Cities Transformation Report
IIASA-Japan Joint Research Project

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Table of Contents

Executive Summary

Why Cities?

With global warming already surpassing 1.1°C temperature increase on average over the past decade compared to pre-industrial periods, the imperative for city transformation to address climate change has never been more pressing. Cities and urban areas, home to around 56% of the global population in 2020 and projected to rise to approximately 63% by 2035, are experiencing the profound impacts of human-induced climate change. These impacts include droughts, heavy rainfall, floods, extreme heat, storm surges, and cyclones. Projections from climate models indicate that these effects will exacerbate in the coming decades, with rising sea levels, coastal erosion, and more frequent coastal flooding posing significant threats to urban populations and infrastructure. {2.1, 3.1, 3.2}

Without immediate and substantial reductions in emissions, global temperature rise is set to exceed 2°C by 2050, further exposing cities and their inhabitants to the adverse effects of climate change. Urban systems were responsible for 29 $GtCO_2$-eq or about 67-72% of global carbon dioxide and methane emissions in 2020[1]. Therefore, cities are crucial for achieving global mitigation targets. As hubs of resource consumption, cities offer unparalleled opportunities for implementing sustainable policies and transitioning towards sustainable low-carbon pathways. The extent to which cities contribute to mitigate emissions or exacerbate the impacts of climate change depends on various factors, including their stage of development, governance structures, available infrastructure, and socio-cultural context. Alternate scenarios assessing urbanization pathways and their implications on global emissions are gaining importance to inform and compare adaptation and mitigation possibilities. {2.1, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 5.1, 5.2, 5.3, 5.4}

The impacts of climate change in cities disproportionately affect marginalized communities, particularly residents in slums and informal settlements. In 2020, over 1 billion people (a quarter of the total urban population) resided in such settlements, with 85% concentrated in sub-Saharan Africa, Central and Southern Asia and Eastern and South-Eastern Asia. Addressing the simultaneous global challenges of climate change and sustainable development requires the transformation of our cities. Focus areas are affordable and durable housing for all, the provision of high-quality urban services and inclusive public and non-motorized mobility options. Further research is imperative to comprehensively understand which planning approaches to urban slum reformation and transformation have proven effective, in which contexts.{2.3, 3.1, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 5.1, 5.2, 6.3, 6.4}

Annually, nearly 2 million premature deaths in cities are attributed to exposure to ambient particulate matter (i.e., $PM_{2.5}$), likely disproportionally affecting low-income populations in informal settlements. This exposure is due to various factors, including inflow of pollution from outside but also local sources such as solid fuel burning for cooking or heating, road traffic, and waste burning. Mitigation of greenhouse gas (GHG) emissions can have co-benefits for air pollution when common sources are reduced. However, efforts aimed at decreasing concentrations of ambient particulate matter typically entail a reduction in both warming and cooling aerosols, resulting in possible trade-offs regarding their climate impact. Other health-related aspects, like active mobility, can benefit from measures targeting GHG reductions. Therefore, integrated mitigation strategies for cities that prioritize health are needed but not yet realized widely. Another knowledge gap exists regarding climate change impacts on air quality. While it is understood that climate change is likely to affect air quality, several aspects of this relationship remain inadequately explored. For example, the development of wildfires and heatwave

[1] excluding emissions from biogenic sources and international shipping and aviation

events and their potential impact on urban air pollution in the future, in certain regions. {2.3, 3.1, 3.2, 4.3, 4.4, 6.1, 6.3}

Systems transformation and enabling conditions

Cities are situated within distinct climates, including tropical, arid, temperate, cold, and polar regions, and geographical attributes such as coastal, inland, and mountain basin locations. Additionally, in aggregate but also within cities, they are at different stages of urban growth and development—emerging, rapidly growing, and established urban areas; and take different urban forms—compact and walkable versus dispersed and auto-centric. These characteristics influence vulnerabilities to climate risks and emissions while also offering opportunities for rapid and deep emissions reductions. Urban systems integrate various sectors, including energy, buildings, transportation, waste management, and land use. Comparing various urban growth typology and urban forms has prompted evaluations of the priority and potential of adaptation and mitigation opportunities within integrated strategies encompassing spatial planning and infrastructure development, electrification, transitioning to net-zero emissions resources, urban green and blue infrastructure, and socio-behavioral considerations. A notable knowledge gap arises concerning the understanding of cities as part of broader complex systems. While cities are not isolated entities, their actions and interactions extend far beyond their boundaries, impacting resource use from their hinterland, and emissions and climate at regional and often global scales. Territorial emissions within city boundaries may be significantly lower than consumption-based emissions. Thus, there is a pressing need to identify and implement policies aimed at reducing emissions associated with supply chains, originating both within cities and from the multi-scale networks they are part of. The fundamental research question lies in how to conceptualize, model, and identify policy leverage points within the intricate web of supply chains affecting cities and influenced by transformations originating in and permeating across urban areas. {2.1, 2.2, 3.1, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 5.1, 5.2}

Rapid and large-scale systems transformation is necessary to achieve ambitious mitigation and adaptation goals. The Avoid-Shift-Improve (ASI) framework is one approach that can support climate actions, particularly climate change mitigation strategies within sectors, namely buildings and transport, but also across urban and other systems, emphasizing demand-side management. The ASI framing includes strategies to *avoid* actions that can significantly reduce energy and material demands. For example, teleworking can reduce the need for transportation. *Shift* strategies involve switching to more efficient service provisioning systems and technologies, such as transitioning from fossil fuel-based to efficient renewable energy sources in buildings and supporting public transportation. *Improve* strategies entail enhancements in the efficiency of available , including the efficient design, construction, retrofitting, and strategies to reduce and alter energy and material consumption through material substitution, as well as electrification in transportation. A critical knowledge gap exists in understanding the variability and limitations of bottom-up studies regarding adaptation and mitigation potential through sectoral solutions, especially in cities across several developing countries. There is a pressing need to enhance our comprehension of the costs and potentials associated with mitigation and adaptation actions in urban and infrastructure systems. Specifically, differentiating these potentials across regions and contexts is essential to support decision-makers, thereby enabling more informed and effective decision-making processes. {4.1, 4.2, 4.3, 4.4, 4.5. 4.6, 4.7}

The acceleration and scaling up of mitigation and adaptation actions in urban areas necessitates a focus on behavioral change and demand-side management. Demand-side actions may extend beyond individual behavioral and lifestyle changes, such as dietary shifts (shifting to a balanced, sustainable, healthy diet), to encompass broader choices in infrastructure and technologies, such as transitioning to renewables and electric vehicles. Behavioral and lifestyle changes offer significant potential for climate change preparation and response, providing rapid mitigation and multiple co-benefits for urban areas. Studies indicate that by 2050, comprehensive demand-side strategies have the potential to decrease global CO_2 and non-CO_2 greenhouse gas emissions in the end-use sectors—buildings, land transport, and food—by 40%–70% compared to the projected emissions for 2050. Among these, behavioral and lifestyle changes, with policy support, can rapidly reduce GHG emissions of end-use sectors by at least 5%, mostly in developed countries, with further reduction (up to 30%) possible by 2050. This reduction can be achieved by combining these changes with improved infrastructure design and access, such as changes in the built environment, new and repurposed infrastructures, and service provision through compact cities, more efficient use of floor space and energy in buildings, and reallocation of street space for active mobility. Implementing these short-term mitigation options can yield significant effects and lay the foundation for initiating and facilitating broader energy system transitions. The mitigation and adaptation potential of behavioral and lifestyle changes in cities can be enhanced by altering urban forms, designing infrastructure and providing services, improving knowledge and awareness, investing in and utilizing renewable technologies, and implementing effective feedback mechanisms. However, while demand-side management, particularly behavioral and lifestyle changes, holds significant potential to enact transformative change, there is a notable lack of empirical studies to comprehensively understand what factors enable these. Additionally, there is a need for models and scenarios capable of capturing the intricate socio-behavioral dynamics and interactions within these systems. {4.3, 4.4, 4.5, 4.6, 5.2, 6.1, 6.2, 6.3}

Smart cities leverage the integration of digital technologies, such as smart grids, IoT, teleworking options, and advanced techniques like big data, artificial intelligence (AI), remote sensing (RS), and geographic information systems (GIS) to revolutionize urban transformation efforts. However, while some of these solutions and policies have been discussed as potential solutions that can optimize energy use, reduce carbon emissions, drive transformative change, and enhance overall sustainability. uncertainties exist around their implementation. It is essential that cities develop tailored, context-specific solutions that can be more easily adopted otherwise these end up being limited utopian visions. {4.4, 4.8, 5.2, 5.3}

In contrast to the slow progress in international climate negotiations, many cities are quickly scaling up bottom-up climate solutions and plans. Cities often move fast because they are hubs of innovation and have a pressing need to respond to climate crises in real time. Effectively implementing and spreading solutions across cities requires aligning the interests of stakeholders within/across levels of decision-making. Interagency coordination mechanisms, multi-level fiscal transfers, and climate assemblies are some of the enabling reforms that can strengthen implementation and bring solutions to scale. Transnational city networks and international partnerships can similarly pave the way for transformative changes--for instance, by encouraging frontrunning cities to innovate and offering less advanced cities opportunities to learn from peers. However, their effectiveness at implementing coordinated actions or supporting the less ambitious cities needs further research. A key knowledge gap exists in incorporating governance, institutions, and enabling reforms into urban modeling scenarios. Balancing the need for institutions that promote rapid change in cities with those that encompass diverse stakeholders, even though the latter may impede swift transformations, poses a great challenge. Addressing this gap requires interdisciplinary research to develop modeling frameworks that accurately reflect the dynamic interplay between governance structures, institutional reforms, and urban development pathways. {5.1, 5.3, 5.4}

Finance, technology, and innovation, coupled with national and international cooperation, are critical facilitators for accelerating both climate adaptation and mitigation actions. Enhanced availability and access to finance, such as investing in green infrastructure and supporting renewable energy projects, enable accelerated climate action. Increased access to finance through novel public-private partnerships, particularly for developing countries, vulnerable groups, regions, and sectors, enhances capacity building, addresses soft limits to adaptation, and mitigates rising risks. Still, there is a lack of knowledge in understanding the financing requirements for mitigation and adaptation efforts in cities with diverse characteristics, including geography, development level, and spatial patterns. Additionally, there is a need to identify novel public-private partnerships that show promise in attracting investments essential for transitioning to sustainable and resilient urban environments. Closing these gaps requires comprehensive research that considers the unique contexts of different cities and explores innovative financing mechanisms and partnership models tailored to their specific needs and challenges. {5.3, 5.4, 6.1, 6.2}

Synergies and trade-offs

Cities often implement mitigation and adaptation actions separately, however several actions can achieve both. For example, passive building design such as insulation and natural ventilation can enhance thermal comfort, reduce vulnerability to temperature extremes, while also reducing energy consumption and associated emissions for heating and cooling. Similarly, urban green spaces can deliver both adaptation and mitigation. On the other hand, some actions can result in conflicts for e.g., (mal)-adaptation actions that increase energy consumption can conflict with mitigation objectives. Limited understanding of costs and benefits and the lack of capacity and resources available to cities limit the implementation of an integrated approach. More research is needed on understanding such integrated actions and their synergies and trade-offs in the near-term as well as how these evolve in the longer-term. A major gap in adopting an integrated approach to mitigation and adaptation in cities is inadequate evidence of costs and finance for implementation. {4.2, 4.3, 4.4, 4.5, 4.6, 6.1}

There is growing evidence on the multiple linkages between climate change and food, water, air quality, health, gender, inequality and other sustainable development objectives. Mitigation and adaptation options are most effective when aligned with economic and sustainable development. Sustainable Development Goals (SDGs) provide a useful framework for integration in designing and transformation of urban energy systems across sectors and scales. Several urban mitigation and adaptation options have synergies with multiple SDGs making cities key actors in delivering targets under SDGs. Taking a broader SDG context can foster synergies or at least minimize possible trade-offs in pursuing a balanced portfolio of options. This implies for example, a comprehensive planning of urban forms and structures and integrated local policies that combine urban functions (e.g., housing, jobs, businesses) in spatial planning with promoting electrification and renewable energy in energy system transformation. {6.1, 6.2, 6.3, 6.4}

Numerous solutions exist that can simultaneously mitigate air pollution and greenhouse gas emissions, thereby creating opportunities for co-benefits that may vary across different regions and cities. For example, cities, with their high population density, offer opportunities for efficient mitigation of air pollution sources through measures like improved public transport infrastructure, leading to multiple benefits. For example, increased share of cycling and walking can improve quality of life (through lifestyle changes, individuals engage in physical exercises) and enhance social cohesion. This strategy is more effective in established cities that are compact and walkable. There is a need for quantifying a full range of co-benefits—including both mitigation (i.e., climate, air pollution, health, equity) and adaptation (i.e., heat island effects). Some solutions are more effective in certain types of cities. As climate change accelerates, climate resilient development (CRD) approaches that integrates mitigation and adaptation responses and sustainable development, can guide new urban development, tailoring CRD planning to city's unique circumstances, including geographical, historical factors, and development goals. Recognizing diverse vulnerabilities within cities, underscores the necessity for a comprehensive approach to urban resilience, encompassing a range of policies from structural improvements to socio-economic measures. However, further research is needed to: a) systematize the concept of urban CRD and develop methods for formulating policies and measures; b) explore best practices and identify common approaches; c) understand the roles of the public and private sectors in realizing urban CRD, including the involvement of financial and business sectors and international support. {5.1, 5.4, 6.1, 6.4}

There is growing evidence on the needs and approaches for urban systems and sectoral transformation (building, transport, land use planning and waste management). However, research on how to achieve transformation within/across urban systems is still ongoing. Given the urgency, research should focus on identifying successful options, how and where they have worked for e.g., in different types of cities (compact cities, mixed land use etc.) and how these can be enabled and upscaled in different contexts. The challenge is how to support cities in setting higher ambition and understanding the factors that can help achieve this. Equity and justice are key elements of the transition. There is a need to support the cities and communities that have not received adequate attention. Established cities will have to shift away from unsustainable patterns of consumption. Rapidly growing and emerging cities have special circumstances- of balancing growth alongside addressing climate change. International cooperation, finance and technical support will be key to realising the global mitigation potential of cities while minimising the adverse impacts of climate change across all settlements globally.

1. Introduction

The International Institute for Applied Systems Analysis (IIASA), in collaboration with its Japan National Member Organization (NMO), supported by Ministry of the Environment Japan (MOEJ) has initiated a joint research endeavor centered on Cities Transformation. The primary aim of this collaborative effort's inaugural phase is the compilation of a fast-track comprehensive report. This report aims to consolidate the current understanding of urban transformations, identifying critical knowledge gaps therein. It serves to support the scientific community, city stakeholders, and policy-makers in discerning areas warranting greater attention and, crucially, further investigation and study. Particularly, it provides updates on the IPCC 7th Assessment Cycle, with a specific focus on its Special Report on Climate Change and Cities.

Commencing with an overview of global urbanization trends, the report delves into the status of informal urban settlement development (Section 2). Subsequently, it comprehensively discusses the physical aspects of climate change, including impacts, vulnerability, adaptation, and mitigation, with a spotlight on air pollution and waste challenges (Section 3). Section 4 shifts focus to systems transformation, examining sectors and cross-cutting perspectives through various case studies. Following this, Section 5 investigates the enabling conditions for city transformations, emphasizing the roles of governance, behavioral and lifestyle changes, innovation and technology, and finance. Expanding further, Section 6 assesses the synergies and trade-offs of mitigation and adaptation strategies, with a particular lens on Sustainable Development Goals (SDGs), health, and well-being. The report concludes by recognizing significant knowledge gaps highlighted through expert insights. We had the privilege of interviewing several experts in the field, including *Xuemei Bai, Shobhakar Dhakal, Arnulf Grubler, and Ayyoob Sharifi*. We extend our sincere appreciation to them for their valuable contribution.

The resulting report will be launched during an international expert workshop and symposium to disseminate the project's findings to the broader public. The event is scheduled for February 27th to 28th, 2024, in Tokyo-Japan.

2. Urban system

2.1. Trends in urbanization

In the scope of metropolises with more than 300,000 inhabitants, there were 1,934 such metropolises around the world in 2020 (UN-Habitat 2022a). In total, these metropolises correspond to about 60% of the global urban population and one third of the total global population. Of these metropolises, 34 accommodate more than 10 million inhabitants. The Asia-Pacific region contains most of the global metropolitan population with 1,038 metropolises. In other regions, this is followed by 325 metropolises in Western Europe, North America, and Australia, 235 metropolises in Africa, 215 metropolises in Latin America, and 121 metropolises in Eastern Europe.

Trends in urbanisation indicate that by 2035, 62.5% of the global urban population may be living in metropolises based on an increase of about 1 billion people and 429 new metropolises, mostly occurring in developing regions (UN-Habitat 2022a). In the timeframe between 2020 and 2035, the average annual growth rate of the metropolitan population is expected to be highest in Africa at 3.25%. In some of the other regions, the average annual growth rate is expected to be 1.7% in Asia-Pacific, 1.1% in

Latin America, 0.8% in Western Europe, and 0.1% in Eastern Europe (UN-Habitat 2022a). In the context of the most populated urban agglomerations at present, New Delhi may surpass Tokyo in housing the largest urban population in 2035 (UN DESA 2019b).

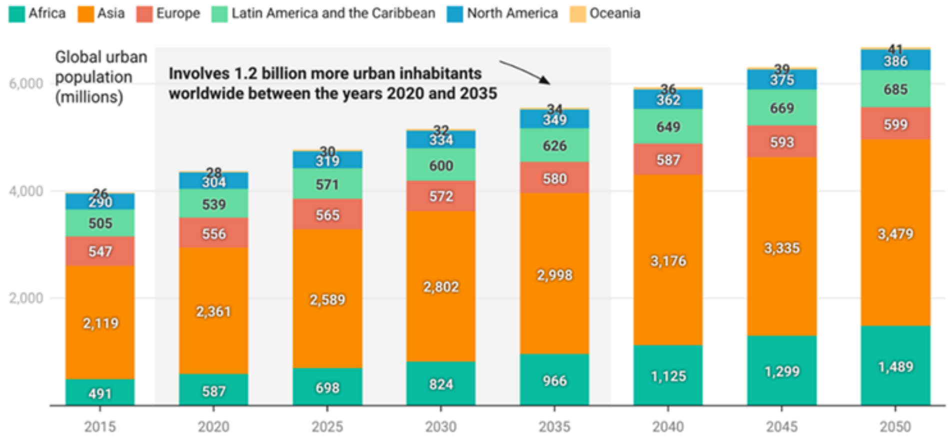

Figure 1 *Global urban population in millions by region with expected UN projections to 2050*

As urban systems, there are interlinkages between land, energy and resource use, transport, buildings and other infrastructure, and socio-behavioural aspects, placing urbanisation at the centre of climate mitigation and adaptation . In 2015, the top 100 urban areas with the highest emissions accounted for about 18% of the global emissions footprint considering CO_2 emissions (Moran *et al* 2018). Moreover, based on urban consumption-based emissions, urban systems were responsible for 29 $GtCO_2$eq or about 67-72% of carbon dioxide (CO_2) and methane (CH_4) emissions in 2020 at the global level, excluding emissions from biogenic sources and international shipping and aviation (Gurney *et al* 2022, Lwasa *et al* 2022). In 2020, the urban consumption-based emissions of 420 urban areas that represented the highest carbon footprints accounted for about 10.7 $GtCO_2$-eq of CO_2 and CH_4 emissions with important mitigation potential in the decades ahead (Kılkış 2022). Scenarios that seek to compare the urban share in global emissions are gaining importance to inform and compare mitigation possibilities and transitions to climate neutrality. In 2050, global urban CO_2 and CH_4 emissions may be as high as 34 $GtCO_2$eq in 2050 with only moderate mitigation efforts or as low as 3 $GtCO_2$eq with ambitious mitigation that includes high rates of electrification and better performances in energy and material efficiency (Gurney *et al* 2022, IPCC 2022c, Lwasa *et al* 2022).

2.2. Urbanisation typologies

Within the diversity of urbanisation, urban areas differ in a multitude of ways, including in aspects of land, energy and resource use, infrastructure, socioeconomic dynamics, surrounding local biomes, and connections to other urban areas in the region and across the world. Urbanisation typologies have emerged as a way of clustering urban areas according to such characteristics as size, urban land use, and development context. From the perspective of *urban growth*, 478 urban areas with more than 1 million inhabitants have been clustered into five possibilities of *stabilized, outward, budding outward, mature upward, and both upward and outward urban growth* (Mahtta *et al* 2022).

The cluster of budding outward is observed mostly in North America, Europe, and China and accounts as the pattern of urban growth for 46% of the total urban land area worldwide. In the stabilised pattern of urban growth, the total urban land area used in Europe and China is substantially less when compared to those of North America (Mahtta *et al* 2022). Again, based on total urban land area, the cluster of upward and outward urban growth is mostly found in China and East and Southeast Asia (Mahtta *et al* 2022). Stabilised urban growth where there is mature infrastructure and negligible urban growth can have higher shares in more established cities. In addition to the dominant patterns of urban growth in a given context, different districts within the same urban area frequently have multiple urban growth patterns, which can represent areas under renovation or even pilot energy-positive districts. For example, Osaka in Japan is composed of mostly mature upward urban growth while there are also patterns of stabilised and budding outward urban growth within the urban area. Similarly, 82% of the 478 urban areas involved a combination of two or three patterns of urban growth (Mahtta *et al* 2022).

Patterns of urban growth have consequences on built-up land area and are influenced by land use efficiencies. In the 40 years between 1970 and 2010, over 60% of reported urban expansion took place on formerly agricultural land (Güneralp *et al* 2020). Land use efficiency, or the ratio of the land consumption rate to the population growth rate, did improve in 58% of functional urban areas during 2000 and 2015 when compared to the timeframe of 1990 and 2000. Even with improving land use efficiencies, however, lead to land use change. In 20% of the functional urban areas, land use efficiency worsened while such analysis is not available for the remaining functional urban areas (Schiavina *et al* 2022).

Urbanization typologies in the latest IPCC assessment (AR6) are defined in two dimensions. First, following the urban growth typology, three main categories are presented as: emerging, rapidly growing, and established urban areas. Second, characteristics of urban form can be either compact and walkable or dispersed and auto-centric(IPCC 2022c, Lwasa *et al* 2022). The cross-comparison of both urban growth and urban form has led to evaluations of the priority and potential of mitigation opportunities within integrated strategies of spatial planning and infrastructure, electrification and switching to net-zero emissions resources, urban green and blue infrastructure, and socio-behavioural aspects (see Sections 4 and 5). It is worth mentioning that in addition to urban growth and urban form typologies, cities are situated within distinct climates, such as tropical, arid, temperate, cold, and polar (Peel *et al* 2007); and possess geographical attributes such as coastal, inland, and mountainbasin locations (IPCC 2022b). From the perspective of adaptation, options can vary for low-lying and coastal urban areas versus inland urban areas or mountainous urban areas. Physical geomorphology characteristics and vulnerabilities extend to the type of settlement (high or low density and informal settlements), the main climate impacts (ocean, terrestrial, atmospheric, and hydrological impacts), and urban economic resources. These factors play a crucial role in determining the efficacy and cost of adaptation as well as mitigation measures. Urban typologies, preferably those that integrate mitigation and adaptation perspectives, are expected to be an important priority for knowledge production in preparation for the Seventh Assessment Cycle.

2.3. Informal urban settlements

In 2020, more than 1 billion people lived in slums and *informal settlements* (a quarter of the urban population), with 85% concentrated in just three regions of Sub-Saharan Africa, Central and Southern Asia and Eastern and South-Eastern Asia (UN-Habitat 2022b). The New Urban Agenda and SDG Target 11.1 require slum transformation, yet following the COVID-19 pandemic, projections suggest another 2 billion people could be living in slums by 2050 (UN-Habitat 2022b, United Nations 2017).

