et al. 2013; World Bank et al. 2013). Estimated global annual carbon sequestration by urban trees is approximately 217 million tonnes (MtC) given an average carbon sequestration density per unit urban tree cover of 0.226 kgC m^{-2} (Nowak et al. 2013). With an average plantable (non-tree and non-impervious) space of 48% globally (Nowak and Greenfield 2020), the carbon storage value could nearly triple if all this space is converted to tree cover. In Europe alone, if 35% of the urban surfaces (26,450 km^2) were transformed into green surfaces, the mitigation potential based on carbon sequestration would be an estimated 25.9 $MtCO_2$ yr^{-1} with the total mitigation benefit being 55.8 $MtCO_2$ yr^{-1}, including an energy saving of about 92 TWh yr^{-1} (Quaranta et al. 2021). Other co-benefits include reducing urban runoff by about 17.5% and reducing summer temperatures by 2.5°C–6°C (Quaranta et al. 2021).

Urban tree carbon storage is highly dependent on biome. For example, carbon sequestered by vegetation in Amazonian forests is two to five times higher compared to boreal and temperate forests (Blais et al. 2005). At the regional level, the estimated carbon storage density rates of tree cover include a range of 3.14–14.1 kgC m^{-2} in the United States, 3.85–5.58 kgC m^{-2} in South Korea, 1.53–9.67 kgC m^{-2} in Barcelona, Spain, 28.1–28.9 kgC m^{-2} in Leicester, England, and an estimated 6.82 kgC m^{-2} in Leipzig, Germany and 4.28 kgC m^{-2} in Hangzhou, China (Nowak et al. 2013). At the local scale, above- and below-ground tree carbon densities can vary substantially, as with carbon in soils and dead woody materials. The conservation of natural mangroves has been shown to provide urban mitigation benefits through carbon sequestration, as demonstrated in the Philippines (Abino et al. 2014). Research on urban carbon densities from the Southern Hemisphere will contribute to better estimates.

On a per-tree basis, urban trees offer the most potential to mitigate climate change through both carbon sequestration and GHG emissions reduction from reduced energy use in buildings (Nowak et al. 2017). Maximum possible street tree planting among 245 world cities could reduce residential electricity use by about 0.9–4.8% annually (McDonald et al. 2016). Urban forests in the United States reduce building energy use by 7.2%, equating to an emissions reduction of 43.8 $MtCO_2$ annually (Nowak et al. 2017).

Urban trees can also mitigate some of the impacts of climate change by reducing the UHI effect and heat stress, reducing stormwater runoff, improving air quality, and supporting health and well-being in areas where the majority of the world's population resides (Nowak and Dwyer 2007). Urban forest planning and management can maximise these benefits for present and future generations by sustaining optimal tree cover and health (also see SDG linkages in Figure 8.4). Urban and peri-urban agriculture can also have economic benefits from 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, extent, and growing conditions of vegetation in cities has an influence on their potential for mitigating climate change (Pregitzer et al. 2021). 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. 2016). 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) (Pregitzer et al. 2019a). In New York City, natural areas are estimated to store a mean of 263.5 MgC ha^{-1} (megagram carbon per hectare), adding up to 1.86 TgC (teragram carbon) across the city, with the majority of carbon (86%) being stored in the trees and soils (Pregitzer et al. 2021). These estimates are similar to per-hectare estimates of carbon storage across different pools in non-urban forest types (Table 1), and 1.5 times greater than estimates for carbon stored in just trees across the entire city (Pregitzer et al. 2021).

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 MgC ha^{-1}. However, non-native exotic invasive species can be prevalent in the understory vegetation layer (<1m height), and account for about 50% of cover in New York City (Pregitzer et al. 2019b).

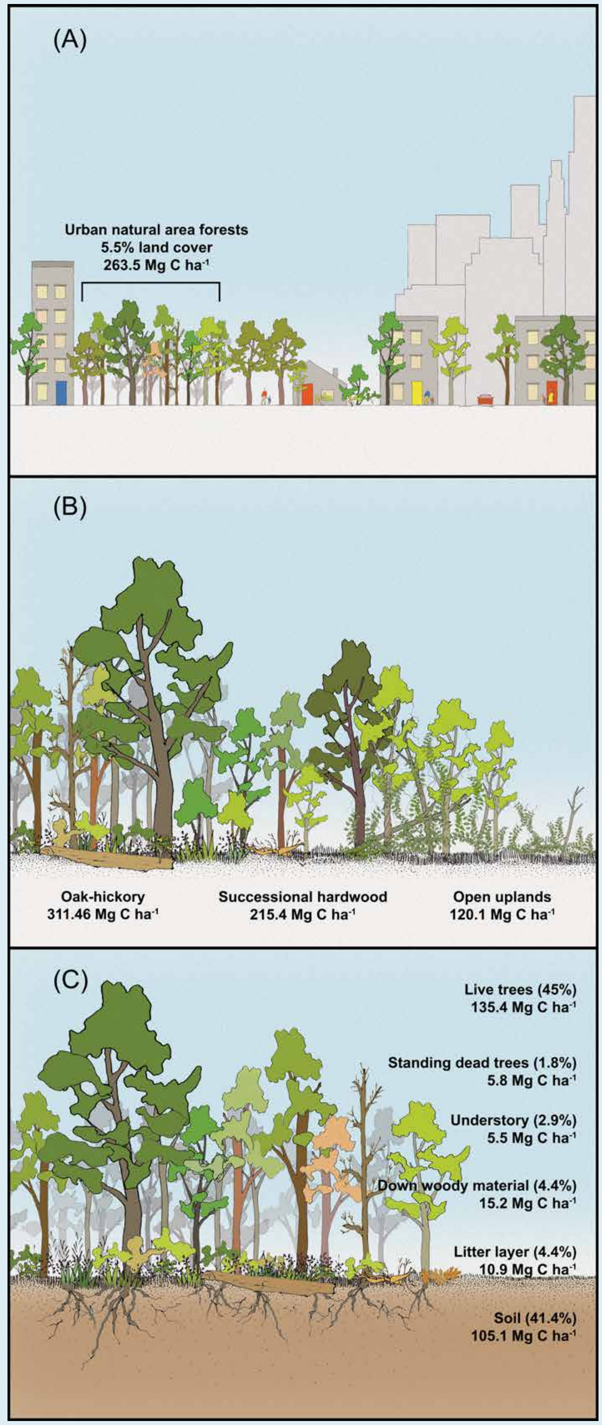
Box 8.2 (continued)

This could lead to a trajectory where exotic understory species, which are often herbaceous, out-compete regenerating trees in the understory layer, alter the soil (Ward et al. 2020), 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 MgC ha^{-1}).

When compared to estimates of carbon storage presented in other studies, the components (pools) of the natural area forests in New York City store carbon in similar proportions to other non-urban forests (see Table 1). This might suggest that in other geographies, similar adjacent non-urban forest types may store similar carbon stocks per unit area (*medium confidence*). 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 to higher access to light, nutrients, and increased temperatures (Gregg et al. 2003; Reinmann et al. 2020).

Higher growth rates coupled with the UHI effect 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 trees in cities, could be found in urban natural area forest patches (*medium agreement*, *limited evidence*). More research is needed to map urban natural areas, assess vegetation, and differentiate tree canopy types (natural versus non-natural) at fine scales within many cities and geographies. Accurate maps, as well as greater 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, 2021); **(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 (1.86 TgC). Source: adapted from Pregitzer et al. (2021).

Box 8.2 (continued)

Box 8.2, Table 1: A selection of benchmark reference estimates of different carbon pools sampled and the related urban considerations to contextualise the results from New York City (NYC), United States (USA) natural area carbon stocks. The benchmark estimates are intended to provide a point of reference to help contextualise the calculations for carbon pools in NYC's forests. Forest carbon is highly variable and dependent on microclimatic conditions such as moisture, microbial communities, and nutrient availability, all of which can be impacted by human activity in urban or altered environments. Standard errors and 95% confidence intervals can be found in Pregitzer et al. (2021). DBH: diameter at breast height; DWM: down woody material; CWM: coarse woody material and FWM: fine woody material. Source: Pregitzer et al. (2021).

Pool considered in NYC natural area	Published estimates of carbon stock ($MgC\ ha^{-1}$)	NYC estimated carbon stock ($MgC\ ha^{-1}$)	Urban considerations
Live trees: all trees (>2 cm DBH) including above and below ground	87.1: northeastern USA (Smith et al. 2013) 73.3: NYC assuming 100% cover (Nowak et al. 2013)	135.4	Lower ozone levels, higher CO_2, warmer temperatures, and higher nutrient deposition could lead to increased growth rates and annual carbon sequestration. However, pollutants in soil (e.g., heavy metals), increased pests, and GHGs in the atmosphere (e.g., NO_X and SO_2) could decrease annual tree growth and carbon sequestration (Gregg et al. 2003)
Groundcover: all vegetation growing <1 m height	1.8: northeastern USA (Smith et al. 2013)	5.5	Anthropogenic disturbance creates canopy gaps that accelerate herbaceous growth; invasive vines are prevalent in urban forests that can alter tree survival and growth and soils (Matthews et al. 2016; Ward et al. 2020)
Standing dead trees	5.1: northeastern USA (Smith et al. 2013) 2.59: Massachusetts (Liu et al. 2006)	5.8	Removal may occur due to safety considerations
CWM: coarse (>10 cm) and FWM (>0.1 cm)	9.18: CWM – New York state 2.52: CWM – Massachusetts (Liu et al. 2006) 6.37: FWM – New York (Woodall et al. 2013) 3.67: FWM northern hardwood; 0 to 227.94: Northern USA (Domke et al. 2016)	15.25 (added together DWM and FWM)	Removal may occur due to safety considerations
Litter and duff: depth measured	12: NYC (Pouyat et al. 2002) 9.36: northern hardwood; 0.04: northern USA (Domke et al. 2016)	10.95	Decomposition increases with temperature (Hanson et al. 2003); decreased ozone levels facilitate litter decay (Carreiro et al. 2009)
Mineral soil (organic 30 cm)	104: to 30 cm depth, NYC (Cambou et al. 2018) 50: to 10 cm depth, NYC (Pouyat et al. 2002)	105.11(30 cm) and 77.78 (10 cm)	UHI and pollution alter the litter chemistry, decomposer organisms, conditions, and resources, which all influence respiration rates (Carreiro et al. 2009); earthworms, prevalent in urban areas, accelerate decay, but some carbon is sequestered in passive pools (Pouyat et al. 2002). Soil could be compacted.

8.4.4.2 Benefits of Green Roofs, Green Walls, and Greenways

Green roofs and green walls have potential to mitigate air and surface temperature, improve thermal comfort, and mitigate UHI effects (Jamei et al. 2021; Wong et al. 2021), while lowering the energy demand of buildings (Susca 2019) (Figure 8.18). Green roofs have the highest median cooling effect in dry climates (3°C) and the lowest cooling effect in hot, humid climates (1°C) (Jamei et al. 2021). These mitigation potentials depend on numerous factors and the scale of implementation. The temperature reduction potential for green roofs when compared to conventional roofs can be about 4°C in winter and about 12°C during summer conditions (Bevilacqua et al. 2016). Green roofs can reduce building heating demands by about 10–30% compared to conventional roofs (Besir and Cuce 2018), 60–70% compared to black roofs, and 45–60% compared to white roofs (Silva et al. 2016). Green walls or facades can provide 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 Mediterranean contexts in Europe (Perini et al. 2017). The potential of saving energy for air conditioning by green facades can be around 26% in summer months. Considerations of the spatial context are essential given their dependence on climatic conditions (Susca 2019). Cities are diverse and emissions savings potentials depend on several factors, while the implementation of green roofs or facades may be prevented in heritage structures.

