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From Low- to Net-Zero Carbon Cities: The Next Global Agenda

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Abstract

This article provides a systematic review of the literature on net-zero carbon cities, their objectives and key features, current efforts, and performance. We discuss how net-zero differs from low-carbon cities, how different visions of a net-zero carbon city relate to urban greenhouse gas accounting, deep decarbonization pathways and their application to cities and urban infrastructure systems, net-zero carbon cities in theory versus practice, lessons learned from net-zero carbon city plans and implementation, and opportunities and challenges in transitioning toward net-zero carbon cities across both sectors and various spatial fabrics within cities. We conclude that it is possible for cities to get to or near net-zero carbon, but this requires systemic

transformation. Crucially, a city cannot achieve net-zero by focusing only on reducing emissions within its administrative boundaries. Cities must decarbonize key transboundary supply chains and use urban and regional landscapes to sequester carbon from the atmosphere. Because of carbon lock-in, and the complex interplay between urban infrastructure and behavior, strategic sequencing of mitigation action is essential for cities to achieve net-zero.

Contents

1. INTRODUCTION: THE URBAN CONTEXT

The evidence is robust and the science is clear: Limiting global warming to 1.5°C will require rapid, widespread, and major transitions in four interconnected systems—energy, land, industrial, and urban and infrastructure, including buildings and transport—and net CO_2 emissions need to be reduced to zero by 2050 (1). Achieving net-zero emissions will require deep decarbonization (see the sidebar titled Deep Decarbonization) and transformational changes in every aspect of the human enterprise, including how the world's urban areas are conceived, designed, built, and powered.

Urban areas play a critical role in mitigating climate change for three reasons. First, their current direct and indirect greenhouse gas (GHG) emissions are a significant portion of the global total. Existing urban areas contribute approximately 75% of fossil fuel CO_2 emissions (2), but this is not distributed equally. For example, a significant share of household consumption-based carbon emissions are associated with a small number of cities, with households in 100 urban areas accounting for 18% of the global carbon emissions (3). From a production perspective, cities with a high concentration of industries and power plants would contribute a high proportion of global GHG emissions.

Second, future urban GHG emissions are anticipated to increase due to growth trends in urban population and urban land and infrastructure. In 2015, approximately 55% of the global population, or 4.2 billion, lived in urban areas. The urban share of the population is projected to increase to 68% by 2050, adding 2.5 billion urban dwellers (4). In order to accommodate and house this growing population, the world will experience an unprecedented growth in urban areas, by 78%–171% between 2015 and 2050 (5). If current trends in urban land use continue—toward low-density, expansive, and car-dependent forms—then urban energy use in 2050 could increase more than threefold over 2005 levels (6), and annual urban resource requirements could grow from 40 billion tonnes in 2010 to 90 billion tonnes by 2050 (7). The growth of cities also means that they offer the biggest opportunity to switch to transformative net-zero production and consumption as set out in this article.

Third, urban areas play a vital role in climate change mitigation due to the long lifespans of buildings and transportation infrastructures. The spatial arrangements of land use and the built environment, the layout of street networks, and the size of the city blocks lock in patterns of behavior and create mutually reinforcing carbon lock-ins that are not easily reversed or changed (8). It is therefore essential to lock in net-zero buildings and infrastructure and to do so quickly.

1.1. Net-Zero Carbon Cities Defined

A growing number of cities are recognizing their potential contribution to mitigate climate change and have aspired to achieve net-zero. As of December 2020, more than 800 cities globally

DEEP DECARBONIZATION

Deep decarbonization is a process by which urban activities achieve zero or near net-zero carbon dioxide (CO_2) emissions. Pathways for deep decarbonization employ systemic changes enabled by future net-zero electricity grids, such as electrification of vehicles and heating and carbon valorization. They also build on the more typical efficiency and renewable actions cities have pursued for low-carbon development in transformative ways in order to achieve >80% reduction goals. Both low-carbon and deep decarbonization will require behavior changes, including conservation behaviors and household and industry adoption of new technologies.

Net-zero carbon cities: achieving an overall zero balance between urban CO_2 emissions and removing carbon from the atmosphere

Goal of net-zero cities: cities that have committed to either a reduction target of 80% or greater in GHG emissions by a given year (often 2050) from baseline or such a decarbonization goal

have made commitments to become net-zero carbon cities (9). Also called climate-neutral cities, net-zero energy cities, carbon-free cities, or carbon-neutral cities, the basic premise is the same: radically reducing GHG emissions from urban activities while simultaneously removing GHG emissions from the atmosphere. Although it is encouraging that an increasing number of cities are making pledges to reach net-zero targets, it is unclear whether they have the political will or capacity to meet their commitments. There are various working definitions of a net-zero city and approaches to achieving net-zero emissions, and transnational networks are actively establishing guidelines, strategies, and protocols to create a common set of definitions and approaches (10–12). Of course, how carbon emissions are measured and what sectors are counted have a large bearing on what is being reduced to zero and by what timeline. For the purpose of this article, we define the goal and timeline of net-zero cities as cities that have committed to an emissions reduction target with a goal of at least an 80% reduction in GHG emissions by a given year from baseline or have signed up to an initiative committing to such a decarbonization goal; the other 20% usually involves regional projects for sequestering carbon, which can be associated with many environmental remediation opportunities such as reforestation, for example.

1.2. Net-Zero Carbon Cities in Historical Context

The idea of retrofitting and reimagining cities to make them more environmentally friendly, socially just, and economically competitive is a recurring theme in the history of cities, especially in the past few decades (13–18). Although the current manifestation of net-zero carbon cities is new, ancient civilizations around the world, including in India, China, and the Middle East, have a long history of maintaining ecological balance and systemic links between cities and hinterlands, for example, through the recycling of urban "night soil" for agriculture.

Past efforts in Europe and America to make cities more environment-friendly and healthy arose from challenges of accelerated urbanization. During the first half of the nineteenth century, Europe's urban population doubled, leading to the development of tenement slums, sewage contamination of urban water supplies, and outbreaks of cholera and other diseases. This led to the Sanitary Reform movement that began in the 1830s, during which cities were systematically retrofitted and rebuilt in accordance with sanitary principles in order to remove filth and disease from burgeoning and overcrowded cities (19). Although considered novel at that time, the separation of water and waste had its origins much earlier; evidence of domestic wastewater drainage can be found in ancient cities around 6500 B.C. (20).

Half a century later, in 1898, the Garden City movement, initiated in the United Kingdom by Ebenezer Howard, was a response to the polluted and overcrowded industrialized cities at the end of the nineteenth century (21). The basic premise was to have a city designed for healthy living of self-contained communities surrounded by greenbelts comprised of open spaces, public parks, and agricultural areas that together would help the city achieve self-sufficiency. About the same time, the rapid increase in the urban population as a percentage of the total population in the United States—from just over 10% in 1840 to nearly half by 1910—led to poor social and environmental conditions in cities. In response to this, the City Beautiful movement ushered in a new aesthetic approach to improve cities through beautification, with special attention on building parks, grand boulevards, and monuments (22). **Table 1** highlights some earlier urban environmental movements related to the current concept of net-zero carbon cities.

2. URBAN CARBON ACCOUNTING

A basic understanding of urban GHG accounting is a prerequisite to assessing net-zero carbon cities. Urban areas are open systems that depend on natural and engineered systems outside of their

Table 1 Precursor urban initiatives and concepts related to net-zero carbon city

Concept/movement	Key ideas	Relevance to net-zero carbon cities
Sanitary reform (1840s)	Removal of filth and eradication of disease, especially cholera Innovations to remove and dispose sewerage and waste and deliver clean water lead to development of water and sewage infrastructure.	Physical infrastructure is fundamental to healthy city functioning.
Garden City (1890s)	Reclaiming nature in city planning, leading to New Town movement in the United Kingdom and colonies and, in turn, low-density, car-dependent suburbs (23) New design principles call for cities and towns to be surrounded by greenspace: gardens, agriculture, recreation area. Within the town, land uses—commercial, residential, industrial, etc.—are spatially differentiated.	Planning paradigms can change the layout of cities but can also have unforeseen implications.
City Beautiful (1890s)	Beautification of cities through construction of parks, grand boulevards, and monuments, with emphasis on street layout and a strong modernist suburban style (23)	Ideas for cities can move around the world and be given different expressions.
Eco-city (1990s)	Well-being of citizens and society through integrated urban planning and management that harness benefits of ecological systems Designing cities on ecological principles and keeping them in balance with nature (24)	Fundamentally questioned modernist planning and set out to transform cities to meet global and local ecological needs such as lower carbon.
Sustainable city (1990s)	Built on ecology but with emphasis on reducing the metabolism of cities, reducing car dependence, and enabling integrated economic and social outcomes (16)	Enabled a model for reducing energy use for global and national sustainability goals.
Water sensitive city (2000s)	Urban water management approach that emphasizes circular design of water systems, such as rainwater harvesting and recycling, green roofs, rain gardens, and bioswales (25)	Water and energy use in cities are closely connected.
Smart city (2000s)	A digitally connected city that uses information and communication technologies (e.g., sensors, Internet of Things) to measure, manage, and improve quality of life and efficiency of urban activities (26, 27)	Reducing energy use and integrating local solar and wind systems into cities is made easier by smart systems.
Low-carbon city (2000s)	Decouples urban economy and activities from fossil fuel use and emphasizes energy efficiency, renewable energy, and green transportation (7, 28, 29)	Focused on carbon as the primary outcome that must be addressed but also with other goals.
Net-zero carbon city	Goes further than low-carbon city to remove all fossil fuels in a bigger system boundary and to regenerate urban and regional landscapes with carbon sequestering landscapes and circular economy strategies (30–33)	All of the above need to be integrated into urban regions.

administrative boundaries to acquire energy, food, and other goods and services and to discharge and assimilate waste. A production-based GHG emissions inventory accounts for GHGs directly emitted over the land area demarcated by a city's administrative boundary. In contrast, the urban carbon footprint (see the sidebar titled Urban Carbon Footprint) concept incorporates GHGs that are caused directly and indirectly by activities within a city, including producing, consuming, and end-of-life along supply chains of goods and services flowing in and out of cities (**Figure 1**).

URBAN CARBON FOOTPRINT

Urban carbon footprint is a transboundary approach to account for carbon emissions to the atmosphere associated with residential, commercial, and industrial activities occurring within a city's administrative boundary. Different approaches have emerged for carbon footprinting based on the activities accounted for, the mechanisms considered (emissions and also subsequent transboundary removal of atmospheric carbon), and the boundary of analysis.

Embodied carbon emissions of a product: emissions caused by extraction of necessary resources, resource processing, product manufacturing, resource and product transportation, and product assembly

Whereas **Figure 1** shows the physical flow of carbon, **Figure 2** shows how urban GHG accounting tracks the GHGs (chiefly CO_2, CH_4, and N_2O emissions represented in CO_2 equivalents) embodied in the flow of goods and services in and out of cities, as well as carbon sequestered or released from stocks within cities. Urban GHG accounting is complicated by the smaller spatial scale and embeddedness of cities within larger-scaled social, ecological, and infrastructural systems (36–38). Over the past two decades, four different urban GHG accounting approaches have emerged (**Figure 2**); each gives rise to a different conceptualization of a net-zero carbon city. Urban GHG accounting and carbon footprinting approaches have been reviewed extensively in the literature (35, 39–41) and are discussed only briefly here in the context of net-zero carbon cities (32).