Wide heterogeneity in patterns of urban informality and a lack of consistent data make it challenging to define and compare such settlements (Banks *et al* 2020, UN-Habitat 2022b). Despite this, six domains usually distinguish informal from formal parts of the city, including *physical, service, social, economic, legal, and environmental dimensions* (Ferroni *et al* 2023). Informal urban or slum dwellers face enhanced deprivations and vulnerabilities (including amplified climate risks, and impacts of shocks like the pandemic), and inequalities in power, resource and financial allocations that limit their opportunities (Boza-Kiss *et al* 2021, IPCC 2023a, Shah 2022) (see 3.1, 5.4, Box 12).

Multiple and sometimes competing planning approaches to urban informality have been tried but slums continue to remain overlooked in urban planning (Debnath *et al* 2020, Sunikka-Blank *et al* 2019, Watson 2009) and face weak governance structures (see 5.1). The challenges of urban sustainability, climate-compatible development and resilience lie in moving towards more inclusive and socially equitable cities (Dodman *et al* 2019). This requires addressing multiple deprivations, by providing accessible and affordable decent housing, mobility services, city infrastructure and basic civic amenities and secure jobs in slums (see 4.1, 4.3, 4.4, 4.5). Service and infrastructure provisioning systems that are more inclusive, efficient and have a lower resource and material footprint can be designed using insights from community-scale life cycle analysis (García-Guaita *et al* 2018) and urban social metabolism studies (Smit *et al* 2019, Teferi and Newman 2017). The potential of green infrastructure as a mitigation strategy in informal settlements is also receiving greater attention (Adegun 2021, Tauhid, Zawani 2018) (see 4.3).

Potential approaches to enhancing resilience of informal settlements include measures that reduce exposure to hazards e.g., by providing access to cool and green spaces, improved water supply and sanitation; inclusive land use planning; resilient housing and infrastructure; and early warning systems (see 3.1). Other measures that reduce vulnerability include improved insurance, healthcare, emergency services, broader disaster risk reduction measures and enhancing equity (Núñez Collado and Wang 2020, Satterthwaite *et al* 2020). Some measures such as cool roofs can support both mitigation and adaptation (Nutkiewicz *et al* 2022). Enabling the provision of clean energy access in urban informal settlements offers multiple wins for climate change mitigation, transition to cleaner energy, reduced indoor air pollution, health and gender equality (Aktas *et al* 2022, Christley *et al* 2021).

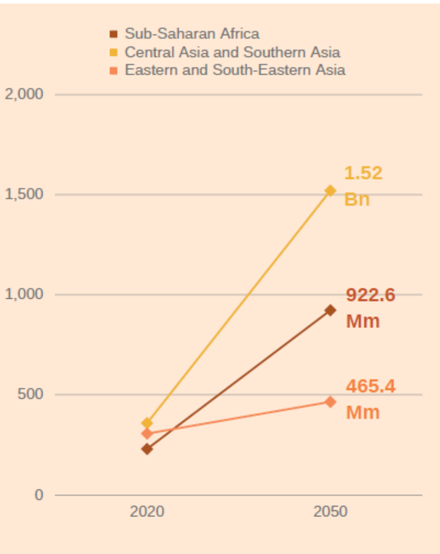

Figure 1 *Projected slum population rise by region based on urban growth predictions. Source:(GAP 2022)*

Transforming informal settlements requires developing affordable and durable housing, providing good quality urban services and inclusive public and non-motorized mobility options (Núñez Collado and Wang 2020). This, however, requires enhancing flows of finance and strengthening the capacity of local administrations and organizations. Just urban governance, community-based processes and engagement, and city-government-led measures that aim to improve built and social environments, as well as economic and social conditions in slums/ informal settlements can enhance resilience to climate-change risks and serve vulnerable groups (Castán Broto 2017, Dodman *et al* 2023, Satterthwaite *et al* 2020) (see Box 12).

3. Impact and risks

3.1. Climate impacts and vulnerability

The density and absolute scale of cities and urban areas results in particularly interesting characteristics relating to robustness and resilience, particularly to climate impacts, which may also vary substantially by geographical location, such as inland, coastal or mountain region. In this sense, robustness means the ability to withstand climate impacts, whereas resilience can mean both the ability to recover quickly (Holling 1973) or the capacity to adapt to change (Thornbush *et al* 2013).

The concentration of people and economic capital radically increases the exposure to climate impacts, making comparatively tiny areas of the Earth's surface, extremely critical from a climate risk perspective (Tuholske *et al* 2021, Rentschler *et al* 2023). The scale and density of urban areas has driven prosperity through the economic provision of infrastructural and social services that constitute civilization, and when adequately prepared, provide robustness and resilience to climate impacts. When unprepared, however, the consequences can be catastrophic with aspects of cities, particularly compact urban form and excessive paved areas, actually exacerbating risk (Dodman *et al* 2022).

Compact urban form implies that per capita and per km^2 services can be provided more cost effectively, whilst absolute scale of cities means that large projects also become economically feasible due to their size. Ultimately cities form dense hubs of interdependent critical infrastructure for services like water supply, energy, wastewater and solid waste management, telecommunications, transport, ports and healthcare facilities (Hu *et al* 2016). The adequate provision of infrastructure systems and services positively contributes to economic growth and tends to reduce vulnerability to climate impacts (Hall *et al* 2016). And due to the size of cities and in case of service failures, backups and redundancies typically exist, for example, multiple transport options, healthcare facilities, communications networks and emergency responder teams, but these services may be overwhelmed if many people or large areas are affected. Ultimately, urban form of cities and the climate risk faced by climate impacts likely constitutes an important, yet poorly understood, characteristic

The density and increased interconnectedness of cities and infrastructure means that when failures occur, they can be catastrophic, as noted by IPCC as potentially *compounding* or *cascading* (Dodman *et al* 2022). Hazards can be spatially and or temporally compounding, such as heat and drought or poor air quality from wildfires, or extreme rainfall coinciding with high tides and storm surges. Cascading effects are where service disruption has impacts elsewhere, such as flooding or wind storms impacting power [Fu 2018] and transport networks, with subsequent disruptions (Panteli *et al* 2017). Design of infrastructure systems that consider cross-sectoral and network dependencies is increasingly considered in planning but difficult to manage in practice (Panteli *et al* 2017).

Many urban areas and cities are also hotspots of vulnerability with large areas of cities and fractions of the global population existing in high-density, low quality informal housing (see section 2.3). Access to and quality of key infrastructure services is often lacking, unreliable and or unequally available (Meller *et al* 2017). Services can provide both robustness during climate extremes as well as resilience afterwards. For example, urban poor communities lack access to decent shelter with electricity for cooling and air filtration, thus are highly vulnerable to heat stress and air quality impacts (Mastrucci *et al* 2019, 2022). The same communities may typically also lack storm water sewerage and flood protection, increasing exposure to extreme rainfall. Improved water supply access and sanitation provide critical reduction of water-borne diseases, like cholera, incidence of which has been shown to increase during following both droughts and floods and climate variability (Grasham *et al* 2019, Moore *et al* 2017). And whilst there is generally high consensus within climate and disaster-risk management that reducing inequality and provision of basic services is key to reducing vulnerability and risk, the IPCC AR6 WG2 found limited evidence that infrastructure projects intended to reduce climate risk also reduce inequality (Dodman *et al* 2022, Sekulova *et al* 2021, Stewart and Deng 2015) (see Box 12).

Sometimes projects (particularly flooding related) intended to alleviate risk for some, can increase risk for others (Chu *et al* 2016). There are inequalities in protection too. Cost-benefit assessments that consider only economic capital at risk, for example for flooding protection, will inevitably favour protection of wealthier neighborhoods (where people also tend to have home and business insurance) and neglect high-density informal settlements populated by uninsured and undocumented people. Thus the risks faced by poorer communities are higher not only because they often face higher exposure and less protection, but also because they are more vulnerable (Hallegatte *et al* 2016). In addition to basic services, some measures aim to withstand climate impacts by ensuring capacity and supply, such as water storage reservoirs and desalination, back-up power supply and gas storage. Additionally, there are measures that provide protection to people, property and infrastructure such as riverine and coastal flood defenses, storm-water sewers, and snow-clearing, for example, where these 'hard' measures, mostly provide robustness and reliability.

The other critical component of vulnerability reduction comes from the 'soft' systems, networks and practices, comprising for example, institutional and organizational strategy, preparedness and response, public education and social services, early-warning systems and emergency responders. These soft systems provide risk reduction that can be more rapidly deployed compared to visible, big-ticket infrastructure projects (Winder Rossi *et al* 2017), but the benefits also more difficult to measure. For example, a rapidly growing number of countries and cities across the world have implemented heat-health action plans to reduce vulnerability to heatwaves (Kotharkar and Ghosh 2022), yet the global number of action plans is unknown, let alone the measures and benefits they bring. Compared to rural areas, compact urban form facilitates the cost-efficient provision of soft measures, but also their speed of deployment. Soft measures can also incorporate social safety nets and systems that can reduce vulnerability and losses. Bank accounts and insurance policies, community networks, social workers, education campaigns and targeted communication, are all systems that can assist the most vulnerable, for example elderly, disabled, and people with low literacy. They are comparatively cheap and fast to implement, yet are most often lacking in exactly places that also lack reliable infrastructure services. Furthermore, even if they exist, the poorest disproportionately struggle to access social protection schemes (Hallegatte *et al* 2016). Particularly with emerging and growing cities, increasing supply and access to adaptation measures fast enough to meet growth, some of which may be unplanned and informal, is a perpetual challenge for urban governance. More assessments that take into account climate impacts, scenarios of vulnerability and adaptation options, such as the one featured in **Figure 2**, are urgently needed, ideally with comparability across different climate impacts.

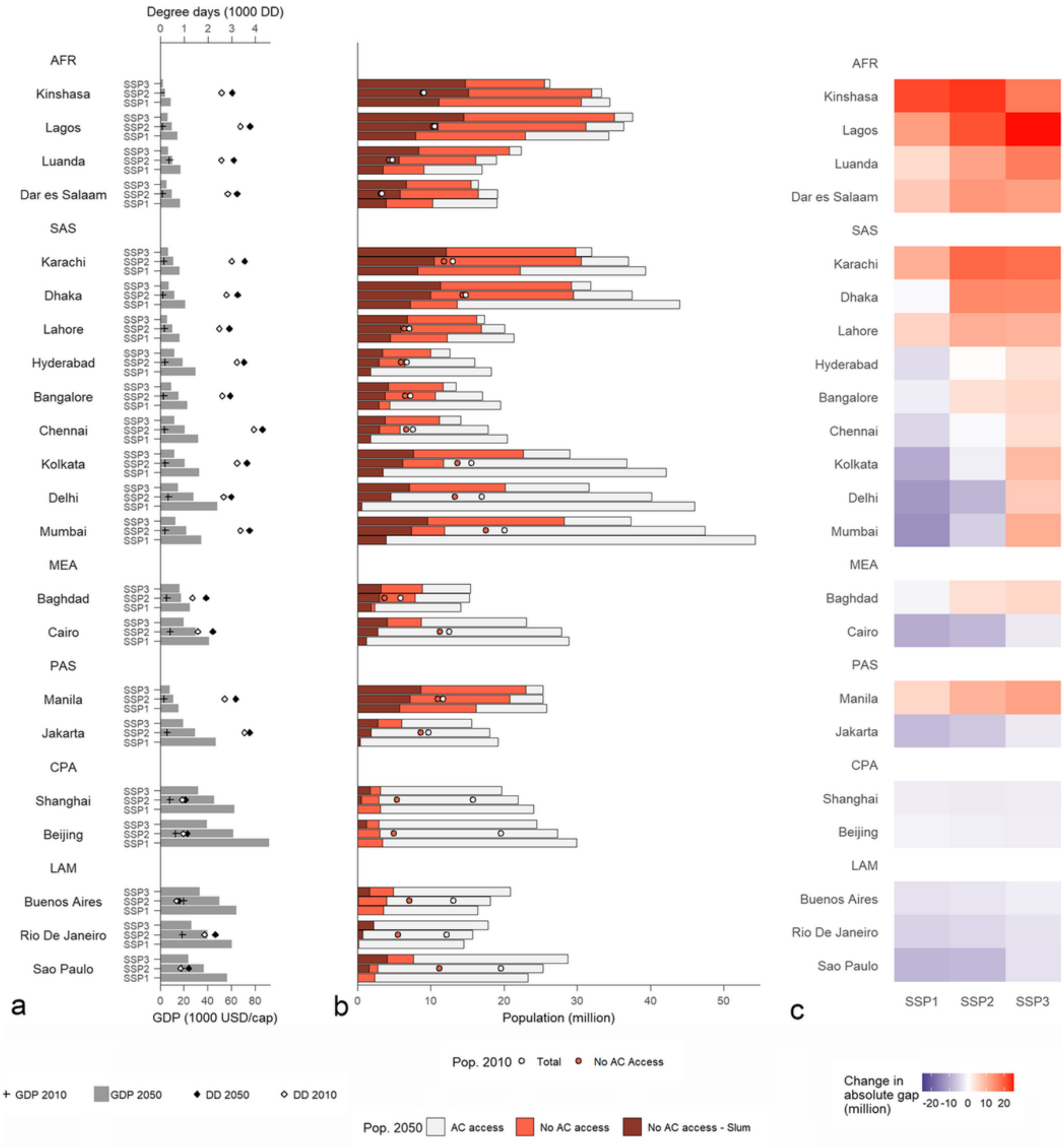

Figure 2 *In a study on 22 megacities in the global south, exposure to heat stress under climate change (2 °C warming) and adaptation through income-based projections of air conditioning access, and energy use was assessed. In sub-Saharan Africa and parts of south Asia, rapidly growing population and warming means an expected growth in the cooling gap (red squares in right column). Wealthier regions in the global south see a reduction, as income levels rise. In a number of south Asian cities, socioeconomic development has a key role, with potential for less (SSP1) or more (SSP3) people in the cooling gap compared to today, developing on the SSP scenario. Source: (Mastrucci* et al *2022).*

3.2. Air pollution and waste

Air Pollution

Cities are in many cases hot spots of air pollution due to high population density, traffic, and concentration of industrial and commercial activity. Since the early industrial revolution, a mix of pollutants from burning coal in industry and households and NH_3 from horse dung and sewage resulted in fast growing pollution problems in cities. Most large European cities, especially where coal was used, suffered from poor air quality at the end of the 19th century. However, urban pollution was widely accepted as a consequence of industrialization and economic development; at least until the infamous Great London Smog episode in 1952. The 1952 London smog with concentrations of smoke and SO_2 exceeding 1000 µg/m^3 caused premature death of estimated 12,000 people, but it also triggered public and political reaction prioritizing air quality regulation (Fowler *et al* 2020). While significant progress has been made in regulating sources of air pollution, an overwhelming fraction of the global urban population is still exposed to air pollution levels unsafe to human health. 95% to 99% of the global total population are estimated to live at concentration levels exceeding guidelines set by the World Health Organization (Amann *et al* 2020, WHO 2021b), and since concentration levels are typically higher in cities this fraction is likely close to 100% for cities.

The main pollutants of concern for urban air pollution are fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and, to some degree, ozone (O_3), depending on the region of the world and progress in implementation of air quality regulation. Estimated concentrations of $PM_{2.5}$ in cities in 2019 are shown in **Figure 3**. $PM_{2.5}$, consisting of primary particles as well as secondary aerosols formed by chemical reactions from precursor emissions of SO_2, NO_x, NH_3, and volatile organic compounds (VOCs), can penetrate deep into the respiratory system, leading to a spectrum of health issues. NO_2 is largely linked to road traffic emissions (but also contributed from other combustion sources such as industry and power generation) and more locally dominated than $PM_{2.5}$, leading to the hotspots in urban NO_2 which have likely considerable health implications: Anenberg et al. (2022) estimated that two out of three new pediatric asthma cases in cities are due to NO_2 exposure. Ground-level ozone, formed by the reaction of precursor pollutants (NO_x, VOCs) in the presence of sunlight, was initially seen as an urban problem in the Los Angeles smog (Blumenthal *et al* 1978). However, ozone concentrations are often lower in cities than in surrounding areas due to titration by local NO emissions. Recently, urban ozone levels have been increasing in some regions because of strong NO_x emission reductions driven by $PM_{2.5}$ policies, putting ozone back on the agenda of urban air pollution. For example, in China ozone concentrations have been increasing at the rate of 2-6.7%/yr in most major cities (Ou *et al* 2020, Wang *et al* 2022).

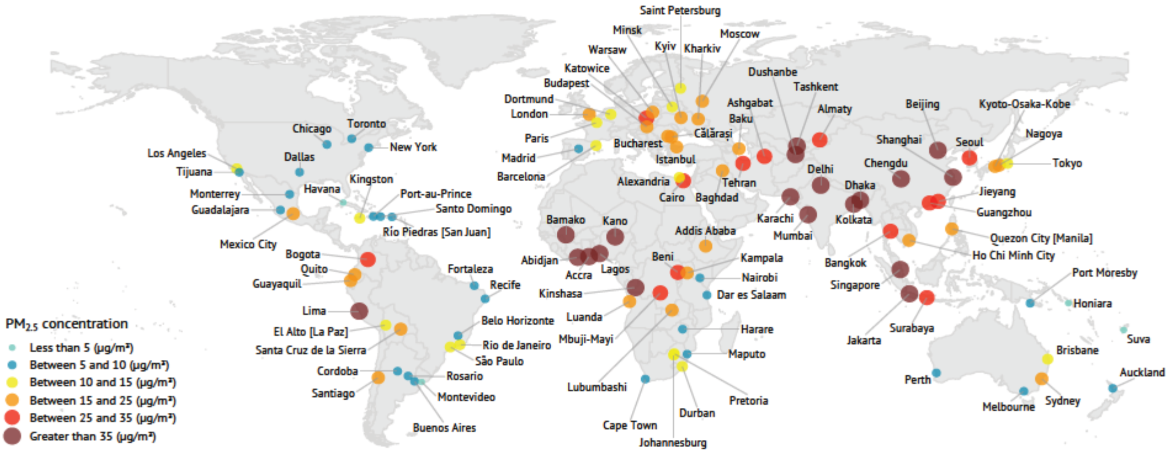

Figure 3 *Population-weighted annual average $PM_{2.5}$ concentrations in the five most populous cities in each region in 2019. Note that the WHO Guideline value for $PM_{2.5}$ is 5µg/m^3. Source:* (Health Effects Institute 2022)

Health impacts include mortality from a range of cardiovascular and respiratory diseases, lung cancer, and diabetes, as well as associated morbidity also from non-fatal diseases. Absolute quantification of the mortality and morbidity burden from air pollution vary depending on methodology details, particularly concentration-response functions (Hystad *et al* 2020), but all studies show a burden of several million cases of premature deaths every year globally. Southerland et al. (2022) estimated an excess of 1.8 million (95% CI 1.34 million–2.3 million) deaths in 2019 in cities due to $PM_{2.5}$ exposure alone.

A substantial part of pollution – especially $PM_{2.5}$ – is transported into the city from outside. Source contributions to urban air pollution in terms of sector and spatial origin vary strongly across regions. A global quantification of typical contributions is not available yet, estimates have been published only for some regions (Kiesewetter and Amann 2014, Khomenko *et al* 2023). Road traffic has contributed strongly to high concentrations of NO_2 and also $PM_{2.5}$. Household heating and cooking contributes both to ambient as well as indoor air pollution. Industrial facilities inside and close to cities are another concern, especially in developing countries where emission control standards are low.

Low-income population in informal settlements and slums is particularly vulnerable to air pollution due to (i) elevated exposure to ambient air pollution from local sources of ambient air pollution such as solid fuel burning for cooking or heating, and waste burning as municipal waste collection systems are either lacking or dysfunctional there (see section 4.5), (ii) exposure to household air pollution due to use of solid fuels for cooking or heating, (iii) low quality housing allowing for complete penetration of polluted outdoor air indoors, (iv) generally worse health conditions and therefore higher vulnerability.

Evidence linking climate change and air quality is mixed, however, in heavily polluted regions, climate driven changes in meteorological conditions, e.g., heatwaves or stagnations, can worsen extreme air pollution episodes (Cai *et al* 2017, Doherty *et al* 2017, Fiore *et al* 2015, Revi *et al* 2022, Zou *et al* 2017). While a warmer climate is expected to lead to increase of tropospheric ozone concentrations over polluted regions and causing significant health impacts, future air quality will be primarily determined by changes in emissions of precursors from anthropogenic sources rather than climate change (Revi *et al* 2022). Climate change can also induce increase in wildfires near cities (Bondur *et al* 2020, Xie *et al* 2020), which could deteriorate air quality locally and regionally, although such projections remain highly uncertain and difficult to project (Revi *et al* 2022). In turn, there is also evidence for feedback from air pollution on local meteorology: Elevated $PM_{2.5}$ can lead to stronger inversion layers because of changes in the radiative balance, further exacerbating the pollution levels (Gao *et al* 2015, Wu *et al* 2019).

Waste

In cities where solid waste management systems are lacking or dysfunctional, health and environmental impacts may occur. Diseases associated with poor waste management include typhoid, cholera, diarrhea, malaria, heart disease and cancer (Siddiqua *et al* 2022, Williams *et al* 2019). Diarrheal diseases affect mainly children under five years of age particularly in low and middle-low-income regions (Ugboko *et al* 2020). Improvements in sanitation services can help to reduce the diarrheal specific mortality in children (McClelland *et al* 2022). In general, it is estimated that between 400,000 and 1 million deaths are associated with poor waste management in cities in the global south (Williams *et al* 2019). Furthermore, the long-term exposure to odours from open waste dumps and inappropriate MSW treatment facilities can increase the risk of respiratory track and central nervous system damage (Fang *et al* 2022) and lead to the surface and groundwater pollution by leachate (Afolabi *et al* 2022, Njoku *et al* 2019), which is a toxic compound with high concentrations of heavy metals and organic matter (Gajski *et al* 2012). Effects of leachates on ecological systems, food chains and human health range from toxicity to carcinogenicity (Khalil *et al* 2018). As cities in the global south are often associated with ineffective waste management systems, population in these areas are more vulnerable to these negative effects (Abubakar *et al* 2022).

