City Climate Finance Gap Fund

GAP FUND TECHNICAL NOTES

SMART CITY SOLUTIONS FOR CLIMATE CHANGE MITIGATION

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Smart City Solutions for Climate Change Mitigation[1]

Overview

This technical note serves as a primer on smart city solutions for climate mitigation in urban areas. It introduces a subset of solutions that have shown great promise in the path toward decarbonization. Note that this primer note does not endorse one solution over another. Each city should evaluate and select from among the solutions presented based on their needs and capacities, and on how they can advance mitigation plans. This note adopts a more specific and differentiated definition for smart city solutions: digital technologies, which are primarily software- and internet-based.

The note has four sections. First, the introduction provides a brief overview of emissions trends in urban areas, highlights the main sectors driving these emissions, and summarizes actions to reduce emissions. Second, the note introduces the concept of Smart City solutions and describes what role they can play in mitigation pathways. Section 3 focuses on the top emitting urban sectors—buildings, transportation, and solid waste—and summarizes vanguard smart city solutions for mitigation. A fourth and final section discusses some key implications and challenges associated with smart city solutions for climate mitigation.

[1] Authored by Patricio Zambrano-Barragán for the City Climate Finance Gap Fund and the Global Smart City Partnership Program. Carlos Bellas Lamas, Tarek Keskes, and Alan David Lee provided valuable feedback on an earlier draft of this note.

Key Takeaways

- Technology, writ-large, plays a crucial role in climate change mitigation actions in cities, particularly through the adoption of more efficient and purely electric systems. Smart city solutions are a subset of these technologies and are here defined as digital and primarily software- and internet-based solutions.
- Digital and software technologies do not immediately yield emissions reductions. Rather, they accelerate change and facilitate mitigation actions through data integration and real-time, decentralized decision-making and policy design.
- This primer summarizes smart city solutions for the top 'opportunity' sectors: buildings, transportation, and solid waste.
    - <u>Buildings</u>: Cutting edge solutions currently seek to dramatically reduce energy use while also finding ways to manage a soon-to-be decentralized, fully electric, and greener energy grid. These solutions include Internet of Things (IoT) automation of building systems; dynamic demand response; and 'behind the meter' distributed energy generation and storage.
    - <u>Transportation</u>: Similarly, a reduction in private vehicle use, a shift toward sustainable transport modes, and improved use of city infrastructure is at the heart of the smart mobility solutions included. These solutions are dynamic road pricing, microtransit, and curb management, which overall have the potential not only to reduce emissions but also to improve equitable access to transportation and city infrastructure.
    - <u>Solid Waste Management</u>: The sector stands out because its primary greenhouse gas (GHG) is methane, which results from the decay of organic matter in landfills as well as from its release during transportation and processing. While biogas recovery can help reduce methane emissions from landfills, the smart city tooling included can help optimize operations along the waste management process: collection, processing and sorting, and final disposal. Solutions range from data-enabled equipment, such as 'smart' waste bins, to the use of sensors to generate relevant data from 'legacy' equipment, such as collection trucks. Through precise and dynamic measuring of waste production and location, operations can reduce the release of methane and minimize emissions associated with inefficient collection operations.

Introduction

Urban areas account for 70% of global greenhouse gas emissions.[2] There are important regional differences. According to the World Bank, in 2015 cities in lower-income countries accounted for about 14 percent of total emissions and those in low-income countries a mere 0.2 percent – a modest contribution compared to cities in higher income countries.[3] However, trends from the last two decades suggest urban emissions and their relative share will increase across all regions. It is thus imperative for cities to identify and act on mitigation options.

The IPCC highlights three broad mitigation strategies for urban areas: reduction in energy use across the board; electrification of urban systems alongside the decarbonization of electricity production; and the promotion of carbon stocks through 'green' and 'blue' infrastructure.[4]

How should cities prioritize mitigation actions? The drivers behind urban emissions can be categorized in five broad groups: 'stationary' energy, especially buildings and built infrastructure; transportation; solid waste; industrial processes and products; and land use change.[5] While the relative share of each of these sectors also varies across cities, the greatest potential for mitigation over the coming decades is in the buildings and transportation sectors, followed by solid waste.[6] As will be discussed in Section 3, these two sectors are not only the top emitters, but are also ripe for transformative action and can thus catalyze considerable emissions reductions. While solid waste management (SWM) is responsible for a lower share of emissions, it is often directly under the control of municipalities, making it comparatively easier for them to implement mitigation actions in this sector. These three sectors are thus the focus of this knowledge note.

The Role of Smart City Solutions in Climate Mitigation

Technology, hand in hand with enabling policy and financial frameworks, plays a central role in urban mitigation. Emissions reductions are attainable through the adoption of scalable technological alternatives, e.g., higher efficiency pumps for heating and cooling; cost-competitive distributed solar systems; biodegradable construction materials; etc. In addition, technology can also facilitate behavioral change through more transparent and immediate access to information.