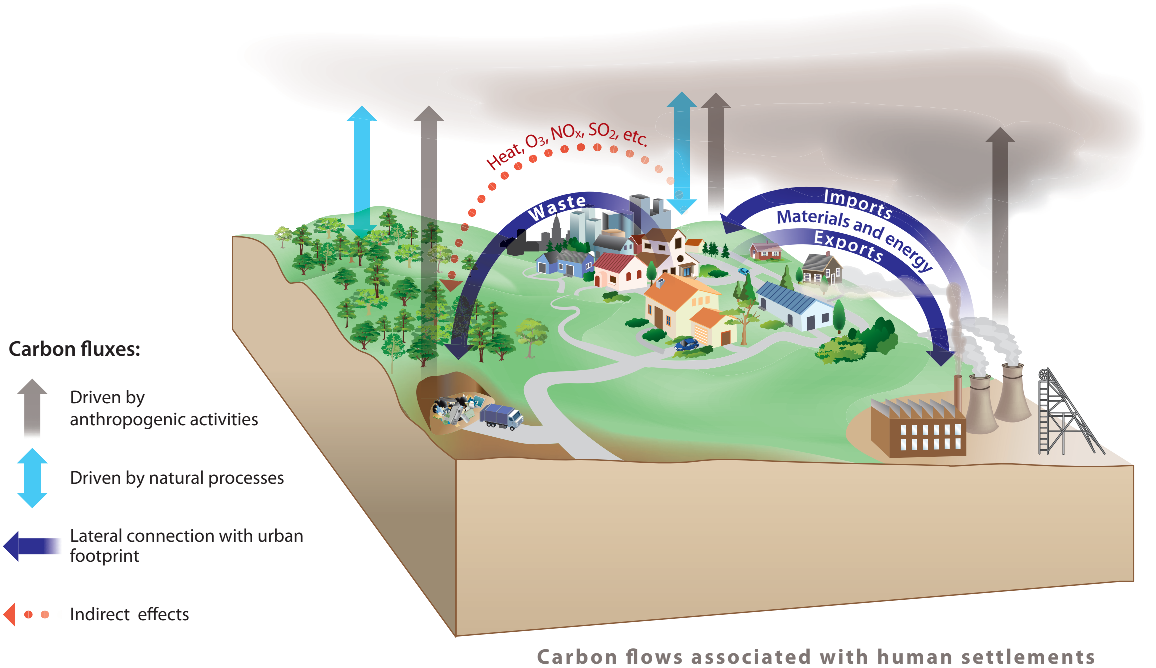


Figure 1

Urban carbon cycle. Carbon fluxes of an urban area and its linkages with urban footprint. Physically, carbon in cities cycles through natural (vegetation and soils) and anthropogenic (buildings, transportation, humans) pools. Gray arrows show carbon fluxes driven by anthropogenic activities. Light blue arrows show carbon fluxes driven by natural processes. Dark blue arrows depict lateral carbon fluxes connecting urban areas with its footprint. The dotted red arrow shows indirect effects of cities on the carbon fluxes of ecosystems located in urban footprint. Figure redrawn from Churkina (34).

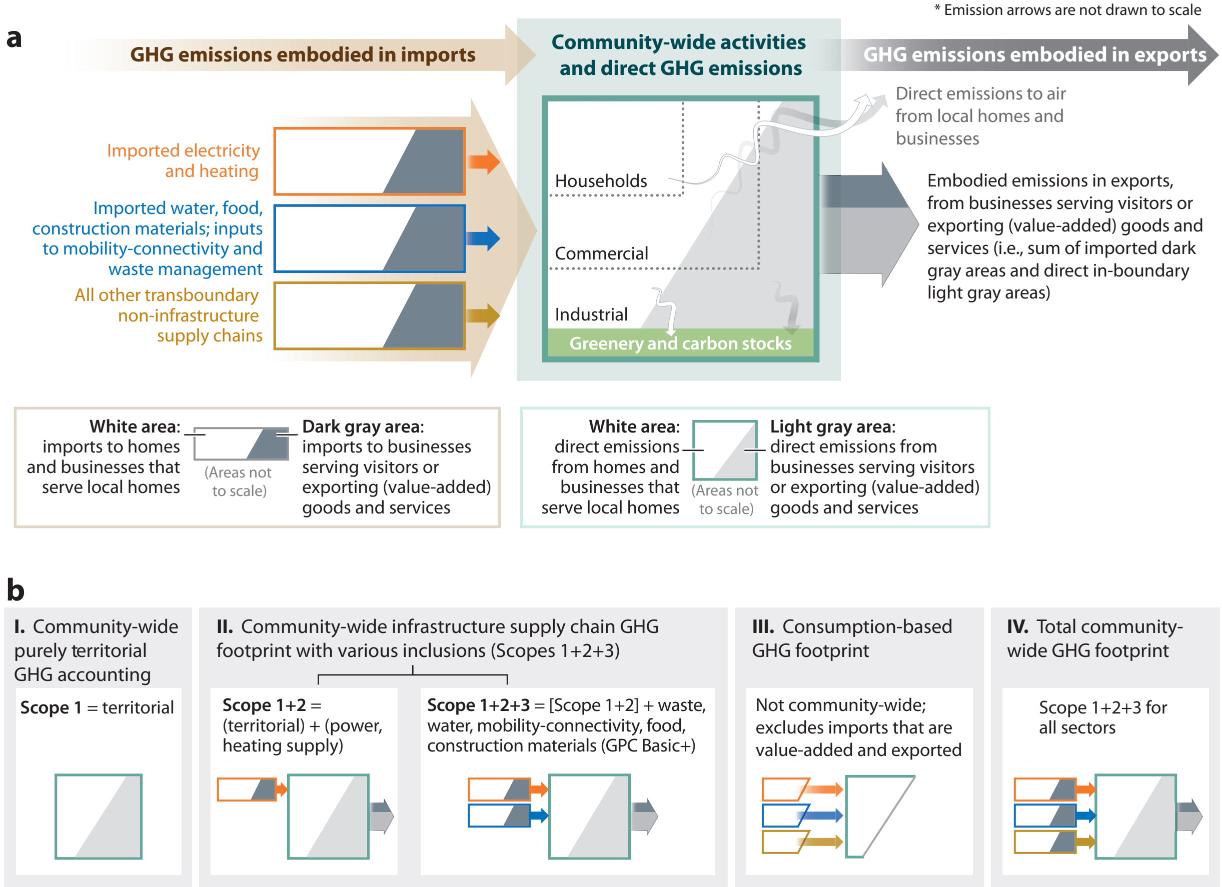


Figure 2

In-boundary and transboundary carbon flows associated with urban activities (residential, commercial, and industrial), mapped to four urban carbon accounting frameworks (numbered I to IV). (*a*) Illustration of direct territorial emission sources and sinks in a city (*squiggly arrows*) along with carbon embodied in imports (*tan arrow*) and exports (*gray arrow*) to and from a city. White areas show carbon emissions (direct and embodied) associated with homes, including from local commercial and industrial business activities that serve local homes. Gray areas show emissions (direct and embodied) associated with commercial and industrial business activities that either serve visitors or export to other communities; lighter and darker shades of gray distinguish between direct emissions and emissions embodied in imports associated with the exporting businesses. Detail is shown on the carbon embodied in imports to the city in three colors: energy sector–related imports (top; *orange text* and *arrow*), imports related to other essential infrastructure and food provisioning sectors (middle; *blue text* and *arrow*), all other goods and services imported into the city (bottom; *brown text* and *arrow*). (*b*) Different combinations of sectors and their white and gray components are counted in the different accounting framework (I–IV). Figure adapted with permission from Chavez & Ramaswami (2013) (Reference 35). Abbreviations: GHGs, greenhouse gases; GPC, the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories.

2.1. Territorial Source-Based Accounting (Scope 1)

Territorial source-based accounting encompasses all sources of GHG emissions that occur within a certain geographic area (40, 42, 43). These emissions are directly emitted (or sequestered) within a certain administrative boundary of a city or metro region and are called Scope 1 emissions. The territorial approach does not account for GHGs of items produced elsewhere that are then imported for local use—including final consumption by local households or re-exported by local businesses. Most cities import electricity, petroleum for mobility, cement for construction, water, and food as basic requirements for life in cities, which motivates the second approach, community-wide infrastructure supply chain footprinting.

A net-zero carbon city from a territorial perspective means eliminating all carbon emissions associated with current sources within the city's administrative boundary; this could be achieved by merely moving sources out of the administrative boundary of the city (which is not desirable) or incorporating more carbon sinks such as planting trees. Also, many territorial emissions, e.g., those associated with airports or marine ports, are not governed by urban policies.

2.2. Community-Wide Infrastructure Supply Chain Greenhouse Gas Footprinting (Scope 1+2+3)

Community-wide infrastructure supply chain GHG footprinting expands on territorial accounting to incorporate GHGs along supply chains of key community-wide infrastructure and food provisioning systems that support residential, commercial, and industrial activities in cities (35–37, 44). Cities with the goal of systemic infrastructure transitions, such as compact development, energy efficiency, and others, which reduce the demand for energy and materials, utilize the community-wide infrastructure supply chain footprinting approach. The community-wide supply chain approach forms the basis for GHG accounting protocols developed by practitioner networks such as ICLEI USA and the World Resources Institute (WRI). Collectively, the seven sectors that provide energy, water, mobility, shelter/buildings, waste management, food, and green public spaces are associated with approximately 90% of global GHG emissions (27).

A net-zero carbon city from a community-wide infrastructure supply chain footprint implies net-zero emissions for some or all of the seven provisioning systems (32): energy supply, mobility, construction materials, waste management, wastewater treatment, food systems, and the carbon sequestration benefits of vegetation. Most current plans for a net-zero carbon city focus on mobility, buildings and energy systems, while others include waste.

2.3. Consumption-Based Greenhouse Gas Accounting

Consumption-based GHG accounting goes beyond the seven key provisioning sectors by assigning source-based GHG emissions from all sectors of the economy wherever they occur globally, to final consumption by households (3, 45) and governments (46, 47) within a city. This approach, however, excludes local operational energy use by businesses (e.g., hotels, restaurants, industries) that serve tourists or export goods and services elsewhere. Thus, consumption-based accounting is not a community-wide account, and its boundary does not align with community-wide urban infrastructure planning noted in the second approach. Instead, the value-add of consumption-based accounting lies in informing households and governments (at any geography) about consumer choices beyond the seven key community-wide infrastructure and food sectors already addressed in community GHG protocols. Examples include purchasing of shoes, paper, furniture, etc. obtained from expenditure surveys.

A net-zero carbon city from a consumption-based perspective implies that all households and government expenditures (including all other consumer goods in addition to infrastructure and food) are net-zero. Beyond infrastructure shaped by city policies, this will require substantial governance of all other goods and services imported by local homes and local governments, well beyond the boundary of any city.

2.4. Total Community-Wide Supply Chain Greenhouse Gas Footprinting

Total community-wide GHG footprinting is an emerging approach that includes up-stream and down-stream supply chain emissions associated with all community-wide activities, i.e., including both local and final consumption by households, government, and exports (47). The challenge is in implementation, because robust city-level, place-specific economic input-output data required for this methodology are not widely available across large numbers of cities (35, 48).

A net-zero carbon city from a total community-wide supply chain footprint would imply that not only imports to local households but also exports from local businesses are net-zero. This will require global governance of carbon embodied in trade, both in and out of cities, well beyond the boundary of any one city.

Importantly, when all the key infrastructure and provisioning systems (i.e., electricity, mobility, food, water supply, construction) are decarbonized in all communities, the carbon embodied in trade will also automatically become net-zero. Thus, a focus on decarbonizing community-wide infrastructure and food systems in cities is both strategic and critical (32).

Low-carbon strategies: typical low-carbon strategies include compact development with provision of transit and nonmotorized options to reduce motorized travel demand, energy-efficient building designs, higher fuel economy vehicles, waste-to-energy technologies, and behavior change

3. A SYSTEMS FRAMEWORK INTEGRATING DEEP DECARBONIZATION PATHWAYS IN CITIES

This section develops a systems framework for deep decarbonization of cities, wherein a net-zero carbon city is visioned as one with net-zero community-wide provisioning systems (32).