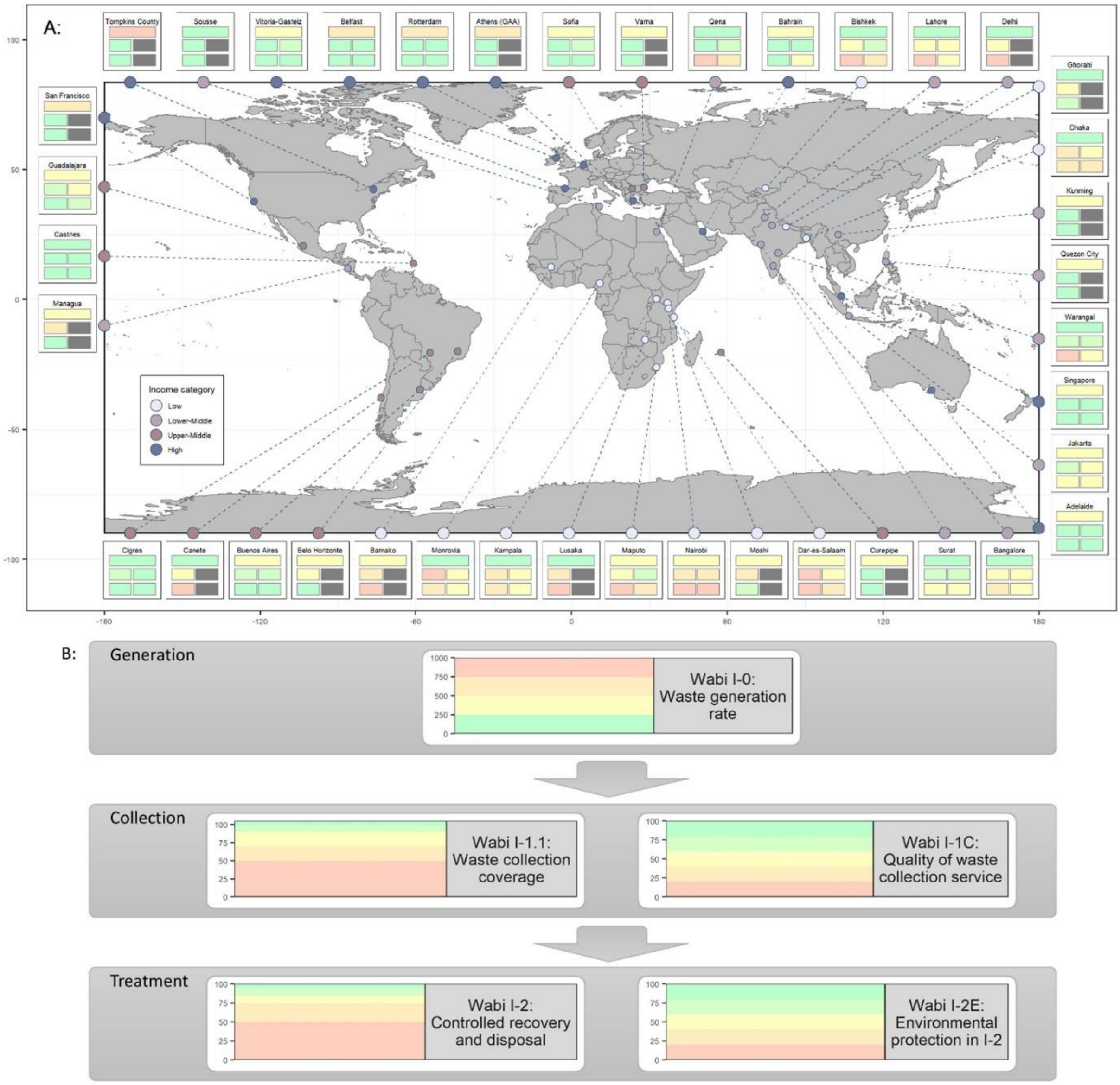

Figure 4 *Cities around the world in which the levels of waste generation and management are assessed with the Wasteaware Benchmark Indicators (WABI). The study includes cities in different income categories. Source: (Velis* et al *2023)*

Apart from the above-mentioned aspects, poor disposal of waste is a major cause of flooding, especially in informal areas or urban slums e.g., in Bwaise in Uganda (Cities Alliance 2021), Port Harcourt and Lagos in Nigeria (Echendu 2023), which have lower resilience and adaptative capacity (see 2.3 and 3.1). Littering of plastic waste can result in the formation of secondary microplastics by fragmentation affecting the whole aquatic system and human health. The presence of plastic debris in the ocean can affect species by entanglement and ingestion that frequently causes death (OECD 2022b, Jambeck *et al* 2015). In addition, plastic pollution bears negative economic consequences for various sectors and industries such as fisheries, aquacultures and the tourism sector, particularly coastal and marine tourism, affecting people's livelihoods (Mittempergher *et al* 2022, Raes *et al* 2022a, 2022b)

Lastly, it is important to recognize that waste generation and management impacts gender in diverse ways. Women waste pickers are in most of the cases exposed to discrimination and exploitation (see Box 12). Men tend to take the lead in the recycling activities (selling recyclables) while women are often left with low-income tasks such as waste picking and separation (UNEP 2023a). In section 4.5 we explore various strategies on how waste systems can be improved to eliminate impacts and contribute to the circularity of materials.

Box 1: WeatherPark (Vienna's strategies for climate change adaptation)

In the face of escalating climate change challenges, Vienna and Austria have picked up pace in implementing measures to address and adapt to the impacts of climate change. Recognizing the urgency, Vienna is adopting a multifaceted approach to climate change adaptation touching upon governance structures, science based assessment tools and the transformation of public space.

Recognising the need for clear and efficient structures within the city administration to successfully navigate climate action, the city of Vienna has restructured its internal responsibilities and has established the Climate Directorate as a central and coordinating unit for climate affairs. Climate policy initiatives in Vienna are further supported by the Vienna Climate Council, a group of experts, scientists and representatives of the civil society, established to advise politics and administration. With the aim of bridging climate mitigation and adaptation the Vienna Climate Guide[2] has been developed as the strategic road map to reach climate neutrality by 2040.

Reaching climate (adaptation) goals further relies on suitable instruments. An urban climate analysis was conducted in 2020 by Weatherpark in cooperation with INKEK. Urban climate analysis involves assessing and understanding the climatic conditions and trends specific to a city or urban area. It describes not only areas prone to overheating but also identifies locations where cold air is produced and the corridors through which this air flows reach the city. This information is crucial for urban development to enhance positive aspects of the city's urban climatic characteristics and find compensatory measures for unprivileged areas.

Urban climate analysis and risk maps play a pivotal role in bolstering climate change adaptation efforts. By assessing the vulnerability of urban areas to climate impacts, such as extreme heat, these analyses enable a well-founded assessment of decisions related to urban climate and provide crucial insights for developing targeted adaptation strategies and suitable, site-specific measures. These tools not only inform decision-makers but also catalyse long-term transformation, embedding climate considerations in urban development processes.

While adaptation needs are clear, and numerous goals, strategies, tools and expertise exists, now the focus needs to shift on consistently pursuing and prioritizing climate goals, supporting them with specific responsibilities and budgets, and establishing new processes and workflows, putting interdisciplinary planning into action.

Box 2: Decoupling GHG emissions from water stress in China

Urbanization has notably expanded wastewater infrastructure, essential for water sustainability, yet this expansion has simultaneously led to increased GHG emissions. These emissions are further amplified when considering the full life cycle of wastewater treatment, which encompasses energy use, infrastructure construction, and sludge disposal. In rapidly urbanizing nations, exemplified by China, where the volume of wastewater is substantial and continually rising, prioritizing the reduction of GHG emissions from wastewater treatment becomes a critical objective within the water-climate nexus. In the last decade, large-scale water treatment in China has reduced urban water stress nearly threefold, while simultaneously increasing life-cycle GHG emissions, specifically methane (CH4) and nitrous oxide (N2O), by 176%, from 41 to 113 Mt CO_2eq (Chen *et al* 2023). Currently, emissions from wastewater treatment and related activities account for approximately 5% of China's total non-CO_2 emissions and are expected to increase to 10% by 2050 (Lin *et al* 2019). If fully implemented by 2030, low-carbon technologies could decrease China's national urban wastewater emissions by 27% across their life cycles (Chen *et al* 2023). Specifically, sludge disposal offers the most significant reduction potential with a 62% decrease in life-cycle GHG emissions, followed by wastewater treatment and water reuse, which could reduce emissions by respectively 22% and 17% (Chen *et al* 2023). Concentrating solely on sludge management, two key approaches emerge. Firstly, employing methane harvesting technologies for efficient CH4 capture from sludge in anaerobic digestion. Secondly, choosing sludge disposal methods like incineration or recycling into building materials, which have a

[2] https://www.wien.gv.at/spezial/klimafahrplan/

lower carbon footprint than landfill disposal (Zhao *et al* 2023). The implementation of circular economy principles and low-carbon technologies in urban wastewater management, especially in rapidly urbanizing countries like China, exemplifies a strong commitment to sustainable water use and carbon neutrality. These initiatives can offer important models for regions, especially in developing countries, grappling with similar challenges in the urban water-climate nexus, thereby making a significant contribution to global sustainability efforts.

4. Systems transformation

Rapid and large-scale system transformation is necessary to achieve ambitious mitigation and adaptation outcomes. Such transformation would include actions **avoid strategies** that can significantly avoid or reduce energy and material demands for e.g. teleworking can reduce the need to transport. **Shift strategies** involve switching to more efficient service provisioning systems and technologies, such as transitioning from fossil fuel-based to efficient renewable energy sources in buildings and supporting public transportation. **Improve strategies** entail enhancements in the efficiency of available technologies, including the efficient design, construction, retrofitting, and strategies to reduce and alter energy and material consumption through material substitution, as well as electrification in transportation. In the subsequent sections, specifically in 4.3 and 4.4, we applied the Avoid-Shift-Improve framework.

4.1. Energy systems

The number and diversity of factors driving urban energy use, their complex interactions, and the linkages to other services and infrastructures render the transformation of urban energy systems a challenging endeavour. The framework for analysis and action provided by the Global Energy Assessment (GEA 2012) includes a city's natural environment (geography, climate and natural resource endowments), its socioeconomic conditions (income, demographic characteristics such as age composition and household size), its position in the regional, national and international economies, the urban form and functions comprising the built environment (entire building stock, the types and uses as well as the design and thermal integrity of buildings) on the one hand and the urbanization patterns (density and location, diversity and segregation of urban activities), and prominently features of its energy systems including institutions and physical assets.

The natural environment of urban settlements determines the boundary conditions for the energy needs and the local energy supply options for urban societies. Some geographical attributes (location, altitude, volcanic and tectonic landforms) are given and stable over the long term, others like climatic conditions (such as temperatures, winds, precipitations), hydrology (runoff, streams, lakes, ground water), the soil layer and natural vegetation might change over decadal scales due to natural and, more recently, anthropogenic reasons. The associated natural resources (atmospheric, surface and mineral) provide opportunities to satisfy human needs depending on the technological abilities to harness them. There is little scope for city dwellers to change, let alone transform, these conditions, hence the principal approach is adaptation in most cases and, in some cases, mitigation in the context of given geographical attributes and resource endowments.

Some socioeconomic attributes of cities evolve from robust underlying development patterns and are difficult to change while others stem from looser social phenomena and are more amenable to change. The higher the national per capita incomes, the larger shares and the more affluent groups of their populations live in cities. Higher incomes lead to the consumption of larger amounts and more convenient forms of energy services both directly and indirectly, although the higher population density enables more efficient provision of services and infrastructures. Moreover, incomes as a driver are intertwined with demographic and behavioural features. Higher incomes are associated with smaller household sizes in terms of person/household and larger per capita living areas on the one hand and more energy-intensive lifestyles on the others. While it appears to be challenging to change the former, there might be a larger scope to transform the latter (see 5.2).

The position of a city in the regional, national and international economies and its interchange of goods and services in this web profoundly drives energy use and GHG emissions whereby local transformational changes can deeply modify its entire economic structure. Depending on the types of key sectors in a city's economy and the associated technologies, GHG emissions reductions can be achieved by sector-internal transformations (e.g. technology switch) or structural changes in which major emitters are shut down and migrate out, albeit with a range of employment, income and other implications.

The opportunities and costs of transformative changes in energy systems of cities differ widely across the range of urban development patterns. The urban form and functions of a city encompasses a wide range of attributes that strongly affect GHG emissions and are essential objects of transformative changes (see 2.2). Large potentials at low costs to establish near- or even net-zero-emissions cities are offered at *emerging* urban areas where new low-carbon infrastructures can be built, compact, co-located and walkable areas established, green and blue endowments preserved, and mixed land use patterns designed. Some of these possibilities are also available in *rapidly growing* cities: co-locating residential and employment areas in compact urban enclosures, leapfrogging to highly efficient and low-carbon technologies, and electrifying urban services. Transforming the energy systems in *established cities* can be challenging and more expensive but certainly possible by increasing urban density (towards compact and diversely used areas), upgrading the energy infrastructure, and replacing or retrofitting buildings. Costs tend to be lower if these interventions are scheduled as part of the regular maintenance, upgrading and renewal cycles. The largest mitigation potentials from spatial planning, urban form and infrastructure are assessed to be available in emerging and rapidly growing cities, while those for electrification and net-zero-emissions are available in all urban forms and growth types (Lwasa *et al* 2022).

Transformation of the physical constituents of urban energy systems is a core element of mitigating climate change and spans from resources and transformation technologies to transmission infrastructure and service delivery. While a city's urban form and development, its socioeconomic characteristics and embedding in external economies as well as its natural environment largely determine the demand for energy (except the energy resources drawn from the environment), the energy system per se principally constitutes the supply side and holds the potential for truly transformational changes. They include electrification of energy services in mobility, especially public transport, thermal comfort services such as heating and cooling systems (particularly renewable energy-based heating and cooling networks), decarbonizing energy and electricity flows, and more broadly progressing to net-zero materials (see section 4.3 and 4.4). Renewable energy sources play a particularly important role (Ulpiani *et al* 2023b). Examples include roofs, terraces and even walls increasingly used for PV power generation (Clarke *et al* 2022, Denton *et al* 2022). Maintaining crucial energy infrastructure networks and services requires adaptation action to enhance the resilience of power systems and improve the reliability of energy supply even under extreme weather events (Adelekan *et al* 2022).

Transforming the institutional features of urban energy systems can profoundly modify energy demand patterns, technological choices and supply arrangements. Demand side management can augment the flexibility of the energy system and hence accommodate greater shares of intermittent energy sources. City, district or locality scale energy organizations of urban residents can invest in energy systems and become prosumers that enable demand flexibility, energy storage and renewable energy production and become important actors in urban energy markets (see 5.3 and 5.4). Key enabling prerequisites for these and many other similar transitions are properly reformed urban policies, regulations and spatial planning as well as properly rearranged governance and institutional frameworks (Babiker *et al* 2022) (see 4.6 and 5.1).

SDGs provide a useful framework for integration in designing and implementing the transformation of urban energy systems across sectors and scales with adequate attention to mitigation and adaptation needs. The broader SDG context is required to foster synergies and avoid, or at least minimize, possible trade-offs in pursuing a balanced portfolio of options for urban energy transformation. Yet this demands a comprehensive planning of urban forms and structures and integrated local policies that combine urban functions (e.g. housing, jobs, businesses) in spatial planning with promoting electrification and renewable energy in energy system transformation (Denton *et al* 2022). Integrated urban planning should also provide for coordinated adaptation and mitigation by mainstreaming climate change issues (Adelekan *et al* 2022) (see 6.1 and 6.2).

4.2. Land, water and food

Land provides the principles of human basic needs such as food supply, freshwater, energy, and other necessary ecosystem services. However, humans have already impacted more than 70% of the global land surface (IPCC 2019). Urban expansion is projected to lead to conversion of cropland, resulting in losses in food production (IRP 2018) and impacting ecosystem services and biodiversity (Li *et al* 2022, Simkin *et al* 2022). This can lead to additional risks for the whole food system. To reduce these impacts, urban and peri-urban food production and management of urban expansion are needed, as well as an increase in urban green infrastructure that can mitigate climate risks in cities (IPCC 2019). There are many synergies between adaptation and mitigation benefits in agriculture, forestry, and other land use. Community-based agriculture, landscape diversification and urban agriculture can be effectively linked to regional climate change mitigation and adaptation strategies, as well as increasing local food security and health benefits (see 6.1). Demand-side measures, such as shifting to sustainable and healthy (such as plant-based) diets and reducing food waste, can also play an important role in transforming overall urban supply and demand systems (IRP 2019, IPCC 2023a) while increasing human wellbeing (Creutzig *et al* 2022). Inclusive decision-making inviting indigenous people and local communities can create great insights into local production and lifestyle options throughout the local human systems (see 5.2). Increased desertification mostly impacted in Asia and Africa regions while North America, South America, Mediterranean, South Africa, and central Asia have huge risks by increase of wildfire. Sea level rise and cyclones are projected to increase land degradation, these combinations will significantly affect the human lives and their ordinary basic needs, which may also lead to regional human conflicts (IPCC 2023a, IPBES 2019).

The recent pandemic (COVID-19) revealed the vulnerability of urban systems in many regions of the world, particularly in terms of food and clean water security for human needs. It was evident that the most globally vulnerable regions with poor basic infrastructure were severely affected. The lack of basic services and the imbalance between supply and demand have a huge direct and indirect impact on quality of life and well-being (Guida and Carpentieri 2021). While forty-five countries required external food aid, food waste increased due to limited access, storage capacity with insufficient infrastructure for supply logistics, and food price volatility, further widening global and regional inequalities (Carducci *et al* 2021). On the other hand, disasters, extreme weather events and climate change often have multiple and long-lasting impacts: deterioration of animal health, contamination of aquaculture facilities, loss of crops, outbreaks of disease or destruction of irrigation systems and other infrastructure. Such impacts are particularly severe in the Least Developed Countries (LDCs)s, where agriculture is the backbone of the economy, contributing up to 20-30 per cent of national GDP and employment (FAO 2021).

Access to water and sanitation is essential for resilient cities, but urban water security is also strongly affected by climate impacts. Freshwater scarcity directly affects the urban poor and residents of informal settlements who do not have sufficient access to water infrastructure (Drangert, 2021). These problems are severely constrained by financial limitations (WHO 2021a).

Furthermore, water, food and energy are highly interconnected, so these systems need to be considered as nexus resources and functions within and across cities and regions (Oki 2012, Van Vuuren *et al* 2019, FAO 2014). Figure 6 describes the impacts of COVID-19 on the water-food-energy nexus in Bhutan. Urban areas were significantly affected by the lack of basic access to food, while rural areas were more affected by the lack of access to basic infrastructure such as transport and health care centres. There were also problems with delays in the implementation of mitigation actions to achieve the NDCs.

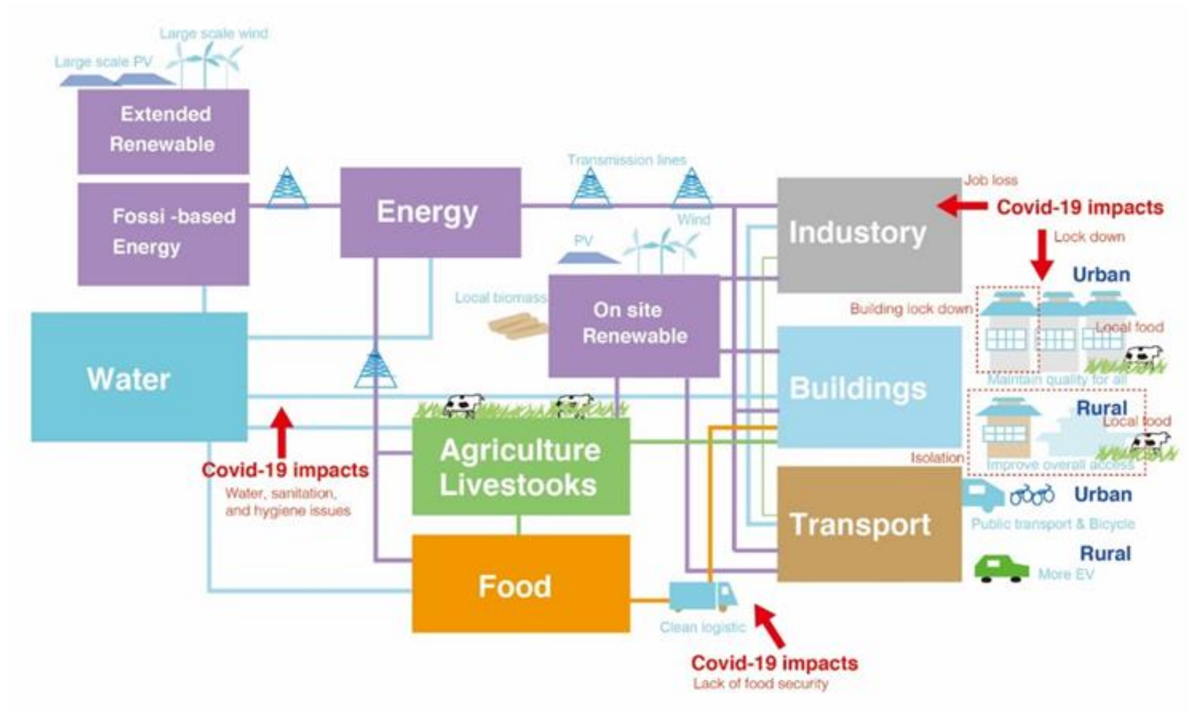

Figure 5 *The COVID-19 impacts on the water-food-energy, and other key mitigation sectors in Bhutan. Source: (Kamei* et al *2021b)*

Cities can be transformed and enhanced by the variations in climate action and comprehensive sustainable development strategies including new innovations and technologies (TWI2050 2019)(see 5.3). The latest consumption-based approach can project a potential saving of 19 billion m^3 of freshwater consumption and a reduction of around 460 m^2 of land degradation per year in C40 cities through sustainable transformation of food consumption (C40 2019). The EU's Farm to Folk strategy is a very comprehensive approach to the whole supply-demand cycle, which strengthens local security and resilience as well as local cultural and social assets (European Comission 2020). Localised, circular urban associated with more decentralised urban forms and functions systems can greatly support intra-urban resource flows and supply resilience, rather than the cross-border domestic flows. The future scenario of Japan built environment developed two alternative sustainability scenarios (SSP1), which include decentralised service infrastructure systems with integration of nature-based solutions, and a more centralised service system that clearly separates served and servant functions (Kamei *et al* 2021a) (see Figure 7). However, with the evolution of the digital society, these factors and the location will be influenced by more human activities. Therefore, new forms of production, recycling, and sharing systems may emerge with more social and technological innovation. The key is to ensure that all local people, including the most vulnerable, have access to basic human needs, which is still very challenging and requires very comprehensive approaches to technical, financial, political and governance systems.

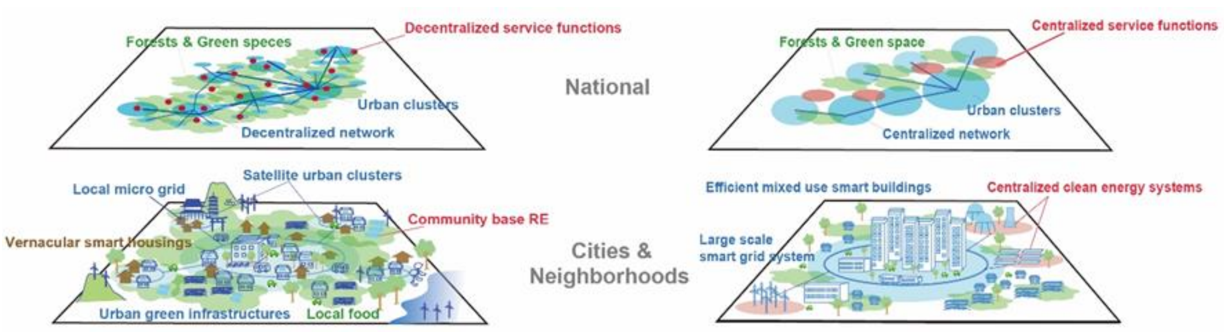

Figure 6 *Alternative urban transition scenarios in SSP1 Japan. Urban functionalities, production & supply systems have different configurations. Both systems have benefits and trade-offs. Source: (Kamei* et al *2021a)*

Venice is a unique example of island isolation and insufficient food production, where the most challenging food and service security was experienced during COVID-19. On the other hand, Mexico is an example of how rapid urban expansion increases the vulnerability of basic access to human needs. Such rapidly urbanised city requires integrated approaches of mitigation and adaptation measures for the basic of their urban infrastructures.