Given how wide-reaching these technology solutions can be, how can we further define smart city solutions in the context of emissions reduction?

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[2] IPCC AR6 WGIII Chapter 8 "Urban Systems and Other Settlements".

[3] Mukim M. and Roberts M., 2023. *Thriving: Making Cities Green, Resilient, and Inclusive in a Changing Climate*. Washington, DC: World Bank.

[4] IPCC AR6 WGIII Chapter 8 "Urban Systems and Other Settlements". p 51.

[5] "Global Covenant of Mayors Common Reporting Framework". 2018.

[6] Coalition for Urban Transitions, 2019. *Climate Emergency, Urban Opportunity*. C40 Cities Climate Leadership Group (C40) and World Resources Institute (WRI) Ross Center for Sustainable Cities. London and Washington, DC. https://urbantransitions.global/urban-opportunity/.

According to the World Bank, a smart city is one "that makes the best use of data, technologies, and other resources to improve city planning and management, service delivery, citizen engagement and accountability."[7] The Bank introduces a helpful distinction between a first technology wave--initial computerization and basic connectivity—and a second, characterized by the use and application of open and big data, artificial intelligence (AI), and the Internet of Things (IoT).

To serve as a primer on smart city solutions for climate mitigation, this document adopts a more specific definition: digital technologies, which are primarily software- and internet-based. This narrower definition is characteristic of 'second wave' technologies, as mentioned above.

It is important to recognize at least two limitations from this definition. First, the success of digital, software- and internet-based solutions depends largely on the availability of broadband infrastructure, particularly regarding solutions that could be implemented by individual households. Given relatively lower levels of internet penetration in parts of the developing world, full-scale implementation of solutions may not be possible, though more limited, fleet- or portfolio-focused deployment, say across a reduced set of buildings owned by a municipal actor, could be achievable.

A second limitation stems from the intangible nature of 'digital' and software, which cannot by themselves reduce emissions. Indeed, this observation explains the main theory of change present in this note: smart city solutions can facilitate and accelerate decisions and actions conducive to mitigation. For example, a digital twin or model of municipal buildings can improve the details and dynamism of energy consumption information, but without a coordinated ability to act on those insights, no demand reduction or savings will be achieved. This view is consistent with the Bank's urbanization policy framework, which places city planning and management at the center of sustainable urban growth. Smart city solutions should enable better planning and management, much like they should catalyze mitigation actions.

Finally, it is important to note salient criticisms smart city solutions in the specific context of climate change mitigation.[8] First, widespread adoption of digital technologies can contribute to environmental degradation by increasing resource use and waste, particularly crucial hardware components such as batteries, which require the extractive sourcing of rare earth materials, may have a comparatively short life span, and produce highly toxic waste. In addition, cutting edge analytics and their associated infrastructure can require large amounts of electricity consumption, which, depending on a city or region's energy mix, could come from highly emitting sources. Actions such as better governance for resource extraction, improving the longevity and durability of devices, or broader efforts to decarbonize the energy mix, should accompany the deployment of digital- and software-based solutions.

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[7] NK Hanna, 2018. *Smart Cities: How Can the World Bank Help Cities Become Smarter? White Paper*. The World Bank: Washington, DC.

[8] Dwivedi et al. 2022. "Climate Change and COP26: Are Digital Technologies and Information Management Part of the Problem or the Solution? An Editorial Reflection and Call to Action". *International Journal of Information Management* 63: 102456.

Smart City Solutions per Urban Sector

The City Climate Finance Gap Fund has two relevant primers that can help readers understand how to quantify emissions and project long-term scenarios for their cities.[9] Relevant to our discussion are two common themes from these resources. First, while there is no single, universal way of 'bucketing' sectors and their respective emissions, most greenhouse gas modeling and measuring tools highlight at least three large categories: buildings, transportation, and solid waste. As mentioned in the introduction, land use change as well as in-boundary industrial processes are also often found as recommended categories in these GHG modeling tools. Second, and more importantly, these Gap Fund primers, as well as the most recent IPCC reports[10], recognize both great variability across urban areas, particularly between the developed and developing world, and yet also highlight clear trends—that buildings and transportation are the top emitting sectors, followed by solid waste, and are thus the ripest for action.[11]

Mitigation solutions in the smart city space are, by definition, new, and thus still need deeper empirical evaluations to measure their actual emissions reduction impact. Where possible, the subsections below highlight the specific mitigation potential of the smart city solutions presented. There are, however, reference studies that showcase overall reduction impacts from technically feasible actions (Table 1). Overall, the solutions featured in this primer are noteworthy for their potential to accelerate technically feasible actions; the best example of this, as will be discussed in more detail, are digital tools that lead to lower demand for energy and for motorized transportation, as well as improvements in the collection and sorting of waste.