3.1. Net-Zero Differs from Low-Carbon Development

Pathways for deep decarbonization require systemic change and are quite different from the more typical actions cities have pursued for low-carbon development. Low-carbon strategies can be quite systemic but do not involve quantitative targets as established in deep decarbonization. Typical low-carbon strategies include compact development with provision of transit and nonmotorized options to reduce motorized travel demand, energy-efficient building designs, higher fuel economy vehicles, waste-to-energy technologies, and behavior change to foster conservation. These can become deep decarbonization tools if associated with required quantitative outcomes that contribute to net-zero. Organizations like ICLEI USA have developed tools such as ClearPath to quantify the impact of these typical conservation and efficiency strategies. A few cities are monitoring progress toward these goals by tracking reductions in metabolic requirements, for example, reduced vehicular travel, buildings' energy use, or waste disposed (e.g., Denver has tracked changes in energy usage and mobility activities since 2005; see the case study below as well as other cities).

However, there are no standards or specific targets for emissions reductions for low-carbon strategies, with the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) showing that the targets vary widely from 20% to 100% (2). Furthermore, analysis of the maximum potential of these typical low-carbon strategies shows that they might achieve, at best, approximately 1% GHG reduction per year in US cities (29), with potentially greater reductions achievable in developing world cities (7). This low rate of carbon mitigation (effectively ~30% by 2050) will not help achieve net-zero goals, although many cities have articulated >80% or even 100% reduction (net-zero) for selected sectors by 2050.

Getting to net-zero, in contrast, involves large-scale systemic changes across all provisioning systems that are founded on a net-zero electricity grid that is enabled by increasingly low-cost renewable electricity. Crucially, achieving net-zero requires the transformation of complex sociotechnical systems and breaking out of the interrelated infrastructural and technological, institutional, and behavioral lock-in that is prone to entrenchment (8, 49). Even within the power sector, researchers highlight that a net-zero strategy will be very different from pursuing more of a low-carbon electric power strategy (50). Thus, the path to net-zero—for both nations and

Carbon valorization: the conversion of gaseous CO_2, and carbon in liquid and solid waste, into value-added products through a range of technologies

Urban industrial symbiosis: co-beneficial exchange of material or energy across two or more entities in urban areas, including industries and co-located urban buildings or utilities

cities—is distinct from a low-carbon pathway and focuses on systemic transformation of all the provisioning systems with clear quantitative outcomes required.

The Deep Decarbonization Pathways Project (51) articulated an early framework for nations to dramatically reduce their GHG emissions. It builds on three interconnected principles: (*a*) reducing energy use through efficiency and conservation measures primarily focused on individual sectors (buildings, mobility, specific industries), (*b*) shifting almost all use of fossil fuels (barring a few key industries) to electrically driven processes, and (*c*) simultaneously shifting to a very low-carbon electrical grid. Quantitative outcomes were modeled.

Detailed strategies have been evaluated for 16 countries at different stages of development, including India (52), China (53), and South Africa (54), as well as emerging cities like Bulawayo, Zimbabwe, which is outlined in a case study below. Because certain sectors such as iron and steel, agriculture, shipping, and aviation will be particularly difficult to decarbonize through direct electrification pathways (55), frameworks for deep decarbonization are now evolving to incorporate additional pathways such as carbon sequestration and carbon valorization, i.e., utilizing renewable electricity to upgrade waste CO_2 streams (including forestry, agricultural, food, and municipal wastes) to fuels and other materials (56–58). Carbon sequestration can be achieved not only through a range of technologies including air capture but also, more cost-effectively, through investments in nature—particularly long-lived trees in and around urban areas.

3.2. Urban Deep Decarbonization Framework

The national deep decarbonization pathways described above provide a broad framework for deep and systemic change but do not specifically incorporate uniquely urban strategies for reducing the fossil fuel requirements of cities while offering a high quality of life (7). This should specifically include efficiency and demand reduction enabled by integrated spatial planning (33) and cross-sector urban industrial symbiosis (59–61). To adapt national deep decarbonization pathways to urban systems, an urban deep decarbonization framework has been developed ["Pathways Toward Net-Zero Carbon Cities and Urban Regions," by A. Ramaswami, K. Tong, Z. Ren, K. Kockelman & K.C. Seto (manuscript under review)], which integrates three overarching strategies: (*a*) reducing urban demand for energy and materials; (*b*) switching energy supply to net-zero carbon electricity, fuels, and materials; and (*c*) enhancing carbon sequestration and stocks (**Figure 3**). The framework in **Figure 3** involves three main strategies—demand reduction, renewable supply, and carbon sequestration—each of which is described briefly in Sections 4–6, respectively, along with pathways for advancing each strategy.

4. REDUCING URBAN DEMAND FOR ENERGY AND MATERIALS

4.1. Pathway 1: Integrated Urban Spatial Planning

The Fifth Assessment of the IPCC Report concluded that four key characteristics of urban form and structure impact urban GHG emissions: density, land use mix, connectivity, and accessibility (2). Effective urban mitigation strategies thus must involve packages of spatial planning strategies, including co-locating high residential with high employment densities, achieving high diversity and integration of land uses, increasing accessibility and investing in public transport, and other demand management measures (2, 7).

Urban areas with a fine-grained urban fabric, where buildings are close together, block dimensions are small, intersection densities are high, and streets are narrow, tend to foster walking compared to coarse-grained settlements where intersection density is low. Pedestrian-friendly street design tends to enable travel in a low-carbon manner and emit less CO_2 in daily travel,

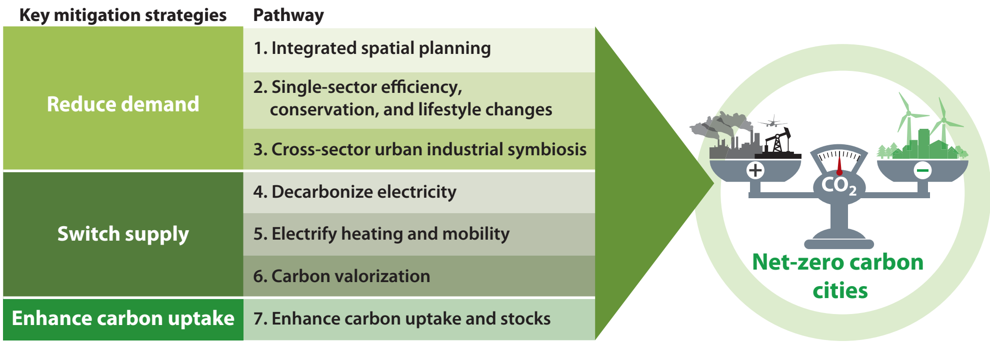


Figure 3

Framework for urban deep decarbonization. This framework combines urban efficiency and conservation; fuel switching to zero-carbon electricity; renewable fuels and materials, including via valorization technologies; and carbon sequestration, including green infrastructure, which may also reduce energy demand. Numbers refer to pathways discussed in the main text. As fuel switching occurs, cities will experience an increase in electricity demand, which should be decarbonized to achieve net-zero outcomes. Figure adapted from "Pathways Toward Net-Zero Carbon Cities and Urban Regions," by A. Ramaswami, K. Tong, Z. Ren, K. Kockelman & K.C. Seto (manuscript under review).

even controlling for residential and travel preferences (62–65). A 5-D framework encompassing density (of population, housing, and jobs), diversity (of land use), design (for multiple transport modes), destination (access), and distance (to transit and for other non-car modes) has been shown to reduce motorized travel (66).

Higher densities along with alternative transit options can impact travel behaviors in the long term by reducing car ownership (67). Cities with similar incomes and climate can have differences in transport fuel consumption of more than ten times due to the differences in their density (67). A study of 274 cities worldwide show that compact urban development can reduce urban emissions by up to 25% compared to a business-as-usual scenario (6). Compact urban development may also stabilize or even reduce private transport share in developing countries (68).

Compact urban form also creates additional efficiencies in buildings, materials and water/wastewater sectors. For example, **Table 2** sets out the range of resources and materials across the different fabrics of Perth, Australia, and mid-rise buildings in India are found to use 30% less material per square foot compared to single-family homes (70). Likewise, material requirements of piping of water and sewerage are also reduced. There can be a trade-off, however, with high-rise buildings, wherein energy use increases with building height in order to provide thermal comfort, elevator functioning and pumping water (71, 72). Overall, a mix of mid- and high-rise buildings in a dense urban fabric can create efficiencies in both buildings and transportation energy use.

Table 2 Waste output variations between urban form types, on the basis of Reference 69

Output (per person per year)	Automobile city	Transit city	Walking city
Waste			
Greenhouse gas (fuel, power, and gas) in tonnes (T)	8.01	5.89	4.03
Waste heat in gigajoules (GJ)	64.14	47.18	32.18
Sewage (including storm water) in kiloliters (Kl)	80	80	80
Construction and demolition waste in tonnes (T)	0.96	0.57	0.38
Household waste in tonnes (T)	0.63	0.56	0.49

Bio-based materials (biomaterials, biomass-based materials): materials produced from biomass of various plants such as trees, grasses, algae, etc.

4.2. Pathway 2: Increasing Single-Sector Efficiency

Within each sector, new technologies offer opportunities for reducing resource requirements while maintaining or enhancing function, constituting the second pathway to decarbonize that builds upon an efficient urban form (Pathway #1). Despite technological innovations, challenges still remain in getting to net-zero within each sector considered separately. These opportunities and challenges are summarized briefly for each sector in the subsequent sections.

4.2.1. Efficient buildings. Buildings can last from 15 years to well over centuries, and over the life span, the use phase of buildings dominates life cycle energy use, typically on the order of 80% (73). As cities decarbonize their electricity supply, the dominant contribution to life cycle GHGs will shift from building operations to building materials. A large spike in carbon emissions is currently generated in the construction stage because manufacturing cement and steel, two of the most widely used materials in modern construction, is very energy intensive. These two materials dominate material energy use worldwide (74). Future gains in energy efficiency per ton of material are estimated to be restricted to 24% for steel and 13% for cement (75). Substituting fossil fuels by renewable energy sources may never decrease CO_2 emissions from steel and cement production to zero because of emissions that stem from accompanying chemical reactions (55). For cement production, approximately 60% of the total emissions (76) stem from calcination with some of it recaptured slowly through the subsequent carbonation of exposed surfaces of concrete structures and waste (77).

In the construction stage, emissions can be reduced by using materials requiring low energy inputs for manufacturing and have relatively low weight, so that less energy is needed also for material transport to the construction site, during building assembly, and potential demolition. Biomass-based materials such as ones manufactured from timber and bamboo satisfy both criteria, as their production has substantially lower emissions than virgin steel and cement and they have lower weight than concrete (78). Using recycled steel and aluminum in construction could also be instrumental in reducing energy use because their manufacturing requires substantially less energy and their carbon emissions are 60–95% lower than the virgin ones (79), but their availability is limited by the amount of scrap collected.

A recent review of net-zero buildings suggests optimization of energy efficiency for all building energy uses, with the remaining energy to be covered from locally produced energy sources (80). The greatest technological challenge is in achieving net-zero energy in high-rise buildings in hot and humid climates. The barrier is cooling of buildings, which also requires dehumidification. Such buildings, even with the highest performance, may use as much as 90–180 kWh per m^2 per year for cooling as compared to the 15 kWh per m^2 per year, which is a feasible minimum for heating (80). The high energy requirements for cooling in hot humid climates will place a large load on a future net-zero emissions grid, increasing its cost.