Box 3: Venice case study

The historical city of Venice and the inland settlements located in its lagoon represent a particularly complex and fragile socio-ecological environment (D'Alpaos 2010). Its natural and landscape components are essentially linked to the urban environment that, despite a declining residential population counting now less than 50.000 inhabitants[3] suffers the pressure of millions of visitors every year. The peculiar lagoon environment, with its biological cycles and the daily tidal flows, strongly influenced the built environment, that resulted in the development of the different areas in accordance with the activity to be supplied. Residential planning and tourist-related businesses were prioritized on the main islands, while other peripherical lands were devoted to food provisioning, such as agriculture activities in Sant'Erasmo and Vignole, as well as extensive aquaculture (Stocco and Pranovi 2023). However, intense human activities causing water and land pollution, exacerbated by climate change impacts, represent a constant and increasing threat for the survival of local agri-food and fishery enterprises. Pre-and post-Covid 19 data, show that mass tourism activities and water traffic are responsible for the majority of the pollutant in the lagoon waters. This, along with severe erosion and rising sea-level, flooding both urban and agricultural areas, act as a barrier to the development of sustainable agricultural and fisheries practices. In the past years several grassroots activities emerged with the support of conscious consumers to provide a new environmentally and socially sustainable business model for food production in the Venice lagoon. Challenges nevertheless emerged in relation

[3] Venice Municipality, Demografic data on residential population https://www.comune.venezia.it/it/content/serie-storiche

to a fast-growing demand for local and genuine produce, lack of funds for infrastructure development of small agriculture enterprises in a land with a vocation mainly toward touristic activities, and increasing cost to insure the crops against risks such as droughts and floods (Ma *et al* 2020). Renewed attention to sustainable peri-urban agricultural production would enhance agricultural entrepreneurship, preserving the agrarian vocation of the hinterland at the same time diversifying food distribution, strengthening local trade and distribution methods compatible with the city capacity.

Box 4: Mexico city case study

Mexico City has estimated its net-zero scenario and worked to define its climate actions to achieve the goal by 2050. The city has extended its great efforts on the transformational climate initiatives under the C40's Climate Action Implementation Programme. This programme includes energy, transport, and integration of governance structures, as well as significant improvements in air quality, green growth and the wellbeing of residents. In line with the major transformations in the transport and energy systems, which are the top priorities in Mexico City, the water system and waste management are emerging as very important issues in the city (Mexico City 2021). In the water system, recent urban sprawl has caused serious cross-cutting problems in providing the basic access for local residents. First, inadequate infrastructure and water storage networks. Second, land subsidence based on the use of ground water, thus the monitoring and planning of sustainable use of existing ground water management is an urgent issue. The other important issue is water disaster prevention. The city has also improved the conduction capacity of rivers, lagoons, and canals, as well as the improvement of the drainage networks. The green infrastructure rehabilitation program has a great positive impact on soil retention, water and watershed recovery. Resilient and equitable land use planning has been a major focus of the city government to maintain its adaptive capacity (Mexico City 2016). On the other hand, circular economy approach with sustainable waste management and agri-food system has been well established by the city under the circular economy law. These also include an integrated approach to sustainable land use, energy generation from waste for a sustainable energy system, and the preservation of urban green spaces and biodiversity for local food production (Mexico City 2021). Although the COVID-19 has impacted on the health of the city's residents and employment opportunities, and making the city's economic recovery more difficult, the Mexico City has great potential for its resilient and equitable sustainable development with a blessed land and warm climate, integrated policies involving all stakeholders can play the significant roles to develop the appropriate and innovative solutions for long-term future.

4.3. Buildings

Buildings and construction account for nearly 40% of global energy-related CO_2 emissions (OECD 2022a). Emissions occur in construction from carbon-intensive materials like cement and steel, and during operation, when energy is used for space heating, cooling, and other end-uses along with refrigerant leaks from cooling systems. In the global south, an unprecedented expansion of the building stock is expected as population growth and urbanization advance (IEA 2019). Promoting buildings with low energy- and material-demand is therefore key to limit future energy and emissions while providing improved access to shelter and thermal comfort (Mastrucci *et al* 2023). In the global north, the mitigation potential largely depends on the renovation and transformation of existing inefficient buildings that will still be standing in the future decades (Edelenbosch *et al* 2021). To decarbonize buildings, a holistic approach is needed and should consider the whole life-cycle of buildings. Demand-side strategies, commonly classified into Avoid, Shift, and Improve strategies, hold an estimated mitigation potential of 61% globally in 2050 compared to a baseline scenario (Cabeza *et al* 2022, Creutzig *et al* 2022). These strategies not only can reduce carbon emissions but also bring co-benefits like clean air, improved health, affordable energy, and more jobs (Creutzig *et al* 2022, Steinemann *et al* 2021, UNEP 2019a).

Avoid strategies

Sufficiency measures entail strategies to reduce energy and material requirements, such as restricting the growth of floor area and optimizing room temperatures for heating and cooling (Sandberg 2021). This can lead to important co-benefits at the urban level, such as reducing waste heat of air conditioners, the urban heat island effect, and pollution from burning fossil fuels for heating (Finn and Brockway 2023, MacNaughton *et al* 2018, Baniassadi *et al* 2022). **Behavior and lifestyle changes** can play an important role in driving energy demand reductions (see section 5.2). **Reducing the floorspace of buildings** lowers material requirements for their construction, energy for space heating and cooling, and built-up land area (Levesque *et al* 2019, Pauliuk *et al* 2021). Fostering co-working, and co-housing, can facilitate the reduction of per-capita floor space and sharing of services (Ivanova *et al* 2020). Urban planning strategies supporting **compact buildings and urban forms**, e.g. switching from single-family to more compact multi-family housing, are critical to avoid sprawling while leveraging synergies in mitigation across the buildings and transport sectors (Creutzig *et al* 2022, Wiedenhofer *et al* 2018) (see section 4.6 and 4.4). **Nature-based solutions** have high potential to address both mitigation and adaptation challenges while offering a range of co-benefits (Atanasova *et al* 2021). Green roofs and facades absorb CO_2, improve air quality, and improve urban well-being (Privitera *et al* 2021).**Circular approaches** offer important opportunities to avoid waste, (see section 4.5) while reducing the needs for virgin raw materials (Hossain *et al* 2020, Pauliuk *et al* 2021). **Repurposing existing buildings** can generate 50-75% fewer emissions than new construction (UNEP 2023b). **Dematerialization, lightweighting design, and urban mining strategies** including recycling and reusing of materials from urban buildings at the end-of-life, contribute to reduce both demolition waste and need for new materials (Koutamanis *et al* 2018).

Shift strategies

Electrification and transition from fossil-fuel-based to efficient renewable energy sources for heating, cooling, cooking and lighting is crucial for GHG mitigation (Daioglou *et al* 2022), with technologies like heat pumps and super-efficient cooling appliances playing a vital role. **Shifting away from non-clean cooking and heating fuels**, such traditional biomass and coal, particularly in developing countries, not only is crucial for mitigation but can also help reduce poverty and has important health co-benefits in reducing indoor air-pollution (Anenberg *et al* 2013, Pachauri *et al* 2021). **On-site renewables**, such as solar PV, wind turbines, city-integrated distributed generation, and micro-grids can improve reliability of energy supply systems while reducing carbon footprints (Chan *et al* 2017) (see 5.3). **District heating and cooling systems** provide further opportunities for sustainably meeting the energy demand of buildings, especially in densely populated urban areas (Lake *et al* 2017).

Improve strategies

Improve strategies refer to improvements in the **efficiency of available technologies** and can entail 30% to 70% of the GHG emission reduction potential in buildings (Creutzig *et al* 2022). **Energy-efficient building envelopes and passive houses**, including insulation and other passive building envelope strategies adapted to the local climate, can reduce operational energy demand and improve indoor comfort (Sadineni *et al* 2011, Dequaire 2012). Top priorities for decarbonizing buildings include adopting **energy-efficient and low-emissions technical systems**, such as heating, ventilation and air-conditioning (HVAC) systems. In addition, promoting energy-efficient appliances and lighting, particularly in developing countries where appliance ownership is increasing rapidly, is essential (Parikh and Parikh 2016). Tailored strategies are required for decarbonizing new and existing buildings. **Net-zero energy buildings** can be achieved for most building types and climates at costs in the range of conventional building construction, and are crucial for achieving net-zero targets (Ürge-Vorsatz *et al* 2020). **Building retrofitting strategies** vary depending on the climate (Kennedy *et al* 2014) and focus on reducing heating and cooling demands. Governments can raise awareness and educate the industry by renovating public building to a zero-energy standard**. Smart homes and the Internet of things (IoT)** can provide new control functionalities for optimizing building operation and supporting user decisions and behavioural changes, offering energy saving potential of 10-40% (Al-Obaidi *et al* 2022, Wilson *et al* 2020, Mastrucci *et al* 2023). **Adoption of low-carbon and bio-based materials** can greatly reduce embodied emissions in building construction. Renewable bio-based materials like timber, bamboo, and biomass offer lightweight construction, low embodied emissions, and longer-term carbon storage (Churkina *et al* 2020, Zhong *et al* 2021). Well-managed bio-based materials could lead to compounded emissions savings of up to 40% in the sector by 2050 (UNEP 2023b). Policy and financial support is needed to ensure their widespread adoption. **Improving the decarbonization of conventional materials that cannot be replaced** is crucial to abate emissions embodied in buildings. This mainly concerns the processing of concrete, steel, and aluminum – three sectors responsible for 23% of overall global emissions today (UNEP 2023b) – as well as glass and bricks. Electrifying production with renewable energy sources, increasing the use of reused and recycled materials, and scaling innovation is essential to decarbonize the built environment along with transforming markets and building cultures. Electrifying production with renewable energy sources, increasing the use of reused and recycled materials, and scaling innovation is essential to decarbonize the built environment along with transforming markets and building cultures.

Various policy instruments and initiatives can address decarbonization in the urban buildings sector.

- **The significance of building codes in decarbonizing buildings:** Building codes are a powerful way to reduce future emissions from buildings, both operational and embodied. They allow for locally adapted designs that valorize local materials and climate knowledge. Local governments can implement low-carbon or zero-carbon building performance/energy standards and regulations or offer incentives and education.
- **Use energy information and behavior change to drive energy efficiency:** Awareness of individual energy consumption is a first step towards behavior change. Traditional energy-saving programs focus on technology and financial incentives. However, energy consumption behavior is not always rational. Therefore, nudges and neighborhood competitions can effectively encourage households to enhance their energy-efficiency by leveraging social and psychological triggers.
- **Leveraging policies and incentives to enhance building sector effectiveness:** Additional policies and financial incentives can improve the effectiveness of building sector decarbonization measures. This includes energy audits, city energy consumption and renewable energy potential maps, building energy efficiency codes, permitting process streamlining, green and net-zero goals, appliance efficiency standards, and tax incentives for energy efficiency and on-site renewable energy systems.

Cities globally are leading in decarbonization efforts, employing green surfaces like roofs and façades, to curb urban carbon emissions, enhanced cooling, and boost biodiversity. The three-pronged Avoid-Shift-Improve approach, outlined here, is crucial for decarbonization of the building sector. Integrating it into construction while respecting local cultures, is essential for emission reduction, human, and biodiversity conservation. Developed economies can renovate aging buildings, whereas emerging ones can use eco-friendly materials, avoiding carbon-intensive methods.

Box 5: Sustainable cooling

With three-quarters of humanity projected to face health risks from deadly heat waves (WHO 2015, IPCC 2021), **providing sustainable cooling for all** is increasingly urgent for urban areas and has important linkages with climate mitigation, adaptation, and multiple SDGs (Khosla *et al* 2020, Mastrucci *et al* 2022). **Building- and urban-level passive and nature-based solutions for cooling**, including cool roofs, green roofs, cool pavements, urban trees, pools and ponds, have a significant mitigation potential and can contribute to reduce urban heat island while improving thermal comfort (Nutkiewicz *et al* 2022, Santamouris *et al* 2017). Most organic materials can reduce urban heat island effects, due to lower heat capacity facilitating night time cooling, while improving in- and outdoor urban thermal comfort and reducing the need for air conditioning. With the global demand for cooling expected to triple by 2050 (IEA 2018), leading to increased GHG emissions, the Montreal Protocol expanded its focus to decarbonize the cooling sector through the Kigali Amendment (KA) by **transitioning to low-GWP refrigerants** (Khosla *et al* 2020, Purohit *et al* 2022). **Improving the energy efficiency** of refrigeration, air-conditioning and heat pump technologies during the KA transition to low-GWP refrigerants can potentially double the climate benefits of the HFC phase-down (WMO 2018). Enhancing energy efficiency not only reduces emissions but also offers climate and health benefits by mitigating air pollution associated with fossil fuel-based electricity generation, and decreasing heat stress-related mortality and morbidity (Feng *et al* 2023), even in the face of increasing cooling demands (Purohit *et al* 2020, Wang *et al* 2020, Watts *et al* 2021). Moreover, incorporating measures to **avoid** refrigerant leakage from cooling technologies and properly disposing of refrigerants at the end of their life can significantly diminish emissions, both prior to and following the transition to low-GWP alternatives to hydrofluorocarbon refrigerants.

4.4. Transport

Decarbonising the urban transport sector is crucial to reducing GHG emissions and improving city air quality (Hofer 2023). Urban areas are often significant sources of transportation-related emissions, accounting for approximately 12% of global GHC emissions (ITF 2023a). Therefore, the transformation of urban transport is essential for sustainable and livable cities. Here are strategies to achieve decarbonisation in the urban transport sector, classified into the Avoid-Shift-Improve approach:

Avoid strategies

Urban planning and zoning: Designing cities with mixed land use, high-density development, and proximity to public transportation hubs reduces the need for long commutes and encourages walking and cycling. Expand the implementation of the **15-minute city or superblocks** (Logan *et al* 2022, Lopez-Carreiro *et al* 2020) . This should be designed along with **Low-Emission Zones**, which restrict the entry of high-polluting vehicles and encourage cleaner transportation options (Hulkkonen *et al* 2020). Pontevedra in Spain, a city of around 100 thousand inhabitants, stands out as a successful implementation of emission reduction in the transport sector in the Global North. The city removed surface parking and calmed traffic across the city, limiting speeds to 30 km/h, adapting the pavement to slower speeds, reducing traffic segregation with priority to pedestrians and cyclists and introducing roundabouts. The town developed walking maps similar to metro maps to help people move quickly and promote **active mobility**. The impact of reduced mobility externalities, such as traffic, noise and pollution, has been immense and aligned with a solid public acceptance of the measures and improvement of the city's economy and vitality. Since 1996, CO_2 emissions have been reduced by over 70% (~88% downtown and ~47% expansion area) (Nieuwenhuijsen 2021, Jiménez-Espada *et al* 2023). Also, the Global South has been advancing in addressing the 15-minute city urban planning paradigm which can address multiple sustainability challenges in large urban areas in developing countries (Allam *et al* 2022). Examples of that can be found in cities like Bogotá, with the project Barrios Vitales

(‘Vibrant Neighbourhoods’) (Freudendal-Pedersen *et al* 2022). This strategy is fundamental in rapidly growing cities, aiming at avoiding long-term problems.
Figure 1 presents the very strong relationship between urban density and the energy consumption in private passenger transport and the potential of better urban planning to reduce transport energy consumption.

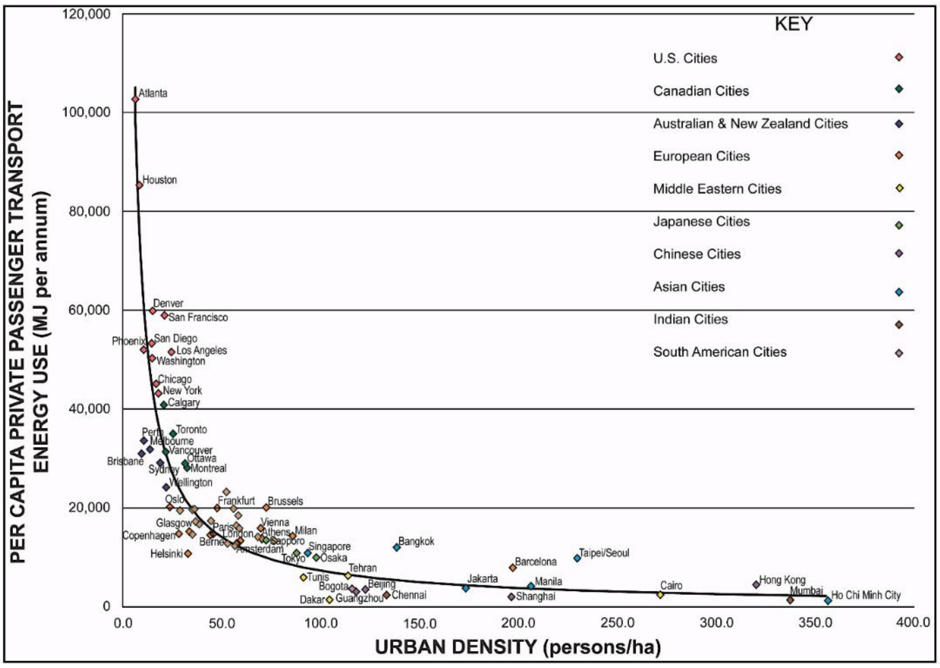

__Figure 7__ Energy intensity use in private passenger transport relation with urban density. Source: (Newman 2014)

Shift strategies

Behavioural change campaigns: Public awareness campaigns can encourage individuals to adopt sustainable transportation options and make conscious choices to reduce their carbon footprint. This has to be allied with the development of tools to easily provide a simple and steady comparison between transport alternatives and their attributes, costs and externalities. This strategy can be key in Rapidly growing cities, especially if compact and walkable.

Promotion of public transport and mobility services: Developing efficient and accessible public transportation systems, including buses, trams, subways, and light rail, and encouraging people to use shared modes of transport rather than private vehicles. This reduces overall emissions and congestion. Success examples can be found in cities with deep transformation of their public transport system. These benefits are more visible in developing countries where developments of full systems allow a better assessment of the benefits. A notable case is the development of the BRT TransMillennio system in Bogota, which led to the saving of 1.6 million tons of CO_2 (ITF 2020). Simultaneously, shared mobility, in its multiple forms, has shown how it can positively contribute to urban decarbonising passenger mobility, especially if promoting high load factors and disincentivising car ownership (ITF 2020). Integrating various transportation modes (e.g., public transit, biking, car sharing) into a unified mobility system simplifies urban travel and reduces reliance on private cars. MaaS can play a key role in smoothing the transition of car-dependent societies to a free-car landscape by providing flexibility, reliability, access and cost-saving potential (Zhao *et al* 2021). This strategy is more effective in established cities where stable land use occupation allows long-term infrastructure investments. The effect of different modes of travel on the climate can be measured in savings per passenger km. According to the International Energy Agency, the carbon intensity per passenger-km of public transport modes in urban contexts ranges between 20% and 30% of the values for private cars. This value can even decrease to less than 5% if cities invest in rail-based electrified solutions.

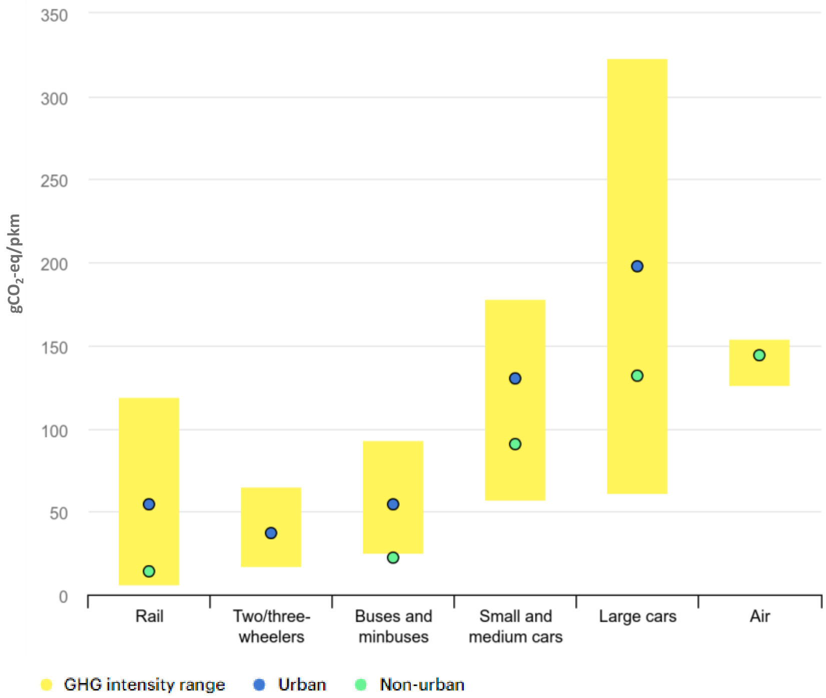

Figure 8 *Carbon intensity of transport modes by passenger-km. Source: (IEA 2020)*

Active mobility infrastructure: Creating safe and convenient infrastructure for walking and cycling promotes non-motorised transportation modes, reducing the need for short car trips and enhancing public health. Cities can reduce their transport-related greenhouse gas emissions by around 25% through combinations of more compact land use and the provision of less car-dependent transport infrastructure. Studies show the shift to walking and cycling significantly increases human wellbeing and health. Increased share of Non-motorised transport (NMT) improve quality of life (through lifestyle changes, individuals engage in physical exercises) and enhance social cohesion (Hanson and Jones 2015, Sagaris 2021). This strategy is more effective in Compact and walkable cities, especially in established.

Urban freight logistics: Implementing efficient last-mile delivery solutions, such as electric cargo bikes and consolidated delivery routes, can minimise emissions from urban freight transport (Aifandopoulou and Xenou 2019, Russo *et al* 2021). The development of infrastructure that provides safe non-motorised last-mile parcel-based deliveries as well as development of consolidation centres and urban lockers can reduce significantly urban freight emissions (McKinnon 2023). Also, the development of urban logistic micro-hubs[4], can allow increasing the share urban deliveries that can become non-motorised (Katsela *et al* 2022). This strategy is more effective in Compact and walkable cities but can establish a hierarchy in delivery cities in disperse and auto-centric cities.

[4] Microhub is a micro-consolidation logistics facility set near a final delivery point (within 1 to 5 km from the final destination). They are also called micro-fulfillment centers, delivery microhubs or micro-distribution hubs. It is a type of urban logistics space that links warehouse centers to final delivery points.

Improve strategies

Fleet electrification: Encouraging the electrification of private passenger vehicles and commercial and delivery vehicle fleets contributes to reducing emissions associated with goods transportation (Roca-Puigròs *et al* 2023). Offering incentives like subsidies, tax breaks, and free parking for electric vehicles can accelerate their adoption among individual vehicle owners (Whittle *et al* 2019). Transitioning buses, taxis, and other shared transportation modes to electric vehicles (EVs) can also significantly lower emissions (Zhou *et al* 2023). The lifecycle GHG emissions of battery electric vehicles (BEV) are approximately 65%. This is more relevant is disperse and autocentric cities where other solutions may be less effective in the short term.

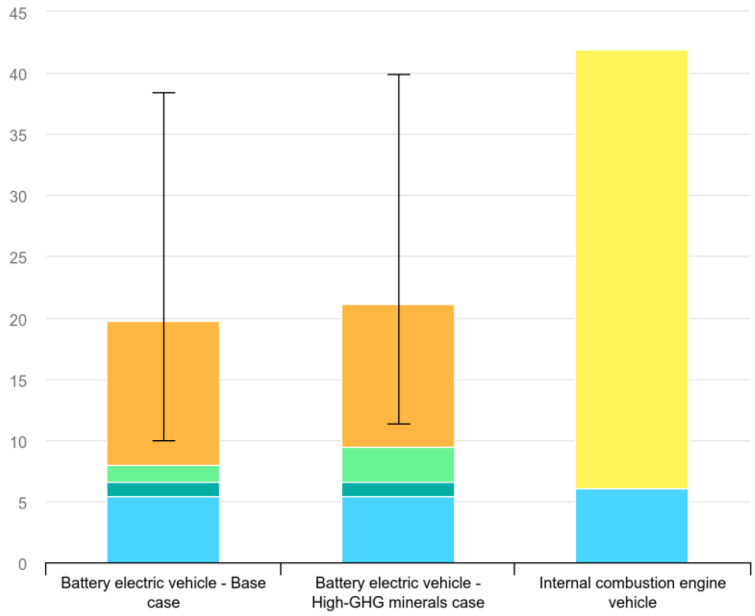

Figure 9 *Comparative carbon intensity of lifetime private cars by engine type. Source: (IEA 2020)*

Most of these policies should be harmonised to create better and more liveable cities. The International Transport Forum has also simulated the integration of all these technological, policy and behavioural adaptations within a complex urban simulation environment in a medium size European city to examine the outcomes of their urban mobility externalities and life quality (ITF 2022a, 2022b, 2023b). The results show that most of the decarbonisation measures for passengers and freight could be significantly efficient, reducing approximately 60% of CO2 emissions, more than 70% local pollutants, consuming proximately 30% less urban space, which could be used for other activities and improve life quality and generate also produce a 15% reduction of road crashes, while preserving similar levels of accessibility.