Green roofs have been shown to have beneficial effects in stormwater reduction (Andrés-Doménech et al. 2018). A global meta-analysis of 75 international studies on the potential of green roofs to mitigate runoff indicate that the runoff retention rate was on average 62% but with a wide range (0–100%) depending on a number of interdependent factors (Zheng et al. 2021). These factors relate to the characteristics of the rainfall event (e.g., intensity) and characteristics of the green roof (e.g., substrate, vegetation type, and size), and of the climate and season type. A hydrologic modelling approach applied to an Italian case demonstrated that implementing green roofs may reduce peak runoff rates and water volumes by up to 35% in a 100% green roof conversion scenario (Masseroni and Cislaghi 2016).

Greenways support stormwater management to mitigate water runoff and urban floods by reducing the water volume (e.g., through infiltration) and by an attenuation or temporal shift of water discharge (Fiori and Volpi 2020; Pour et al. 2020). Using green infrastructure delays the time to runoff and reduces water volume but depends on the magnitude of floods (Qin et al. 2013). Measures are most effective for flood mitigation at a local scale; however, as the size of the catchment increases, the effectiveness of reducing peak discharge decreases (Fiori and Volpi 2020). Reduction of water volume through infiltration can be more effective with rainfall events on a lower return rate. Overall, the required capacity for piped engineered systems for water runoff attenuation and mitigation can be reduced while lowering flow rates, controlling pollution transport, and increasing the capacity to store stormwater (Srishantha and Rathnayake 2017). Benefits for flood mitigation require a careful consideration of the spatial context of the urban area, the heterogeneity of the rainfall events, and characteristics of implementation (Qiu et al. 2021). Maintenance costs and stakeholder coordination are other aspects requiring attention (Mguni et al. 2016).

Providing a connected system of greenspace throughout the urban area may promote active transportation (Nieuwenhuijsen and Khreis 2016), thereby reducing GHG emissions. Soft solutions for improving green infrastructure connectivity for cycling is an urban NBS mitigation measure, although there is *low evidence* for emissions reductions. In the city of Lisbon, Portugal, improvements in cycling infrastructure and bike-sharing system resulted in 3.5 times more cyclists within two years (Félix et al. 2020). In Copenhagen, the cost of cycling (0.08 EUR km^{-1}) is declining and is about six times lower than car driving (Euro 0.50/km) (Vedel et al. 2017). In addition, participants were willing to cycle 1.84 km longer if the route has a designated cycle track and 0.8 km more if there are also green surroundings. Changes in urban landscapes, including through the integration of green infrastructure in sustainable urban and transport planning, can support the transition from private motorised transportation to public and physically active transportation in carbon-neutral, more liveable and healthier cities (Nieuwenhuijsen and Khreis 2016; Nieuwenhuijsen 2020). Car infrastructure can be also transferred into public open and green space, such as in the Superblock model in Barcelona's neighbourhoods (Rueda 2019). Health impact assessment models estimated that 681 premature deaths may be prevented annually with this implementation (Mueller et al. 2020) and the creation of greenways in Maanshan, China has stimulated interest in walking or cycling (Zhang et al. 2020).

8.4.5 Socio-behavioural Aspects

Urban systems shape the behaviour and social structures of their residents through urban form, energy systems, and infrastructure – all of which provide a range of options for consumers to make choices about residential location, mobility, energy sources, and the consumption of materials, food, and other resources. The relative availability of options across these sectors has implications on urban emissions through individual behaviour. In turn, urban GHG emissions, as well as emissions from the supply chains of cities, are driven by the behaviour and consumption patterns of residents, with households accounting for over 60% of carbon emissions globally (Ivanova et al. 2016). The exclusion of consumption-based emissions and emissions that occur outside of city boundaries as a result of urban activities, however, will lead to significant undercounting. For example, a study of 79 major cities found that about 41% of consumption-based carbon footprints (1.8 $GtCO_2$-eq of 4.4 $GtCO_2$-eq) occurred outside of city boundaries.

Changes in behaviour across all areas (e.g., transport, buildings, food) could reduce an individual's emissions by 5.6–16.2% relative to the accumulated GHG emissions from 2011 to 2050 in a baseline scenario modelled with the Global Change Assessment Model (van de Ven et al. 2018). In other models, behaviour change in transport and residential energy use could reduce emissions by 2 $GtCO_2$-eq in 2030 compared to 2019 (IEA 2020b) (Chapter 5). Voluntary behaviour change can support emissions reduction, but behaviours that are not convenient to change are unlikely to shift without changes to policy (Sköld et al. 2018). Cities can increase the capability of citizens to make sustainable choices by making these choices less onerous, through avenues such as changing urban form to increase locational and mobility options and providing feedback mechanisms to support socio-behavioural change.

Transport emissions can be reduced by options including telecommuting (0.3%), taking closer holidays (0.5%), avoiding short flights (0.5%), using public transit (0.7%), cycling (0.6%), car sharing (1.1%), and carpool commuting (1.2%); all reduction estimates reflect cumulative per capita emission savings relative to baseline emissions for the period 2011–2050, and assume immediate adoption of behavioural changes (van de Ven et al. 2018). Cities can support voluntary shift to walking, cycling, and transit instead of car use through changes to urban form, such as TOD (Kamruzzaman et al. 2015), increased density of form with co-location of activities (Ma et al. 2015; Ding et al. 2017; Duranton and Turner 2018; Masoumi 2019), and greater intersection density and street integration (Koohsari et al. 2016). Mechanisms such as providing financial incentives or disincentives for car use can also be effective in reducing emissions (Wynes et al. 2018) (Section 8.4.2).

Adopting energy efficient practices in buildings could decrease global building energy demand in 2050 by 33–44% compared to a business-as-usual scenario (Levesque et al. 2019). Reductions in home energy use can be achieved by reducing floor area (0.5–3.0%), utilising more efficient appliances and lighting (2.7–5.0%), optimising thermostat settings (8.3–11%), using efficient heating and cooling technologies (6.7–10%), improving building insulation (2.9–4.0%), optimising clothes washing (5.0–5.7%), and optimising dishwashing (1–1.1%) (Levesque et al. 2019). Building standards and mandates could work towards making these options required or more readily available and accessible. Residential appliance use, water heating, and thermostat settings can be influenced by feedback on energy use, particularly when paired with real-time feedback and/or instructions on how to reduce energy use (Kastner and Stern 2015; Stern et al. 2016; Wynes et al. 2018; Tiefenbeck et al. 2019). The energy-saving potentials of changing occupant behaviour can range between 10% and 25% for residential buildings, and between 5% and 30% for commercial buildings (Zhang et al. 2018). Households are more likely to invest in energy-related home technologies if they believe it financially benefits (rather than disadvantages) them, increases comfort, or will benefit the natural environment (Kastner and Stern 2015). Social influences and availability of funding for household energy measures also support behaviour change (Kastner and Stern 2015).

8.4.5.1 Increasing Locational and Mobility Options

Spatial planning, urban form, and infrastructure can be utilised to deliberately increase both locational and mobility options for socio-behavioural change in support of urban mitigation. The mitigation impacts of active travel can include a reduction of mobility-related lifecycle CO_2 emissions by about 0.5 tonnes over a year when an average person cycles one trip per day more, and drives one trip per day less, for 200 days a year (Brand et al. 2021). Urban areas that develop and implement effective 15/20-minute city programmes are very likely to reduce urban energy use and multiply emission reductions, representing an important cascading effect.

Accessibility as a criterion widens the focus beyond work trips and VKT/VMT, paying attention to a broader set of destinations beyond workplaces, as well as walking and biking trips or active travel. It holds promise for targeting and obtaining greater reductions in GHG emissions in household travel by providing access through walking, biking, and public transit. Accessibility as a criterion for urban form has been embedded in neighbourhood form models since at least the last century and in more recent decades in the 'urban village' concept of the New Urbanism (Duany and Plater-Zyberck 1991) and TODs (Calthorpe 1993). However, accessibility did not gain much traction in urban planning and transportation until the last decade. The experience of cities and metropolitan areas with the COVID-19 pandemic has led to a further resurgence in interest and importance (Handy 2020; Hu et al. 2020), and it is becoming a criterion at the core of the concept of the 15/20-minute city (Moreno et al. 2021; Pozoukidou and Chatziyiannaki 2021). Initially, neighbourhoods have been designed to provide quality, reliable services within 15 or 20 minutes of active transport (i.e., walking or cycling), as well as a variety of housing options and open space (Portland Bureau of Planning and Sustainability 2012; Pozoukidou and Chatziyiannaki 2021; State Government of Victoria 2021). Community life circles strategy for urban areas has also emphasised walking access and health (Weng et al. 2019; Wu et al. 2021). The growing popularity of the 15/20-minute city movement has significant potential for reducing VMT/VKT and associated GHG emissions.

8.4.5.2 Avoiding, Minimising, and Recycling Waste

The waste sector is a significant source of GHG emissions, particularly CH_4 (Gonzalez-Valencia et al. 2016; Nisbet et al. 2019). Currently, the sector remains the largest contributor to urban emissions after the energy sector, even in low-carbon cities (Lu and Li 2019). Since waste management systems are usually under the control of municipal authorities, they are a prime target for city-level mitigation efforts with co-benefits (EC 2015, 2020; Gharfalkar et al. 2015; Herrero and Vilella 2018; Zaman and Ahsan 2019). Despite general agreement on mitigation impacts, quantification remains challenging due to differing assumptions for system boundaries and challenges related to measuring avoided waste (Zaman and Lehmann 2013; Bernstad Saraiva Schott and Cánovas 2015; Matsuda et al. 2018).

The implementation of the waste hierarchy from waste prevention onward, as well as the effectiveness of waste separation at source, involves socio-behavioural options in the context of urban infrastructure (Sun et al. 2018a; Hunter et al. 2019). Managing and treating waste as close to the point of generation as possible, including distributed waste treatment facilities, can minimise transport-related emissions, congestion, and air pollution. Home composting and compact urban form can also reduce waste transport emissions (Oliveira et al. 2017). Decentralised waste management can reinforce source-separation behaviour since the resulting benefits can be more visible (Eisted et al. 2009; Hoornweg and Bhada-Tata 2012; Linzner and Lange 2013). Public acceptance for waste management is greatest when system costs for citizens are reduced, there is greater awareness of primary waste separation at source, and there are positive behavioural spill-overs across environmental policies (Milutinović et al. 2016; Boyer and Ramaswami 2017; Díaz-Villavicencio et al. 2017; Slorach et al. 2020). In addition to the choice of technology, the costs of waste management options depend on the awareness of system users that can represent time-dependent costs (Khan et al. 2016; Chifari et al. 2017; Ranieri et al. 2018; Tomić and Schneider 2020). Waste management systems and the inclusion of materials from multiple urban sectors for alternative by-products can increase scalability (Eriksson et al. 2015; Boyer and Ramaswami 2017; D'Adamo et al. 2021). As a broader concept, circular economy approaches can contribute to managing waste (Box 12.8) with varying emissions impacts (Section 5.3.4).