4.2.2. Efficient vehicles. The transportation sector (personal mobility and freight) contributes approximately 20% of global GHGs. Single-sector efficiency can generate some advances, such as arising from light-weighting of vehicles perhaps by 10%. Furthermore, changing vehicle-fuel technologies can also contribute to reductions in energy use, such as hybrid electric, plug-in electric, natural gas, and bioethanol-powered vehicles. Life cycle analysis is needed to show how close to net-zero emissions is possible and, in particular, whether renewable power is used to fuel them (81).

Electric vehicles (EVs) are growing globally at more than 40% per year and are expected to reach at least 25% of the vehicle fleet by 2040 (82), with others suggesting higher figures as electromobility becomes cheaper than internal combustion engine–based mobility in 2022

(83). Most of the growth in EV's has been in China, but leapfrog adoption of EVs has started in developing cities; some are therefore predicting even higher adoption rates (84) with the last diesel and gasoline cars being produced in the 2020s.

Green infrastructure: a strategically planned network of natural and seminatural areas with other environmental features designed and managed to deliver various ecosystem services such as water purification, air quality, and space for recreation and climate mitigation and adaptation

4.2.3. Green infrastructure. Green infrastructure is a strategically planned network of natural and seminatural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, as well as space for recreation and climate mitigation and adaptation (**https://ec.europa.eu/environment/nature/ecosystems/index_en.htm**). Green infrastructure includes horizontal and vertical gardens, parks, urban forests, street trees, and urban agriculture. Green infrastructure mitigates emissions of CO_2 from cities in various ways, including direct uptake of carbon dioxide (see Pathway 7, below), and they also help adapt cities through shading and evapotranspiration that cool cities. Green infrastructure is not yet included in the carbon offsets of cities, but this could be done in the future as more cities adopt protocols already available to assess the impact of biogenic carbon sequestration (32, 85).

4.3. Pathway 3: Cross-Sector Urban Industrial Symbiosis

Urban industrial symbiosis refers to the exchange of waste heat and materials across sectors, i.e., across industries, buildings, and municipal infrastructure (waste management, landfills, wastewater treatment) in cities. This includes many potential exchanges, the largest of which include eco-industrial parks, wherein waste and energy exchange among multiple industrial manufacturing plants in and around urban areas, and the exchange of waste heat between industrial, commercial, and residential sectors most in the form of district heating systems. The decarbonization actions in 1,604 industrial parks in China have been found to reduce 315–2,300 million metric tonnes of CO_2 (59). Several studies of cities in the United States and the European Union (EU) have shown remarkable potential for harvesting waste heat from industries and grocery stores for heating and cooling residential/commercial buildings in cities (86). Many cities practice waste-to-energy generation, food composting, as well as methane recovery from wastewater recovery (87–89).

5. SWITCHING SUPPLY TO NET-ZERO CARBON ELECTRICITY, FUELS, AND MATERIALS

5.1. Pathway 4: Decarbonize Electricity

A net-zero carbon electricity grid is the foundation of supply side strategies that aims to provide net-zero carbon energy and materials to support all provisioning systems, including buildings, energy use, mobility, and light industrial energy use that may be readily shifted to electric power. However, very high temperature industries such as iron and steel, fertilizer production, as well as aviation sectors will probably use renewably created hydrogen to be able to contribute to net-zero outcomes as well as consuming some electricity. Buildings, light industry, and mobility shifts from fossil fuel to electric power will require almost a doubling of electricity generation, which must also be net-zero carbon unless significant reductions in demand occur with this. This presents a significant challenge, yet some of this increase can be met by solar and wind becoming the cheapest forms of power, as well as battery storage becoming highly efficient and cost-effective (90, 91).

The new patterns of urbanism that are emerging around these systems are already showing why cities will become much more distributed into local areas of infrastructure management due to the simplicity of solar, in particular, being able to produce power at or next to the site where it is needed—but they will still fit into a city-wide or region-wide grid system for equity and balance as well as efficiency (92–94). The rapid growth in solar has now moved into shared solar systems for medium- and high-density housing enabled by localized solar utilities with batteries and other technologies for enabling sharing such as community-based storage and block chain–based management (35, 44, 95).

Renewable resources such as solar photovoltaics (PV) can be installed at the household, community, and grid scale. There is a dearth of models that link the utility-scale energy resource models with the detailed distribution-level power-sector models needed within cities. Planners as well are grappling with the architecture of integration at intraurban scales. These will need to be developed as part of the staging of net-zero city strategies.

5.2. Pathway 5: Electrifying Mobility and Heating/Cooking Systems

The net-zero carbon electric grid is the lynchpin for achieving a net-zero carbon future only when key urban activities such as mobility and heating are switched from the use of fossil fuels to zero-carbon electricity. The ensuing transitions are briefly summarized below.

5.2.1. Renewable-electric mobility. Disruptive electric mobility combines the efficiency of electric drive vehicles with the supply of increasingly low-cost renewable energy, which may be generated locally (i.e., at home-scale or community-scale solar-powered microgrids), or via the larger power grid (96). EVs are already being used to fit cleverly into home PV and battery systems with the high potential for vehicle-to-grid transfers of power to enable extra storage options in the grid. Electric transit is also beginning to be switched to renewable power as demand for clean transport grows across cities (67) and new ways of financing this demand are being found (97), thus enabling cities to both reduce the need for energy as well as enable transit to be based on renewable power. Recharging of electric cars and electric transit (buses, trains, and trams) will be needed at certain parts of the city where solar collectors can be built to satisfy this demand. The obvious solution for planners is to find how recharge hubs can be fitted into station precincts thus mainstreaming both solar and electric transport. Achieving a balance between cars and transit will still be needed in a net-zero city. Otherwise the demand for renewables will exceed the supply if all sectors transition to renewables.

Urban planning needs to participate in the development of the power grid more toward localized or community-based management of power within a broader grid system and in how electric transport fits into this. The idea of local shared mobility that is electric and autonomous and feeds into stations along a fast, electric, corridor-based transit system seems to resolve many of the planning issues in this transition (98). However, it will require detailed urban planning to enable the walkable precincts at stations to remain attractive for the knowledge economy while enabling the fast corridor service between these stations. The role of walkable urban design, solar design, water sensitive design, and biophilic design will be critical at stations, and the commitment to transit along street corridors will need to be the highest priority for transport engineering. All new urban development will need to mainstream this combination of solar, EVs (both in cars and transit), and well-positioned recharge hubs and will require strategic and statutory plans to adopt these into their short- and long-term decision-making (91). The result is likely to show how solar will be able to transform cities and grids much faster than ever considered possible by utilities and by national governments.

5.2.2. Electric heating and cooking transitions. Both heating and cooking are embedded in the direct use of fossil fuels in most cities. Cooking is increasingly able to be switched to inductive electric stoves that are safer and can be renewably powered, but heating is more complex. Whereas air conditioning is operated on electricity, heating systems are operated on coal, fuel oil, or natural gas, contributing to significant CO_2 emissions and air pollutant emissions. The renewables-based electric heating transition involves switching from fossil fuel–based heating using boilers that generate steam or hot water for space heating, to electric-driven heat pumps for heat transfer using renewable electricity. The heat pumps can be air-source heat pumps or ground-source heat pumps, which directly pump heat from outdoors during winter for heating and transfer heat from indoors during summer for cooling. Heat pumps are generally more efficient than fossil fuel boilers in a moderately cold climate, offering both fuel and cost savings. Research conducted in all US counties demonstrated substantial variation in the feasibility and cost of a fully renewable plus battery storage and supported transition to electric heating (99). Overall, these results indicate that there may be cost savings of retaining a small amount of natural gas heating, particularly in cold climates, but this will hamper net-zero outcomes if renewable gas is used (described next). Other studies have indicated much more positive outcomes in costs and emissions from new technology heat pumps in buildings and appliances including cooking (100, 101).

5.3. Pathway 6: Renewable Fuels and Materials via Carbon Valorization

Carbon valorization has been defined as converting gaseous CO_2, and carbon in liquid and solid waste, into value-added products through a range of technologies (102, 103). When these technologies are driven by zero-carbon/renewable electricity, there is potential to create additional carbon storage as well as products that can be used in infrastructure and provisioning systems (104). In this way, carbon valorization is distinct from the material energy exchanges that were referenced in urban industrial symbiosis because of the active use of renewable electricity to drive the technological processes. Examples relevant to provisioning systems include the production of renewable natural gas and other value-added products such as carbon rich materials from CO_2 captured from industrial exhaust (e.g., power plants, cement plants, steel plants, and indeed any industrial product) through renewability-driven electrochemical processes (103).

Likewise, there is the potential to develop biomass-based materials using renewable energy in the process. Cross-laminated timber made from industrial processes using renewable energy sources in the nearly closed loop wood production cycle has been demonstrated in mid- and high-rise construction in several world cities (105, 177). For biomass-based materials, an important consideration is whether they will result in long-term carbon sinks (106). The widespread availability of low-cost solar energy enables carbon valorization.

6. PATHWAY 7: ENHANCING URBAN CARBON UPTAKE AND STOCKS

Carbon uptake within city limits or associated regions can offset emissions of carbon dioxide from cities. There are two main pathways for direct carbon uptake in cities. The first one is carbonation of cement containing materials, when atmospheric CO_2 reacts with CaO in concrete to form calcite ($CaCO_3$). Carbonation is the process opposite to calcination, which is used in cement production. The carbonation process is relatively slow because CO_2 has to diffuse into the solid material and dissolve in its pore fluid. The second one is photosynthetic carbon uptake by green plants. US urban forests can capture in one year as much carbon as the US concrete infrastructures in a century (107).

Rates of carbon sequestration by urban vegetation depend on the plant forms, species, climate zone, as well as intensity of vegetation management. Grasses are reported to have carbon uptake between −80 and 140 gC per m^2, trees between 15 and 94 gC per m^2, and green roofs between 73 and 276 gC per m^2 (107). Urban vegetation is a carbon sink (107), but its carbon sequestration is offset by carbon release with landscape maintenance such as irrigation, fertilization, lawn mowing, as well as tree and shrub pruning (108, 109). The urban territorial emissions of carbon currently dwarf the carbon uptake by green infrastructures. In China, green infrastructures offset 0.33% of the carbon emissions from fossil fuel combustion ranging from 0.01% in Hohhot to 22.45% in Haikou (110). In the city of Boston, USA, total annual carbon uptake by urban forests was equivalent to <1% of estimated annual fossil CO_2 emissions for the city (111). Urban trees in the United States sequester approximately 25.6 million tons of carbon (112).

Using carbon rich materials in the design of urban infrastructures can enhance urban carbon stocks considerably in addition to reducing emissions of carbon (78). Carbon rich materials are ones that store substantial carbon amounts per unit of volume such as biomass-based materials. A five-story residential building structured in timber can store three-fold more carbon than the natural forest with the highest carbon density aboveground (78).

7. CASE STUDY: ASPIRATIONAL NET-ZERO CARBON CITIES

7.1. Bulawayo, Zimbabwe

Bulawayo is the second largest city of Zimbabwe and has an urban population of between 680,000 and 1.5 million according to official and unofficial estimates (113). The city showed rapid growth, like most African cities during the twentieth century; however, it slowed and reversed during the first decade of the twenty-first century due to substantial economic decline in the last years of the Mugabe Government. It is now growing again with a new emphasis on achieving the United Nations Sustainable Development Goals (SDGs) (113); hence, the case study is important for showing how cities can help reshape development around such issues as net-zero (114). The SDGs have been adopted as part of the Strategic Plan for Bulawayo (115, 116), and the next steps involve finding opportunities for investment that can enable a future net-zero city (117).