Decarbonising urban transport requires a holistic approach considering urban planning, technology, policy, and community engagement. Tailoring strategies to each city's specific needs and characteristics is essential for successful decarbonisation efforts (see more in section 5).

4.5. Waste Management

Urban areas are currently responsible for 70% of the global municipal solid waste (MSW) generation (Gómez-Sanabria *et al* 2022). High-income countries generate around 34% of the MSW per year, although they account for just 16% of the global population (Kaza *et al* 2018). High-income countries tend to cope with the quantities of MSW generation in cities by defining clear institutional responsibilities, investing in infrastructure, deploying policies and instruments, and developing inhouse capacity (Wilson *et al* 2023). In addition, the level of collection rates and waste management is at the same quality level between urban and rural areas. At lower income levels, waste collection coverage and the level of waste management tend to decrease and the waste management gap between urban and rural areas increases, being the rural areas often neglected (Velis *et al* 2023). For example, lower-middle- (e.g., Accra, Lahore, Colombo) and low-income (e.g., Kabul, Butwal, Lome, Dar Es Salaam) cities are estimated to have a waste collection coverage of 60% and 80%, respectively, while the collection coverage in high-income cities is > 98% (e.g., Dublin, Seattle, Osaka) (Kaza *et al* 2018). In general, most of lower-middle and low-income countries are still struggling to manage MSW due to the lack of suitable management systems, resulting from the shortage of funds, poor planning, poor implementation of law, absence of defined institutional responsibilities and lack of technology and expertise (Ghanimeh *et al* 2019, Kaza *et al* 2018, Manaf *et al* 2009). Although MSW collection in selected cities in the lower-middle - and low-income level have shown advances (Velis *et al* 2023), often, poorly managed landfills, open burning, and littering are the main ways of waste disposal (Gómez-Sanabria *et al* 2022, Kaza *et al* 2018). In general, rural areas tend to have low waste collection rates, leading in many cases to increases of open burning and illegal waste dumping (Gómez-Sanabria *et al* 2022). Emissions from landfills contribute about 15% to global anthropogenic CH_4 emissions (Höglund-Isaksson *et al* 2020), open burning of MSW contributes 11% to total global particulate matter less than 2.5µm ($PM_{2.5}$) emissions and 6-7% to total global black carbon (BC) emissions (Gómez-Sanabria *et al* 2022, Hoesly *et al* 2018, Klimont *et al* 2017) and estimates show that urban areas are responsible for 80% of land-based litter reaching aquatic ecosystems (Gómez-Sanabria and Lindl 2023). Therefore, a rapid global transition to **Circular Waste and Resource Management** systems will be crucial to deliver the Global Methane Pledge, the Sustainable Development Goals (specifically, SDG 11, SDG 12 and indirectly to all of them) and air and water quality targets. The following strategies highlight opportunities of transformation in the solid waste sector that can deliver co-benefits to climate, air and water pollution, sustainability and circularity thereby reducing negative impacts on human health, environment, and quality of life:

Reduction of waste generation: MSW generation tends to increase with GDP growth (Gómez-Sanabria *et al* 2022, Kaza *et al* 2018, Höglund-Isaksson 2012). As increases in GDP per capita are expected in cities in the global south, it is important **to develop policies and strategies to decouple waste from economic growth**. Currently, the global north (except for some countries such as The Netherlands and Japan) has not been able to reduce MSW generation per capita (Van Ewijk and Stegemann 2016). However, some examples of actions tackling the reduction of waste generation include the recently EU proposed target of reducing food waste generation by 10% in the processing and manufacturing of food and by 30% in retail, food services and household by 2030 (European Parliament 2023), legislation to regulate plastic bags and single-use plastic items (UNEP 2019b), although its implementation is highly uncertain specially in the global south, and the most recent Resolution to End plastic pollution by the United Nations Environment Assembly in 2022 (UNEP 2022). In addition, the EU Parliament recently adopted a stronger position on the "right to repair" setting new rules to encourage consumers to repair instead of replacing. Sellers would have to prioritize repair and provide spare parts for replacement. These rules aimed to reduce mass consumption and therefore avoid waste generation (European Parliament 2023). As waste generation is the outcome of a linear system of production and consumption, implementing circular solutions by industries, sectors and products through strategies such as rethinking and redesigning (maximizing waste prevention and minimizing resource input) is crucial in closing the loop and decarbonizing the systems (Kara *et al* 2022).

Waste sorting and collection: Although waste collection has increased in urban settings, waste collection services still need to be extended to cover all population in cities in the global south (Velis *et al* 2023). Most of the waste collected is mixed waste and therefore hinders the circularity of resources.

However, low-income cities could jump directly to the establishment of **source-separated waste collection systems** (wet/dry – food and garden waste/inorganics) to avoid the “technical fix” and move towards more circular systems (Wilson *et al* 2023)**.** This action directly supports the diversion of organic waste from landfills thereby avoiding future methane emissions and improving the quality of waste that can potentially be composted or anaerobically digested making easier to meet the technical standards for its use and the recovery of nutrients (see 4.7). In addition, source-separated collection of inorganics reduces its contamination having a direct positive effect in reusing and recycling rates of materials (circularity of resources).

Waste and resource management infrastructure: Local conditions and community integration are the most important aspects to consider when improving/developing waste management systems. It has been proven that not in all cases technologies deployed in the global north serve the propose in the global south due to the different waste characteristics (generation and composition), infrastructure, financial availability and technical capacity (Wilson *et al* 2023). The development of circular systems should include in addition to recycling facilities, the upgrading of uncontrolled-unmanaged disposal sites to sanitary landfills (or at least controlled) with leachate treatment and systems to capture landfill gas and a ban on open burning of waste. It also should ensure a **just transition of the informal waste and recycling sector and the development of Extender Producer Responsibility (EPR) schemes** (Wilson *et al* 2023). Improvements in waste management systems will directly reduce methane emissions, air pollution and land-based marine litter (Gómez-Sanabria and Lindl 2023).

Institutional arrangements and sustainable finance: The adoption of circular waste management systems will require well **established institutional responsibilities at city level and creditworthiness**[5] to implement the required polices and to unlock larger and long-term sustainable investments. Many cities in the global south have limited public budgets and therefore look for private financing and international support to develop new waste infrastructure (CACC 2024). Investments are local, but benefits are global (Wilson *et al* 2023).

Monitoring, Reporting and Verification Framework (MRV): The establishment of a MRV framework allows to collect data and information to identify current waste characteristics and management and to track progress of actions to achieve various objectives in a standardize manner. The global standardization of waste statistics and related information is needed to have a consistent and reliable information on emission mitigation actions, to measure progress on SDGs and to quantify the circularity of resources (Gómez-Sanabria *et al* 2022, Gómez-Sanabria and Lindl 2023).

4.6. Spatial planning and urban forms

Cities grew by 1.5% per year between 2000 and 2015, mainly in low- and middle-income countries (UN DESA 2019a). This has led to the complexity of urban boundaries as cities have grown beyond the boundaries of their municipalities. An urban agglomeration is defined as including the contiguous territory which consists of administrative boundaries and adjacent suburban and peri-urban areas. On the other hand, metropolitan areas can be defined as including socially and economically linked rural areas. (UN-Habitat 2020) Urban agglomeration patterns are different in different global regions, based

[5] The City Creditworthiness Initiative supports local governments leaders in building access to long-term financing for investment https://www.citycred.org/

on political, social, cultural, economic, technical, and climatic factors, such as regional complex organisations (Birch 2014). While these urban configurations have the potentials to shape the climate mitigation and adaptation strategies, they can also exacerbate the climate risks. (Rosenzweig *et al* 2018).

Transitions, nature of urban form, and basic infrastructure. Newman and Kenworthy (1996) presented the empirical evidence on the relationship between density and location of jobs and fuel consumption. In terms of energy efficiency and reduction of CO_2 emissions, the driving forces analysed were travel time and distance. They identified the relationship between home and workplace as a significant influence on, and key driver of, fuel consumption and emissions.

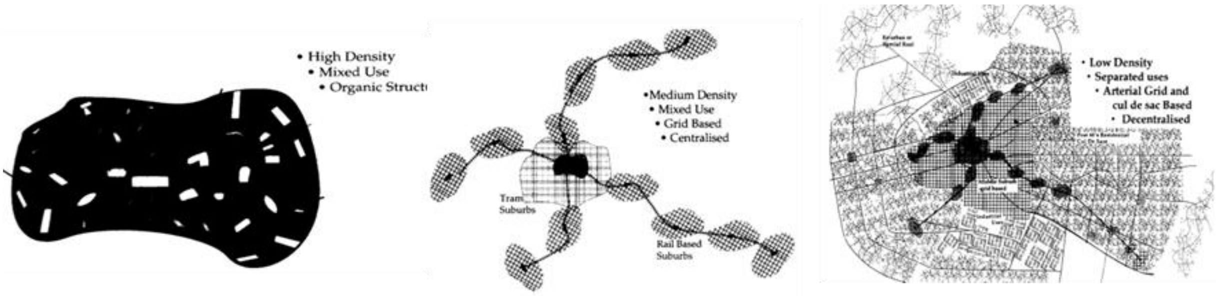

***Figure 10** Historical pattern of urban form. (Left) describes the historical walking city that existed in Europe until 1850. (Centre) is the transit city that developed in the industrial world between 1850 and 1940. (Right) is the automobile city that emerged after 1940. Source: (Newman and Kenworthy 1996)*

Newton(2000) analysed the relationship between technological change and urban form. In this analysis, he found that urban form has expanded along with new transport technologies, such as public transport, cars, high speed trains and digital systems. The distance that can be travelled within a given travel time budget was also examined as an influence on the size of the city (Marchetti 1994). On the other hand, Hall (1999) has observed new emerging phenomena of functional megaregions, which have different structure from the historical megalopolis, which is constituted mainly by economic activities. The emerging megaregions are constituted with a variety of service functions, such as agriculture, energy, local business, cultural space and green recreational spaces within the urban networks (Hall 2009). Cities are major platforms of consumptions. Technological innovation can also change the human lifestyles, urban networks, spatial functions and the physical form of cities (GEA 2012, Keirstead and Shah 2013, Batty 2018). Figure 12 shows an example of a future urban form transition analysis for Tokyo. SSP1 represents two alternatives: polycentric urban transformation can capture more diversity, historical identities, community vitality and quality public spaces, while monocentric urban forms capture more efficiency in energy use, especially in buildings and transport (Kamei *et al* 2016, 2019).

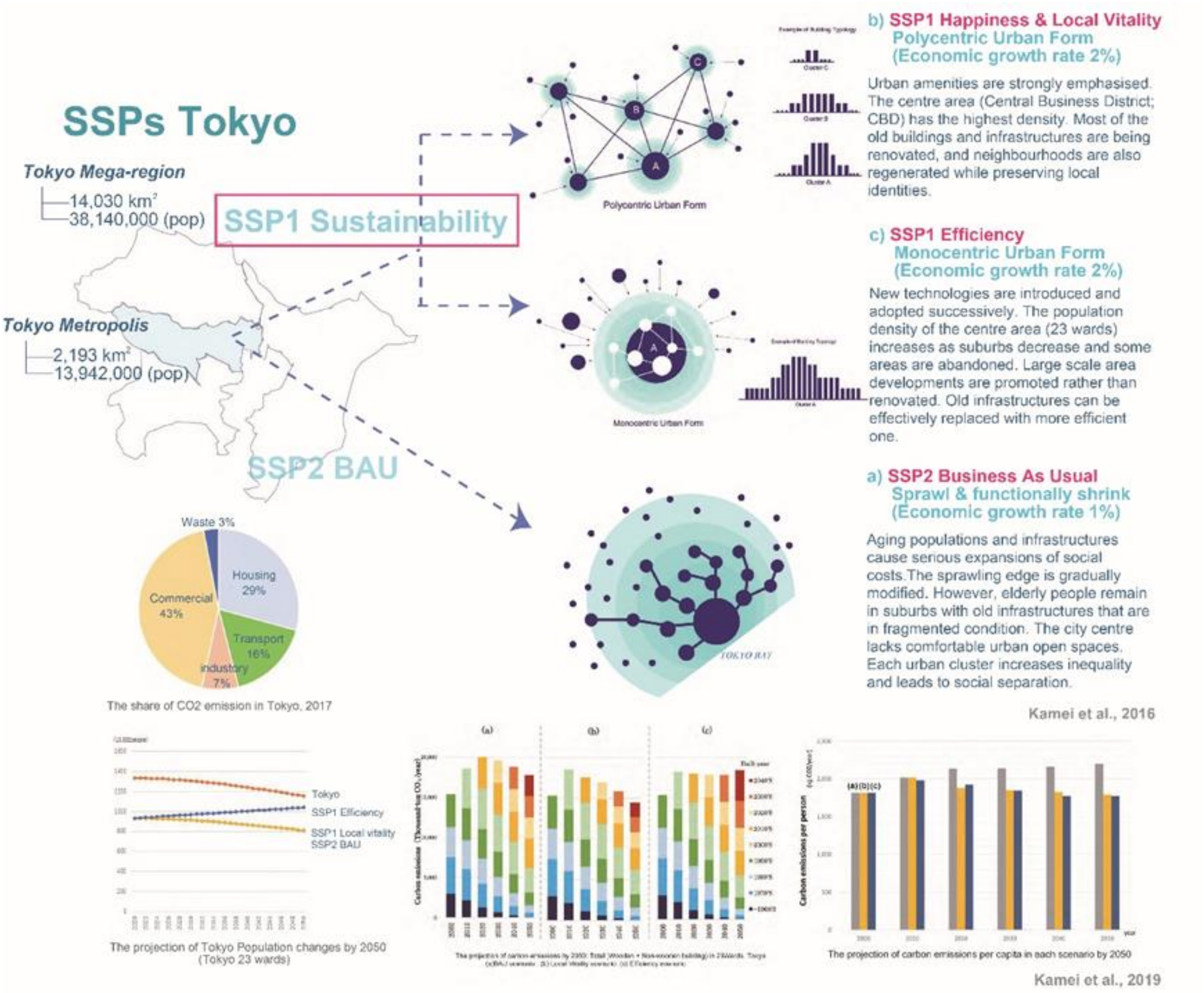

***Figure 11** Tokyo's alternative urban transition analysis, which applies the SSPs framework, shows carbon emissions in the building sector by 2050 in three scenarios (Kamei* et al *2016, 2019).*

Towards sustainable planning perspectives: key determinants of spatial organisations. In the last decades, rapidly growing middle-income countries in East Asia and Latin America formulate vast urban agglomeration which consists with polycentric semi urban and small villages (Asian Development Bank 2014). Advances in communications infrastructure, such as digital technologies, and their innovation in the 21st century are transforming human activities within cities, as well as travel patterns and distances (TWI2050 2019, Batty 2020). Urban form, density and functionality have a major impact on resource use. However, there are some trends of urban expansion and density reduction following increases in per capita income. The global survey showed that in 3,646 large cities with around 2 billion inhabitants, a 1.8% increase in urban land cover was associated with a 10% increase in GDP per capita (Angel *et al* 2012). The systematic approach to resource and energy use is a more significant driver of resource consumption. One of the key implications of urban efficiency may be a property of the shape of urban footprints rather than density (IRP 2018). In addition, harmonising the natural environment has great benefits for improving air quality, heat mitigation, carbon sequestration and disaster prevention. Furthermore, the connection with the Earth's natural system and biosphere can revitalise local natural resources, including local food, water, energy and other products, as natural land supports basic human needs, ecosystem functions and the overall well-being, including vulnerable and high-risk residents (IPBES 2019). The vernacular human settlements are well adapted to the local climate and resource use, which can minimise energy consumption through the use of natural ventilation, as well as providing sufficient living space (Kamei *et al* 2021a) (see Figure 13 SSP1 beyond growth scenario).

Green and blue infrastructure can provide vital functions in cities. Tree canopies reduce heat stress, improve the physical and mental health of residents, and protect local biodiversity (Keeler *et al* 2019). Urban water management ensures flood safety, protects property values, and provides active recreation for residents, which also reduces the adverse health effects of water pollution (Buckley and Brough 2017).

***Figure 12** An example of the future built environment with different scenarios of urban form transition in Japan, SSP1 beyond growth scenario is characterized by nature positive development & local circular economy (Kamei* et al *2021a)*

Box 6: Bhutan case study

Urbanisation has been accelerated with the recent rapid economic growth and urban development, while Bhutan's NDCs emphasise carbon neutral development in line with GNH perspectives (RGoB, 2015; RGoB NDCs, 2021). Rapid urbanization profoundly changed the lifestyle of Bhutanese. The number of motorcycles has increased from 30,000 in 2005 to over 86,000 in 2017 (MoWHS 2017). The National Environmental Commission (NEC) has projected that per capita carbon emissions will increase by more than 60% by 2030, mainly driven by the buildings, transport, and industry sectors (NEC 2012). On the other hand, the household expenditure in urban areas is twice as high as in rural areas due to the high cost of housing rent and daily services, widening the social inequalities (NSB 2017). Based on the analysis of Bhutan's sustainable path (SSP1), balanced urban-rural development, small-scale efficient infrastructure deployment such as small hydro power plant, community scale energy grid for RE mix, decentralized water treatment plant, sufficient food storage systems are key to sustain local natural resources, culture and heritage, labour force and quality of life (Kamei *et al* 2021c). Recent increases in natural hazards and the COVID-19 pandemic have further alarmed urban expansion, and unequal investment in large cities can increase rural vulnerability, degradation of forests (currently 70% of national coverage), and increase the risk of local basic needs (food, water and energy). Therefore, community-based local structural plans need to be developed to secure local resource production systems as well as local and national supply chain systems. Bhutan has made some urgent adjustments to its local structure plans to adapt to such social risks. Healthy living environments with walking and cycling, smart agriculture also need to be integrated into local development plans.

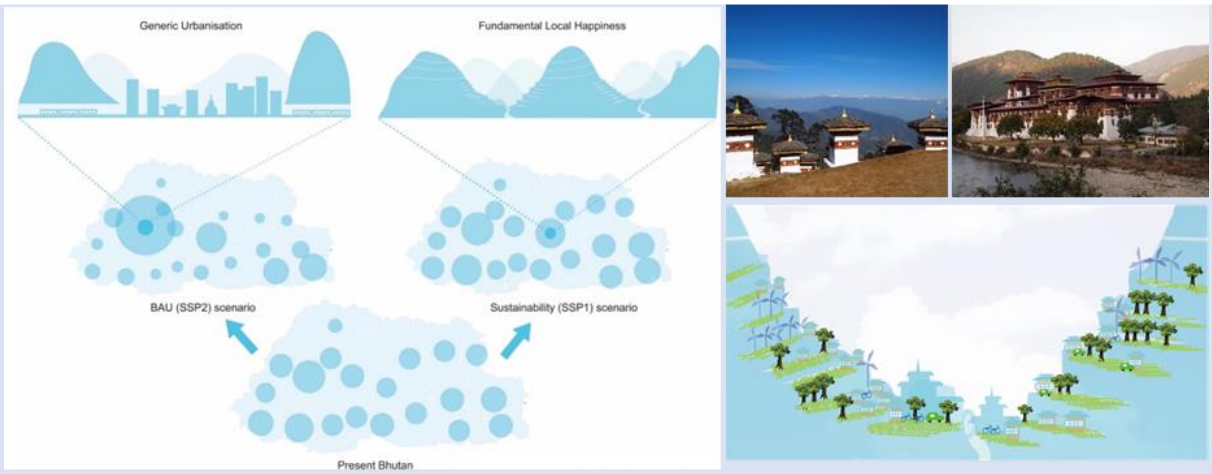

Figure Box 7 *Bhutan's future development prospects in SSP1 and SSP2 (left), and key features of local landscapes in SSP1 (right)* (Kamei *et al* 2021c)

4.7. Nutrients management

Nutrients such as reactive nitrogen (Nr) - comprising all nitrogen compounds other than molecular nitrogen, N_2 - are essential to grow food and hence sustain human life on earth. Anthropogenic activities have led to an excess of Nr compounds which adversely impact climate change, ecosystems and human health (De Vries 2021). Due to their high population density, urban areas are a place of high anthropogenic activity and consequently high Nr consumption with currently 79% of food being produced for cities (FAO 2023). Intensified Nr consumption also leads to intensified and potentially harmful Nr losses to water and the atmosphere. For Bangkok and Shanghai, for example, a high impact on urban water bodies was found with the pollution in Shanghai leading to the water being deemed unsafe for human consumption (Færge *et al* 2001, Gu *et al* 2012).
Urbanization, particularly in coastal cities, also emerges as a significant driver of eutrophication in marine ecosystems, primarily attributable to agricultural nutrient runoff into rivers, airborne inputs and wastewater discharges. Even in the case of the Baltic Sea, where approximately 72% of the total population in its catchment area is connected to tertiary wastewater treatment plants, an alarming 96% of its area falls below the estimated thresholds for achieving a Good Environmental Status regarding eutrophication, thereof also directly hampering the advancement of SDG 14.1 on marine pollution (HELCOM 2021, 2023). In addition to these observed ecosystem impacts, the increased exposure of urban population to Nr emissions negatively impacts human health. In 2019, it was estimated that globally, two-thirds of the 1.85 million new asthma cases attributed to nitrogen dioxide (NO_2) occurred in urban areas (Anenberg *et al* 2022).

Depending on local conditions such as industrial or agricultural production levels as well as population density, different Nr flows need to be addressed for a sustainable transformation towards reducing such environmental impacts, increasing recycling and improving the well-being of a city's inhabitants. A comparison of four different cities (two of them Chinese, one Polish and one Austrian) showed that, especially in the Chinese cities, largest Nr flows were linked to food production and potential threats to the environment and human health through high Nr input to urban plant areas (crop-, green- and horticultural land) while in the city of Vienna, for instance, the largest Nr flows were linked to food consumption showing high potential for nutrient recycling from wastewater (Kaltenegger *et al* 2023).

Urban nitrogen budgets (UNBs) play a pivotal role in identifying and prioritizing such central Nr flows that require attention (Kaltenegger *et al* 2023). In a budget approach, flows are assessed both between and within environmental pools, aiming to provide a holistic view of the environmental impacts associated with Nr. Guidance is derived from national budgets, using the stock-and-flow approach from the Guidance Document for National Nitrogen Budgets (UNECE 2013), which specifically covers Nr pools (sectors) such as 'air', 'water', 'households', 'wastewater', and 'industry. Through their multi-sectoral approach, nitrogen budgets allow to identify systemic solutions that target a root problem rather than simply transferring pollution between sectors and recipients. To mitigate underlying issues like eutrophication and soil acidification, several studies suggest a combination of measures. These include dietary changes (such as reduced meat consumption), which additionally improve human health (see Section 5.2), reduced use of synthetic fertilizer application, and improved Nr fertilization management (Zhan *et al* 2021, Cui *et al* 2022, Billen *et al* 2021).