[9] "Primer on Urban Form and Greenhouse Gas Emissions" and "Urban Greenhouse Modelling Tools", available at https://www.citygapfund.org/knowledge-hub-0.

[10] IPCC AR6 WGIII, 2021. Chapter 8 "Urban Systems and Other Settlements".

[11] There is a variety of GHG accounting frameworks, each of which can yield different estimates, emissions responsibilities, and, as a result, associated mitigation options. In the case of urban emissions, the IPCC (2021) highlights three main frameworks: territorial accounting; supply chain foot printing; and consumption-based carbon footprint accounting. Urban emissions typically include territorial accounting, or emissions generated within city boundaries, as well as embedded or 'lifecycle' emissions, which additionally consider emissions from both the direct use of energy in each sector, as well as the energy necessary to produce the materials used in urban infrastructure. Given this approach, urban emissions figures often do not include high-emitting sectors typically found outside administrative boundaries, such as industry and energy production.

Table 1. Overview of Emissions Reduction Potential per Sector and Featured Smart City Solutions[12]

	Buildings	Transportation	SWM
Emission Reductions Potential by 2050 (GtCO2-e)	8.95	3.29	0.84
Share of Urban Abatement Potential by 2050	57.7%	21.2%	5.4%
Technically Feasible Mitigation Actions	• Decarbonization and decentralization of electricity • Use of low-carbon fuels • Heating, cooling, and appliance efficiency • Reduced energy and resource demand in construction and building operations	• Decarbonization and decentralization of electricity • Use of low-carbon fuels • Increased vehicle efficiency • Reduced demand for motorized travel and shift to non-motorized modes	• Recycling • Landfill methane capture and use • Waste prevention
Featured Smart City Solutions	• IoT automation of building systems • Dynamic demand response • 'Behind the meter' distributed energy	• Dynamic road pricing • Microtransit and mobility as a service • Curb management	• IoT-based waste management optimization

1. Buildings

Buildings account for 6% of global emissions and 28% of energy-related emissions (38% if we include emissions from building construction).[13] Besides construction-related emissions, building emissions come from the energy required for day-to-day operations in buildings. Heating, ventilation, and air conditioning (HVAC) systems are the top consumers of energy, followed by

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[12] Adapted from Coalition for Urban Transitions, 2019. For details on the methodology used for numerical estimates, see, from this source, "Annex 1: Technically feasible urban mitigation potential of buildings, transport, waste, and energy sectors", authored by the Stockholm Environment Institute (SEI).
[13] United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.

domestic hot water, lighting, cooking, and appliances (as with previous figures, there is regional variability).[14] Mitigation strategies are critical--the worldwide footprint of buildings could double by 2060[15]--and should prioritize the top drivers of energy use.

While innovations in construction methods and materials can certainly improve energy efficiency in new or retrofit buildings, we highlight three pioneering areas among smart city solutions to curb demand and improve efficiency: **Internet of Things (IoT) automation of building systems; dynamic demand response; and 'behind the meter' distributed energy generation and storage**.

IoT Automation

Automation in buildings is not new. Most HVAC machines offer some degree of scheduling and basic "smart" systems and thermostats can, for example, prompt online supervisors to act upon a specific device or machine, or allow households to improve heat and cooling schedules according to historic usage. IoT automation, however, sits at the overlap of key innovations. First, this approach relies on two-way communication through wireless sensors and actuators that can both send and receive signals through a single interface. Second, newer systems are cloud- and software-based, making interoperability, management, and upgrades seamless and cost-effective. Finally, these innovations allow for the deployment of machine learning and AI tools (including large language models (LLMs) that can interactively manage systems predictively) using not only internal data, but also incorporating external data streams from, say, weather and electricity markets (Box 1.1).

Building automation has notable operational challenges. First, readers may consider these solutions primarily for existing buildings, i.e., to retrofit their assets. When assessing commercially available and open-source options, operators must ensure that the hardware effectively generates data with the desired granularity (for subsystems within HVAC assets, for example) and periodicity. In addition, not all sensors can act as actuators and enable cloud-based, automated action. Second, even the best reliable network of sensors must be translated into a coherent representation or model of assets that can then be remotely controlled (e.g., SCADA - Supervisory Control and Data Acquisition – systems, which help operators model and control the building ecosystem). Making sense of an endless stream of data from multiple assets is a non-trivial challenge and requires harmonious interactions between software and hardware solutions as well as across all the 'humans in the loop', especially building operators and process engineers/modelers (it should be noted that one potential promising application of LLMs is the ability to 'read' and rapidly integrate data from sensors, thus obviating the need to individually explore and select relevant attributes from thousands of data streams). This difficulty could lead cities to buy bundled packages that may deliver some but not all expected results (for example, scheduled automation but no predictive analytics; insufficient privacy and digital security services; solutions that do not help teams become

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[14] M. Gonzalez-Torres, L. Perez-Lombard, Juan F. Coronel, Ismael R. Maestre, Da Yan. "A review on building energy information: Trends, end-uses, fuels and drivers". *Energy Reports* 8 (2022) 626-637.