7.1.1. Leapfrogging toward sustainable development in the next economy. Bulawayo is looking to leapfrog into the future using the most appropriate technologies now becoming available (91, 118). The idea in leapfrog development is jumping over existing technology to the next generation of technology when investing in new technology (119). Bulawayo has seen the collapse of its industrial base in the first decade of the twenty-first century and is looking to create a new economy quickly. The literature on leapfrogging suggests that this is possible if the cities and nations involved are able to create the kind of supportive governance base that can welcome and enable demonstrations and create partnerships for financing (119–121).

The technologies relevant to leapfrogging Bulawayo into being a low- to net-zero emissions city include renewable power (especially solar with batteries), electromobility (especially new transit and micromobility), smart technologies that assist the grid and help reduce wastage of resources, and circular economy technologies for waste management (91). One of the first projects to enable this kind of leapfrogging is with Trackless Trams (TTs) and solar energy that are being strongly pushed by the City of Bulawayo (122).

7.1.2. Trackless Trams and solar energy for net-zero leapfrogging. Trackless Trams are a new transit system that has the potential to aid emerging cities to technologically leapfrog in transport, especially through its potential to attract urban development around stations to enable private finance partnerships (123). The technology uses batteries rather than overhead wires and can be recharged at stations where urban development partnerships can build net-zero

Figure 4

Trackless Tram in Yibin, China. A Trackless Tram uses Lidar and sensors to guide a tram. It does not need a traditional track and is somewhat like a bus+train+tram. Photo by Daniel Conley.

solar-powered developments in both transport and buildings. The TTs are able to run down main roads without rail tracks as they are guided bus systems (97) (see **Figure 4**).

The expectation is that a successful technological leapfrog will facilitate the adoption of a progressive sociotechnical regime that will lead to socioeconomic development that creates a net-zero carbon city (117). The Trackless Tram–solar power system certainly meets those requirements. One of the main looked-for attributes of a technology needed to augment leapfrogging is the ease of implementation and deployment. TTs can be easily deployed and integrated into parts of the city. Acquiring and utilizing TTs for commercial purposes is less challenging. A TT can considerably minimize the current problem of having numerous cars and small buses or jitneys on the road. At the same time, a TT has the interoperability and matching technological proficiencies and utilization to build on the know-how of most developing cities. They can be a major connector across cities linked by first and last mile service through small buses and jitneys and connect to major centers like the central business district (CBD) as well as bus or train stations.

7.1.3. Other net-zero projects for Bulawayo. Bulawayo is looking to decommission the city's old 90 MW thermal power station located in the CBD to build an equivalent sized solar power station on the outskirts of the city. A 100 MW solar facility will be a big step for Bulawayo toward being a net-zero carbon city and will require batteries including those associated with the TTs station precincts. As there is such a low power use at present it is possible for Bulawayo to be fully powered by solar within 3 to 5 years.

7.2. Canberra, Australia

The first urban area in Australia to set a process toward net-zero for the whole urban region is Canberra [or in jurisdictional terms, the Australian Capital Territory (ACT)]. Canberra is a small city in global terms (420,000 in 2019) but is the largest inland city in Australia and has a history of strong urban planning with climate change objectives (124).

The ACT passed their Climate Change and Greenhouse Gas Reduction Act in 2010, which set in motion a series of plans and processes managed by a Climate Council of local experts and stakeholders who set 5-year goals and report regularly on progress. The steps that were set out

Table 3 Climate Strategy actions and estimated emissions reduction in 2020 for Canberra, Australia

Sector	Actions	Emissions reduction (tonnes CO_2e)
Residential sector energy use	6	218,000
Non-residential sector energy use	3	181,000
Transport sector emissions	1	138,000
Waste sector emissions	1	16,000
Energy supply sector emissions	3	1,471,000
Climate change adaptation	3	Not applicable (NA)
Monitoring and reporting	1	NA
Total	18	2,024,000

are summarized in their most recent *Climate Change Strategy 2019–2025* (125), which committed Canberra to reducing emissions from 1990 levels by 40% in 2020, achieved based on a major shift in power purchasing to renewables (see below), 50–60% by 2025, 65–75% by 2030, 90–95% by 2040, and 100% by 2045.

The targeted emissions reductions by sector are in **Table 3** showing the Climate Strategy number of actions and expected emissions reductions by 2045. The strategies set out in the table are from the original Climate Strategy illustrating how each sector assists in creating the net-zero outcome, with the vast majority coming from the electricity supply system.

Since this Climate Strategy was set in motion, most of the above actions have been completed. Canberra has

1. Created Zero Emissions Power using 100% renewable power through purchasing only this power for all its citizens and businesses from the National Electricity Grid.
2. Developed a Zero Emissions Transport Strategy based on a new Light Rail system and a Zero Emissions Bus Strategy and moved toward improving the cycling system and creating a more compact city. The Light Rail has been dramatically successful in taking people out of cars and creating real estate value increases along the corridor vastly more than expected. The Zero Emissions Bus Strategy to 2040 is a detailed plan building EV buses locally and enabling new depots to recharge their buses using solar on their roofs and thus receiving grid balancing payments; the strategy involves intensive workforce retraining.
3. Outlined a range of other strategies that will now concentrate on removing gas from households and industry and on Living Infrastructure (greening), Water, and Waste as well as tree planting in the region; water sensitive urban design and circular economy strategies are also being detailed.

Canberra has a strong political base for achieving these strategies with the government being re-elected based on the net-zero strategy and its achievements in being ahead of its transition so far.

Low-carbon city: a city with low CO_2 emissions and high uptake of carbon from the atmosphere, but not reaching a zero balance between the two

7.3. Chongming, China

Chongming Island was once the most rural area of Shanghai. In 2001, the Shanghai Municipal Government (SMG) proposed the vision of turning Chongming into a low-carbon eco-island to explore developing low-carbon cities in China. One of the SMG's actions in the early stage was to initiate the planning for a low-carbon city. In 2004, the SMG organized a planning competition to draft the Chongming Master Plan and invited four internationally renowned

Figure 5

Solar panel roof and wind power plant in Chongming. Photo by Xin Ao. The image was taken in February of 2021. The building on the right is Dongtan Tourist Service Center, which is covered with a solar panel roof. On the left of the image is a wind power plant, one of the seven wind farms in Chongming.

design and urban planning firms. The plan proposed by the American firm Skidmore, Owings & Merrill won the first prize, and later also won the 2005 Regional and Urban Design Award of the American Institute of Architects (126). In 2010, the SMG further drew up Chongming Eco-Island Construction Outline, which developed a framework and a set of 22 systematic indicators to transform Chongming into a low-carbon eco-island in 2020 (127).

The approach to reduce GHG emissions in Chongming involves six sectors:

1. Buildings: All new buildings are required to use energy-saving materials such as local biomass-based materials and recycled steel and bricks in the process of construction. More than 95% of the construction waste should be recycled and reused. These buildings are encouraged to use solar energy (see **Figure 5**). Existing buildings have been transformed into energy-saving buildings.
2. Energy: Chongming developed a comprehensive plan to promote the utilization of renewable energy such as wind energy, solar energy, and biogas energy. The Bao Town Coal power plant, once a large GHG emitter, was closed. Wind farms and solar PV power stations have been constructed. By the end of 2015, seven wind farms, solar PV power stations with a total installed capacity of 2,600 kW, and four biogas projects had been built in Chongming (128).
3. Mobility: Chongming has built a "public transit + active transportation" system. All public buses have been upgraded to EVs. Hundreds of shared EV and bicycle stations have been established. A total of 500 km of ecological greenways and cycleways have been constructed for travel on foot or bicycle (128).
4. Wastewater: Four sewage treatment plants were constructed in the towns of Chengqiao, Xinhe, Baozhen, and Chenjia. More than 90% of wastewater has been collected to the plants for recycling by advanced and low-carbon techniques (128).
5. Waste: A comprehensive waste treatment plant, six domestic waste compression transfer stations, and two sanitary landfill sites have been built in Chongming (128). The plant can treat approximately 380 tons of waste per day, and the domestic waste recycling rate has reached 100%. An organic fertilizer treatment center was built for processing agricultural wastes, and the manure resources were used for biogas production.

Biogas: a mixture of gases anaerobically derived from organic matter such as plant biomass, municipal waste (e.g., sewage or solid), or agricultural waste (e.g., manure, straw, etc.), etc.

Table 4 Main evaluation indices for Chongming Eco-Island development, on the basis of References 124, 125, and 128

	Indices	Targets (2020)	Achievements (2019)
Building	New-built green buildings	100%	100%
Energy	Renewable energy power-generating capacity	200,000–300,000 kW	376,900 kW
	Standard coal consumption per GDP	0.6 tons	0.3 tons
Mobility	The proportion of new energy buses	100%	100%
Wastewater	Wastewater treatment rate	90%	92.95%
Waste	Domestic waste recycle rate	100%	100%
	Manure resources utilization rate	85%	100%
	Agricultural straw utilization rate	95%	97.6%
Green infrastructure	Coverage of forest	28%	27.4%
	Coverage of wetland	43%	42%
	The proportion of ecological protection area	83.1%	67.54%

6. Green infrastructure: Dongping Forest Park and Pearl Lake Park are the main conservation lands in Chongming. Ecological corridors pass through the island and work together with lakes to improve the quality of the eco-environment, and to help offset the GHG emissions.

Several reports have been released to evaluate Chongming's efforts for decarbonization, from the United Nations Environmental Program's Assessment Report to the Shanghai Development and Reform Committee's Report (see **Table 4**). Although the contents of these reports focused on different aspects, most of them affirmed Chongming's achievements in building environment-friendly energy and green infrastructure, and in reducing GHG emissions, but also pointed out the challenge that Chongming faced (126, 129):

1. Environment-friendly energy: Chongming continues to decarbonize its energy system. It first developed a wind farm in 2008, offsetting 27,200 tons released of CO_2 each year (130). In 2019, the renewable energy generating capacity of Chongming was 376,900 kW. Today Chongming exports renewable energy to other parts of Shanghai (131).
2. Green infrastructure: The forest and wetland are well developed in Chongming. The coverage of forest and wetland reached 27.4% and 42% in 2019 (131). It is estimated that Chongming's green land can sequester approximately 500,000 tons of CO_2e in 2020, which can offset more than 10% of its GHG emissions (132).
3. Relatively low speed of economic development: Under the strict ecological requirements, factories that did not meet the requirements were shut down. Their land has been converted into green parks and infrastructure with public investments (132). As the industrial development in towns did not meet the expectations, a large share of residents remained unemployed (133, 134).

Looking back on the achievements and challenge of Chongming Eco-Island, the development of a low-carbon eco-island has been successful in reducing local demand for energy and materials, enhancing its carbon sink, and switching to a net-zero carbon energy system. The case of Chongming demonstrates that the path toward a net-zero carbon city is possible and feasible but requires systematic planning and concrete actions.