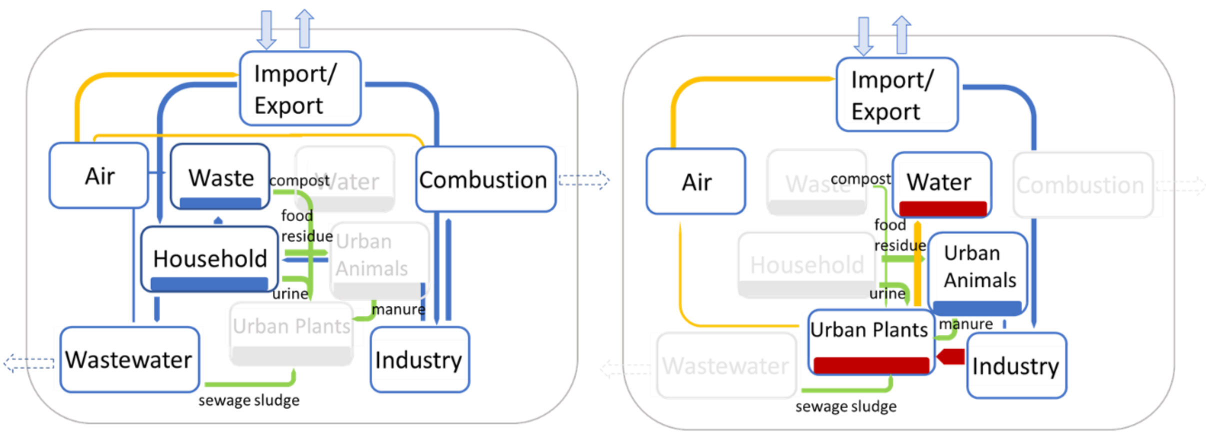

Figure 13 *Urban Nr budgets representing a more consumption-based system (left) and a more agriculture production-based system (right). Yellow lines mark Nr losses, red lines and bars mark potential threats and green lines mark potential for improved Nr recycling*

UNBs also contribute to the identification of Nr recycling opportunities. Wastewater from households, recognized as one of the largest Nr flows, holds substantial Nr recycling potential, as up to 80% of Nr in wastewater is denitrified and lost during treatment (Svirejeva-Hopkins *et al* 2011, Kaltenegger *et al* 2023). Using struvite precipitation, both nitrogen and phosphorus can be recovered from wastewater (Van Der Hoek *et al* 2018). However, recycling can start even earlier with urine recycling, as urine contains the largest proportion of nitrogen (90 %), phosphorus (50–65%), and potassium (50–80 %) among household blackwater (Hilton *et al* 2021, Rose *et al* 2015). Although industrialized urine treatment reactors are yet to be widely established, there are a few cases in France where innovative individual systems for urine collection and treatment have been implemented (Larsen *et al* 2021, Joveniaux *et al* 2022). In addition to wastewater recycling, increased separation and recycling of biodegradable waste through composting can enhance a city's circularity while simultaneously reducing methane emissions (see 4.5).

Box 7: Nitrogen losses and recovery

While the Austrian capital of Vienna pledged climate neutrality by 2040 and has put forward a climate plan, a smart city strategy, a heat island strategy and a heat action plan, most of these strategies only focus on Greenhouse Gases and do not consider Nr (Stadt Wien 2023). As Nr can be an environmental threat as well as an important resource, we took a closer look at the pathways of Nr through the densely populated city core (Vienna municipality) and the peri-urban surrounding area (administratively subsumed as NUTS-3 areas Vienna North and Vienna South). We identified significant differences in Nr flows and consumption patterns between these areas (Kaltenegger *et al* 2023). In the Vienna core area, the largest Nr flows are linked to human consumption of food and other goods, and their

subsequent disposal as waste and wastewater. More than 40% of Nr imported into the core area is converted to non-reactive N_2 through wastewater treatment. The city's surrounding area serves as a hub of agricultural and industrial production with over 50% of imported Nr being exported as products. These pattern differences in Nr flows pose distinct challenges and opportunities.
In the surrounding area, 13% of Nr import leaches into groundwater from agricultural land, leading to elevated nitrate levels in groundwater that need to be addressed to avoid adverse impacts on human health (BML 2023). In the core area, waste and wastewater represent a significant potential for Nr recycling. Recovered Nr from biodegradable waste, urine and sewage sludge has the potential to meet the entire mineral Nr fertilizer requirement of the Vienna core area and up to 60% of the requirement for the surrounding area (Kaltenegger *et al* 2023).

4.8. Cross-cutting: Smart cities and digitalization

Impacts of smart transition on CO_2 emissions

Proponents of the 'Smart Transition' outline a vision of the future in which mobility will be framed as a personalized service' available on demand, with individuals having instant access to a seamless system of clean, green, efficient and flexible transport to meet all of their needs (Docherty *et al* 2018). More or less, our world is in such a rapid transition. This subsection provides an overview of the impact of smart transitions in terms of CO_2 emission reductions. Arguably one of the most important aspects of smart transition is vehicle electrification. The impacts of the increase of the electric vehicles (EVs) depend on power supply configuration, vehicle mileage, drivers' behavioral characteristics, etc. (Guo *et al* 2022, Yap *et al* 2022). Combination with other technologies such as dynamic wireless power transfer (Shimizu *et al* 2020) and roof-top photovoltaics (Kobashi *et al* 2021) are suggested to be effective options toward CO_2 reduction. The second aspect is the shift from car ownership to use. Sharing services such as vehicle-sharing, ride-sharing, ride-hailing, and ride-pooling, as well as Mobility as a Service (MaaS), a user-centered framework for providing a portfolio of multimodal mobility services, have been introduced. At present, there are mixed findings on their impacts in the literature (Mouratidis *et al* 2019, Labee *et al* 2022, Zhu and Mo 2022). The third aspect is the introduction of autonomous vehicles (AVs), which has enormous potential to transform urbanization patterns and urban design. The literature in transportation and urban economics suggests that transportation and land use interact (see Figure 4.8-2, from (Yamagata and Seya 2013)), and therefore smart transitions may have a non-negligible impact on land use. Urban form is due matter in reducing CO_2 emissions (Section 4.6), so it is important to project such impacts. Amongst the scenario studies exploring how AVs may impact cities in the long term, several aspects of impacts on urban form have been considered, including parking (Stead and Vaddadi 2019). Take Japan, for example, 49% of cars in Yokohama are used only on weekends and remain parked on weekdays (Yamagata and Seya 2015). This means that land is not being used effectively and there is an excess use for parking space (Shoup 2021). There is both optimistic and pessimistic views about the impacts of AVs on land use and parking. A pessimistic view on parking includes that a growth in AV ownership and use leads to an increase in demand for parking spaces in the city, which leads to dispersed urban form. Simulation tool is do useful, to understand what may happen because of the introduction of AVs (Gelauff *et al* 2019). The impact of new mobility, such as urban air mobility, should also be evaluated (Park *et al* 2022, Yedavalli and Cohen 2022, Brunelli *et al* 2023), and we are developing a new urban model for this purpose.

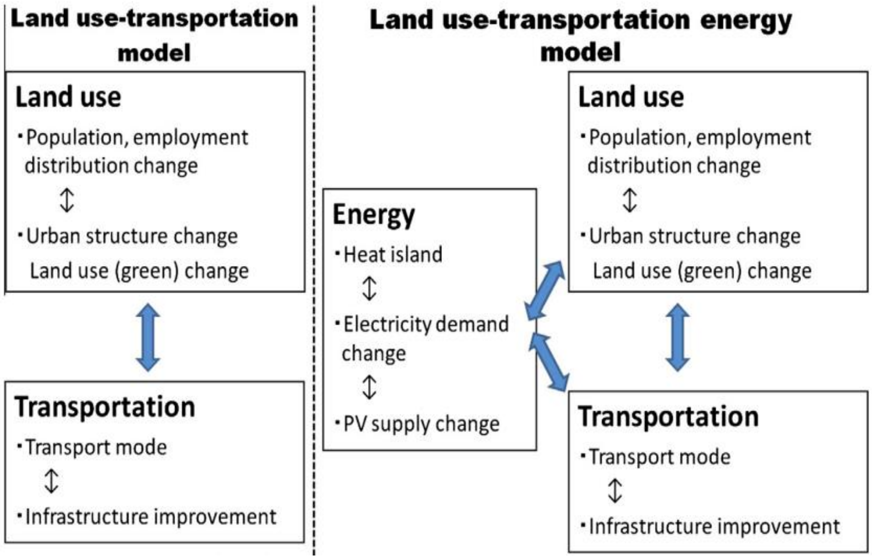

Figure 14 *Concept of an integrated land use-transportation energy model: possible interaction between land use-transportation and energy (Source: Yamagata and Seya, 2013, modified)*

Behavior change analysis using big data and AI methods

An increasing number of geo-referenced bigdata including remotely sensed images, people tracking data, vital monitoring data, and many others are nowadays available. Recent development of machine learning (ML) and AI algorithms enables us to apply these bigdata for modeling and monitoring complex urban phenomena and supporting urban management including monitoring, prediction, and simulation of people behavior, prediction of infection spread (Jiang *et al* 2022), urban design optimization Chang et al., 2019), and evaluation of risks related to environment, crime, and others (Adachi and Nakaya 2022).

In environmental literature, ML-based people behavior analysis attracts considerable attention in terms of its usefulness for urban environmental management focusing on carbon emission, energy use, and disaster risk. For example, an analysis considering building use and transportations of individual people helps evaluating energy use in individual buildings and road links that are useful for energy management. Through such an evaluation of micro-scale energy demand and supply, (Yamagata *et al* 2014, 2016) optimized local communities for sharing renewable energy through a ML-based optimization technique. Community clusters are allowed to vary over time dependent on urban activities and people behavior change to meet available renewable energy amount as much as possible with energy demand within each community. Their studies highlighted the usefulness of ML for energy management.

Consideration of future scenarios is an important topic in ML-based energy management. For example, a scenario with natural disaster will be useful for modeling people behavior change under disaster and evaluating its influence on energy resilience. Scenarios are also useful to draw changes in urban form, demographic structure, introduction of new technologies (e.g., wireless power transfer). Simulation of energy use considering detailed people behavior and optimize energy management through ML techniques such as surrogate modeling techniques will be an interesting future task.

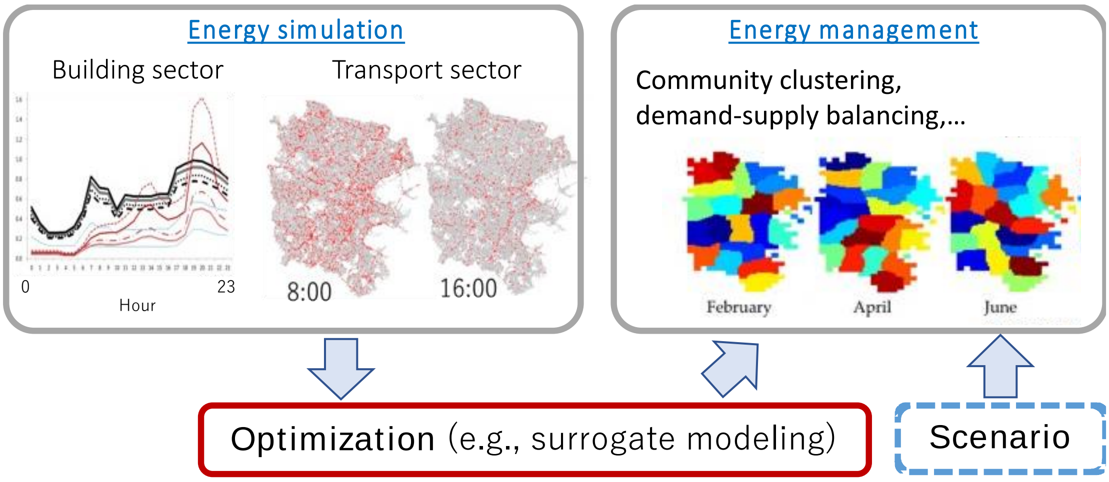

Figure 15 *Image of ML-based optimization for energy management. Through surrogate modeling, community clusters or other parameters characterizing energy management can be optimized based on energy simulation result*

GIS visualization of decarbonization policies

To achieve decarbonization in urban areas, it is necessary to gain a comprehensive understanding of the present situation and the impact of various strategies for urban development. A lot of data sources are available, offering detailed information regarding the spatial and temporal aspects of CO_2 emissions. (Creutzig *et al* 2019) summarized the potential of advanced technologies such as big data, artificial intelligence, and machine learning in addressing climate change within urban contexts. Furthermore, (Gurney *et al* 2015) emphasized the significance of assessing CO_2 emissions at a human scale for the purpose of formulating effective decarbonization measures, validating their efficacy, and influencing behavioral changes. (Yamagata *et al* 2017) made a pilot study on a visualization technique for urban CO_2 emissions using geographic information systems (GIS). Their "urban carbon mapping" method enables the visualization of trends over time and space by assessing CO_2 emissions at the level of individual buildings and road segments on an hourly basis (see Figure). These insights have step into an expanding stage with abundant spatio-temporal data and computing platform.

A digital twin environment will play an important role in decarbonized sustainable smart cities. An integration of GIS and BIM is rapidly growing to deal with broad and micro digital information (e.g., (Xia *et al* 2022)). This trend will be extended further with the development of international urban base-registries (e.g., OpenStreetMap Foundation and Overture Maps Foundation) and its openness. The coming environments and analytical techniques will help to simulate and visualize urban decarbonization scenarios at human scale. Its spatio-temporal detail visualization in digital twin environments will be useful to show the patterns of CO_2 emissions in urban areas, offering insights corresponding to the activities of the local people and for decarbonization policies of local stakeholders. These studies will also help to build a communication framework for carbon accounting in urban areas. (Ramaswami *et al* 2021) pointed out the lack of international consensus regarding the methods for accounting CO_2 emissions in urban areas. Consequently, various approaches have been explored, as reviewed by (Yin *et al* 2022). The digital twin environments will be expected to contribute to clarify and current situation and progress of decarbonization policies and carbon accounting.

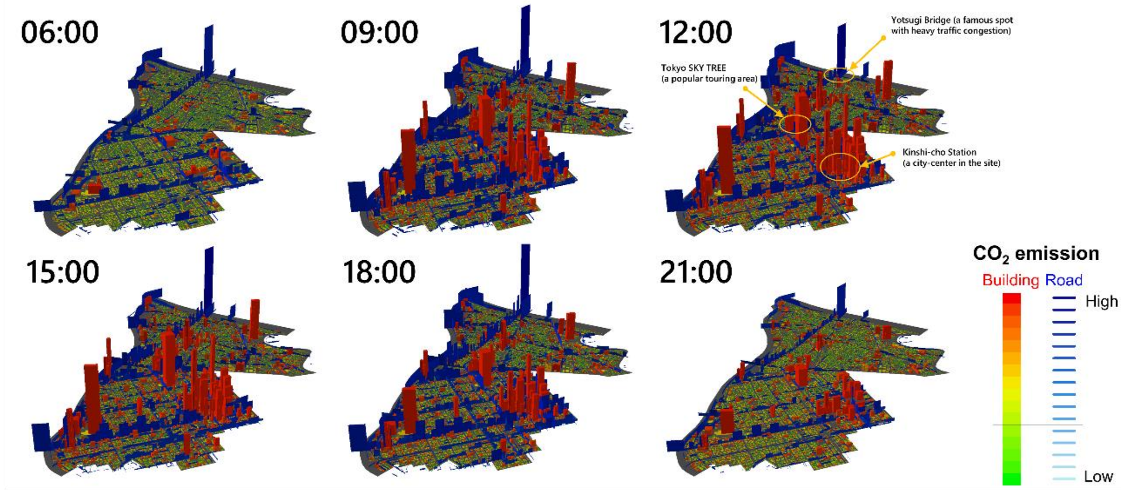

Figure 16 *An example of spatio-temporal detailed visualizations: urban carbon mapping (Site: Sumida ward, Tokyo, Japan)*

5. Enabling conditions for systems transformation

5.1. Governance and institutions

Many of the transformational changes outlined in previous sections require institutions (rules, norms and conventions) and governance (structure, processes and actions) arrangements that align the interests of actors within and across different levels of decision-making. Early studies on climate institutions and governance often concentrated on how to align the interests of national governments at the international level. This focus recently shifted toward institutions and governance forms that promote bottom-up solutions, with an emphasis on cities (Osofsky 2010).

In the context of climate mitigation and adaptation, cities have garnered significant attention due to their role as dynamic hubs of innovation and experimentation (see 5.3). They serve as testing grounds for pioneering regulatory instruments and novel climate responses that break from conventional approaches, making them invaluable sources for replicating successful practices (Larsen *et al* 2021, Joveniaux *et al* 2022). Successful examples include forward-looking emission trading schemes such as developed in Tokyo, Japan (Roppongi *et al* 2017) or Surat, India (Greenstone *et al* 2019), and transformations of the transport infrastructure (see Section 4.4) such as in Pontevedra, Spain (Jiménez-Espada *et al* 2023).

At the same time cities also **face challenges** when implementing and scaling climate solutions. Cities and municipalities often wait for nationwide adoption of key legislation before being able to implement necessary climate mitigation policies in the local context, as was for example the case with building codes in Canada (Burch 2010). In fact, nearly **every mitigation strategy encounters institutional hurdles** that must be overcome to facilitate their widespread adoption (Revi *et al* 2022).

Overcoming these challenges necessitates **governance structures** that enable cooperation of actors and transfers of resources across **multiple levels** (Betsill and Bulkeley 2006, Bulkeley and Betsill 2013). Forms of multilevel governance can motivate cities to adopt increasingly ambitious climate goals as appears to be occurring in Japan (See Box 9). A related approach to overcoming barriers is to build partnerships with rural areas to address resources concerns and develop scalable models of change (See Box 10 on The Regional Circular and Ecological Sphere).

In certain instances, the necessary support to overcome obstacles is facilitated through the collaborative efforts of multi-jurisdictional and multi-sectoral sub-national networks that exchange valuable insights from experiences in other cities. As of 2022, more than 1000 cities worldwide have reported their climate actions to the Carbon Disclosure Project (CDP), following a shared standard (CDP 2023). Additionally, over 12,000 cities globally have become active members of the Global Covenant of Mayors for Climate and Energy (GCoM) and committed to a variety of climate-related actions, encompassing mitigation, adaptation, and financial initiatives (Global Covenant of Mayors 2023), and in many instances these municipalities participate in multiple voluntary transnational climate initiatives (Hsu et al., 2022), such as for example C40 (C40 2023). These networks not only provide knowledge but also serve as sources of inspiration for cities to bolster their climate ambition (Davidson *et al* 2019). In addition to national-level support, **administrative capacity** and **network membership**, the added development benefits of climate actions or co-benefits can be key factors (in a much longer list) that might explain urban climate ambition (Eisenack and Roggero 2022). In fact, cities often craft solutions to climate that align well with development priorities like those covered in the Sustainable Development Goals (SDGs) (IGES 2023, Puppim de Oliveira *et al* 2017, Rabe 2007). To illustrate, cities in the United States such as Austin, Texas, have placed justice issues at the core of their Climate Equity Plan (City of Austin 2020).

Box 8: Surat cap-and-trade program

The state of Gujarat in India has launched the world's first clean air market for particulate pollution in the city of Surat. Since its inception in 2019, this innovative program has successfully reduced particulate pollution from over 150 coal-burning factories by approximately 24% (EPIC 2022), all without increasing operating costs for these industries. The Surat *cap-and-trade* program represents a significant shift in environmental regulation in India. In the past, the Gujarat Pollution Control Board (GPCB) relied on *command-and-control* regulations (Greenstone *et al* 2023), mandating industries to install specific pollution control equipment due to a lack of reliable emissions data. However, the *cap-and-trade* program aims to change this by allowing industries to find the most cost-effective ways to comply with pollution regulations. Under the program, industries that can reduce emissions at a lower cost can sell their excess emissions reductions to industries facing higher abatement costs. This system harnesses market forces to improve environmental outcomes.

The Surat program embarked on a journey to enhance pollution control by establishing continuous emission monitoring protocols and reliable systems. It furnishes real-time emissions data, bolstering enforcement. The *cap-and-trade* system places a limit on total particulate emissions from industries, preventing pollution from surpassing defined thresholds. The Surat model has the potential to broaden its scope to address various pollutants and regions across India, serving as a potent tool for reducing pollution. For instance, Ahmedabad recently implemented an *emission trading scheme*, making it the second Indian city to focus on controlling particulate pollution. This initiative aims to regulate industrial emissions and reduce pollution on a statewide level. Furthermore, the Punjab government has recently committed to implementing a comparable system in Ludhiana. Both Surat and Ludhiana host some of India's largest industrial clusters.

Nevertheless, India's regulatory framework may require structural reforms to fully support such programs, as current laws lack flexibility, mainly permitting heavy penalties or industry shutdowns for non-compliance (Peng *et al* 2021, Bello 2022). Introducing monetary charges as an option within the legal framework is crucial for wider adoption. Additionally, independent calibration of monitoring devices is essential to ensure accuracy and prevent industry bias. Lessons from the Surat project can enhance India's pollution control efforts and inspire global adoption for improved air quality and public health.

Box 9: Japan's initiatives on decarbonizing and city-to-city collaboration

Regional Decarbonization Roadmap (RDR).

To achieve carbon neutrality in 2050, Government of Japan committed to reduce GHG emissions in 46% by 2030[6]. Subsequently, local government leaders/ministers discussed decarbonization measures in regional initiatives and RDR was formulated. This roadmap includes regional growth strategy and decarbonization projects through the maximum use of regional resources (e.g. renewable energy). The basic strategy of RDR is that to local decarbonization contributes to local development that solves local problems and improves the attractiveness and quality of local communities through the establishment of 1) "regional growth strategy", 2) "Decarbonization projects through the maximum use of regional resources (e.g. renewable energy)". As their impacts and co-benefits, by mobilizing policies over the next five years to actively support human resources, technology, information, and finance, it is expected to create at least 100 "decarbonization leading regions" by 2030 and disseminate advanced models nationwide and achieve decarbonization ahead of 2050.

City-to-City Collaboration Program (C3P).
C3P is an initiative aimed at fostering knowledge sharing for decarbonization among cities in Japan and beyond. Presently, the initiative comprises 20 cities in Japan and 49 cities spanning across 13 countries. Ministry of the Environment Japan (MOEJ) supports C3P between cities in Japan/abroad to promote sharing of knowledge for decarbonization. As representative examples of success cases of C3P, the first is the case of Tokyo Metropolitan Government - Kuala Lumpur City. The building system was established in Kuala Lumpur, that was adapted to local conditions with reference to the TMG's green building system. As a result of support for the creation of scenarios for decarbonization by TMG, Kuala Lumpur City declared its 2050 Zero Carbon Declaration last year. The second is the case of Yokohama City - Da Nang City in Vietnam. The cooperation between the two cities led to the introduction of high-efficiency pumps at the Da Nang Waterworks Corporation. This case also led to the introduction of high-efficiency pumps in other cities in Vietnam, and horizontal deployment is underway. Thus, MOEJ contribute to the realization of decarbonized cities around the world by spreading the decarbonization domino from Japanese cities to overseas cities.

Box 10: Regional Circulating and Ecological Sphere

In recent years, Japan has promoted an approach known as the regional circulating and ecological sphere (RCES) to address climate and other sustainability challenges. RCES has several distinguishing characteristics that make it appealing to localities with different resource endowments and shifting demographics. At its core, RCES aims to strengthen the integration between climate change, biodiversity, and circular economy in local planning. In addition, it encourages the creation of resource sharing agreements between urban areas and rural areas to optimize resource flows. This may entail, for instance, more populated cities that lack land to invest in and purchase renewables from less populated rural areas with greater land (Sukhwani *et al* 2019, Takeuchi *et al* 2019).
The RCES approach is not only written into Japan's fifth basic environmental plan, it is also being adopted in many locations throughout the country. For instance, Hyogo prefecture has actively developed biomass power as an alternative to fossil fuels while preserving local ecosystems. Meanwhile, Sado Island has worked to underline its shift to becoming a carbon neutral and nature positive leader. Importantly, the RCES model has not only been gaining traction in Japan. Efforts to adapt some of the core principles—an integrated approach and resource sharing between urban and rural areas—are also gaining adherents in places such as Udon Thani, Thailand and Nagpur, India.