The generation and composition of waste varies considerably from region to region and city to city. So do the levels of institutional management, infrastructure, and (informal) work in waste disposal activities. Depending on context, policy priorities are directed towards reducing waste generation and transforming waste to energy or other products in a circular economy (Diaz 2017; Ezeudu and Ezeudu 2019; Joshi et al. 2019; Calderón Márquez and Rutkowski 2020; Fatimah et al. 2020). Similarly, waste generation, waste collection coverage, recycling, and composting rates, as well as the means of waste disposal and treatment, differ widely, including the logistics of urban waste management systems. Multiple factors influence waste generation, and regions with similar urbanisation rates can generate different levels of waste per capita (Kaza et al. 2018).

Under conventional practices, municipal solid waste is projected to increase by about 1.4 Gt between 2016 and 2050, reaching 3.4 Gt in 2050 (Kaza et al. 2018). Integrated policymaking can increase the energy, material, and emissions benefits in the waste management sector (Hjalmarsson 2015; Fang et al. 2017; Jiang et al. 2017). Organisational structure and programme administration poses demands for institutional capacity, governance, and cross-sectoral coordination for obtaining the maximum benefit (Hjalmarsson 2015; Kalmykova et al. 2016; Conke 2018; Marino et al. 2018; Yang et al. 2018).

The informal sector plays a critical role in waste management, particularly but not exclusively in developing countries (Linzner and Lange 2013; Dias 2016). Sharing of costs and benefits, and transforming informality of waste recycling activities into programmes, can support distributional effects (Conke 2018; Grové et al. 2018). Balancing centralised and decentralised waste management options along low-carbon objectives can address potential challenges in transforming informality (de Bercegol and Gowda 2019). Overall, the positive impacts of waste management on employment and economic growth can be increased when informality is transformed to stimulate employment opportunities for value-added products with an estimated 45 million jobs in the waste management sector by 2030 (Alzate-Arias et al. 2018; Coalition for Urban Transitions 2020; Soukiazis and Proença 2020).

8.4.6 Urban-Rural Linkages

Urban-rural linkages, especially through waste, food, and water, are prominent elements of the urban system, given that cities are open systems that depend on their hinterlands for imports and exports (Pichler et al. 2017), and include resources, products for industrial production or final use (Section 8.1.6). As supply chains are becoming increasingly global in nature, so are the resource flows with the hinterlands of cities. In addition to measures within the jurisdictional boundaries of cities, cities can influence large upstream emissions through their supply chains, as well as through activities that rely on resources outside city limits. The dual strategy of implementing local actions and taking responsibility for the entire supply chains of imported and exported goods can reduce GHG emissions outside of a city's administrative boundaries (Figure 8.15).

Waste prevention, minimisation, and management provides the potential of alleviating resource usage and upstream emissions from urban settlements (Swilling et al. 2018; Chen et al. 2020a; Harris et al. 2020). Integrated waste management and zero-waste targets can allow urban areas to maximise the mitigation potential while reducing pressures on land use and the environment. This mitigation option reduces emissions due to (i) avoided emissions upstream in the supply chain of materials based on measures for recycling and the reuse of materials; (ii) avoided emissions due to land-use changes as well as emissions that are released into the atmosphere from waste disposal; and (ii) avoided primary energy (see Glossary) spending and emissions. Socio-behavioural change that reduces waste generation, combined with technology and infrastructure according to the waste hierarchy, can be especially effective. The mitigation potential of waste-to-energy depends on the technological choices that are undertaken (e.g., anaerobic digestion of the organic fraction), 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 anaerobic digestion plants can increase when power, heat and/or cold is co-produced (Thanopoulos et al. 2020).

Urban food systems, as well as city-regional production and distribution of food, factors into supply chains. Reducing food demand from urban hinterlands can have a positive impact on energy and water demand for food production (Eigenbrod and Gruda 2015) (see 'food system' in Glossary). 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). Urban governments could also support shifts towards more climate-friendly diets, including through procurement policies. These strategies have created economic opportunities or have enhanced food security while reducing the emissions that are associated with waste and the transportation of food. 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 pursued by both developing and some developed country cities. There is increasing evidence for economically feasible, socially acceptable, and environmentally supportive urban and peri-urban agricultural enterprises although these differ between cities (Brown 2015; Eigenbrod and Gruda 2015; Blay-Palmer et al. 2019; De la Sota et al. 2019). The pathways include integrated crop-livestock systems, urban agroforestry systems, aquaculture-livestock-crop systems, and crop systems (Lwasa et al. 2015), while the mitigation potential of urban and peri-urban agriculture has *medium agreement* and *low evidence*. Strategies for urban food production in cities have also relied on recycling nutrients from urban waste and utilisation of harvested rainwater or wastewater.

Systems for water reallocation between rural areas and urban areas will require change by leveraging technological innovations for water capture, water purification, and reducing water wastage either by plugging leakages or changing behaviour in regard to water use (Eigenbrod and Gruda 2015; Prior et al. 2018). Reducing energy use for urban water systems involves reducing energy requirements for water supply, purification, distribution, and drainage (Ahmad et al. 2020). Various levels of rainwater harvesting in urban settings for supplying end-use water demands or supporting urban food production can reduce municipal water demands, including by up to 20% or more in Cape Town (Fisher-Jeffes et al. 2017).

8.4.7 Cross-sectoral Integration

There are two broad categories of urban mitigation strategies. One is from the perspective of key sectors, including clean energy, sustainable transport, and construction (Rocha et al. 2017; Álvarez Fernández 2018; Magueta et al. 2018; Seo et al. 2018; Waheed et al. 2018); the coupling of these sectors can be enabled through electrification (Section 8.4.3.1). The other looks at the needs for emissions through a more systematic or fundamental understanding of urban design, urban form, and urban spatial planning (Wang et al. 2017; Privitera et al. 2018), and proposes synergistic scenarios for their integration 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 (*high agreement*, *robust evidence*) (Álvarez Fernández 2018; Tarigan and Sagala 2018).

The effects of urban carbon lock-in on land use, energy demand, and emissions vary depending on 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 achieving net-zero GHG emissions as it aims to shorten commuting distances and is able to make use of NBS for energy and resilience (*high agreement*, *medium evidence*). 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 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 lifecycle material-related GHG emissions (UNEP IRP 2020).

The context of urban areas as the nexus of both sectors (i.e., energy, and urban form and planning) 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 strategic densification can increase the GHG reduction potential and lower resource impacts. While resource efficiency measures are estimated to reduce GHG emissions, land use, water consumption, and metal use impacts from a lifecycle assessment perspective by 24–47% over a baseline, combining resource efficiency with strategic 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 indicates 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 is important for accelerating GHG reductions in urban areas (Sethi et al. 2020); this is also important for reducing reliance on carbon capture and storage technologies (CCS) at the global scale (Figures 8.15 and 8.21).

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. 2020c). Although not as prevalent as those for efficiency, municipal administration, and urban planning measures (Hsu et al. 2020c), 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. 2020c). Indeed, single-sector versus cross-sector strategies for 637 cities from a developing country can enable an additional 15–36% contribution to the national climate mitigation reduction potential (Ramaswami et al. 2017a). The strategies at the urban level involved those for energy cascading and exchange of materials that connected waste, heat, and electricity strategies (Section 8.5 and Box 8.4).

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 (Dienst et al. 2015; Maier 2016; Affolderbach and Schulz 2017; Roldán-Fontana et al. 2017; Zhao et al. 2017a; Beygo and Yüzer 2017; Lwasa 2017; Pacheco-Torres et al. 2017; Alhamwi et al. 2018; Kang and Cho 2018; Lin et al. 2018; Collaço et al. 2019) (Figures 8.19 and 8.21, and Section 8.SM.2).

8.5 Governance, Institutions, and Finance

Governance and other institutions act as core components to urban systems by facilitating and managing linkages between different sectors, geographic regions, and stakeholders. This position renders subnational governments and institutions key enablers of climate change mitigation (Seto et al. 2016, 2021; Hsu et al. 2018, 2020c; Vedeld et al. 2021) (Section 8.4.1). Indeed, since AR5 more research has emerged identifying these actors as vehicles through which to accelerate local-to-global efforts to decarbonise (IPCC 2018a; Hsu et al. 2020b; Salvia et al. 2021; Seto et al. 2021) (Chapter 13, Sections 4.2.3, 14.5.5, 15.6.5 and 16.4.7, and 'subnational actors' in Glossary). The current extent (Section 8.3.3) and projected rise (Section 8.3.4.2) in the urban share of global emissions underscores the transformative global impact of supporting urban climate governance and institutions (Section 8.5.2). Further, the multisector approach to mitigation emphasised in this chapter (Sections 8.4

and 8.6, and Figure 8.21) highlights the need for facilitation across sectors (Figure 8.19).

8.5.1 Multi-level Governance

IPCC SR1.5 identified multi-level governance (see Glossary for full definition) as an enabling condition that facilitates systemic transformation consistent with keeping global temperatures below 1.5°C (IPCC 2018a, pp. 18–19). The involvement of governance at multiple levels is necessary to enable cities to plan and implement emissions reductions targets (*high confidence*) (Seto et al. 2021) (Boxes 8.3 and 8.4). Further, regional, national, and international climate goals are most impactful when local governments are involved alongside higher levels, rendering urban areas key foci of climate governance more broadly (*high confidence*) (Fuhr et al. 2018; Kern 2019; Hsu et al. 2020b).

Since AR5, multi-level governance has grown in influence within the literature and has been defined as a framework for understanding the complex interaction of the many players involved in GHG generation and mitigation across geographic scales – the 'vertical' levels 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; Fuhr et al. 2018; Peng and Bai 2018; Kern 2019), as well as the complex linkages between them (Vedeld et al. 2021). This more inclusive understanding of climate governance provides multiple pathways through which urban actors can engage in climate policy to reduce emissions.

8.5.1.1 Multi-level, Multi-player Climate Governance in Practice

A multi-level, multi-player framework highlights both the opportunities and constraints on local autonomy to engage in urban mitigation efforts (Castán Broto 2017b; Fuhr et al. 2018; Vedeld et al. 2021). When multiple actors – national, regional, and urban policymakers, as well as non-state actors and civil society – work together to exploit the opportunities, it leads to the most impactful mitigation gains (Melica et al. 2018). 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. 2020b,a; Seto et al. 2021).

For example, Sections 8.4.3. and 8.4.5 highlight how instigating the electrification of urban energy systems requires a 'layered' approach to policy implementation across different levels of governance (see Section 8.4.3.1 for specific policy mechanisms associated with electrification), with cities playing a key role in setting standards, particularly through mechanisms like building codes (Hsu et al. 2020c; Salvia et al. 2021), as well as through facilitation between stakeholders (e.g., consumers, government, utilities) to advocate for zero-emissions targets (Linton et al. 2021; Seto et al. 2021). Local governments can minimise trade-offs associated with electrification technologies by enabling circular economy practices and opportunities (Pan et al. 2015; Gaustad et al. 2018; Sovacool et al. 2020). These include public-private partnerships between consumers and producers, financial and institutional support, and networking for stakeholders like entrepreneurs, so as to increase accessibility and efficiency of recycling for consumers by providing a clear path from consumer waste back to the producers (Pan et al. 2015; Prendeville et al. 2018; Fratini et al. 2019). Box 8.3 discusses the mitigation benefits of coordination between local and central government in the context of Shanghai's GHG emissions reduction goals.

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 multi-level governance, such as innovation, legitimacy, and institutional fit, as well as the resources, capacity, and knowledge available to subnational technicians and other officials (Widerberg and Pattberg 2015; Valente de Macedo et al. 2016; Green 2017; Roger et al. 2017). 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 (Sections 8.5.4 and 8.5.5).