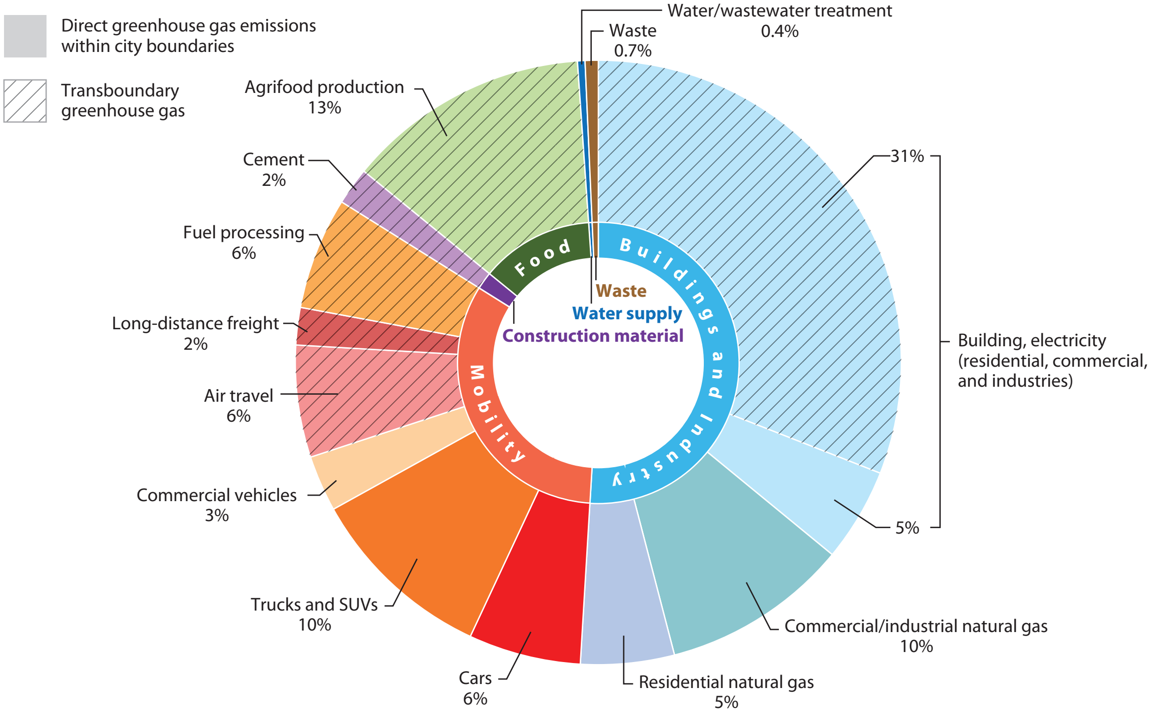


Figure 6

Community-wide infrastructure supply chain greenhouse gas (GHG) emission footprints for Denver, USA for 2005. Delineating emissions associated with six sectors: energy supply to buildings and industry (*light blue*); mobility including tailpipe emissions from vehicles, airline travel, and fuel processing (*red*); water supply and wastewater treatment (*dark blue*); waste management (*brown*); construction materials (cement in *purple*); and agrifood production (*green*). Hatched areas indicate transboundary infrastructure GHGs. Figure adapted with permission from Ramaswami et al. (2012) (Reference 38).

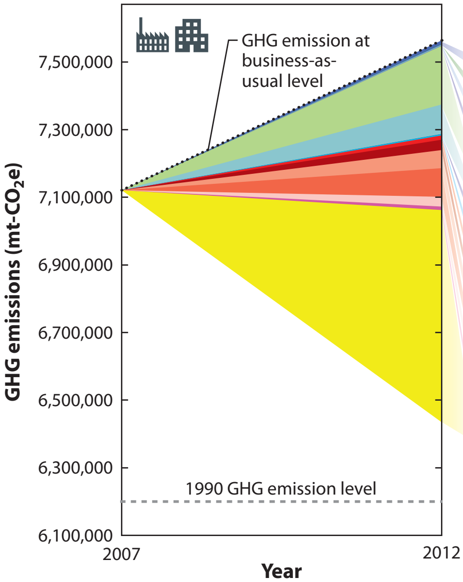
7.4. Denver, USA

Denver, a city of approximately 600,000 people, started work in 2005 on developing a GHG account, which has since been used for low-carbon city planning and implementation. The baseline GHG account for Denver follows the advanced community-wide infrastructure supply chain approach, covering all seven key physical provisioning systems. Transboundary GHG contributions are large, as shown in the hatched portions of **Figure 6**. **Figure 6** indicates that approximately 50% of Denver's community-wide GHG footprint is due to electricity and natural gas use by homes and businesses; approximately 25% is due to various mobility modes in addition to which a further 8% is from transboundary refining of petroleum fuels for use in transportation. Additional Scope 3 contributions, totaling ∼15%, were nonenergy emissions from food supply, emissions embodied in cement used for construction, as well as water supply, wastewater treatment, and waste management (38).

Denver's first Climate Action Plan was signed by the Mayor in 2007 and implemented over the next five years with the initial goal of reducing community-wide emissions per capita by 10% by 2012. Denver succeeded in this effort due to the region's electricity becoming cleaner given the passage of the State of Colorado's renewable portfolio standards and additional city scale climate actions. Indeed, modeling of typical efficiency and conservation programs—with high and low level participation rates—showed that even in the best case, emissions reductions from efficiency can be expected to be less than 1% per year, with much less mitigation possible in the transportation sector compared to energy use in buildings (29) (see **Figure 7**). Denver has been one of few cities that has tracked the progress of its climate action plans (30), including the numbers of homes retrofitted, high efficiency appliance rebates used, etc.

In 2018, Denver advanced from their earlier low-carbon goal to deep decarbonization seeking to reduce emissions by 80% by 2050 (135). Recognizing that typical low-carbon efficiency and

a Buildings and facilities sector



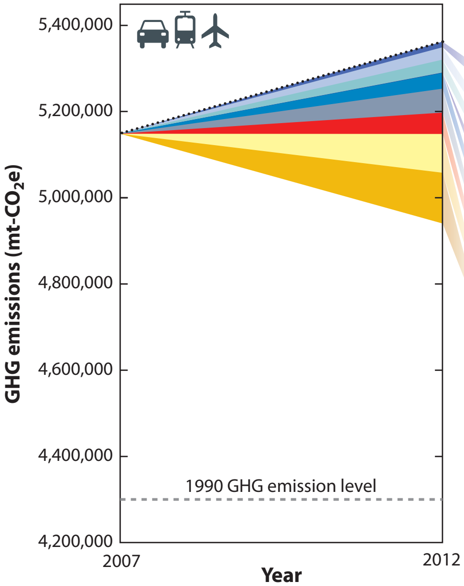
GHG mitigation actions	SCALE	Primary actor(s)	% mitigation contribution
Free compact fluorescent lamp giveaways	INDIVIDUAL	U, P	0.100%
Basic home upgrade, free for low income homes		U, P	0.010%
Door-to-door weatherization outreach		U, P	0.100%
Higher cost home energy upgrades via low interest loans		U, P	0.003%
Voluntary green electricity purchases by 3% of population		U	2.400%
Commercial-industrial demand-side management		U, D	1.200%
Voluntary new "green" buildings		D	0.010%
Voluntary energy displays		U	0.050%
Opt-in bond program	CITY	P	0.170%
Time of sale mandate		P	0.400%
Date certain regulations		P	0.700%
Energy displays — mandated		P	1.100%
Electricity with 4.4% carbon tax		P	0.300%
Mandated "green" buildings		P	0.140%
Renewable portfolio standard	STATE	P	8.300%

Voluntary actions primarily initiated by **individual users (U)** and **infrastructure designer-operators (D)**

Policy actions (P) at the city scale

Policy actions (P) at the state or regional scale

b Transportation sector: surface and airline travel (wells-to-wheels)



GHG mitigation actions	SCALE	Primary actor(s)	% mitigation contribution
50% fleet upgrades	INDIVIDUAL	D	0.20%
Individualized travel marketing program		P	0.60%
Employer-based commuter programs		U, D	0.60%
Fivefold increase in bike mode share		U, P	0.01%
Telepresence for 3.3% of air travelers		U	0.70%
Airline offsets by 5% of air travelers		U	1.00%
Smart growth planning	CITY	D, P	0.90%
Low rolling resistance tires	STATE	P	1.80%
Pay-as-you-drive auto insurance		P	2.30%

(*Caption appears on following page*)

Figure 7 (*Figure appears on preceding page*)

Typical low-carbon actions focusing on efficiency and conservation contribute relatively little to GHG mitigation in established cities such as Denver, CO, USA, hence the need for systemic transformations for deep decarbonization. Details of the Denver case study (2007–2017) are shown here, for (*a*) buildings and facilities sector and (*b*) transportation sector including surface and airline well-to-wheels GHG emissions. Short-term (5-year) GHG mitigation wedges for Denver show impacts of various actions by actor category. Voluntary actions primarily initiated by individual users (U) and infrastructure designer-operators (D) are shown in blue−green. Policy actions (P) at the city-scale are in red−orange, and those at the state- or regional-scale are in yellow. GHG mitigation is shown both in terms of mass (CO_2e) mitigated on the *y*-axis, as well as the % contribution associated with each action in tables on the right: Many individual actions are not apparent due to their very small impact (<1%) on % GHG mitigation, as reported in the right most column of the table of each panel and also computed in **Table 1**. These smaller impact actions appear grouped together, whereas the higher impact actions appear individually distinct. Abbreviations: GHG; greenhouse gases. Figure adapted with permission from Ramaswami et al. (2012) (Reference 29).

conservation strategies, while important, would not yield substantial reductions rapidly, Denver is incorporating many of the systemic changes proposed in **Figure 3** (30). These include mitigation through fuel switching, converting building heating and transportation to electricity, and relying on the long-term plan of the local electric utility—Xcel Energy—which has announced plans for net-zero emissions electricity by 2050 (136). The projected reductions for Denver with systemic changes that convert heating systems and mobility systems to electricity are estimated to achieve close to 80% reduction for these two sectors (30). As indicated in the previous section, transitions to electric heating and mobility will increase electricity demand (which will itself be transitioning to zero-carbon electricity). Thus, Denver and other cities might see an initial increase in GHG emissions before they peak and then reduce. The anticipated reductions by 2050 are slightly short of the 80% mitigation goal, due to which additional circular economy and sequestration efforts are being considered.

The case study illustrates key points highlighted in the framework section. First, typical city low-carbon actions focused solely on efficiency and conservation will not reduce GHG emissions rapidly, particularly in established cities like Denver where much of the building stock is old. Thus, even with incentives for green buildings, the proportion of homes or appliances being retrofitted/replaced each year is very low. Second, to achieve greater mitigation, systemic changes such as electrification of heating and mobility systems will be necessary. Third, even with these changes, getting to 80% reduction by 2050 will be challenging not only in Denver but also in all cities worldwide. Indeed, new strategies including massive investments in tree canopy, cross-sector symbiosis, and circular economy strategies will all be additional levers for cites like Denver to explore to fully realize a net-zero goal. These green infrastructure and cross-sector strategies can contribute up to 3% mitigation annually (see 85 for tree canopy effects) and will be significant in the path to a net-zero city.

8. FROM PATHWAYS TO PRACTICE

Cities can achieve carbon neutrality by a combination of reducing energy and resource use, reducing waste, and increasing carbon sinks, while simultaneously improving human livability within global and local constraints. Any settlement can work toward net-zero carbon while attending to local issues at the same time. Local governments can provide housing, jobs, and services while at the same time integrating into their net-zero plans consideration for local environmental issues such as groundwater replenishment, wastewater and air pollution remediation in local waterways and airsheds, soil carbon replenishment in surrounding agricultural areas, and regeneration of forest and park areas. Each of these can be related to the net-zero carbon agenda.

8.1. Governance

Many activities that affect the GHG emissions of a city occur beyond administrative boundaries. As such, actions to achieve net-zero outcomes require governance at both micro scales within the city as well as coordination more broadly across higher levels of governance (e.g., regional, national, international). Furthermore, the sociopolitical and geographic context in which cities operate varies considerably, requiring different governance approaches. Most cities are not managed at a whole region scale but have some kind of governance that can set up a net-zero governance process. City centers and inner urban fabrics are very different in their decarbonization potential than outer and peri-urban areas (137). Given this complexity, achieving deep decarbonization in cities will require institutional and policy support from multiple parties and multiple levels of governance (138–140). To that end, cities need to consider multiple institutions and actors, and multiple levels of governance, in crafting their GHG reduction strategies—particularly for community-wide transformation (141).