[15] UN Environment and International Energy Agency, 2017. Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017.

data-enabled, etc.). These are tradeoffs that cities must always consider when procuring this and other Smart City solutions.

Box 1.1 Beyond Scheduled Automation

A recent IoT pilot in New York City, partially funded by grants from the New Energy Nexus (a global funder and accelerator of clean energy ventures), generated three times as much energy savings as manual automation systems. Run in partnership with the company 75F, the pilot deployed a single integrated hardware and software solution that, through a universal and open-source interface (which can work with other building management applications that might already be installed), enabled two-way communication with multiple buildings and systems. In another demonstration project in partnership with one of Ohio's main energy distributors, the same company's predictive analytics delivered energy savings as well as a reduction on maintenance visits to numerous customer sites. According to a self-reported impact study, when compared to scheduled automation, this bundled solution reduced energy consumption by two thirds from cooling and by half from heating.

Sources:

New Energy Nexus. "USA Impact Report 2021". https://www.newenergynexus.com/wp-content/uploads/2022/04/USA-Impact-Report-2021.pdf. Last accessed: June 1, 2023.

75F. https://www.75f.io/case-studies/. Last accessed: June 1, 2023.

Dynamic demand response

Similar to automation, demand response programs—where occupants or managers change their consumption habits to help manage overall load—have been around for decades. There are various benefits to demand response, which seeks to shed load during peak demand as well as shift load during moments when demand increases. These shifts make it easier for power generators to ramp up equipment and can decrease fuel consumption.[16] More importantly, demand response contributes to the integration of intermittent renewable energy sources, such as solar and wind power, as it can shift or shed load to accommodate low or high renewable generation and can ultimately minimize the need to build new plants or capacity to cover increased demand.[17]

Integrated IoT systems such as those described in the previous section can enhance the effectiveness of demand response initiatives by turning devices on and off remotely or in a predictive fashion. But even comparatively less sophisticated solutions can dynamize demand

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[16] T. Müller, D. Möst. "Demand Response Potential: Available when Needed?" *Energy Policy* (2018), 10.1016/j.enpol.2017.12.025.
[17] A. Kies, B.U. Schyska, L. Von Bremen. "The demand side management potential to balance a highly renewable European power system" *Energies* (2016), 10.3390/en9110955.

response for households: device-specific sensors (e.g., for washing machines, heat pumps, or refrigerators) can act based on external data, particularly electricity prices. These smart home systems can reduce energy costs at home while reducing load during peak demand. Some among these solutions are better suited for locations where consumers have visibility of, and can react to, changes in electricity spot prices, which allows for dynamic decisions about *when* to purchase power. Still other applications interact with grid operators instead to achieve similar results for load management (Box 1.2).

Box 1.2. Balancing the Grid Through Dynamic Demand Response

There is an increasing diversity of solutions that can help households as well as power operators balance energy demand. For example, Danish company True Energy was launched to help EV owners find the times of day when it would be cheapest to recharge their car's battery. By aggregating spot market price data and connecting to the EV's systems, the company's app-based tool can help users decide where to charge for minimum distance or optimize for low CO2 emissions as well as low cost. From these beginnings, the company then launched similar tools for other home appliances and devices, thus giving homeowners full view of when to turn on high power devices such as washing machines. This solution helps households manage demand at home while working in conjunction with grid operators that are capable of trading electricity on an hourly as well as a long-term basis.

In contrast to the Scandinavian example above, Boston-based Sense seeks to help in electricity markets where households do not directly interact with spot markets. This solution helps households manage energy use through the installation of sensors directly on the electric panel. Sense's software applies machine learning algorithms to distinguish the electricity 'voice' of each device in the panel, and then provides insights to lower bills and improve efficiency.

Yet another example, from the company Flair, offers a combination of hardware and software solutions to improve 'zone' temperatures at home. While equipment-specific solutions complement more common technologies such as smart thermostats (which refine and improve scheduled automation), these can still deliver important benefits at scale. Earlier this year, the company set up California's Peak Perks, in partnership with Leap, an energy market service provider. Peak Perks provides incentives to households to allow for coordinated, remote management of multiple HVAC systems in a community to manage load and minimize the use of 'dirty' power sources.

Sources:

True Energy. https://www.trueenergy.io/. Last accessed: June 1, 2023.

Sense. "Fast Facts". "https://sense.com/downloads/Sense_Fast_Facts_2-2020.pdf. Last accessed: June 1, 2023.

Leap. "Flair and Leap Announce Demand Response Program for California Homeowners". April 22, 2022. https://leap.energy/news-and-resources/article/flair-and-leap-announce-demand-response-program-for-california-homeowners. Last accessed: June 1, 2023.