5.2. Behavioural and lifestyle changes

Behavioural and lifestyle change is both key to preparing for and responding to climate change, as well as an important but underutilized driver that can be cultivated to rapidly mitigate its impact (Dietz *et al* 2009, IPCC 2023a, Niamir *et al* 2020b, van Valkengoed and Steg 2019). This transformative approach

[6] Japan's Long-term Strategy under the Paris Agreement, 2021 https://www.env.go.jp/en/headline/index.html

not only contributes to climate change adaptation and mitigation in cities but also generates **multiple co-benefits**, including the enhancement of **human well-being**, the promotion of **economic growth**, and the facilitation of **synergies within both mitigation and adaptation strategies** (Creutzig *et al* 2022, He *et al* 2022, Niamir and Pachauri 2023).

The **impact of disasters and the time required for recovery** are significantly influenced by the behavior and actions of individuals, communities, businesses, and government organizations (Meriläinen 2020, Noll *et al* 2023, Räsänen *et al* 2020). For example, studies show how limitations in existing flood risk assessment methods, which often account for human behavior in limited terms, can be addressed through innovative flood-risk assessments integrating behavioral adaptation dynamics (Aerts *et al* 2018, Taberna *et al* 2023).

Implementing behavioral and lifestyle changes has the potential to **rapidly reduce global GHG emissions by a minimum of 5% by 2050**. This reduction can be further amplified when coupled with supportive policies and investments in infrastructure design and accessibility (IPCC 2022c). Studies show that changes in behavior and lifestyle in various sectors, such as transport, buildings, and food consumption, could lead to an individual's emissions being reduced by **5.6–16.2%** relative to the projected cumulative GHG emissions by 2050 in urban areas (Sköld *et al* 2018, van de Ven *et al* 2018).

Cities can promote behavioral and lifestyle changes through the modification of urban forms, strategic infrastructure design, increase knowledge and awareness, investment in and utilization of renewable technologies, provision of services, and the implementation of effective feedback mechanisms.

- Investments in **urban infrastructure** emerge as a significant avenue for fostering behavioral changes and lifestyles conducive to climate resilience. Incorporating features such as compact urban design and easily accessible public transport systems can create environments that encourage higher use of public and active transport and consequently higher satisfaction and has been shown to provide public health benefits (Stevenson *et al* 2016, Kim and Yoo 2019, Mouratidis *et al* 2019, Sha *et al* 2019).

- **Access to information** is critical for adapting to climate risk and reducing vulnerability to hazards, yet access to this information is often not equally available (Jones *et al* 2015, Mitheu *et al* 2022). Addressing this disparity is essential for promoting equitable preparedness and response measures. In addition, individual's perceptions of risk and concern regarding climate change tend to vary in response to media coverage and significant weather or socio-political events (Capstick *et al* 2015). The promotion of learning and coping capacity is essential to support resilient adaptation pathways (Jäger *et al* 2015). Awareness and knowledge play a crucial role in triggering individual behavior and lifestyle choice, contributing significantly to energy demand management and the mitigation of climate change (Vassileva *et al* 2013, Kobus *et al* 2015, Galli *et al* 2020, Jakučionytė-Skodienė *et al* 2020, Niamir *et al* 2020a).

- **Digitalisation** will have a major influence on lifestyles particularly through choices relating to work, leisure, and shopping. These will have a significant impact on emissions, in particular transportation through shared mobility and online shopping. Lifestyles are closely linked to urban form which often changes slowly. The development of urban form would therefore require careful consideration to build in flexibility and resilience that can accomodate and support the future changes through digitalisation (Lyons *et al* 2018).

Behavioral interventions are more apt to gain acceptance when they conform to cultural practices, norms, and beliefs. The success of initiatives targeting behavioral change hinges on acknowledging and respecting diverse cultural contexts. To enhance the feasibility of adaptation and mitigation strategies, particularly those entailing behavioral and practice alterations, it is crucial to recognize and integrate people's values, beliefs, indigenous knowledge, and local knowledge systems. Additionally, amplifying the voices of women and vulnerable groups contributes to the effectiveness of these interventions (Clancy and Mohlakoana 2020, Feenstra and Clancy 2020) (see Box 12).

5.3. Innovation and technology

Innovation is central to urban transformation in two distinct ways. First, transforming cities to embark on more sustainable pathways inherently requires changes in technology, infrastructures, and behavior, which involve the dynamics that existing work on innovation and technological change analyzes and can inform. Second, for multiple reasons, cities are key originators, developers, and promulgators of global processes of innovation. Thus, a key point in this section is that cities are generators of innovations that affect the rest of the world, as well as that affect cities themselves.

Innovation is central to urban transformation. In this context, we use the IPCC definition of innovation, which assumes a "systemic perspective" for how actors and institutions interact in the invention, development, and adoption of new modes of providing and using services (Blanco *et al* 2022). In its original conception from Schumpeter, innovation involves a sequence of activities from developing novel concepts (invention), implementation of those concepts to work in real world settings (innovation), and spread of those practices to other users over time (diffusion) (Schumpeter 1934). While sometimes depicted as being centrally focused on hardware, the concept of innovation is much more general (Arthur 2009) and has long involved the activities of human agents, social movements, and behavioral change. Innovation processes can occur as technological, social, and behavioral changes and typically a successful innovation includes a mix of all three, but the relative shares of each can be quite different and result in varying processes of change. Clearly the linkages among hardware, social aspects, and institutions are where innovations fully take hold and for which cities are well suited hosts. Thus, many of the dynamics discussed in this report, including finance, behavioral change, and others, have strong systemic connections to innovation dynamics. The development of theoretical frameworks, measurement, indicators, and above all case studies of success and failure (Grubler and Wilson 2014), can add insight on pathways to transformation. For example, much of the work on enabling conditions for successful innovations can have important insights for urban transformations (Blanco *et al* 2022).

Cities are key facilitators of global innovation. Cities are enablers of invention, innovation, and diffusion of novel provision of services. As such cities are central to global transformation. The role of cities for global innovation rests on three assertions:

1. Cities are dynamic agglomerations of density and thus are supportive of experimentation (Broto and Bulkeley 2013). This generation of novelty is central to innovation and can occur in technology, behavior, social, and infrastructure. The propensity of cities to support novelty and diversity in approaches plays a role in how productive this generative aspect becomes (Florida 2002). Further protected niches, for example due to idiosyncratic conditions of particular cities can provide a nascent means to develop and demonstrate scale (Schot and Geels 2008).
2. Peer effects within cities catalyze early adoption and can move promising ideas to implementation (Wolske *et al* 2020). The innovation literature makes clear that neighbors, coworkers, and other acquaintances provide a low-cost vector of trusted information to

overcome the traditional hesitancy observed to novelty and change, especially for behavioral innovations Catalini and Tucker 2016, Fletcher and Ross 2018). Proximity and dense networks of social relations enable adoption by providing high value sources of reliable information (Xiong *et al* 2016).

3. Connected cities serve as diffusers of innovations to other cities. Cities are not only generative and testbeds for novelty but also can demonstrate viability of behavior, technology, and rules, which can be transferred to other jurisdictions (Lengyel *et al* 2020). Links between cities, even at the level of individuals, can be crucial for this process (Valente 1996). Cities tend to be hubs of innovation that can give rise to new outside-the-box climate responses (Hölscher *et al* 2019). For example, cities in Latin America invested in bus rapid transit (BRT) programmes to increase mobility and lower emissions that have sparked BRT waves in Africa, Asia, and North America (Stevens 2008).

A final note on innovation for urban transformation is the importance of seeing innovation as a force that can be directed to public purpose and human needs (Mazzucato 2021). While clearly the innovation literature shows the role of serendipity and technological opportunity, innovations are the result, typically of decades of human choices and institutional design (Mowery and Rosenberg 1998). Some of these decisions most central to cities include: shared expectations about direction of change, orienting incentives toward public purpose, coordination of infrastructure, and policy experimentation (Wilson *et al* 2023). We see versions of these among other factors in the section of this report on governance.

5.4. Finance

The role of finance in developing more sustainable cities is crucial. Sustainable cities are designed to have a minimal environmental impact while enhancing the well-being of residents and businesses. Financing sustainable cities involves investing in infrastructure, technology, and services that promote environmental, social, and economic sustainability. However, a recent overview of 362 ambitious European cities found that over 70% of them have no estimation of the capital requirements for their transformation, nor explored adequate ways to access financial markets (Ulpiani *et al* 2023a). The finance sector can contribute to the development of sustainable cities in several ways (Mazutis and Sweet 2022):

- Investing in green infrastructure: Green infrastructure includes parks, green roofs, and urban forests that help manage stormwater, reduce the urban heat island effect, and improve air quality. Financing green infrastructure projects can help cities become more sustainable and resilient to climate change.
- Supporting renewable energy projects: Investing in renewable energy sources such as solar and wind power can help cities reduce their carbon footprint and dependence on fossil fuels. Financing these projects can be done through public-private partnerships, by attracting private investment, or by developing innovating public-private loan schemes for households (Ulpiani *et al* 2023a).
- Promoting energy efficiency: Financing energy-efficient buildings and retrofitting existing structures can help reduce energy consumption and greenhouse gas emissions. This can be achieved through mechanisms such as green bonds, which are used to fund projects with environmental benefits (Tuyon *et al* 2023), but also by innovative loan schemes, crowdfunding mechanisms, or tax design (Ulpiani *et al* 2023a).
- Funding public transportation: Investing in public transportation systems can help reduce traffic congestion, air pollution, and carbon emissions. Financing public transportation projects can be done through a combination of public funds, private investment, and innovative financing mechanisms.

- Supporting social and affordable housing: Financing social and affordable housing projects can help address the housing crisis in many cities while ensuring that low-income residents have access to sustainable and affordable housing options.
- Encouraging sustainable business practices: Finance can play a role in promoting sustainable business practices by providing incentives for companies to adopt environmentally friendly practices and technologies. This can be done through mechanisms such as green loans, which offer lower interest rates for projects that meet certain sustainability criteria (Edmans and Kacperczyk 2022).

The limited available estimations of financing needs in cities point to a very wide range of 0.1 to 10 billion Euro per city (Ulpiani *et al* 2023a). Most cities currently rely mostly on traditional financing instruments like public financing and national/European subsidies, but also start to explore more innovative financial instruments like Energy Performance Contracting (EPC) and social and green bonds (Ulpiani *et al* 2023a). At the same time, cities are a breeding ground for new financial approaches like innovative financial products (e.g. public-private loans, tax incentives, leasing options), new financial arrangements (e.g. publicly owned companies, power purchase agreements, novel public-private combinations) and engagement with the finance sector (e.g. one-stop-shops, foundations, sponsorships) (Ulpiani *et al* 2023a). Access to capital for cities in developing countries would be a higher barrier, and could benefit from active engagement of cities in the UNFCCC stakeholder process for financing mitigation efforts to propose concrete innovative solutions (Edmans and Kacperczyk 2022).

Box 11: Multi-level governance - Linz and Graz

Adaptation must be structurally anchored and profoundly integrated into existing structures and processes. Currently, there is still a lack of climate mainstreaming and proofing, clear responsibilities, competent and qualified personnel for climate change adaptation at all levels of administration, a central coordination point at national level that can allocate funds and provide information and support for cities and municipalities (see e.g. Germany: Center for Climate Adaptation[7]) and a lack of legal requirements in Austria (see e.g. Germany: first climate adaptation law[8]).

Nevertheless, we do see positive examples of cities turning in the direction of strategic climate adaptation efforts.

The pursuit of a structured process was positively recognized for the city of Linz in a 2021 report[9] by the Austrian Court of Auditors, albeit Linz started their adaptation efforts relatively late compared to other (Austrian) cities. In 2019 the city administration and Weatherpark GmbH started with collecting and assessing existing urban climate information and their utilization. This formed the basis for specific recommendations e.g. to create an urban climate analysis and to create and fill the position of an urban climatologist within the city administration, which were both approved and implemented by the City Council. In June 2023 a climate adaptation concept was even approved unanimously.

The city of Graz is also putting its climate governance on a new footing with the Climate Information System (KIS) Graz: a dynamic platform, incorporating relevant urban climate data based on simulations, measurement data, thermal flights and drone flights. The KIS portal forms the basis not only for urban planning but also for organizational and political decisions, for synergies with existing policy plans, for building a network of various actors across disciplines, establishing new ways of cooperation and collaboration while pursuing a long-term transformation process.

[7] https://zentrum-klimaanpassung.de/

[8] https://www.bmuv.de/themen/klimaanpassung/das-klimaanpassungsgesetz-kang

[9] https://www.rechnungshof.gv.at/rh/home/news/Anpassung_an_den_Klimawandel.html

Box 12: Climate and Social Justice

Social justice at community, household and individual levels looks at what a "just" society would look like and how to promote it, and at the injustices people face because of the places they live in (e.g., disadvantaged places such as informal settlements (see 2.3) or factors such as race, gender, ethnicity, class, religion, age, sexual orientation, disability, income (i.e., disadvantaged groups they belong to) and how these intersect. Different forms of justice are relevant here: distributive, procedural, recognitional, corrective and transitional justice as well a considerations about spatial and temporal scope, and metrics or indicators how distributional justice is tracked (Zimm *et al* 2024). Climate impacts and risk (see 3) raise various justice concerns in urban spaces as they often disproportionally impact the livelihoods and wellbeing of disadvantaged groups. For example, urban heat islands are a particular city-level phenomenon which affect disadvantages groups more strongly. There is increasing awareness that climate action also has the potential to unleash additional injustices for vulnerable groups. For adaptation and mitigation actions, urban population living in informal settlements or renters, predominantly disadvantaged groups, often fall short of public support, cannot participate actively in the transition and are dependent on authorities or homeowners. They suffer from unequal access to environmental amenities (i.e., recreational and green space) and decent living services, and lacking involvement in spatial planning and development decisions (e.g., relocation of flood prone areas, green gentrification (Cucca and Thaler 2023, Cucca *et al* 2023). Housing (see 4.3) and mobility (see 4.4) are deeply embedded in unequal economic and social structures, raising several justice concerns and challenges with regards to accessibility, affordability and livability in a transition.

Spatial planning is an urban policy field that has enormous justice implications with regards to climate change impacts, adaptation, and mitigation. Other key delivery areas with justice implications include food, housing, health, mobility, education, labour, and recreation (RTPI 2020).

Climate and social justice can be a useful policy lever to develop measures that promote greenhouse gas emissions reductions and adaptation options while reducing the risk of adverse impacts:

- Improve policymakers' awareness of structural and historical social injustices and local characteristics and assess policy actions and tools' impacts across all forms of justice, to ensure that decisions towards more sustainable urban futures are taken (Diezmartínez and Short Gianotti 2022, Della Valle *et al* 2023).
- Collect relevant data and monitoring indicators and social justice criteria and install advisory bodies (Diezmartínez and Short Gianotti 2022).
- Take local knowledge into account and aim for more participatory decision-making in the context of urban climate policy planning to support social justice causeses (Granberg and Glover 2021).

Box 13: Cost of inaction of tackling air pollution in the ASEAN region

The large costs associated with the implementation of mitigation measures can often be a barrier to rapid action. Cost of inaction assessments can be used to help overcome this barrier by quantifying the economic costs of not implementing such measures. The cost of inaction refers to the negative consequences or losses that result from failing or delaying action. In terms of air pollution, this typically refers to the multiple impacts, including health, biodiversity, and climate change, as well as the other impacts from not implementing policies to reduce air pollution and not realizing the co-benefits that could come from their implementation.

Exposure to air pollution is a leading cause of premature mortality globally and is also associated with multiple morbidity outcomes, such as lost workdays, and increases in hospital and emergency room visits (Institute of Health Metrics and Evaluation 2020, Ru *et al* 2023). These health impacts have a direct economic cost. A cost of inaction assessment for three ASEAN countries found that failure to act on air pollution could result in health-related economic costs of US$ 1.2 billion in Cambodia, US$ 43 billion in Indonesia, and US$ 18 billion in Thailand, which is equivalent to 2.6-3.1% of each country's GDP in 2030. Implementing identified clean air solutions could significantly reduce these costs[10] (Klimont and Slater 2023).

[10] https://iiasa.ac.at/policy-briefs/oct-2023/cost-of-inaction-tackling-air-pollution-in-asean-region

The health impacts of poor air quality are often felt most in urban environments. Consequently, a large proportion of the economic costs from air pollution if no action is taken will be felt in urban areas. Simultaneously, there will be multiple other co-benefits and consequently cost savings for urban environments from the implementation of policies designed to improve air quality. For example, transport policies to promote active travel would simultaneously reduce air pollution, GHG emissions, congestion and increase the physical activity levels of the population (see 4.4). Not achieving these benefits in the future would have further negative economic costs for cities which could be significantly reduced if the policy is implemented.

Box 14: Cities and CDR

Carbon Dioxide Removal (CDR) stands as one of strategies for tackling climate change, and cities are emerging as players in this effort (Kinnunen *et al* 2022, Rodriguez Mendez *et al* 2023). Yet, to optimize the effectiveness of this strategy, addressing uncertainties, risks, and implementing large-scale deployment are crucial considerations.

As urban areas commit to achieving net-zero carbon emissions, CDR options are increasingly explored and implemented at the local level. Cities contribute to carbon sequestration through various means, such as promoting urban vegetation, utilizing biogenic construction materials, and deploying biochar (Smith *et al* 2023). The unique urban environment, with its diverse infrastructure and population density, presents both challenges and opportunities for effective CDR implementation. Localized downscaling analyses are essential to accurately assess the potential, technological feasibility, and social acceptance of CDR options in urban settings (Minx *et al* 2018, Fuss and Johnsson 2021). By taking a proactive role in carbon sequestration measures, cities not only contribute to global climate change mitigation but also enhance the resilience and sustainability of their own communities.

The storage of carbon in the built environment can be achieved through innovative materials and construction practices (Smith *et al* 2023, UNDP 2022). For instance, the use of wood-based construction materials represents a sustainable alternative, as wood captures and stores carbon during its growth and can continue to do so as part of a building (Kinnunen *et al* 2022, Arehart *et al* 2021, Rodriguez Mendez *et al* 2023). Additionally, biochar as an additive to construction materials introduces a novel approach, involving the incorporation of biochar—a carbon-rich material produced through the pyrolysis of organic matter—into construction materials (Zhang *et al* 2022, Goel *et al* 2021). This not only sequesters carbon but also enhances the properties of the materials. These approaches not only contribute to carbon neutrality but also align with the broader goal of sustainable and eco-friendly construction practices, promoting a more environmentally conscious built environment.

6. Synergies and trade-offs

6.1.Mitigation and Adaptation synergies and tradeoffs

There is a strong case for cities to address climate change through integrated responses by linking adaptation and mitigation at the planning and implementation stages. Actions that deliver both mitigation and adaptation include sustainable urban planning and infrastructure design, including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design. These options can also reduce flood risks, pressure on urban sewer systems, and urban heat island effects and can deliver health benefits from reduced air pollution (IPCC 2021). Building design measures for e.g. passive design and improved insulation can reduce emissions associated with heating and cooling while also reducing impacts from extreme heat. Increasing albedo in street canyons during summer can lower surface temperatures and boost the yield of wall-mounted photovoltaic cells, offering a dual benefit for climate change mitigation and adaptation (Oswald *et al* 2019, Revesz *et al* 2020).

Some mitigation actions can result in trade-offs or conflicts with adaptation or vice versa (Sharifi 2020). For example, compact urban form can increase urban heat island effects. Adaptation options, particularly grey infrastructure or increased use of groundwater pumps to manage floods or interventions requiring higher energy demand can increase greenhouse gas emissions. Increasing green cover in urban areas can conflict with policies to ensure compact development while higher air conditioning use can increase energy use .

Traditionally, urban actions have focused either on mitigation or adaptation. This could lead to missed opportunities, lower efficiency of allocated resources and policy conflicts (Grafakos *et al* 2019). Particularly in the global South, there is limited capacity within local governments to plan for such responses, assess costs and benefits of different actions and implementation challenges due to the lack and costs of finance. Evidence from Europe shows that cities which have stronger mitigation commitments are more likely to adopt adaptation policies. (Lee *et al* 2020) A major gap in adopting an integrated approach to mitigation and adaptation in cities is inadequate evidence of costs and finance for implementation (Grafakos *et al* 2020). In many contexts, implementation of actions happens in a project-delivery mode based on available finance, often from higher levels of government (UNEP-CCC 2023). National adaptation plans can influence local adaptation actions (Lee *et al* 2020). Other enabling conditions in literature include the need for a joint climate plan supported by a joint institutional set up within city governments (Göpfert *et al* 2019). (UNEP-CCC 2023) Cities can act as leaders setting more ambitious targets compared to national governments. Often such leader cities are large cities, often capital cities with a few exceptions (Kern 2019). There is evidence of city networks having supported urban innovations and climate action in many cities however, their effectiveness at implementing coordinated actions or supporting the less ambitious cities needs further research.

6.2. Urban climate actions and Sustainable Development Goals

There is growing evidence on the multiple linkages between climate change and food, water, air quality, health, gender and other sustainable development objectives (Boyd *et al* 2022) and mitigation and adaptation options are most effective when aligned with economic and sustainable development (IPCC, 2018). Cities can impact sustainability directly from activities within the boundary as well as at the regional or global level through supply chains, food and material consumption and waste (Wiedmann and Allen 2021).

Cities can be key actors in delivering targets under SDGs. Emerging evidence indicates several urban climate actions that have synergies with Sustainable Development Goals. Many cities have been at the frontlines of efforts to not only address climate change but the SDGs. This is partially because the SDGs includes a specific goal that focuses chiefly on cities (SDG 11) (IGES 2020). It is also because, as illustrated in the figure below, there are many synergies between other SDGs (including SDG 13 on climate) and the seven thematic targets under SDG 11 (this does not include the three targets-related to means of implementation) (Ozawa-Meida *et al* 2021).

Mitigation actions with synergies with multiple SDGs include switching to renewable energy, shifts to public transport, active transport and electrification, and green and blue infrastructure. Reducing demand for travel, floor space, switching to plant-based diets can support targets for SDGs 2, 3, 7, 11, 12, 14 and 15 in addition to climate action (SDG 13) (Roy *et al* 2021, IPCC 2022c). Synergies and trade-offs are highly dependent on the scale and context. Coordinated actions can enhance these synergies, for example urban planning that enables compact development with higher share of walking and electric transport (Lwasa *et al* 2022). The co-benefits framing can be a useful approach to identifying and implementing coordinated actions and accelerating climate action. There could be trade-offs, for instance urban green spaces could involve trade-offs with equity.

There are gaps in understanding of benefits and trade-offs between climate actions and sustainable development, particularly how these affect different groups. Lack of data particularly for small and medium-sized cities in developing countries make it challenging to quantitatively assess progress on SDGs for different cities (Liu *et al* 2023). Recent studies highlight the need to develop new methodologies or modify existing frameworks to measure these interactions (Fox and Macleod 2023) as well as detailed and place-based cases documenting urban policies and outcomes, synergies and trade-offs that emerged and how these were addressed (Rozhenkova *et al* 2019, Halsnæs *et al* 2023). Addressing trade-offs may require special attention during policy implementation.