Figure 8 presents an analysis of the climate action plans of 296 cities with published climate strategy documents and net-zero targets, defined here as those that either have committed to either a target with a goal of at least an 80% reduction in GHG emissions by a given year from baseline or have signed up to an initiative committing to a decarbonization goal (143). Their geographic distribution is highly skewed toward Europe and North America (**Figure 9**). The analysis illustrates divergences between Global North and Global South cities' approaches to net-zero—and how these are situated in a larger governance context. Cities located in developing countries are more likely to specify local and community actions, and adaptation to climate change and risk mitigation, as well as more prominently mention targeted actions in the water and waste sectors.

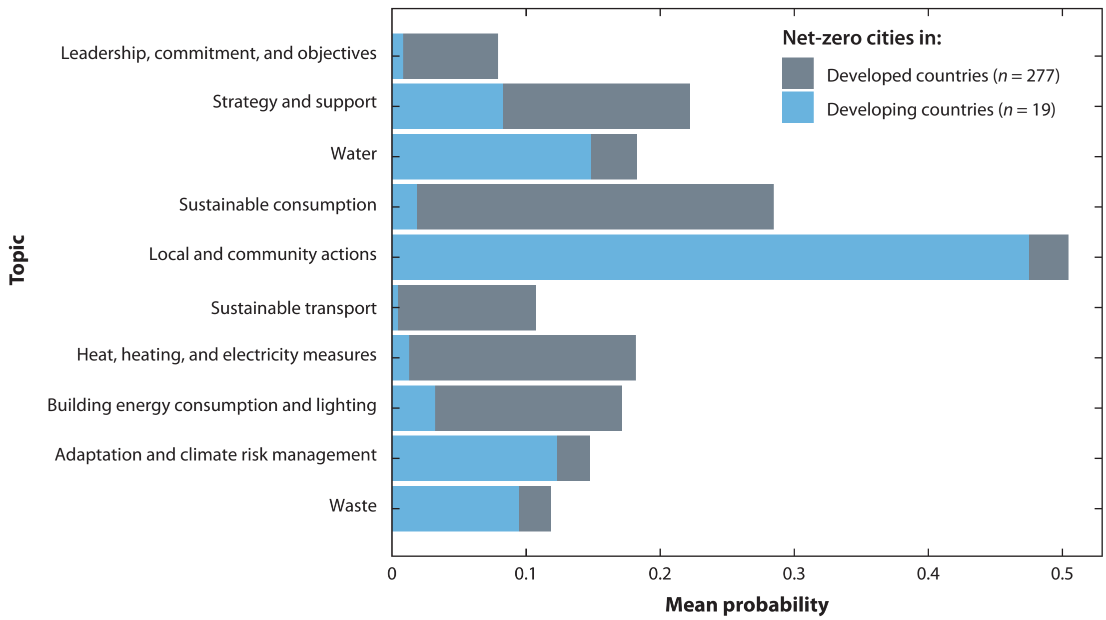


Figure 8

An analysis of 296 cities' net-zero climate action strategies utilizing natural language processing and machine learning techniques. The x-axis shows per-document-per-topic probabilities for each of the 10 topics analyzed. See Reference 142 for methodological details.

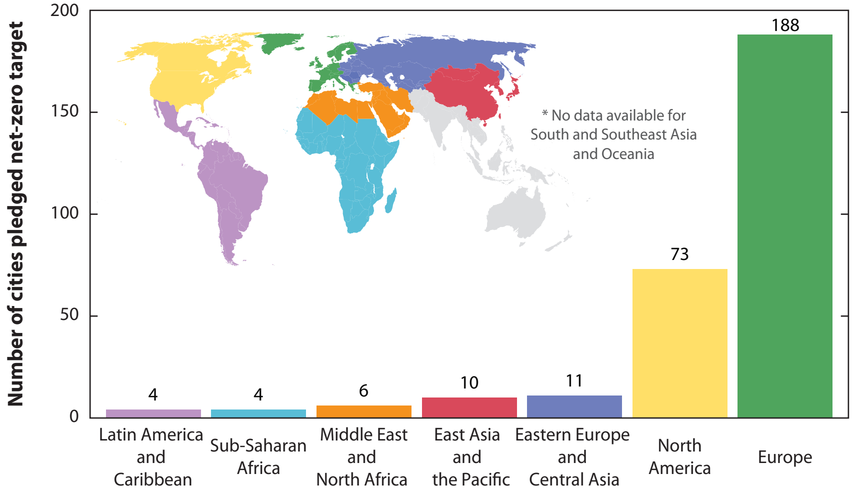


Figure 9

Distribution of 296 cities that have pledged net-zero targets and published climate strategy documents. Data from Reference 142.

The emphasis on climate adaptation and risk reduction echoes national-level climate strategies from developing countries, which have also been found to predominantly emphasize the need for climate adaptation and vulnerability reduction (142). Amman, Jordan, for example, in its "A Vision for 2050 Amman" climate plan (144), has identified specific targets for waste reduction and improving wastewater and water efficiency, in addition to energy efficiency and sustainable transport, to achieve its 2050 net-zero target. Durban, South Africa, identifies key climate-related risks as part of their net-zero climate action plan. In addition to its 2030 100% net-carbon-zero new buildings and municipal infrastructure targets, the city has also set adaptation-related targets, including a 100% increase in alternative water supply capacity (145). Cities in the Global North are much more likely to mention sustainable consumption and transport, actions focused on buildings, lighting, and efficiency, as well as the importance of leadership.

A policy analysis of the climate plans for 23 cities[1] in the Global North found that a majority relied on multiple actors (e.g., private companies, NGOs, transnational networks such as C40 or the Carbon Neutral Cities Alliance) and different levels of governance (e.g., policies at the district level and national level) to implement their decarbonization strategies. In addition, all 296 of the cities in **Figure 8** are members of at least one transnational or international climate initiative.

A report by the Coalition for Urban Transitions estimates that without considering decarbonization of the electric grid, local governments hold authority over approximately 28% of their emissions reduction potential, whereas the national and regional levels direct 35%, and the remaining 37% is diffused across interactions among multiple levels and actors (138, 146). According to the report, national governments can best support city-level decarbonization in three ways:

[1]These include Adelaide, Australia; Amsterdam, The Netherlands; Austin, Texas, USA; Boulder, Colorado, USA; Copenhagen, Denmark; Glasgow, Scotland, UK; Hamburg, Germany; Helsinki, Finland; London, England, UK; Melbourne, Australia; Minneapolis, Minnesota, USA; New York City, New York, USA; Oslo, Norway; Portland, Oregon, USA; San Francisco, California, USA; Seattle, Washington, USA; Sydney, Australia; Stockholm, Sweden; Toronto, Canada; Vancouver, Canada; Washington, DC, USA; Wellington, New Zealand; Yokohama, Japan.

by (*a*) "clarifying" the roles of different levels of governance and policy, (*b*) supporting city-level initiatives through financial and institutional support, and (*c*) facilitating "a culture of experimentation and participation around climate action" through coordinating the myriad public and private actors involved in decarbonization (138). A study of 1,000 EU Covenant of Mayors' cities gives further credence to the importance of polycentric, multilevel cooperation in decarbonization. Those cities under governments with more ambitious national plans tended to have larger emissions reduction over time; those located in national contexts with weaker national climate policies tended to have greater participation in transnational climate networks such as the EU Covenant of Mayors and benefited from the presence of regional coordinators that assisted with articulating climate strategies and calculating baseline and inventory emissions (140).

Coordination among multiple actors and several levels of governance is especially crucial for city strategies that target scales beyond city operations. For example, although nearly all the cities reviewed in the 23-city policy analysis include electrifying their municipal vehicle fleet in their action plans, only a few include mechanisms that facilitate electrification beyond city operations. For the City of Adelaide, Australia, the City Council and regional Government of South Australia co-fund the Sustainability Incentives Scheme. The mechanism offers grants for initiatives like EV charging stations and solar PV panels for residences, commercial areas, and nonprofits (147). Other cities rely on financial incentives and regulations from other levels of government and private business. In Wellington, New Zealand, the city's net-zero blueprint relies on the potential for national policy action—such as purchase subsidies and vehicle import standards—as part of its blueprint to electrify public and privately owned vehicles (148).

Broader governance mechanisms that support city-level net-zero goals are particularly important in decarbonizing the electric grid, given these systems often operate at a larger scale than the city level (see Section 5.1) (138, 149). To this end, Denver and Boulder, Colorado, are relying in part on the statewide Colorado Renewable Energy/Portfolio Standard—a referendum passed directly by voters in 2004—to achieve their emissions reduction goals to decarbonize the electric grid (135, 150, 151).

Regional, national, and international governance scales not only provide a policy framework for city GHG emissions reduction, but they are also a target of cities' attempts to scale up their influence to higher levels of governance. A review of EU member cities' climate action plans illustrates this phenomenon. All of the EU member cities reviewed in the 23-city analysis (e.g., Amsterdam, Copenhagen, Hamburg, Helsinki, and Stockholm) cited EU climate policy, such as the EU Carbon Trading Scheme, as part of the political framework of their decarbonization strategy (152–154). In addition, nearly all of these cities declared their intentions to lobby or otherwise influence the EU to enact more stringent policies and to go above and beyond its standards (152, 154–156). Stockholm's 2040 fossil-fuel-free strategy declared that its decarbonization policy is "outside the purview of the city" and so part of its "long-term strategy includes a number of investigative assignments, the aim of which is ultimately to influence Swedish and European legislation" (155).

8.2. Spatial Planning Tools

The sectoral approach to net-zero has many advantages, as each sector has its own statutory responsibilities that can be changed to enable low- or net-zero carbon outcomes. However, sectors overlap in their responsibilities. The academic literature in this area is accelerating on the nexus between transport, power, water, waste, buildings, communications, health, biodiversity, and land for open space (157, 158). The literature suggests that cities must be treated as systems where policies are directed at how the whole urban system can be changed (159, 160). However, cities

Table 5 Resource input variations between urban form types, on the basis of Reference 69

Input (per person per year)	Automobile city	Transit city	Walking city
Resources			
Fuel in megajoules (MJ)	50,000	35,000	20,000
Power in megajoules (MJ)	9,240	9,240	9,240
Gas in megajoules (MJ)	4,900	2,940	2,940
Total energy in gigajoules (GJ)	64.14	47.18	32.18
Water in kiloliters (Kl)	70	42	35
Food in kilograms (kg)	451	451	451
Land in square meters (m^2)	547	214	133
Urban footprint in hectares (ha)	2.29	1.97	1.78
Basic raw materials (BRM) for new building types per person			
BRM 1: sand in tonnes (T)	111	73	57
BRM 2: limestone in tonnes (T)	67	44	34
BRM 3: clay in tonnes (T)	44	29	23
BRM 4: rock in tonnes (T)	66	43	33
Total BRM in tonnes (T)	288	189	147

are built in small parcels or precincts one at a time and are different in their form and functions. Hence, different solutions are needed for different parts of the city, as shown in Section 4.1 on land use, which explains increasing density will help reduce oil consumption, but if too dense it will make it harder to use solar on rooftops as a solution for reducing fossil fuels in power.

Thomson & Newman (69) have produced a detailed analysis of the urban metabolism in Perth to demonstrate how it varies across the three urban fabrics. **Tables 2** and **5** show the variations in energy, water, land, food, basic raw materials, and waste in the three areas of the city. The fundamental structural difference in the three urban fabrics dominates the differences between the three kinds of urban systems. If cities are to respond to climate change, then the tools discussed in this article need to be applied carefully to each area with a basis of respecting their fabric and its functions.