Behind the meter

'Behind the meter' solutions, also referred to as 'smart dock' or 'microgrid', are at the vanguard of urban energy systems. They combine three elements. First, they rely on smart meters, which provide granular and more frequent records on usage data, which in turn enables demand response programs, dynamic pricing, and better deployment of renewable generation. Distributed generation is a second aspect, since households or businesses with their own renewable sources can sell back energy to the grid when production exceeds demand, and virtually turn homes or districts into batteries.[18] As cities increase their electric vehicle (EV) charging infrastructure, they can add this as potential energy sources as well: not only can distributed charging spots send back power to the grid, but a fleet of EVs can act as electricity storage, which can in turn complement the use of intermittent sources of power such as solar and wind.[19] Battery storage capacity close to the point of consumption (thus 'behind the meter') is a third and critical element. Storage can be used in combination with smart meters and distributed generation to 1) store power during low use hours and 2) feed power back to the grid to ease load or address intermittency from renewable sources.[20] In sum, behind the meter solutions work as microgrids that can supply energy when load is peaking, thus maximizing overall efficiency and reducing reliance on fossil fuel sources that would otherwise have to be quickly turned on (Box 1.3).

Behind the meter solutions require several prerequisite conditions to work. First, there must be considerable capital investments in distributed generation and battery storage, from commercial and residential stakeholders alike (investments that evidently would be beneficial in terms of mitigation). Second, as shown in the previous section, to achieve desired reductions in energy usage and dynamic demand management, individual or district actors require digital tools to monitor generation and demand at the source, and its relative impact on the grid. Third, from a policy perspective, not only should there be incentives (tax, grant, or other subsidies) to facilitate deployment across cities, but special attention should be placed on market and regulatory structures both to enable participants to feed power back to the grid but also to incentivize energy-saving behaviors.[21]

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[18] See IRENA (2019), *Innovation landscape brief: Behind-the-meter batteries*, International Renewable Energy Agency, Abu Dhabi.
[19] For a more detailed discussion, see IRENA, 2019, *Innovation Outlook: Smart Charging for Electric Vehicles*, International Renewable Energy Agency, Abu Dhabi.
[20] Boampong R. and Brown D. "On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design". *Energy Economics* 86 (2020) 104682.
[21] Zhou, S. and Brown M. "Smart meter deployment in Europe: A comparative case study on the impacts of national policy schemes". *Journal of Clean Energy Production* 144 (2017) 22-32; Sareen S. and Rommetveit K. "Smart gridlock? Challenging hegemonic framings of mitigation solutions and scalability" Environmental Research Letters 14 (2019) 075004.

Box 1.3 Turning Homes and Charging Infrastructure into Batteries

In 2021, New York-based Blueprint Power received a US$3 million demonstration award to provide decentralized energy generation from a single real estate development: LeFrak City, in Corona, Queens. Blueprint Power combines elements of IoT automation--a single interface to monitor all energy-related aspects of the built environment--with modeling tools to determine how best to interact with the power grid. In addition, the demonstration project will also optimize EV charging infrastructure by using buildings as decentralized power sources, thus reducing installation and operation costs. New York State Energy Research and Development Authority hails this demonstration project for its potential to help it reach its emissions reduction targets by 2040. A similar example comes from Chelsea, Massachusetts, where authorities plan to have an integrated cloud-based management of distributed solar energy across municipal buildings by 2023. This microgrid, which will include its own battery storage, will provide a central interface to make decisions about disconnecting from, or delivering energy to, the city's power grid.

Sources:

New York State Energy Research and Development Authority (NYSERDA). "NYSERDA and Blueprint Power Announce $3 Million Award for Energy Management Technology that Enables Buildings to Provide Grid Flexibility". June 9, 2021. https://www.nyserda.ny.gov/About/Newsroom/2021-Announcements/2021-06-09-NYSERDA-and-Blueprint-Power-Announce-3-Million-Award-for-Energy-Management-Technology-that-Enables-Buildings-to-Provide-Grid-Flexibility. Last accessed: June 1, 2023.

R. Vick. "NYSERDA partnership to bring 150 electric vehicle charging stations to LeFrak City". The Queens Eagle. June 14, 2021. https://queenseagle.com/all/nyserda-partnership-to-bring-150-electric-vehicle-charging-stations-to-lefrak-city. Last accessed: June 1, 2023.

Massachusetts Municipal Association (MMA). "Chelsea develops microgrid for public buildings". January 2022. https://www.mma.org/chelsea-develops-microgrid-for-public-buildings/. Last accessed: June 1, 2023.

Mother Jones. "The Little City that Could: For Chelsea, a new microgrid means energy resilience". https://www.motherjones.com/environment/2023/04/microgrids-chelsea-massachusetts-environmental-justice-climate-resilience/. Last accessed: June 1, 2023.