When sufficient local autonomy is present, local policies have the ability to upscale to higher levels of authority, imparting influence at higher geographic scales. Established urban climate leaders with large institutional capacity can influence small and mid-sized cities, or other 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 (Chan et al. 2015; Kern 2019; Seto et al. 2021) (Section 8.5.3). Increasingly, subnational actors are also influencing their national and international governments through lobbying efforts that call on them to adopt more ambitious climate goals and provide more support for subnational GHG mitigation efforts (Linton et al. 2021; Seto et al. 2021). These dynamics 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 (Section 8.5.3). This phenomenon is recognised in the Paris Agreement, which, for the first time in a multilateral climate treaty, referenced the crucial role subnational and non-state 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 NUA 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, in partnership with private sector representatives and NGOs, who pledged to enact the goals of the Paris Agreement through their own spheres of influence (Cities for Climate 2015). Similar Summits have been held at each subsequent UNFCCC COP (Hsu et al. 2018). Like transnational climate 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 (Cities for Climate 2015; Castán Broto 2017b).

Box 8.3: Coordination of Fragmented Policymaking for Low-carbon Urban Development: Example from Shanghai, China

As a growing megacity in the Global South, Shanghai represents the challenge of becoming low carbon despite its economic growth and population size (Chen et al. 2017). Shanghai was designated as one of the pilot low-carbon cities by the central government. The city utilised a coordination mechanism for joining fragmented policymaking across the city's economy, energy, and environment. The coordination mechanism was supported by a direct fund that enabled implementation of cross-sector policies beyond a single-sector focus across multiple institutions while increasing capacity for enabling a low-carbon transition for urban sustainability (Peng and Bai 2020).

Implementation and governance process

In Shanghai, coordination between the central and local governments had an instrumental role for encouraging low-carbon policy experimentation. Using a nested governance framework, the central government provided target setting and performance evaluation while the local government initiated pilot projects for low-carbon development. The policy practices in Shanghai surpassed the top-down targets and annual reporting of GHG emissions, including carbon labelling standards at the local level, pilot programme for transitioning sub-urban areas, and the engagement of public utilities (Peng and Bai 2018).

Towards low-carbon urban development

New policy measures in Shanghai were built upon a series of related policies from earlier, ranging from general energy saving measures to air pollution reduction. This provided a continuum of policy learning for implementing low-carbon policy measures. An earlier policy was a green electricity scheme based on the Jade Electricity Program while the need for greater public awareness was one aspect requiring further attention in policy design (Baeumler et al. 2012), supporting policy-learning for policies later on. The key point here is that low-carbon policies were built on and learned from earlier policies with similar goals.

Outcomes and impacts of the policy mix

Trends during 1998 and 2015 indicate that energy intensity decreased from about 130 tonnes per million RMB to about 45 tonnes per million RMB and carbon intensity decreased from about 0.35 Mt per billion RMB to 0.10 Mt per billion RMB (Peng and Bai 2018). These impacts on energy and carbon intensities represent progress, while challenges remain. Among the challenges are the need for investment in low-carbon technology and increases in urban carbon sinks (Yang and Li 2018) while cross-sector interaction and complexity are increasing.

8.5.2 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 (UNEP) 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. Non-state action on net-zero GHG or CO_2 emissions continues to be emphasised (UNEP 2021) (Box 8.4). 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 cities in the United States 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 260 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).

Some studies suggest that 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' between emissions trajectories consistent with least-cost scenarios for limiting temperature rise below 1.5°C or 2°C (Blok et al. 2012). In some countries, such as the United States, where national climate policies have been curtailed, the potential for cities' and regions' emissions reduction pledges to make up the country's Nationally Determined Contribution under the Paris Agreement 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 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). 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). 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.

8.5.3 Urban Climate Networks and Transnational Governance

As of 2019, more than 10,000 cities and regions (Hsu et al. 2020a) have recorded participation in a transnational or cooperative climate action network, which are voluntary membership networks of a range of subnational governments such as cities, as well as regional governments like states and provinces (Hsu et al. 2020a). These organisations, often operating across and between national boundaries, entail some type of action on climate change. Among the most prominent climate networks are GCoM, ICLEI, and C40, all of which ask their members to adopt emission reduction commitments, develop climate action plans, and regularly report on emissions inventories.

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, 2020b; Westman and Broto 2018; Kern 2019; Seto et al. 2021). Their impact comes through (i) providing resources for cities and regions to reduce their GHG emissions and improve environmental quality more generally, independent of national policy; (ii) encouraging knowledge transfer between member cities and regions; and (iii) acting 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. In one of the largest studies of subnational climate mitigation action, more than 93% of just over 6000 quantifiable subnational climate commitments come from cities and regions based in the European Union (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 megacities (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 (for more on transnational climate networks and transnational governance more broadly, see Sections 13.5 and 14.5).

Box 8.4: Net-zero Targets and Urban Settlements

Around the world, net-zero-emissions targets, whether economy-wide or targeting a specific sector (e.g., transport, buildings) or emissions scope (e.g., direct scope 1, or both scope 1 and 2), have been adopted by at least 826 cities and 103 regions that represent 11% of the global population with 846 million people across six continents (NewClimate Institute and Data-Driven EnviroLab 2020). In some countries, the share of such cities and regions has reached a critical mass by representing more than 70% of their total populations with or without net-zero-emissions targets at the national level.

In some cases, the scope of these targets extends beyond net-zero emissions from any given sector based on direct emissions (see Glossary) and encompass downstream emissions from a consumption-based perspective with 195 targets that are found to represent economy-wide targets. These commitments range from 'carbon neutrality' (see Glossary) or net-zero GHG emissions targets, which entail near elimination of cities' own direct or electricity-based emissions but could involve some type of carbon offsetting, to more stringent net-zero-emissions goals (Data-Driven EnviroLab and NewClimate Institute 2020) (for related definitions, such as 'carbon neutrality', 'net-zero CO_2 emissions', 'net-zero GHG emissions', and 'offset', see Glossary).

Currently, 43% of the urban areas with net-zero-emissions targets have also put into place related action plans while about 24% have integrated net-zero-emissions 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 600 cities are pursuing 100% renewable energy targets (REN21 2019, 2021) with some cities already achieving it.

Box 8.4 (continued)

The extent of realising and implementing these targets with the collective contribution of urban areas to net-zero-emissions 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. 2020c; Sethi et al. 2020; UNEP IRP 2020). In turn, the transformation of urban systems can significantly impact net-zero-emissions trajectories within mitigation pathways. Institutional capacity, governance, financing, and cross-sector coordination is crucial for enabling and accelerating urban actions for rapid decarbonisation.

8.5.4 Financing Urban Mitigation

Meeting the goals of the Paris Agreement will require fundamental changes that will be most successful when cities work together with provincial and national leadership and legislation, third-sector leadership, transformative action, and supportive financing. Urban governments often obtain their powers from provincial, state and/or national governments, and are subjected to laws and regulations to regulate development and implement infrastructure. In addition, the sources of revenue are often set at these levels so that many urban governments rely on state/provincial and national government funds for improving infrastructure, especially transit infrastructure. The increasing financialisation of urban infrastructures is another factor that can make it more difficult for local governments to determine infrastructure choices (O'Brien et al. 2019). Urban transit system operations, in particular, are heavily subsidised in many countries, both locally and by higher levels of government. 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 multi-level governance responses to ensure meeting decarbonisation targets. The reliance on state and national policy and/or funding can accelerate or impede the decarbonisation of urban environments (McCarney et al. 2011; McCarney 2019).

The world's infrastructure spending is expected to more than double from 2015 to 2030 under a low-carbon and climate-resilient scenario. More than 70% of the infrastructure will concentrate in urban areas by requiring USD4.5–5.4 trillion per year (CCFLA 2015). However, today's climate finance flows for cities or 'urban climate finance', estimated at USD384 billion annually on average in 2017/18, are insufficient to meet the USD4.5–5.4 trillion annual investment needs for urban mitigation actions across key sectors (CCFLA 2015; CPI and World Bank 2021; Negreiros et al. 2021). Low-carbon urban form (e.g., compact, high-density, and mixed-use characteristics) 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 (*medium evidence*, *high agreement*) (Global Commission on the Economy and Climate 2014; Foxon et al. 2015; Bhattacharya et al. 2016; Floater et al. 2017; Colenbrander et al. 2018b).

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. During the COVID-19 pandemic, cities tend to rely more on intergovernmental transfers in the form of stimulus packages for economic recovery. Nonetheless, the risk of high carbon lock-ins is likely to increase in rapidly growing cities if long-term urban mitigation strategies are not incorporated into short-term economic recovery actions (Granoff et al. 2016; Floater et al. 2017; Colenbrander et al. 2018b; CPI and World Bank 2021; Negreiros et al. 2021). Indeed, large and complex infrastructure projects for urban mitigation are often beyond the capacity of both national government and local municipality budgets. Additionally, the COVID-19 pandemic necessitates large government expenditures for public health programme and decimates municipal revenue sources for urban infrastructure projects in cities.

To meet the multi-trillion-dollar annual investment needs in urban areas, cities in partnership with international institutions, national governments, and local stakeholders increasingly play a pivotal role in mobilising global climate finance resources for a range of low-carbon infrastructure projects and related urban land use and spatial planning programmes across key sectors (*high confidence*). In particular, national governments are expected to set up enabling conditions for the mobilisation of urban climate finance resource 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. 2018b; Zhan and de Jong 2018; Hadfield and Cook 2019; CPI and World Bank 2021; Negreiros et al. 2021).

Indeed, 75% of the global climate finance for both mitigation and adaptation in 2017 and 2018 took the form of commercial financing (e.g., balance sheets, commercial-rate loans, equity), while 25% came in 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 gaining access to international credit markets. Cities without international creditworthiness currently rely on local sources, including domestic commercial banks (*medium evidence*, *high agreement*) (Global Commission on the Economy and Climate 2014; CCFLA 2015; Floater et al. 2017; Buchner et al. 2019).

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 other various climate mitigation projects across the global regions since 2013. The world's green bond market reached USD1 trillion in cumulative issuance, with issuance of USD280 billion in 2020, during the

COVID-19 pandemic. While green municipal bonds still account for a small share of the whole green bond market in 2020, scale is predicted to grow further in emerging markets over the coming years. Green municipal bonds have great potential for cities to expand and 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, planning and design, and operation. Indeed, the demand for green bonds presently outstrips supply as being constantly over-subscribed (*robust evidence*, *high agreement*) (Global Commission on the Economy and Climate 2014; Saha and D'Almeida 2017; Amundi and IFC 2021).

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 ongoing 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 programme 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 are likely to reduce the default risk for investors through portfolio diversification and create robust pipelines for a bundle of small-scale projects (Granoff et al. 2016; Floater et al. 2017; Saha and D'Almeida 2017).

In principle, the upfront capital costs of various low-carbon infrastructure projects, including the costs of urban climate finance (dividend and interest payments), are eventually transferred to users and other stakeholders in the forms of taxes, charges, fees, and other revenue sources. Nevertheless, small cities in developing countries are likely to have a small revenue base, most of which is committed to recurring 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. 2018b; Zhan and de Jong 2018; Zhan et al. 2018a).

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 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 low-density urban expansion 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 the application of green building technologies (*robust evidence*, *high agreement*) (Suzuki et al. 2015; Floater et al. 2017; Colenbrander et al. 2018b).