Table 1 *Cities and SDGs. Many cities have been at the frontlines of efforts to not only address climate change but the SDGs. This is partially because the SDGs includes a specific goal that focuses chiefly on cities (SDG 11). It is also because, as illustrated in the figure below, there are many synergies between other SDGs (including SDG 13 on climate) and the seven thematic targets under SDG 11 (this does not include the three targets-related to means of implementation).*

SDG 11 Targets	**SDGs**															
	1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	17
Target 11.1: Safe and affordable housing	X							X	X	X	X	X		X	X	X
Target 11.2: Affordable and sustainable transport systems	X						X	X	X	X	X	X		X	X	X
Target 11.3: Inclusive and sustainable urbanization	X	X	X	X	X		X	X	X	X		X			X	X
Target 11.4: Protect the world's cultural and natural heritage												X	X	X		
Target 11.5: Reduce the adverse effects of natural disasters	X		X			X						X	X	X	X	
Target 11.6: Reduce the environmental impacts of cities						X	X				X	X	X	X		
Target 11.7: Provide access to safe and inclusive green and public spaces					X					X		X	X	X		

The following section discusses the linkages between climate action and health and wellbeing(Boyd *et al* 2022)

6.3. Health and wellbeing

Most of the sources of air pollutants are also emitting greenhouse gases. At the same time, several air pollutants play important roles in the Earth's energy balance, e.g., aerosols that can cause both cooling, by reflecting incoming sunlight back to space (sulfates, particulate organic carbon) and warming by absorbing and releasing heat in the atmosphere (black carbon) (IPCC 2023b). Black carbon and organic carbon are components of primary $PM_{2.5}$ while sulfates are part of secondary PM2.5. A strategy to reduce concentrations of ambient particulate matter will most often result in decline of both carbonaceous particles as well as SO_2, a precursor of sulfate, leading to trade-offs with respect climate impact of such policies. However, several policies addressing these air pollutants will also result in reduction of carbon dioxide offsetting these climate trade-offs in the long term. Ozone, a pollutant and a greenhouse gas, is a product of reaction of NOx and VOC in sunlight and policies addressing ozone will have synergistic effects for air quality and climate. Overall, many solutions can reduce air pollution and greenhouse gas emissions at the same time, thus creating opportunities for co-benefits (Anenberg *et al* 2019), which can vary regionally.

The air quality policies can have health benefits beyond air pollution, for example physical activity. Many findings on health co-benefits (Haines *et al* 2009) are particularly true for cities where consumption levels are generally higher than in rural areas. Dietary change towards less meat consumption has direct health benefits, leads to reductions in methane emissions, and reduced NH_3 emissions improving $PM_{2.5}$ levels.

Due to the population density, cities also offer potential for efficient mitigation of many key sources of air pollution. For example, expanding district heating, developing efficient public transport or improved cycling infrastructure will lead to multiple benefits, including reduced emissions of air pollutants and GHG, better air quality, improved wellbeing.

How transformations involving behavioural changes in urban areas can be stimulated, and what their costs and benefits are, is still a subject of research. Quantifying costs and benefits, and also cost of inaction, could help policymakers to motivate investments. Research has often focused more on 'what-if' analysis quantifying the benefits of reaching a hypothetical target (e.g. the WHO guideline values) rather than demonstrating feasible ways for getting there. Potentials vary from city to city so very likely no one silver bullet solution exists, but 1) there are likely no-regret measures that are universal, and 2) there is a need for tools that can be calibrated to conditions in individual cities to identify cost-effective solutions there while being coupled to background conditions. Also, how different socioeconomic groups are affected and could potentially benefit from mitigation measures

6.4. Climate Resilient Development

Recently, climate resilient development (CRD) has been recognized as an important concept aiming for an approach that integrates climate change responses and sustainable development. The IPCC defines CRD as "the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all." In order to realize a sustainable society, there is a need to restore the interrelationship between climate system, ecosystems and human society back to a positive one, and to strengthen the resilience of society and natural systems. Cities with concentrated populations and human activities are key areas where CRD can be realized (IPCC 2023a).

Patterns of sustainable urban development vary depending on geographical and historical situations of cities. Therefore, a unique development strategy is needed depending on the types of cities. In formulating urban development strategies matching to the characteristics of these cities, it is required to adopt integrated approach that focuses on the existence of vulnerable areas and people and involves all stakeholders.

In addition, cities have different types of vulnerabilities depending on their historical background and development stage. There are a variety of factors contributing to the vulnerability of cities, including informal settlements where large populations live, unplanned development in low-lying areas vulnerable to natural disasters, and underdeveloped disaster reduction and life-line infrastructures. Taking into account that severe climate disasters would likely increase in a changing climate, there is a need to scale up measures, for example, advance notification of disaster risks, early evacuation, and support for post-disaster rescue, recovery, and reconstruction. Further research is urgently needed to better understand elements of urban resilience and how these could be implemented.

CRD in cities cannot be realized without considering its hinterland. Local sustainability is ensured once interactions of people, the flow of energy, water, and goods between cities and rural areas are maintained. It is important to utilize the economic power of cities to contribute to the development of the entire areas, including their neighboring regions.

7. Knowledge Gaps

7.1 Literature-based

Section 2
Urbanisation trends place importance on multi-level scenarios that align the local with the global. Dedicated knowledge production continues to be required for informing on mitigation potentials and their comparisons. Another possibility arises from the need for analysing global urban emissions scenarios according to the transient climate response to cumulative CO_2 emissions that can provide a better understanding of the possible impacts of urban areas within mitigation efforts. {Section 2.1}

An understanding of urban typologies is essential for synthesizing mitigation and adaptation options across the diversity of cities while knowledge gaps exist. Understanding what type of solutions can work in different types of cities can be a useful input Urban typologies that are able to integrate both mitigation and adaptation perspectives are needed and expected to be an important priority for knowledge production in the preparation of the Special Report on Climate Change and Cities in the Seventh Assessment Cycle of the IPCC. {Section 2.2}

Data on and characterization of urban informal settlements remains scarce. Specifically, which planning approaches to urban slum reformation and transformation have worked, in which contexts, and why remains under-researched. {Section 2.3}

Section 3
From the physical perspective detailed, city-level modelling of climate impacts remains a challenge – for example the impacts of extreme rainfall or heatwaves and urban heat island effect, vary substantially based on factors such as urban form and microclimate. These are not captured well by global climate and impact models and are challenging to model at the urban scale in detail, subsequently making it difficult to do comparison across many cities. {Section 3.1}

From the vulnerability and soft adaptation perspective, they are typically difficult to quantify and model, can vary hugely by local context even within urban areas, and can change rapidly making observations and data collection timely and expensive. Huge uncertainties in quantitative vulnerability assessment of clouds the overall picture of climate risk. {Section 3.1}

Climate change will have impacts on air quality however, several aspects are not well understood and require further research as well as strengthening efforts to increase capacity and quality of monitoring air quality in the cities and beyond. The latter will also allow to better understand and validate pollution source contribution which is essential to underpin the development of policies addressing both regional and local policies as only coordinated action would bring desired air quality improvements and will come at lower cost. {Section 3.2}

Development of wildfires and their impact on cities' air pollution in the future, considering climate change, is potentially important, at least for some regions, but poorly understood and researched. {Section 3.2}

Section 4
The balance of trade-offs and synergies associated with efficiency gains and other attributes of urban energy use is not well understood and requires further analyses. {Section 4.1}

The prospects for transforming energy use and related GHG emissions resulting by inducing or enforcing changes in urban lifestyles in the context of increasing incomes, floor space per capita and personal mobility are uncertain. {Section 4.1}

The future impacts of climate change on different global regions are not sufficiently analysed, while food security in vulnerable regions has been identified *(with high confidence)* as increasing to high risk between 1.5 ℃ to 2.0℃ (IPCC 2022). Cultural and heritage aspects on water, food, health, ecosystem and infrastructure are not well investigated. {Section 4.2}

While current technologies offer notable energy and cost savings, as well as additional benefits, achieving the net zero targets in the buildings sector will necessitate enhanced policy support such as implementation of minimum performance standards and building energy codes. {Section 4.3}

The imperative shift to low-GWP refrigerants and energy-efficient cooling, as mandated by the Kigali Amendment to the Montreal Protocol for climate change mitigation, faces challenges due to critical knowledge gaps. These gaps involve inadequate data on low-GWP refrigerant performance, material compatibility issues, and obstacles in availability and cost. Addressing these gaps is essential, particularly for energy efficiency, which requires accurate real-world measurements, solutions for hot climates, and retrofitting measures for existing buildings. Limited awareness and technical capacity highlight the need for comprehensive standards in handling low-GWP refrigerants. {Section 4.3}

Limited analysis of the role of behavioral change campaigns and creation of new social norms, allowing a transition from ownership to usership. {Section 4.4}

Analysis of the economic and social outcome of rebalancing investment of transport investment towards more sustainable transport modes. {Section 4.4}

The absence of quantitative information related to waste generation, composition and management hampers the implementation of circular waste management systems and introduces significant uncertainty into the quantification of environmental co-benefits as well as into the assessment of the circularity of materials {Section 4.5}

Urban form, density and functionality have a major impact on the urban footprint and its efficiency, however, a more systemic approach needs to be explored with some possible drivers such as impacts of digitalization, global shocks {Section 4.6}

The lack of detailed sub-regional statistics of in- and export of goods from other countries as well as surrounding areas to cities and households introduces a large uncertainty into urban nitrogen budgets that needs to be reduced in the future. {Section 4.7}

Section 5

How can governance, institutions and enabling reforms be reflected/captured in modelling scenarios in cities {Section 5.1}

How to reconcile the tension between the need for institutions that accelerate changes in cities and more institutions that work across sectors, include stakeholders and may slow down those changes {Section 5.1}

There is a notable lack of empirical studies to comprehensively understand what factors enable behavioral and lifestyle changes. Additionally, there is a need for models and scenarios capable of capturing the intricate socio-behavioral dynamics and interactions within urban systems. {Section 5.2}

What factors foster healthy functioning of cities' innovation enablers: experimentation, peer effects, and connectedness? {Section 5.3}

What governance regimes can shape and accelerate innovation to support urban transformation for public purpose? {Section 5.3}

What are the financing needs for mitigation and adaptation in cities with different characteristics, such as in geography, development level, spatial patterns, etc. {Section 5.4}

What novel public-private partnerships are most promissing and successful to attract the investments required for the transition to sustainable and resilient cities? {Section 5.4}

Section 6
While a number of studies show synergies or urban climate actions with SDGs, there is a need to develop methodologies to measure these interactions and more detailed place-based studies, particularly for the less studied regions and cities. {Section 6.1}

Understanding of the potential and means of initiating behavioural change relevant for air pollution. {Section 6.3}

Quantification of impacts and benefits from mitigation measures/policies, addressing urban and regional air pollution, to different socioeconomic groups. {Section 6.3}

Systematizing the concept of urban CRD and developing methods for formulating policies and measures on urban CRD. {Section 6.4}

Overview of the current efforts made cities and international development organizations on urban CRD. Exploring the best practices and identifying common approaches from them. {Section 6.4}

To identify the synergies and trade-offs between climate change measures and sustainable urban development towards their integration. To develop methodologies to evaluate urban policies and measures to make full use of synergies and to avoid or limit trade-offs. {Section 6.4}

Knowledge on the roles of public and private sectors in realizing urban CRD. In particular, consideration should be given to the movement by financial and business sectors, as well as the current situation and future prospect of international support to developing countries. {Section 6.4}

The roles of stakeholders including city residents and ways to involve them towards urban CRD including public relations, outreach, and human capacity development. {Section 6.4}

7.2. Experts opinions

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Six priorities were highlighted as crucial for addressing urban challenges (Bai *et al* 2018):

1. Expanding observations to collect a wider range of urban data.
2. Understanding the complex interactions of climate processes within cities.
3. Studying informal settlements to better address their unique needs.
4. Supporting transformation with bold strategies for creating low-carbon, resilient cities.
5. Harnessing disruptive technologies to leverage the digital revolution.

6. Recognizing the global sustainability context and understanding the impacts of urban processes elsewhere.

Two key advancements have been observed since this publication:

- Advancements in urban planning tools.
- Promotion of nature-based solutions to address urban challenges.

Based on Bai (2023), three additional areas warrant attention:

1. Escalating vulnerabilities and risks faced by cities due to climate change, with a particular emphasis on city officials needing a firmer grasp of these existential threats.
2. Understanding how major economic and social centers will respond to shocks.
3. Recognizing the interconnected, amplified, nested, and compounding nature of risks and vulnerabilities in cities.

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1. **Systemic transformation:** there has been significant research on transformation in particular sectors (building, transport and waste management); however, the discussion of how to achieve transformation within/across urban systems is still not well-developed. In this connection, there is a need to better specify/clarify how different types of cities (compact cities, mixed land use etc.) can work across sectors and achieve systemic changes.
2. **Full identification of co-benefits**: there is a need for quantifying a full range of co-benefits—including both mitigation (climate, air pollution, health, equity) and adaptation (i.e. heat island effects).
3. **Clarifying the boundaries of a city**: there still remain some differences in views on what constitutes a city. In particular, one of the challenges is that there is not always a clear overlap between the geographic and administrative (action) boundaries of a city.
4. **Deepening understanding of urban governance**: There still remains limited discussion of how to govern a city and to further elaborate on governance models (multi-level, polycentric). This is particularly important for governance that would across different scales and generate scalable change.
5. **Understanding the place and role of informal settlements**: There is still limited research on the importance of informal settlements and their role in sustainable development and resilience building.
6. **Leveraging disruptive technologies**: There is still limited understanding on the potential of disruptive technologies, especially digitalization, in urban contexts. On a related point, there is a need to explore what kinds of policy levers are needed to use those technologies to make big changes.
7. **Urban finance**: There is a need to understand how cities can acquire and mobilize the resources for systemic multi-sector transformations. In this connection, it was suggested to review the key results from the Edmonton conference on cities and the global action agenda.

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In his fundamental text Some Propositions about Sustainability Harvey Brooks (1988) observes: "The criteria for sustainability have to ultimately [be] defined over a spatially heterogeneous system consisting of a cluster of interacting spatially related systems, [that are] not necessarily in geographic proximity to each other." Brooks' observation still frames the most fundamental challenge and research question on Cities Transformations: How to understand, to empirically describe, and from a policy perspective, to operationalize leverage points in transformations in the metabolism of cities which are inherently open systems. Cities critically depend on, in fact are defined by, cascading exchanges of resources, information, people, and power. These have been recognized and underlie the bases of urban economic geography, central place and world cities theories ever since Thünen, Christaller, and Knox (1826).

It is agreed that the impacts of local transformations on climate neutrality or on sustainability in general cannot be determined when looking at a city in isolation. Territorial based GHG emission inventories show how small actually the direct territorial emissions of a city are in comparison to their imported embodied emissions (if they are captured at all in territorial emission inventories). Conversely, consumption based emission accounting explicitly quantifies the magnitude of these embodied emission by product/end-use type, but fail to date to describe the complex layered supply networks behind them. Consumption based accounting also offers no insights into policy relevant leverage points to reduce emissions associated with supply chains, both originating within a given city, or from the multi-scale, multi-input supply/delivery networks a city is integrated in.

The fundamental research question remains therefore how to conceptualize, model, and to identify policy leverage points in a complex web of supply chains that affect cities and are in turn affected by transformations originating in and percolating across cities. The challenges are daunting as one needs to deal simultaneously with network flows of physical resources, money, information, and control (hard and soft power), that each have distinct characteristics and interdependencies and that have traditionally been framed and modeled via distinct approaches and methods including Systems Science, Input-Output Analysis and more recently also Complexity Science. Integration of different disciplines and methodologies and harnessing the potential of digitalization to overcome the perennial data challenges for understanding "the web of a city" and the "web of cities" simultaneously are required. The research path ahead may be long and steep, but is of outmost relevance and above all intellectually exiting.

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City transformations require concerted efforts across multiple sectors and scales, as well as addressing various existing gaps. One key gap concerns the actions, measures, and scenarios for urban planning, design, and governance that can foster and support less car-oriented cities. Automobile dependence has been a major source of many environmental, social, and economic problems that cities have faced since the early 20th century. Several planning movements and paradigms, such as the 'neighborhood unit', have attempted to tackle this issue. However, they have often been deemed unrealistic and ineffective in transforming the urban landscape and enhancing walkability and proximity. A new concept that has emerged recently is the 15-minute city, which aims to promote proximity-based urban planning and design. This concept differs from previous ones by acknowledging the role of smart solutions and technologies in shaping urban mobility patterns. However, the concept and its implementation prospects are still fraught with uncertainties and ambiguities. While the concept has the potential to facilitate transformative changes in cities, it may also end up being a utopian vision if the uncertainties are not adequately addressed. Therefore, more efforts are needed to fill the gaps related to this concept and its implications for urban transformations.

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Glossary

Compound risks

Arise from the interaction of hazards, which may be characterised by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors ((Intergovernmental Panel on Climate Change (IPCC) 2023).

Cascade risks

Cascading impacts from extreme weather/climate events occur when an extreme hazard generates a sequence of secondary events in natural and human systems that result in physical, natural, social or economic disruption, whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multi-dimensional, and are associated more with the magnitude of vulnerability than with that of the hazard ((Intergovernmental Panel on Climate Change (IPCC) 2023), modified from (Pescaroli and Alexander 2015).

Informal Settement

There are several different definitions and understandings of slums and informal settlements. According to one, "A slum is defined as "a contiguous settlement where the inhabitants are characterized as having inadequate housing and basic services. A slum is often not recognized and addressed by the public authorities as an integral or equal part of the city. It is an area which combines to various extents the following characteristics: insecure residential status, inadequate access to safe water, inadequate access to sanitation and other infrastructure, poor structural quality of housing, overcrowding." (UN-Habitat 2003 - The challenge of slums – Global report on human settlements). Households lacking any of the following conditions: (1) access to improved water; (2) access to improved sanitation facilities; (3) sufficient living area—not overcrowded; (4) structural quality/durability of dwellings; and (5) security of tenure are recognized by UN-Habitat as being slum/informal settlement households.

Informal Settement - physical, service, social, economic, legal, and environmental dimensions

Physical and service domains often refer to aspects of spatial segregation, zoning, exclusion, and deprivation in access to basic services, city amenities and infrastructure. From a social perspective, informality is often associated with immigrants, diversity, and marginalization. Informality, in economic terms, is viewed as unregistered and unregulated economic activity and at times a lack of access to or exclusion from markets and resources. Legally, practices or behavior existing outside the planned system of regulation, including building laws, tenurial and property laws, define informality. The necessity of existing outside of regulated zones or legal bounds is often a survival strategy and not a question of choice. In the environmental domain, informality is often characterized by heightened exposure to environmental risks, pollution, environmental degradation, and poor waste management and drainage.

Urban

The categorisation of areas as 'urban' by government statistical departments is generally based either on population size, population density, economic base, provision of services, or some combination of the above. Urban systems are networks and nodes of intensive interaction and exchange including capital, culture, and material objects. Urban areas exist on a continuum with rural areas and tend to exhibit higher levels of complexity, higher populations and population density, intensity of capital investment, and a preponderance of secondary (processing) and tertiary (service) sector industries. The extent and intensity of these features varies significantly within and between urban areas. Urban places and systems are open with much movement and exchange between more rural areas as well as other urban regions. Urban areas can be globally interconnected facilitating rapid flows between them – of capital investment, of ideas and culture, human migration, and disease (IPCC 2022a).

Urbanisation

Urbanisation is a multi-dimensional process that involves at least three simultaneous changes: (i) land-use change: transformation of formerly rural settlements or natural land into urban settlements; (ii) demographic change: a shift in the spatial distribution of a population from rural to urban areas; and (iii) infrastructure change: an increase in provision of infrastructure services including electricity, sanitation, etc. Urbanisation often includes changes in lifestyle, culture, and behaviour, and thus alters the demographic, economic, and social structure of both urban and rural areas (Stokes and Seto 2019; Seto et al. 2014; UNDESA 2018). See also Urban, and Urban Systems (IPCC 2022a).

Urban growth typology

Urban growth relates to an increase in urbanized land cover. The dynamics of this growth can be clustered into urban growth typologies. In the literature, five clusters are identified based on the dynamics of the mix of outward and upward urban growth. Stabilised urban growth has negligible outward growth in the horizontal dimension and very low upward growth in the vertical dimension. Outward urban growth has a dominance of growth in urban extent horizontally. Budding outward represents nascent and slow paced urbanisation. Mature upward involves some upward growth in the urban area. Upward and outward has simultaneous urban growth in both dimensions. These clusters have been merged into "emerging, rapidly growing and established" in IPCC AR6 WGIII.

Urban Systems

Urban systems refer to two interconnected systems: first, the comprehensive collections of city elements with multiple dimensions and characteristics: a) encompass physical, built, socioeconomic-technical, political, and ecological subsystems; b) integrate social agent/constituency/processes with physical structure and processes; and c) exist within broader spatial and temporal scales and governance and institutional contexts; and second, the global system of cities and towns (IPCC 2022a).

Abbreviations list

AR6 Sixth Assessment Report
ASEAN Association of South-East Asian Nations
AV Autonomous Vehicles
BEV Battery Electric Vehicle
BRT Bus Rapid Transit
CDP Carbon Disclosure Project
CDR Carbon Dioxide Removal
CI Confidence Interval
COVID-19 Coronavirus disease 2019
CRD Climate Resilient Development
EPR Extender Producer Responsibility
EPC Energy Performance Contracting
EV Electric Vehicle
GCoM Global Covenant of Mayors for Climate and Energy
GDP Gross Domestic Product
GHG Greenhouse Gas
GNH Gross National Happiness
GPCB Gujarat Pollution Control Board
GWP Global Warming Potential
IPCC Intergovernmental Panel of Climate Change
KA Kigali Amendment
LDC Least Developed Countries
LMIC Low or Middle Income Countries
MaaS Mobility as a Service
MRV Monitoring, Reporting and Verification
MSW Municipal Solid Waste
NDC Nationally Determined Contributions
NMT Non-Motorised Transport
NUTS Nomenclature of territorial units for statistics (abbrev. from the French version Nomenclature des Unités Territoriales Statistiques)
RCES Regional Circulating Ecological Sphere
SDG Sustainable Development Goals
SSP Shared Socioevonomic Pathway
UNB Urban Nitrogen Budget
UNFCCC United Nations Framework Convention on Climate Change
US$ United States Dollar
WABI Wasteaware Benchmark Indicators

Chemical compounds:
BC black carbon
CO_2 carbon dioxide
CH_4 methane
HFC hydrofluorocarbon
NH_3 ammonia
NO nitrogen monoxide
NO_2 nitrogen dioxide
NO_x nitrogen oxides
Nr reactive nitrogen
SO_2 sulfur dioxide
$PM_{2.5}$ particular matter less than 2.5μm
VOC volatile organic compound

In References:
ADB Asian Development Bank
BML Federal Ministry Republic of Austria, Agriculture, Forestry, Regions and Water Management (Bundesministerium Land- und Forstwirtschaft, Regionen und Wasserwirtschaft)
C40 A global network of mayors of world’s leading cities that are united in action to confront the climate crisis

CCAC	Climate and Clear Air Coalition
EPIC	Energy Policy Institute
FAO	Food and Agriculture Organization of the United Nations
GEA	Global Energy Assessment
HELCOM	The Baltic Marine Environment Protection Commission (the Helsinki Commission)
IDB	Inter-American Development Bank
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
IRBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IRP	International Resource Panel
ITF	International Transport Forum
OECD	Organization for Economic Cooperation and Development
RGoB	Ministry of Foreign Affairs and External Trade Royal Government of Bhutan
TWI2050	The World in 2050
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Assembly
UNECE	United Nations Economic Commission for Europe
UNEP-CCC	UNEP Copenhagen Climate Centre
UN-Habitat	United Nations Human Settlements Programme
WHO	World Health Organization
WMO	World Meteorological Organization

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