2. *Transportation*

The transport sector was responsible for close to 30% of global emissions in 2019.[22] Despite reductions associated with COVID-19 lockdowns, overall transportation activity and associated emissions have since rebounded. Urban transport emissions vary across cities depending on factors such as level of economic development, urban form, and type of fuel used. Generally, though, the biggest contributor of GHG emissions in cities is on-road transportation (versus rail, aviation,

[22] United Nations Human Settlements Programme (UN-Habitat) (2022). *World Cities Report 2022*. Nairobi.

and waterways).[23] Mitigation pathways that can achieve the most impact include widespread electrification of fleets and power sources, improvements to vehicle and engine performance, and avoidance of journeys and a shift to low-carbon transport modes.[24] These mitigation actions are essential to reaching net-zero reduction targets for the sector of over 20% by 2050.[25]

As the discussion on the buildings sector shows, in addition and complementary to the adoption of new technologies for electrification, materials, and fuels, smart city solutions can be most effective in reducing demand and encouraging modal shifts (as well as reducing air and noise pollution). We highlight smart solutions that improve **dynamic road pricing**, as well as newer aspects of shared mobility and 'mobility-as-a-service', particularly **microtransit**. In addition, '**curb management**', which refers to more efficient usage charging for public road infrastructure, is a vanguard application of smart city solutions.

Dynamic road pricing

Road pricing is a staple of transportation systems. Though the concept includes carbon pricing and taxes on fuel usage, it is more commonly associated with charges imposed on drivers when accessing specific areas or zones or when driving during high congestion times (most readers will be familiar with tolls, which charge drivers for use of a particular road or highway at a fixed point). Besides income generation, road pricing can help curb demand by imposing explicit costs for vehicle use. Studies show that road pricing can reduce emissions by 2-13% and car travel by 4-22%; road pricing that specifically curbs travel and high fuel consumption, versus congestion, is comparatively more effective at emissions reductions.[26]

Regarding smart city solutions, road pricing technologies already have a considerable degree of automation. For example, many cities currently rely on cameras for license plate recognition and direct billing to drivers. However, *dynamic* data integration can reflect not only whether a particular vehicle enters a specific road or zone, but also other key variables such as type of vehicle and fuel, precise time of day and location, actual distance travel, and real time traffic condition—making road pricing schemes more precise and effective at achieving desired outcomes (Box 2.1). Data integration across the fleet can help cities move away from flat charges toward dynamic prices, as well as allow for more equitable charging by estimating toll redistribution for lower income users, given the skewed impacts from 'blind' road pricing schemes.[27]

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[23] T. Wei, J. Wu, and S. Chen. "Keeping Track of Greenhouse Gas Emission Reduction Progress and Targets in 167 Cities Worldwide". *Frontiers in Sustainable Cities* 3 (2021).

[24] IPCC AR5 WGIII Chapter 8 "Transport".

[25] Coalition for Urban Transitions, 2019. *Climate Emergency, Urban Opportunity*. C40 Cities Climate Leadership Group (C40) and World Resources Institute (WRI) Ross Center for Sustainable Cities. London and Washington, DC. https://urbantransitions.global/urban-opportunity/.

[26] Axsen J., Plotz P. and Wolinetz M. "Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport". *Nature Climate Change* 10 (2020): 809-818.

[27] Levinson D., "Equity Effects of Road Pricing: A Review". *Transport Reviews* 30:1 (2010) 33-57.

Box 2.1 Leaving Tolls Behind

Smart road use pricing consists of the following common principle: determine road usage from *within* the vehicle, through on-board units (known as OBUs among tolling experts) and smartphone apps, and minimize reliance on toll plazas and external monitoring infrastructure. While it is too early to determine whether phone-based monitoring is sufficiently precise, ongoing improvements may make this a ubiquitous choice for road use pricing. Examples include Oregon's OreGO, a system that charges drivers based on the distance they travel using a mobile app. The app uses the phone's Global Positioning System (GPS) to track the vehicle's location and distance traveled, and the driver is charged a rate per mile driven.

Singapore and Jakarta have also deployed forms of smart road use pricing, albeit without the use of mobile phones. Both are examples of electronic road pricing (ERP) schemes that use an OBU to communicate with gantries above the road and charge drivers for road use. These systems also deploy automatic number plate recognition and real-time traffic data analysis to manage traffic flow and adjust toll rates based on demand.

Nairobi, Kenya, has also recently implemented another precursor to smart road use pricing: the Nairobi Intelligent Transit System (NaTIS; implemented in partnership with Korean development agency KSP), a real-time traffic data analysis system in Nairobi that uses sensors and cameras to collect traffic data and manage traffic flow. It can help future implementation of smart road use pricing by dynamically adjusting toll rates based on the level of congestion to encourage drivers to travel during off-peak hours or use alternative modes of transportation, and by using GPS data to track vehicle usage and charge drivers accordingly.

Sources:

Oregon Department of Transportation. "OReGO: Oregon's Road Usage Charge Program". *https://www.oregon.gov/odot/programs/pages/orego.aspx*. Last accessed: June 1, 2023.