For the implementation of land-based funding, property rights are essential. However, weak urban-rural 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 is expected to 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 P2P basis without centralised intermediate parties and produce land-based funding opportunities for low-carbon infrastructure and real estate development district-wide and city-wide in unconventional ways (Veuger 2017; Nasarre-Aznar 2018).

The consolidation of local transaction records into national or supranational registries is likely to support large-scale land formalisation, but most pilot programmes 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, compactness, and land-use mixture, to disincentivise urban expansion and emissions growth around city-fringe locations (*medium confidence*) (Allam and Jones 2019).

8.5.5 Barriers and Enablers for Implementation

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). In some cases, these private interests are tied up with international flows of capital. 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).

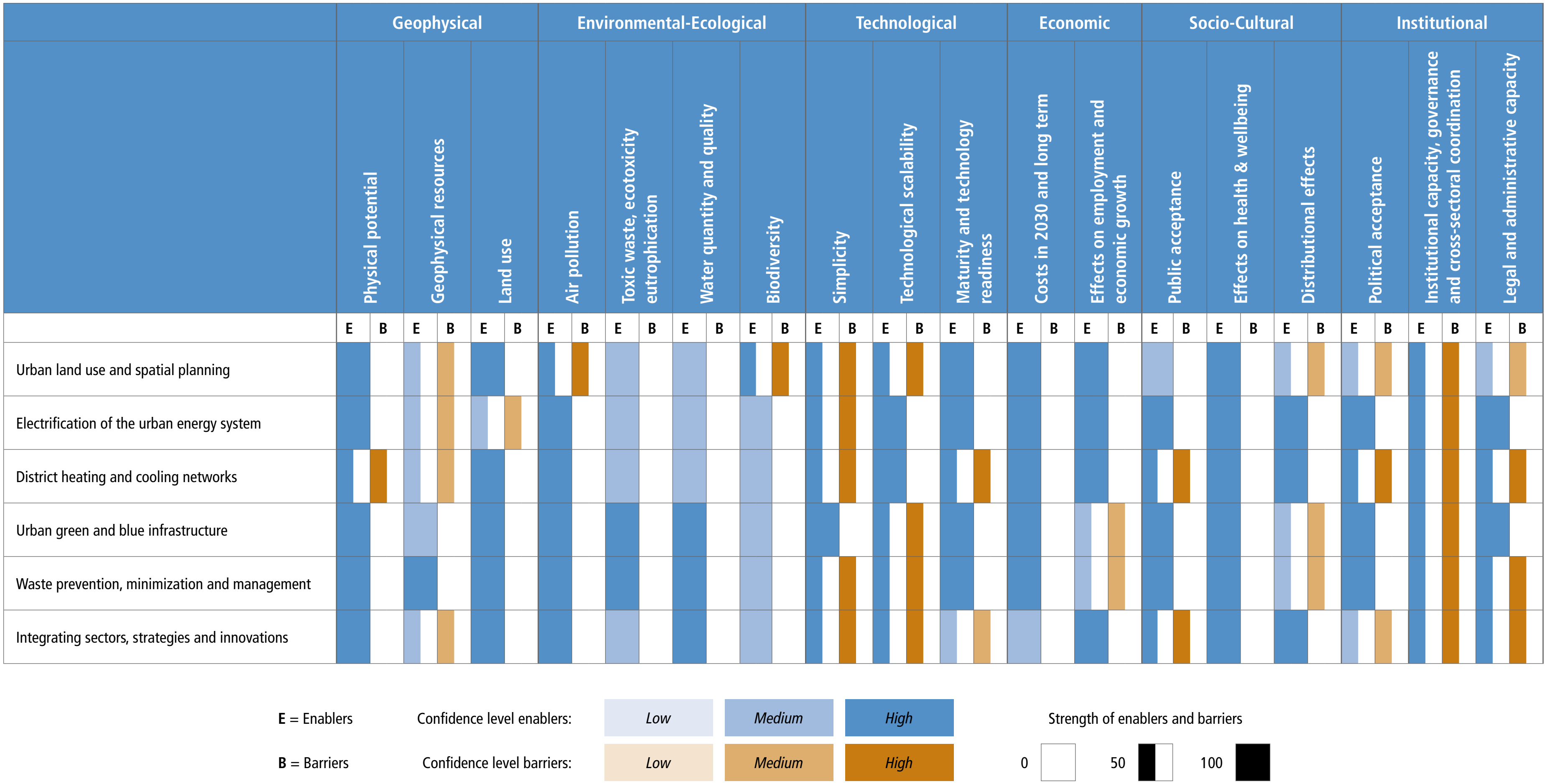
Yet urban mitigation options that can be implemented to transform urban systems involve the interplay of multiple enablers and barriers. Based on a framework for assessing feasibility from a multi-dimensional perspective, feasibility is malleable and various enablers can be brought into play to increase the implementation of mitigation options. The scope of this assessment enables an approach for considering multiple aspects that have an impact on feasibility as a tool for policy support (Singh et al. 2020). In Figure 8.19, the assessment framework that is based on geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions is applied to identify the enablers and/or barriers in implementing mitigation options in urban systems. The feasibility of options may differ across context, time, and scale (Section 8.SM.2). The line of sight upon which the assessment is based includes urban case studies (Lamb et al. 2019) and assessments of land use and spatial planning in IPCC SR1.5 (IPCC 2018a).

Across the enablers and barriers of different mitigation options, urban land use and spatial planning for increasing co-located densities in urban areas has positive impacts in multiple indicators, particularly reducing land use and preserving carbon sinks when the growth in urban extent is reduced and avoided, which if brought into interplay in decision-making, can support the enablers for its implementation. Improvements in air quality are possible when higher urban densities are combined with modes of active transport, electrified mobility as well as urban green and blue infrastructure (Sections 8.3.4, 8.4 and 8.6). The demands on geophysical resources, including materials for urban development, will depend on whether additional strategies are in place with largely negative impacts under conventional practices. The technological scalability of multiple urban mitigation options is favourable while varying according to the level of existing urban development and scale of implementation (Tables 8.SM.3 and 8.SM.4).

Similarly, multiple mitigation options have positive impacts on employment and economic growth, especially when urban densities enable productivity. Possible distributional effects, including availability of affordable accommodation and access to greenspace, are best addressed when urban policy packages combine more than one policy objective. Such an approach can provide greater support to urban mitigation efforts with progress towards shifting urban development to sustainability. The electrification of the urban energy system involves multiple enablers that support the feasibility of this mitigation option, including positive impacts on health and well-being. In addition, increases in urban densities can support the planning of district heating and cooling networks that can decarbonize the built environment at scale with technology readiness levels increasing for lower temperature supply options. Preventing, minimising, and managing waste as an urban mitigation option can be enabled when informality in the sector is transformed to secure employment effects and value-addition based on the more circular use of resources (Sections 8.4.3 and 8.4.5, and Tables 8.SM.3 and 8.SM.4 in Supplementary Material 8.2).

As a combined evaluation, integrating multiple mitigation options in urban systems involves the greatest requirement for strengthening institutional capacity and governance through cross-sectoral coordination. Notably, integrated action requires significant effort to coordinate sectors and strategies across urban growth typologies (Sections 8.4 and 8.6, and Figure 8.21). Institutional capacity, if not strengthened to a suitable level to handle this process – especially to break out of carbon lock-in – can fall short of the efforts this entails. These conditions can pose barriers for realising cross-sectoral coordination while the formation of partnerships and stakeholder engagement take place as important enablers. Overcoming institutional challenges for cross-sectoral coordination can support realising synergies among the benefits that each mitigation option can offer within and across urban systems, including for the SDGs. These include those that can be involved in co-located and walkable urban form together with decarbonising and electrifying the urban energy system as well as urban green and blue infrastructure, providing the basis for more liveable, resource efficient and compact urban development with benefits for urban inhabitants (Section 8.2).

Figure 8.19: Feasibility assessment based on the enablers and barriers of implementing mitigation options for urban systems across multiple dimensions. The figure summarises the extent to which different factors would enable or inhibit the deployment of mitigation options in urban systems. These factors are assessed systematically based on 18 indicators in 6 dimensions (geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions). Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Supplementary Material 8.SM.2 provides an overview of the extent to which the feasibility of options may differ across context, time and scale of implementation (Table 8.SM.3) and includes line of sight upon which the assessment is based (Table 8.SM.4). The line of sight builds upon urban case studies in (Lamb et al. 2019) and assessments for land use and urban planning (IPCC 2018a) involving 414 references. The assessment method is further explained in Annex II, Section 11.



8.6 A Roadmap for Integrating Mitigation Strategies for Different Urbanisation Typologies

The most effective and appropriate packages of mitigation strategies will vary depending on several dimensions of a city. This section brings together the urban mitigation options described in Section 8.4 and assesses the range of mitigation potentials for different types of cities. There is consensus in the literature that mitigation strategies are most effective when multiple interventions are coupled together. Urban-scale interventions that implement multiple strategies concurrently through policy packages are more effective and have greater emissions savings than when single interventions are implemented separately. This is because a city-wide strategy can have cascading effects across sectors, that have multiplicative effects on GHG emissions reduction within and outside a city's administrative boundaries. Therefore, city-scale strategies can reduce more emissions than the net sum of individual interventions, particularly if multiple scales of governance are included (Sections 8.4 and 8.5). Furthermore, cities have the ability to implement policy packages across sectors using an urban systems approach, such as through planning, particularly those that affect key infrastructures (Figures 8.15, 8.17 and 8.22).

The way that cities are laid out and built will shape the entry points for realising systemic transformation across urban form and infrastructure, energy systems, and supply chains. Section 8.3.1 discusses the ongoing trend of rapid urbanisation – and how it varies through different forms of urban development or 'typologies' (Figure 8.6). Below, Figure 8.20 distils the typologies of urban growth across three categories: emerging, rapidly growing, and established. Urban growth is relatively stabilised in established urban areas with mature urban form while newly taking shape in emerging urban areas. In contrast, rapidly growing urban areas experience pronounced changes in outward and/or upward growth. These typologies are not mutually exclusive, and can co-exist within an urban system; cities typically encompass a spectrum of development, with multiple types of urban form and various typologies (Mahtta et al. 2019).

Taken together, urban form (Figure 8.16) and growth typology (Figure 8.20) can act as a roadmap for cities or sub-city communities looking to identify their urban context and, by extension, the mitigation opportunities with the greatest potential to reduce GHG emissions. Specifically, this considers whether a city is established with existing and managed infrastructure; rapidly growing with new and actively developing infrastructure; or emerging with large amounts of infrastructure build-up. The long lifespan of urban infrastructure locks in behaviour and committed emissions. Therefore, the sequencing of mitigation strategies is important for determining emissions savings in the short and long term. Hence, different types of cities will have different mitigation pathways, depending upon a city's urban form and state of that city's urban development and infrastructure; the policy packages and implementation plan that provide the highest mitigation potential for rapidly growing cities with new infrastructures will differ from those for established cities with existing infrastructure.