Two additional fabrics can be created for the purposes of this article, as a city clearly needs to relate to its edges, bioregion, and associated remote settlements: a peri-urban/rural bioregional village fabric and a remote settlement fabric that service roles for the city such as mining camps, indigenous settlements, and recreational villages used by residents for holidays. Peri-urban and rural villages are usually part of the electricity, water, and waste grids; remote settlements are off such grids. These parts of the urban region are separate but increasingly joined into the perspective of how cities work, especially how they can create opportunities for carbon offsets or carbon sequestration as part of net-zero strategies. They are fundamental to a city's functioning in terms of its natural resources and materials as well as its waste management and ecological functions and hence need to be considered in the net-zero climate change agenda.

Seven net-zero urban spatial planning tools—decarbonization through solar design, electric transit activated corridors, local shared e-mobility and walkability, water sensitive urban design, circular economy urban design, biophilic and permaculture design, and integrated planning processes—are applied to the five urban fabrics outlined (**Table 6**). The opportunity for planners is to mainstream net-zero outcomes into their urban planning for each part of the city. There are obviously some differences in how the seven tools can be applied, but some are essential for all fabrics, especially the final tool, which is an integrated approach to planning.

Table 6 A planning framework for achieving net-zero carbon city outcomes, on the basis of References 161

Net-zero urban spatial planning tools	Central city walking	Inner city transit	Outer suburb automobile	Peri-urban and rural bioregional	Remote settlement
1. Decarbonization through solar design	Strong transport carbon reductions but harder to do solar on buildings; can do solar design for energy efficiency	Easier to do solar on buildings and harder on transport carbon reductions; solar design for efficiency essential	Very easy to do solar on buildings and much harder on transport carbon reductions; solar design for efficiency essential	Strong transport carbon reductions but harder to do solar on buildings	Easier to do solar on buildings and harder on transport carbon reductions
2. Electric transit activated corridors	Electric metro trains, buses, and Trackless Trams need to service city centers with very few electric cars.	Electric metro trains, buses, and Trackless Trams need to service stations on corridors with some electric cars feeding in.	Electric metro trains, buses, and Trackless Trams can be built to service corridors but most transport will be electric cars.	Electric buses and Trackless Trams have some potential but most transport will be electric cars.	Electric cars, trucks, and motorbikes only
3. Local shared e-mobility and walkability	Last mile support for transit focused on central function of walkability	Essential support for transit stations along with walkability	Necessary to build into any new and old station precincts but must mostly accommodate electric cars	Electric bikes can work.	Very little role
4. Water sensitive urban design	Water efficiency easily created in dense buildings but recycling more difficult where space is constrained	Water efficiency easily created in medium-density buildings and some recycling where space less constrained	All aspects of water sensitive urban design are possible once space is set aside.	Recycling of wastewater and stormwater can be fully integrated.	Recycling of wastewater and stormwater can be fully integrated.
5. Circular economy urban design	Low-carbon materials for buildings and infrastructure possible All forms of waste can be recycled once collected.	Low-carbon materials for buildings and infrastructure possible All forms of waste can be recycled once collected.	Low-carbon materials for buildings and infrastructure possible All forms of waste can be recycled once collected.	Low-carbon materials for buildings and infrastructure possible Not all forms of waste can be recycled unless done locally.	Low-carbon materials for buildings and infrastructure possible Not all forms of waste can be recycled unless done locally.
6. Biophilic and permaculture design	Biophilic buildings with green walls and roofs and small pocket parks	Emphasis on biophilic buildings, small pocket parks, and green corridors	Emphasis on larger landscape-oriented development	Landscapes for carbon offsets; permaculture design the most appropriate for villages	Landscapes for carbon offsets; permaculture design the most appropriate for villages
7. Integrated planning processes	Essential for achieving net-zero	Essential for achieving net-zero	Essential for achieving net-zero	Essential for achieving net-zero	Essential for achieving net-zero

8.3. Summarizing Urban Fabrics and Their Net-Zero Spatial Planning Potential

The urban fabrics in **Table 6** are summarized below to show how spatial planning can enable net-zero outcomes.

1. Central city walking cities are less able to install solar PV but are ideal for walkable active transport and micromobility, as well as biophilic urbanism in the form of green roofs and green walls (162, 163).
2. Transit city corridors are better for solar PV and batteries and are ideal for transit, micromobility, and active transport, with some potential circular economy and biophilics with permaculture possibilities (perhaps in community spaces).
3. The middle and outer suburbs of the automobile era are very good for solar PV, as demonstrated in Australian cities where most of the poorer outer suburbs installed PV first (93); they are also good for circular economy processing and permaculture, which need more space, but these areas are likely to require EV cars and buses due to their car dependence along with some new transit activated corridors helping overcome automobile dependence.
4. Rural villages and peri-urban areas will need to form new localized centers in order to make the most of the benefits of power and transport with integrated solar-PV-batteries-electromobility and with some agricultural vehicles electrified. Peri-urban areas are likely to be able to have some rail access but are more likely to need EV car-share or cooperative bus services to link them to it and hence to the city. Local transport can use such vehicles and also electric bikes. Peri-urban areas will grow in their usefulness to the rest of the city for the following types of functions:
   - Local food production based on intensive permaculture that has short food miles and local types of food;
   - Waste-recycling centers and other new circular economy industries that cannot fit into the more built-up part of the city, for example, the recycling of treated wastewater to recharge groundwater systems;
   - Utility-scale solar and wind farms and in future hydrogen-based industry; and
   - Carbon sequestration in soils and trees for offsetting the city's excess greenhouse emissions.

9. OPPORTUNITIES AND BARRIERS TO NET-ZERO

The pathway for cities to decarbonize is complicated by a variety of political and economic challenges. Politically, the challenges for cities to decarbonize are often described as institutions, infrastructure, norms, and practices that have a tendency to lock in carbon-intensive emission pathways (8, 164). Aligning with national government infrastructure and planning processes as well as financial budgeting will be critical for cities to have the appropriate fiscal authority and autonomy to raise necessary financing for zero-carbon transitions. Multi-level coordination is particularly key for municipalities to achieve net-zero goals due to the fragmented nature of infrastructure and technology ownership, which frequently results in mismatches between supply and demand as in, e.g., electricity, buildings, and vehicles (165). For example, in the United States, nearly 3,000 electricity distribution or utility companies were operating in 2017 (166). Coordinating with a diversity of actors, who may have diverging priorities and who may be out of a municipality's immediate regulatory jurisdiction but still supplying electricity, is a challenge cities will face in achieving decarbonization goals, particularly for indirect emissions related to purchased electricity or emissions outside of a city's immediate boundary.

The WRI's State of Climate Action Report (167) acknowledges insufficient progress toward achieving key decarbonization targets in the buildings sector, with some regions heading in the wrong direction. The scale of the financial investment needed to transition the world to net-zero is immense: The Organisation for Economic Co-operation and Development (OECD) estimates $6.9 trillion USD per year is required in infrastructure investments to 2030 to meet the Paris Agreement's 1.5°C goal (168). At the same time, governments and public investment are vastly insufficient to meet the nearly fivefold annual increases in low-carbon energy and energy efficiency required (1). In the developing world, core infrastructure investment will need to increase from $2 trillion USD per year to between $3.5–5 trillion in 2030 (169), although the market changes that have happened post-COVID may be accelerating Net Zero investments (91).

Global investment in low-carbon infrastructure from private institutional investors in the recent past only comprises less than 1% of overall investment portfolios (170). A major challenge for cities to implement net-zero plans is to meet the growing investment demand required to transform energy, transport, building, and water infrastructure in a post-COVID-19 world. One concern is that governments will prioritize COVID-19 economic recovery over investments to achieve net-zero. A study of the economic recovery packages for 149 countries, 80% of which are in the OECD, found that stimulus investments dwarf financial commitments to meet the Paris Agreement and that committed climate investments through the next ten years are inadequate to limit global warming to 1.5°C (171). However, there are some positive signs. More than 500 of the world's biggest financial institutions are part of the Climate Action 100+ initiative, which requires net-zero outcomes from the $52 trillion that they control [Climate Action 100+ (**https://www.climateaction100.org/progress/net-zero-company-benchmark/**)].

There are many ways of seeing the COVID-19 pandemic and the subsequent economic collapse as an opportunity for net-zero carbon cities. The first opportunity it produces is a kind of transformation to relocalizing the economy and creating a more walkable local city (172). The rediscovery of local parks and electromobility opportunities such as electric bikes, shared bikes, and electric assisted bikes has been a feature of many cities, but there is now accelerating commitment to active transport infrastructure (173, 174). The second opportunity is in the new investment factors for the emerging new economy, which include radically low interest rates, government recovery funds, and international financing requirements—many of which are jumping onto net-zero carbon cities. The economic case has been made that COVID-19 stimulus funds could be used to "build back better" and achieve both climate and economic recovery goals (175). This kind of accelerated change after economic collapse has been a feature of all five waves of innovation since industrial times (91) and the new sixth wave is featuring net-zero carbon (as in the Paris Agreement) as well as net-zero poverty (as in the SDGs).

But there will be a new and more dramatic responsibility that is likely to involve cities in the future as climate change impacts continue to grow, and the IPCC has foreshadowed the need to go beyond net-zero and begin reducing the concentration of CO_2 in the atmosphere back to manageable levels as global carrying capacities are already being exceeded. This will require cities, or at least some cities, to regenerate the atmosphere by extracting more and more CO_2 from the atmosphere. The main mechanism for this is likely to be regenerating the settlement bioregion's catchment with plantings that sequester carbon and build up soil carbon. This agenda needs to be considered by cities as they prepare for their future commitments and how they can demonstrate such leadership in advancing the global agenda for carbon removal (176).

10. CONCLUSIONS

Net-zero carbon cities are starting to happen. Cities are the main source of economic growth, innovation, and opportunities for many of the future populations on Earth. Cities must therefore lead the world into this new and exciting opportunity to be net-zero. If cities are slow on this agenda, there is little hope that the world can limit global warming. This is the challenge facing all urban residents, businesses, communities, and governments. There are limits to what each person, business, group, or agency can do, but together, in a city, the scale and the layers of opportunities are multiplied and amplified. The techniques and tools as set out in this article are developing to assist cities report and manage their strategies to create net-zero carbon futures. The first cities are showing that change can happen. They must now accelerate to include cities across the world in a global partnership.

SUMMARY POINTS

1. It is possible for cities to get to or near net-zero carbon, but this requires systemic transformation.
2. A net-zero carbon city is not the same as a low-carbon city. Net-zero carbon cities are more transformative (>80% reduction in fossil fuels) compared to low-carbon cities (rarely >20% reductions).
3. There are three primary strategies and seven pathways for cities to achieve net-zero carbon, and all require going beyond administrative boundaries of cities.
4. Net-zero carbon strategies will vary by climate, city type, and level of development with potential for leapfrogging in emerging cities. There is not a one-size-fits-all strategy for all cities, but achieving net-zero carbon will require implementing all seven pathways.
5. Sequencing of urban net-zero actions matters—because of carbon lock-in and the complex interplay between infrastructure and behavior.
6. There are different conceptualizations of net-zero carbon, but increasingly standards and certification are enabling more certainty.
7. Enormous opportunities exist for doing net-zero carbon development at the city scale in terms of sectors and within each spatially different urban fabric across each city.

FUTURE ISSUES

1. What is the urban mitigation wedge for achieving climate neutrality in the context of national and global deep decarbonization?
2. What conditions are necessary (political, institutional, economic) for cities to transition to net-zero carbon?
3. How does the relative contribution of the pathways vary by city type, level of urbanization and development, and institutional quality?
4. What is the potential for urban-rural circular economy?

5. How can carbon sequestration and storage become a feature of city planning through reforestation both within and around cities and incorporation of carbon rich materials in infrastructure design?
6. How will future urbanization, especially the innovation and adoption of alternative approaches such as distributed energy, electromobility, carbon rich building materials, and urban form accelerate a transition to net-zero carbon urban futures?

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