Singapore Land Transportation Authority. "Electronic Road Pricing (ERP)". *https://onemotoring.lta.gov.sg/content/onemotoring/home/driving/ERP.html*. Last accessed: June 1, 2023.

Intertraffic. "The Future of Road User Charging". June 15, 2022. https://www.intertraffic.com/news/the-future-of-road-user-charging. Last accessed: June 1, 2023.

KSP, 2022. "Support for Implementing Intelligent Traffic Systems in Nairobi Metropolitan Region, Kenya". *https://www.ksp.go.kr/english/pageView/info-eng/701*. Last accessed: June 1, 2023.

Microtransit and mobility as a service

Microtransit is part of a larger umbrella term, shared mobility, that refers to on-demand, typically privately-operated transportation modes, such as car- and bike-sharing. Citizens around the world are likely already familiar with services such as Uber, which, while increasing convenience for users, can cause congestion and a reduction in demand for public transportation.[28] Microtransit maintains the on-demand convenience of shared mobility, but typically has a different purpose: to complement fixed-route public transportation in less accessible areas and during underserved times of day and night (Box 2.2). Microtransit also operates within defined zones and broad schedules, but updates routes and service depending on real-time demand. A study projects that large-scale deployment of microtransit solutions can reduce traffic by 15-30%, based on data from pilot deployment across four cities in the United States launched between 2017 and 2019.[29]

Microtransit relies on integrated digital tools to plan, book, and pay for transport, either public or private; this mode of orchestration is referred to as mobility as a service (MaaS). As mentioned, private ride hailing companies that fit into the MaaS model do not necessarily seek to optimize congestion or broader mitigation goals. For shared mobility and microtransit to achieve broader public benefits, a comprehensive approach to MaaS is needed—one that not only maintains incentives for operators to participate in local markets, but that sets up clear requirement and rules (e.g., complementarity with public transit, focus on accessibility, data privacy protection, etc.).[30]

For developing country cities, deploying MaaS can unlock integration across multiple dimensions (data, service, and policy) as well as offering a unique opportunity to link informal transit services with the broader mobility system.[31] In recent years, there have been numerous efforts across developing country cities to collect, generate, analyze, and disseminate transit data—especially for informal transportation. Examples include Digital Transport 4 Africa and DATUM (with partners that include the World Bank, the Inter-American Development Bank, the World Resources Institute, and MIT), both of which support public sector and civil society organization to map and disseminate open data about informal transit systems in Africa and Latin American and the Caribbean, respectively.[32] While these informal transit mapping efforts make the most of open-source technology solutions (including use of the open transit standard GTFS, which can integrate with user interfaces such as Google Maps), their ultimate goal is to improve informal transit service and to facilitate its integration into broader transportation systems. In the context of this note, these efforts require complementary and specific policy guidance that echo the broader mitigation pathways discussed above (i.e., decarbonization/electrification, improved efficiency, and reduced private vehicle demand) to achieve emissions reductions.

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[28] Institute for Transportation and Development Policy, 2021. *The Future of Paratransit and Shared Mobility*. ITDP and VREF. New York.

[29] J. Hazan, N. Lang, AK Wegscheider, and B Fassenot, 2019. *On-demand Transit Can Unlock Urban Mobility*. Boston Consulting Group and BCG Henderson Institute.

[30] Ditmore C.J. and Miller A. "Mobility as a Service Operating Model to Enable Public Policy." Transportation Research Record 2021, Vol. 2675(11) 141–149.

[31] Bianchi Alves, B. et al. 2021. Adapting Mobility-as-a-Service for Developing Cities: A Context-Sensitive *Approach*. Washington, D.C.: World Bank.

[32] See https://digitaltransport4africa.org/ and https://datum.la/. For policy recommendations on the role of informal transit systems, see the Global Network for Popular Transportation https://www.populartransport.net/. Last accessed: June 1, 2023.

Box 2.2 Microtransit Alternatives for Low Density Cities

Just under half of the more than 400 companies currently operating in the microtransit space started after 2021, which speaks to how new and yet untested this solution still is. New York-based Via is the largest, operating in 25 cities in the United States. According to the company's own analysis, microtransit solutions in cities like Sacramento, California--launched thanks to an initial US$12 million grant from the Sacramento Transportation Authority--have achieved a 22% reduction in CO_2 emissions and boast over 10,000 shared trips per month in zones where public transportation service is limited. Scaling this model can be challenging, however: while ideally tailored for communities that do not have a car and cannot easily access public transportation, these also tend to be people with limited access to mobile technology. In addition, increased demand for microtransit vans can lead to long wait times, the solution to which could be the expansion of the fleet at potentially higher per-ride costs, or, indeed, a shift back to buses and 'traditional' public transportation options.