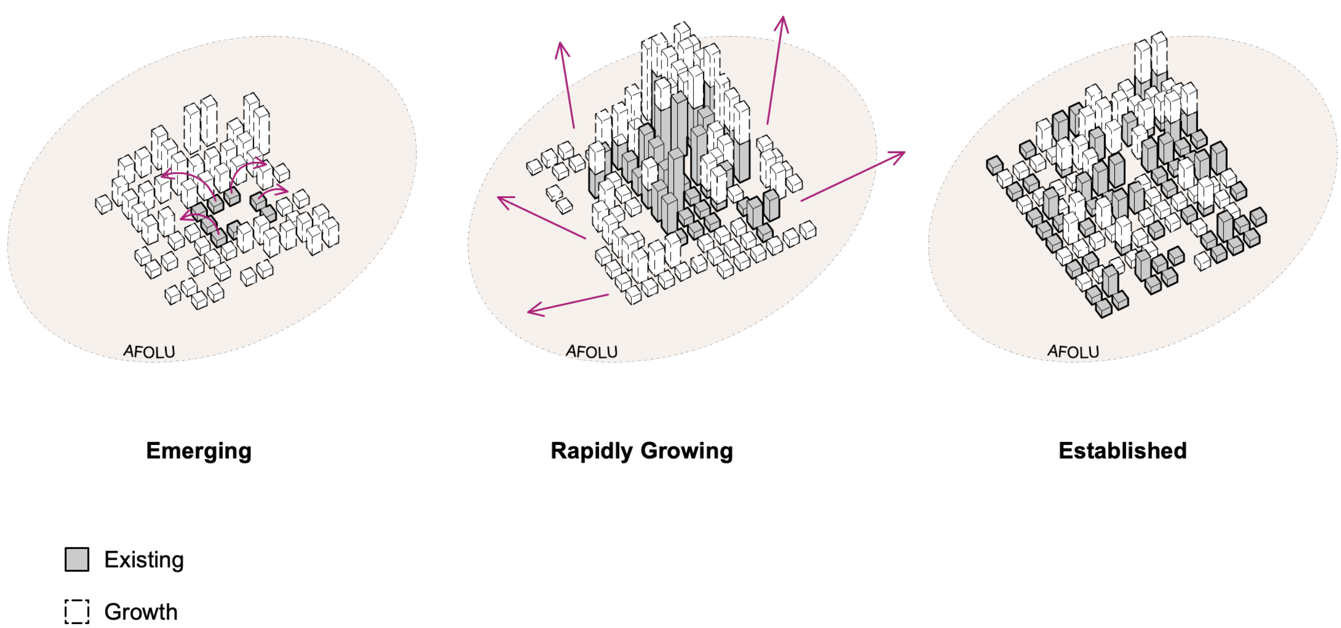


Figure 8.20: Urban growth typologies define the main patterns of urban development. Emerging urban areas are undergoing the buildup of new infrastructure. These are new urban areas that are budding out. Rapidly growing urban areas are undergoing significant changes in either outward and/or upward growth, accompanied by large-scale development of new urban infrastructure. Established urban areas are relatively stable with mature urban form and existing urban infrastructures. Each of these typologies represents different levels of economic development and state of urbanisation. Rapidly growing urban areas that are building up through vertical development are often those with higher levels of economic development. Rapidly growing urban areas that are building outward through horizontal expansion are found at lower levels of economic development and are land intensive. Like with urban form, different areas of a single city can undergo different growth typologies. Therefore a city will be comprised of multiple urban growth typologies. Source: synthesized from Mahtta et al. (2019) and Lall et al. (2021).

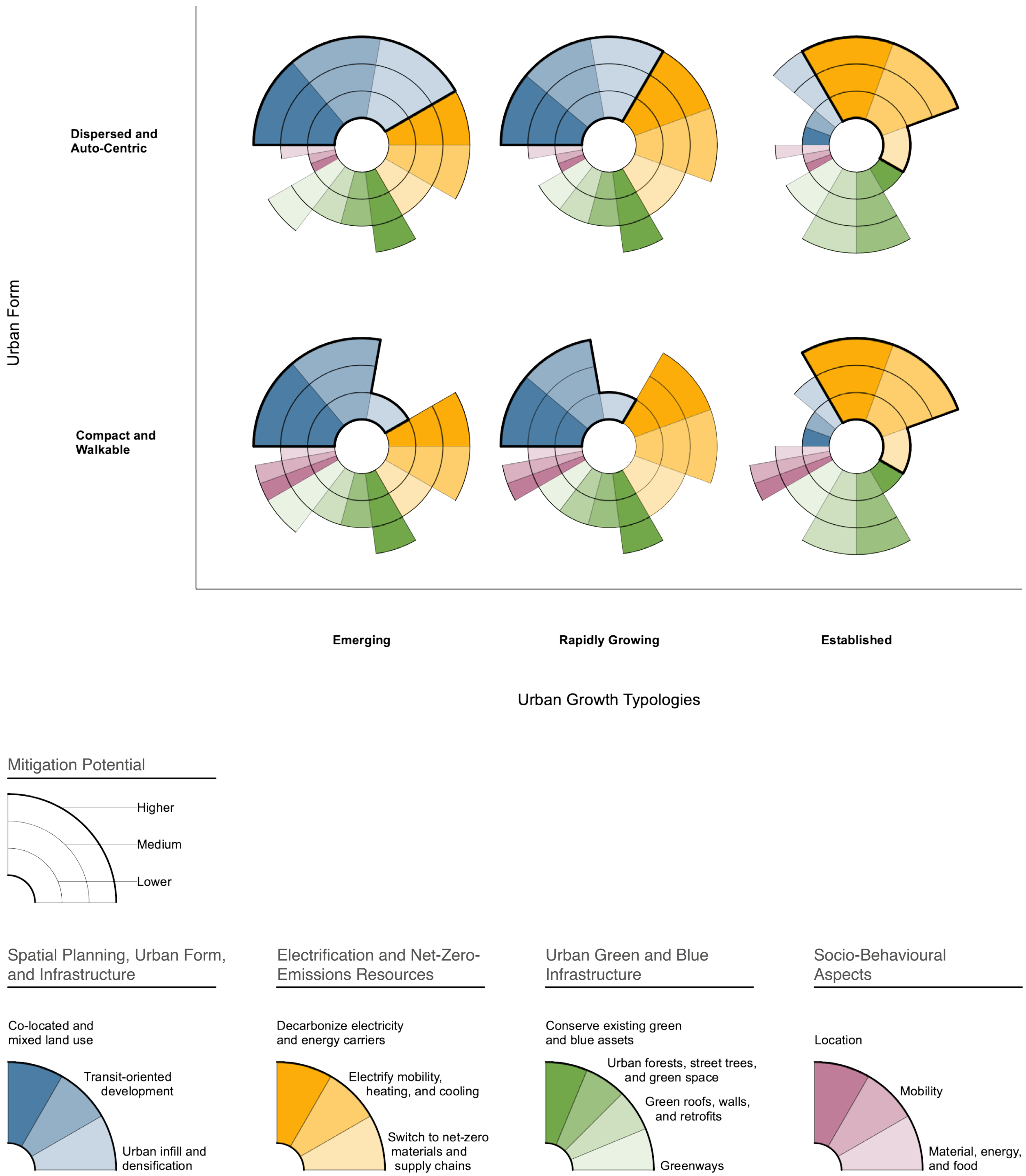


Figure 8.21: Priorities and potentials for packages of urban mitigation strategies across typologies of urban growth (Figure 8.20) and urban form (Figure 8.16). The horizontal axis represents urban growth typologies based on emerging, rapidly growing, and established urban areas. The vertical axis shows the continuum of urban form, from compact and walkable, to dispersed and auto-centric. Urban areas can first locate their relative positioning in this space according to their predominant style of urban growth and urban form. The urban mitigation options are bundled across four broad sectors of mitigation strategies: (i) spatial planning, urban form, and infrastructure (blue); (ii) electrification and net-zero-emissions resources (yellow); (iii) urban green and blue infrastructure (green); and (iv) socio-behavioural aspects (purple). The concentric circles indicate lower, medium, and higher mitigation potential considering the context of the urban area. For each city type (circular graphic) the illustrative urban mitigation strategy that is considered to provide the greatest cascading effects across mitigation opportunities is represented by a section that is larger relative to others; those strategy sections outlined in black are 'entry points' for sequencing of strategies. Within each of the larger strategy sections (i.e., spatial planning, urban green and blue infrastructure, etc.), the size of the sub-strategy sections are equal and do not suggest any priority or sequencing. The relative sizes of the strategies and extent of mitigation potential are illustrative and based on the authors' best understanding and assessment of the literature.

Mitigation options that involve spatial planning, urban form, and infrastructure – particularly co-located and mixed land use, as well as TOD – provide the greatest opportunities when urban areas are rapidly growing or emerging (Section 8.4.2). Established urban areas that are already compact and walkable have captured mitigation benefits from these illustrative strategies to various extents. Conversely, established urban areas that are dispersed and auto-centric have foregone these opportunities, with the exception of urban infill and densification that can be used to transform or continue to transform the existing urban form. Figure 8.21 underscores that urban mitigation options and illustrative strategies differ by urban growth typologies and urban form. Cities can identify their entry points for sequencing mitigation strategies.

The emissions reduction potential of urban mitigation options further varies based on governance contexts, institutional capacity, and economic structure, as well as human and physical geography. According to the development level, for instance, urban form can remain mostly planned or unplanned, taking place spontaneously, with persistent urban infrastructure gaps remaining (Lwasa et al. 2018; Kareem et al. 2020). Measures for closing the urban infrastructure gap while addressing 'leapfrogging' opportunities (see Glossary) for mitigation and providing co-benefits represent possibilities for shifting development paths for sustainability (Cross-Chapter Box 5 in Chapter 4).

8.6.1 Mitigation Opportunities for *Established* Cities

Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, encouraging modal shift, electrifying the urban energy system, as well as infilling and densifying urban areas.

Shifting pathways to low-carbon development for established cities with existing infrastructures and locked-in behaviours and lifestyles is admittedly challenging. Urban infrastructures such as buildings, roads, and pipelines often have long lifetimes that lock-in emissions, as well as institutional and individual behaviour. Although the expected lifetime of buildings varies considerably by geography, design, and materials, typical lifespans are at minimum 30 years to more than 100 years.

Cities where urban infrastructure has already been built have opportunities to increase energy efficiency measures, prioritise compact and mixed-use neighbourhoods through urban regeneration, advance the urban energy system through electrification, undertake cross-sector synergies, integrate urban green and blue infrastructure, 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 system. Retrofitting buildings with state of the art deep-energy retrofit measures could reduce emissions of the existing stock by about 30–60% (Creutzig et al. 2016a) and in some cases up to 80% (Ürge-Vorsatz et al. 2020) (Section 8.4.3).

Established cities that are compact and walkable are likely to have low per capita emissions, and thus can keep emissions low by focusing on electrification of all urban energy services and using urban green and blue infrastructure to sequester and store carbon while reducing urban heat stress. Illustrative mitigation strategies with the highest mitigation potential are decarbonising electricity and energy carriers while electrifying mobility, heating, and cooling (Table 8.3 and Figure 8.19). Within integrated strategies, the importance of urban forests, street trees, and green space as well as green roofs, walls, and retrofits, also have high mitigation potential (Section 8.4.4 and Figure 8.18).

Established cities that are dispersed and auto-centric are likely to have higher per capita emissions and thus can reduce emissions by focusing on creating modal shift and improving public transit systems in order to reduce urban transport emissions, as well as focusing on infilling and densifying. Only then can the urban form constraints on locational and mobility options be effective at reducing transport-based emissions. Among mitigation options based on spatial planning, urban form, and infrastructure, urban infill and densification has priority. For these cities, the use of urban green and blue infrastructure will be essential to offset residual emissions that cannot be reduced because their urban form is already established and difficult to change.

System-wide energy savings and emissions reductions for low-carbon urban development are 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). Such actions include guiding residential living area per capita, limiting private vehicle growth, expanding public transport, improving the efficiency of urban infrastructure, enhancing urban carbon pools, and minimising waste through sustainable, ideally circular, waste management (Lin et al. 2018). Through a coordinated approach, urban areas can be transformed into hubs for renewable and distributed energy, sustainable mobility, as well as inclusivity and health (Newman et al. 2017; Newman 2020).

Urban design for existing urban areas includes strategies for urban energy transitions for carbon neutrality based on renewable energy, district heating for the city centre and suburbs, as well as green and blue interfaces (Pulselli et al. 2021). Integrated modelling approaches for urban energy system planning, including land use and transport and flexible demand-side options, is increased when municipal actors are also recognised as energy planners (Yazdanie and Orehounig 2021) (Section 8.4.3). Enablers for action can include the co-design of infill residential development through an inclusive and participatory process with citizen utilities and disruptive innovation that can support net-zero-carbon power while contributing to 1.5°C pathways, the SDGs, and affordable housing simultaneously (Wiktorowicz et al. 2018). Cross-sectoral strategies for established cities, including those taking place among 120 urban areas, also involve opportunities for sustainable development (Kılkış 2019, 2021b).

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 remain within planetary boundaries while being inclusive of the urban poor (Friend et al. 2016). At the urban policy level, an analysis of 12,000 measures in urban-level monitoring emissions inventories based on the mode of governance further suggests that local authorities with lower population have primarily 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. 2020b). Policies that relate to education and enabling were uniformly adopted regardless of population size (Palermo et al. 2020b). Multi-disciplinary teams, including urban planners, engineers, architects, and environmental institutions, can support local decision-making capacities, including for increasing energy efficiency and renewable energy considering building intensity and energy use (Mrówczyńska et al. 2021) (Section 8.5).

8.6.2 Mitigation Opportunities for *Rapidly Growing* Cities

Rapidly growing cities with new and actively developing infrastructures can avoid higher future emissions through using urban planning to co-locate jobs and housing, and achieve compact urban form; leapfrogging to low-carbon technologies; electrifying all urban services, including transportation, cooling, heating, cooking, recycling, water extraction, wastewater recycling, and so on; and preserving and managing existing green and blue assets.

Rapidly growing cities have significant opportunities for integrating climate mitigation response options in earlier stages of urban development, which can provide even greater opportunities for avoiding carbon lock-in and shifting pathways towards net-zero GHG emissions. In growing cities that are expected to experience large increases in population, a significant share of urban development remains to be planned and built. The ability to shift these investments towards low-carbon development earlier in the process represents an important opportunity for contributing to net-zero GHG emissions at the global scale. In particular, evidence suggests that investment in low-carbon development measures and reinvestment 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 cities in 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 informal settlement clearance (Teferi and Newman 2018). Scalable options for decentralised energy, water, and wastewater systems, as well as spatial planning and urban agriculture and forestry, are applicable to urban settlements across multiple regions simultaneously (Lwasa 2017).

Rapidly urbanising areas can experience pressure for rapid growth in urban infrastructure to address growth in population. This challenge can be addressed with coordinated urban planning and support from enabling conditions for pursuing effective climate mitigation (Section 8.5 and Box 8.3). The ability to mobilise low-carbon development will also increase opportunities for capturing co-benefits for urban inhabitants while reducing embodied and operational emissions. Transforming urban growth, including its impacts on energy and materials, can be carefully addressed with the integration of cross-sectoral strategies and policies.

Rapidly growing cities have entry points into an integrated strategy based on spatial planning, urban form and infrastructure (Figure 8.21). For rapidly growing cities that may be co-located and walkable at present, remaining compact is better ensured when co-location and mixed land use, as well as TOD, continues to be prioritised (Section 8.4.2). Concurrently, ensuring that electricity and energy carriers are decarbonised while electrifying mobility, heating and cooling will support the mitigation potential of these cities. Along with an integrated approach across other illustrative strategies, switching to net-zero materials and supply chains holds importance (Section 8.4.3). Cities that remain compact and walkable can provide a greater array of locational and mobility options to the inhabitants that can be adopted for mitigation benefits. Rapidly growing cities that may currently be dispersed and auto-centric can capture high mitigation potential through urban infill and densification. Conserving existing green and blue assets, thereby protecting sources of carbon storage and sequestration, as well as biodiversity, have high potential for both kinds of existing urban form, especially when the rapid growth can be controlled.

8.6.3 Mitigation Opportunities for *New and Emerging* Cities

New and emerging cities have unparalleled potential to become low- or net-zero-emissions urban areas while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and TOD, that also preserve existing green and blue assets.

The fundamental building blocks that make up the physical attributes of cities, such as the layout of streets, the size of the city blocks, the location of where people live versus where they work, can affect and lock in energy demand for long time periods (Seto et al. 2016)

(Section 8.4.1). A large share of urban infrastructures that will be in place by 2050 has yet to be constructed and their design and implementation will determine both future GHG emissions as well as the ability to meet mitigation goals (Creutzig et al. 2016a) (Figure 8.10 and Table 8.1). Thus, there are tremendous opportunities for new and emerging cities to be designed and constructed to be low-emissions while providing high quality of life for their populations.

The UN International Resource Panel (IRP) estimates that building future cities under conventional practices 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 and emerging cities 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.

Minimising and avoiding raw material demands depends on alternative options while accommodating the urban population. In addition, operational emissions that can be committed by new urban infrastructure can range between 8.5 $GtCO_2$ and 14 $GtCO_2$ annually up to 2030 (Erickson and Tempest 2015). Buildings and road networks are strongly influenced by urban layouts, densities, and specific uses. Cities that are planned and built much differently than today through light-weighting, material substitution, resource efficiency, renewable energy, and compact urban form, have the potential to support more sustainable urbanisation and provide co-benefits for inhabitants (Figures 8.17 and 8.22).

In this context, illustrative mitigation strategies that can serve as a roadmap for emerging cities includes priorities for co-located and mixed land use, as well as TOD, within an integrated approach (Table 8.3 and Figure 8.19). This has cascading effects, including conserving existing green and blue assets (e.g., forests, grasslands, wetlands), many of which sequester and store carbon. Priorities for decarbonising electricity and energy carriers while electrifying mobility, heating, and cooling take place within the integrated approach (Section 8.4.3). Increasing greenways and permeable surfaces, especially from the design of emerging urban areas onward, can be pursued, also for adaptation co-benefits and linkages with the SDGs (Section 8.4.4 and Figure 8.18).

In low-energy-driven 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, such as the use of solar gain for space heating, or of thermal mass to moderate indoor temperatures, 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 net-zero CO_2 or net-zero GHG emissions, as well as renewable energy targets, in mind. Energy master planning of urban areas that initially target net-zero operational GHG emissions can be supported with energy master planning from conceptual design to operation, including district-scale energy strategies (Charani Shandiz et al. 2021).

Raw material demands and committed emissions from building urban areas

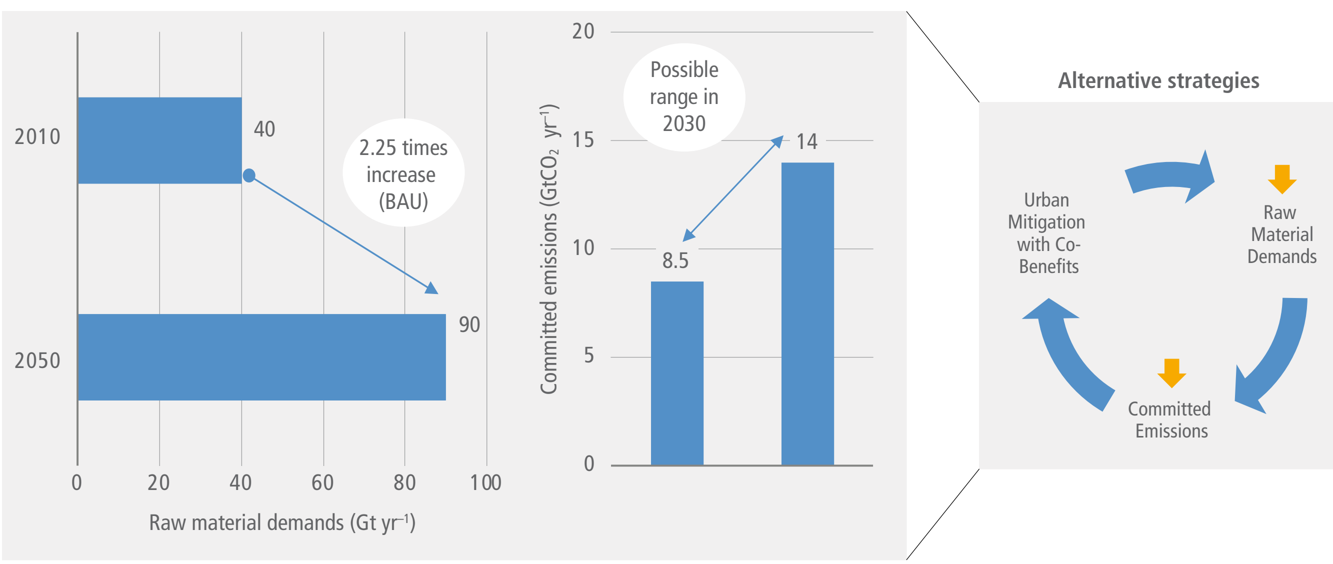


Figure 8.22: Raw material demands and committed emissions from building urban areas. The horizontal bars represent the projected increase in raw material demands in the year 2050. The vertical bars represent the possible range of committed CO_2 emissions in 2030. The importance of alternative solutions to reduce raw material demands and committed emissions while increasing co-benefits is represented by the circular process on the right-hand side. Ranges for committed emissions from new urban infrastructure are based on Erickson and Tempest (2015) SEI WP 11. Source: drawn using data from Erickson and Tempest (2015) and Swilling et al. (2018).

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' (see Glossary), 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).

To minimise carbon footprints, new cities can utilise new intelligence functions as well as changes in energy sources and material processes. Core design strategies of a compact city can be facilitated by data-driven decision-making so that new urban intelligence functions are holistic and proactive rather than reactive (Bibri 2020). In mainstream practices, for example, many cities use environmental impact reviews to identify potentially negative consequences of individual development projects on environmental conditions on a piecemeal project basis.

New cities can utilise: system-wide analyses of construction materials, or renewable power sources, that minimise ecosystem disruption and energy use, through the use of lifecycle 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 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 UHI phenomena, 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 lifecycle 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 cities (Müller et al. 2013; Carpio et al. 2016; Liu et al. 2016a; Ramage et al. 2017; Shi et al. 2017a; Stocchero et al. 2017; Bai et al. 2018; Zhan et al. 2018b; Swilling et al. 2018; Xu et al. 2018b; UNEP IRP 2020) (Figure 8.17). The capacity to implement relevant policy instruments in an integrated and coordinated manner within a policy mix while leveraging multi-level support as relevant can increase the enabling conditions for urban system transformation (Agyepong and Nhamo 2017; Roppongi et al. 2017).

The integration of urban land use and spatial planning, electrification of urban energy systems, renewable energy district heating and cooling networks, urban green and blue infrastructure, and circular economy can also have positive impacts on improving air and environmental quality with related co-benefits for health and well-being (Diallo et al. 2016; Nieuwenhuijsen and Khreis 2016; Shakya 2016; Liu et al. 2017; Ramaswami et al. 2017a; Sun et al. 2018b; Tayarani et al. 2018; Park and Sener 2019; González-García et al. 2021). Low-carbon development options can 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 to enhance 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).

There are readily available solutions for low-carbon urban development that can be further supported by new and emerging ones, such as tools 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 reinvestment 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; Brozynski and Leibowicz 2018).

Low-carbon urban development that triggers economic decoupling can 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) (Section 8.2).

Information and communications technologies can play an important role for integrating mitigation options at the urban systems level for achieving zero-carbon cities. Planning for decarbonisation at the urban systems level involves integrated considerations of the interaction among sectors, including synergies and trade-offs among households, businesses, transport, land use, and lifestyles. The utilisation of big data, artificial intelligence and internet of things (IoT) technologies can be used to plan, evaluate and integrate rapidly progressing transport and building technologies, such as autonomous EVs, zero-energy buildings, and districts as an urban system, including energy-driven urban design (Creutzig et al. 2020; Yamagata et al. 2020). Community-level energy sharing systems will contribute to realising the decarbonisation potential of urban systems at community scale, including in smart cities (Section 4.2.5.9, Box 10.1, and Cross-Chapter Box 11 in Chapter 16).

8.7 Knowledge Gaps

While there is growing literature on urban NBS, which encompasses urban green and blue infrastructure in cities, there is still a knowledge gap regarding 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. In moving forward with the research agenda on cities and climate change science, transformation of urban systems will be critical; however, understanding this transformation and how best to assess mitigation action remain key knowledge gaps (Butcher-Gollach 2018; Pathak and Mahadevia 2018; Rigolon et al. 2018; Anguelovski et al. 2019; Buyana et al. 2019; Trundle 2020; Azunre et al. 2021).

There is a key knowledge gap in respect to the potential of the 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

The COVID-19 pandemic has disrupted many aspects of urban life while raising 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 last into the future. The science is unclear as to the links between urban characteristics and COVID-19, and involves multiple aspects. For example, some research shows higher COVID-19 infection rates with city size (e.g., Dalziel et al. 2018; Stier et al. 2021), 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 for metropolitan population.

Densely populated 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 address 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. 2020b), while urban areas with cleaner air from clean energy and greenspace, can provide advantages.

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; Maroko et al. 2020; Lamb et al. 2021). The evidence for the connection between household crowding and the risk of contagion from infectious diseases is also strong. A 2018 World Health Organization (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).

Though preliminary, some studies suggest that urban areas saw larger overall declines in emissions because of lower commuter activity and associated emissions. For example, researchers have explored the COVID-19 impact in the cities of Los Angeles, Baltimore, Washington, DC, and San Francisco Bay Area in the United States. 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 2020 compared to previous years (Yadav et al. 2021).

At the global scale COVID-related lockdown and travel restrictions reduced daily CO_2 emissions by –17% in early April 2020 compared to 2019 values (Le Quéré et al. 2020; Liu et al. 2020b), though subsequent studies have questioned the accuracy of the indirect proxy data used (Oda et al. 2021). Research at the national scale in the United States found that daily CO_2 emissions declined –15% during the late March to early June time period (Gillingham et al. 2020). Research in China estimated that the first quarter of 2020 saw an 11.5% decline in CO_2 emissions relative to 2019 (Zheng et al. 2020; Han et al. 2021). In Europe, estimates indicated a –12.5% decline in the first half of 2020 compared to 2019 (Andreoni 2021). Rebound to pre-COVID trajectories has been evidenced following the ease of travel restrictions (Le Quéré et al. 2021). It remains unclear to what extent COVID resulted in any structural change in the underlying drivers of urban emissions.

Changes in local air pollution emissions, particularly due to altered transportation patterns, have caused temporary air quality improvements in many cities around the world (see critical review by Adam et al. 2021). Many outdoor air pollutants, such as particulates, nitrogen dioxide, carbon monoxide, and volatile organic compounds declined during national lockdowns. Levels of tropospheric ozone, however, remained constant or increased. 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).

Related to the transport sector, the pandemic has resulted in concerns regarding the safety of public transport modes, which has resulted in significant reductions in public transport ridership in some cities (Bucsky 2020; de Haas et al. 2020) while providing opportunities for urban transitions in others (Newman AO 2020). Considering the significance of public transportation for achieving low-carbon and inclusive urban development, appropriate response measures could enhance health safety of public transport modes and regain public trust (Sharifi and Khavarian-Garmsir 2020). Similarly, there is a perceived correlation between the higher densities of urban living and the risk of increased virus transmission (Hamidi et al. 2020; Khavarian-Garmsir et al. 2021).

While city size could be a risk factor with higher transmission in larger cities (Hamidi et al. 2020; Stier et al. 2021), there is also evidence showing that density is not a major risk factor and indeed cities that are more compact have more capacity to respond to and control the pandemic (Hamidi et al. 2020). Considering the spatial pattern of density, even distribution of density can reduce the possibility of crowding that is found to contribute to the scale and length of virus outbreak in cities. Overall, more research is needed to better understand the impacts of density on outbreak dynamics and address public health concerns for resilient cities.

Cities could seize this opportunity to provide better infrastructure to further foster active transportation. This could, for example, involve measures, such as expanding cycling networks and restricting existing streets to make them more pedestrian- and cycling-friendly contributing to health and adaptation co-benefits, as discussed in Section 8.2 (Sharifi 2021). Strengthening the science–policy interface is another consideration that could support urban transformation (Cross-Chapter Box 1 in Chapter 1).

8.7.2 Future Urban Emissions Scenarios

The urban share of global emissions is significant and is expected to increase in the coming decades. This places emphasis on the need to expand development of urban emissions scenarios within climate mitigation scenarios (Gurney et al. 2021, 2022). The literature on globally comprehensive analysis of urban emissions within the existing IPCC scenario framework remains very limited, curtailing understanding of urban emissions tipping points, mitigation opportunities and overall climate policy complexity. A review of the applications of the SSP-RCP scenario framework also recommended downscaling global SSPs to improve the applicability of this framework to regional and local scales (O'Neill et al. 2020). This remains an urgent need and will require multidisciplinary research efforts, particularly as net-zero-emissions targets are emphasised.

8.7.3 Urban Emissions Data

Though there has been a rapid rise in quantification and analysis of urban emissions, gaps remain in comprehensive global coverage, particularly in the Global South, and reliance on standardised frameworks and systematic data are lacking (Gurney and Shepson 2021; Mueller et al. 2021). The development of protocols by (BSI 2013; Fong et al. 2014; ICLEI 2019b) that urban areas can use to organise emissions accounts has been an important step forward, but no single agreed-upon reporting framework exists (Lombardi et al. 2017; Chen et al. 2019b; Ramaswami et al. 2021). Additionally, there is no standardisation of emissions data and limited independent validation procedures (Gurney and Shepson 2021). This is partly driven by the recognition that urban emissions can be conceptualised using different frameworks, each of which has a different meaning for different urban communities (Section 8.1.6.2). Equally important is the recognition that acquisition and analysis of complex data used to populate urban GHG inventory protocols remains a barrier for local practitioners (Creutzig et al. 2019). 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 in spite of recent efforts (Moran et al. 2018; Zheng et al. 2018; Harris et al. 2020; Jiang et al. 2020; Wei et al. 2021; Wiedmann et al. 2021).

Similarly, independent verification or evaluation of urban GHG emissions has seen a large number of research studies (e.g., 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 (Gurney and Shepson 2021).

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 and scaling is an essential near-term need.

Frequently Asked Questions (FAQs)

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

Over half of the world's population currently resides in urban areas – a number forecasted to increase to nearly 70% by 2050. Urban areas also account for a growing proportion of national and global emissions, depending on emissions scope and geographic boundary. These trends are projected to grow in the coming decades; in 2100, some scenarios show the urban share of global emissions above 80%, with 63% being the minimum for any scenario (with the shares being in different contexts of emissions reduction or increase) (Sections 8.3.3 and 8.3.4). As such, urban climate change mitigation considers the majority of the world's population, as well as some of the key drivers of global emissions. In general, emissions scenarios with limited outward urban land expansion are also associated with a smaller rise in global temperature (Section 8.3.4).

The urban share of global emissions and its projected growth stem in part from urban carbon lock-in – that is, the path dependency and inertia of committed emissions through the long lifespan of urban layout, infrastructures, and behaviour. As such, urban mitigation efforts that address lock-in can significantly reduce emissions (Section 8.4.1). Electrification of urban energy systems, in tandem with implementing multiple urban-scale mitigation strategies, could reduce urban emissions by 90% by 2050 – thereby significantly reducing global emissions (Section 8.3.4). Urban areas can also act as points of intervention to amplify synergies and co-benefits for accomplishing the Sustainable Development Goals (Section 8.2).

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

The most impactful urban mitigation plans reduce urban GHG emissions by considering the long lifespan of urban layout and urban infrastructures (Sections 8.4.1 and 8.6). Chapter 8 identifies three overarching mitigation strategies with the largest potential to decrease current, and avoid future, urban emissions: (i) reducing or changing urban energy and material use towards more sustainable production and consumption across all sectors including through spatial planning and infrastructure that supports compact, walkable urban form (Section 8.4.2); (ii) decarbonise through electrification of the urban energy system, and switch to net-zero-emissions resources (i.e., low-carbon infrastructure) (Section 8.4.3); and (iii) enhance carbon sequestration through urban green and blue infrastructure (e.g., green roofs, urban forests and street trees), which can also offer multiple co-benefits like reducing ground temperatures and supporting public health and well-being (Section 8.4.4). Integrating these mitigation strategies across sectors, geographic scales, and levels of governance will yield the greatest emissions savings (Sections 8.4 and 8.5).

A city's layout, patterns, and spatial arrangements of land use, transportation systems, and built environment (urban form), as well as its state and form(s) of development (urban growth typology), can inform the most impactful emissions savings 'entry points' and priorities for urban mitigation strategies (Sections 8.4.2 and 8.6). For rapidly growing and emerging urban areas, there is the opportunity to avoid carbon lock-in by focusing on urban form that promotes low-carbon infrastructure and enables low-impact behaviour facilitated by co-located medium to high densities of jobs and housing, walkability, and transit-oriented development (Sections 8.6.2 and 8.6.3). For established cities, strategies include electrification of the grid and transport, and implementing energy efficiency across sectors (Section 8.6.1).

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

There are two different emissions estimation techniques applied, individually or in combination, to the four frameworks outlined in Section 8.1.6.2 to estimate urban GHG emissions: 'top-down' and 'bottom-up'. The top-down technique uses atmospheric GHG concentrations and atmospheric modelling to estimate direct (scope 1) emissions (see Glossary). The bottom-up technique estimates emissions using local activity data or direct measurements such as in smokestacks, traffic data, energy consumption information, and building use. Bottom-up techniques will often include indirect emissions (see Glossary) from purchased electricity (scope 2) and the urban supply chain (scope 3). Inclusion of supply-chain emissions often requires additional data such as consumer purchasing data and supply chain emission factors. Some researchers also take a hybrid approach combining top-down and bottom-up estimation techniques to quantify territorial emissions. Individual self-reported urban inventories from cities have shown chronic underestimation when compared to estimates using combined top-down/bottom-up atmospherically calibrated estimation techniques.

No approach has been systematically applied to all cities worldwide. Rather, they have been applied individually or in combination to subsets of global cities. Considerable uncertainty remains in estimating urban emissions. However, top-down approaches have somewhat more objective techniques for uncertainty estimation in comparison to bottom-up approaches. Furthermore, supply chain estimation typically has more uncertainty than direct or territorial emission frameworks.

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