Sources:

Via. "SmaRT Ride Case Study - Sacramento Regional Transit Authority". https://ridewithvia.com/resources/case-studies/. Last accessed: June 1, 2023;

B. Donahue, "Microtransit Programs Promise Transportation for All", CityLab. Feb 5, 2022. https://www.bloomberg.com/news/features/2022-02-05/microtransit-programs-promise-on-demand-transportation-for-all. Last accessed: June 1, 2023.

Curb management

This is a nascent smart solution that allows for dynamic management of key public road infrastructure: paid parking slots, micro-mobility docks (e.g., landings for shared scooters and ebikes), and commercial loading spaces. In the aftermath of the COVID-19 pandemic, new competing uses have emerged, such as popular sidewalk and street space dedicated to parklets and food services ("streateries"), and an increase in parcel and on-demand delivery services.[33] EV charging stations may soon become ubiquitous as well, further increasing claims on public infrastructure. Through the digitalization of curb assets (ideally following open standards and readily available APIs, such as SharedStreet's and the Open Mobility Foundation's Curb Data Specification[34]) and management of curb demand (for example, by limiting where and when delivery trucks can unload,

[33] OECD/ITF, 2018. *The Shared-Use City: Managing the Curb*. International Transport Forum at the OECD. Geneva.

[34] Sharedstreet's CurbLR incorporates curb regulation information onto a common digital model of the street network and its elements; see https://www.sharedstreets.io/curbLR/. The Curb Data Specification (CDS) offers a set of application programming interfaces (APIs) to integrate digital models of curbs as well as enable a single interface to monitor use, communicate with third party actors, and monitor performance and results; see https://www.openmobilityfoundation.org/about-cds/.

or by reducing vehicular traffic to accommodate pedestrian-friendly spaces), policies and associated fees can be adapted dynamically to ensure more equitable use—thereby helping cities achieve desired outcomes such as reduced traffic and pollution (Box 2.3).

The potential for curb management to achieve wholesale reduction in GHG emissions is still untested. Nevertheless, there are two key reasons to include this solution in this primer. First, it represents a concrete application of so-called 'digital twins', or a digital model of physical city assets, to help public sector actors improve transit and logistics management. The pilots included also demonstrate the importance (and feasibility) of maintaining common operating standards across digital tools for city planning. Second, we highlight this example for its capacity not just to achieve outcomes in terms or reduced traffic, but also to improve the use and availability of public space, which, in turn, unlocks valuable opportunities for cities to improve urban carbon stocks.

Box 2.3 Beyond Parking: The Evolution of Curbspace Management

Over the last decade, cities like Los Angeles and San Francisco have aggregated various data, primarily from parking meters and geospatial analysis, to understand parking behavior and implement variable pricing strategies. With the rise of on-demand mobility, the next wave of pilots in cities such as Washington D.C. and Seattle sought to optimize pick up and drop off zones through 'geofencing' (geographic areas of the city where specific restrictions apply, usually depending on the time of day or week), with positive results. In the last two years, however, numerous new ventures have emerged to digitize curb assets and aggregate data from the diverse set of actors that command use of sidewalks and streets. California-based Populus works in over 100 cities in the United States and Israel, where its primary approach is to work with fleet operators (shared mobility companies, delivery services, etc.) to geotrack their operations and then combine these data with inputs such as historic parking patterns ultimately to dynamically guide curb usage. The company offers a tiered payment system to cities and collects fees on their behalf, thus eliminating the need for traditional ticketing and enforcement.

A different approach to curb management comes from the city of Philadelphia, which launched a six-month long pilot in late 2022. This "Smart Loading Zones" pilot is run in partnership with Pebble, an offshoot of Google's Sidewalk Labs, which similarly aggregates disparate data sources to optimally match delivery drivers to parking spots, thus reducing illegal parking and freeing up curb use. The Philadelphia pilot relies on the Open Mobility Foundation's CDS and its set of open tools to represent and manage curbspace. The pilot will run until mid 2023 in 21 locations across the city and is expected to improve efficiency and safety for delivery drivers while minimizing unsafe and illegal parking, thus improving curb usage for all users.

Sources:

C. Diehl, A. Ranjabari, and A. Goodchild. "Curbspace Management Challenges and Opportunities from Public and Private Sector Perspectives", Transportation Research Record 2021 2675 (11): 1413-1427.

J. Surico, "Can Technology Help Cities Manage Curbs Better?", New York Times. August 24, 2022. https://www.nytimes.com/2022/08/24/business/curbside-management-cities-technology.html. Last accessed: June 1, 2023.

L. Bliss and A. Small. "The Race to Code the Curb". Bloomberg Citylab. April 19, 2019. bloomberg.com/news/articles/2019-04-02/the-startups-tracking-how-cities-use-curb-space. Last accessed: June 1, 2023.

Philadelphia Office of Innovation and Technology. "City Announces New SmartCityPHL Pilot Project Focused on Loading Zones in Center City". October 3, 2022. *https://www.phila.gov/2022-10-03-city-announces-new-smartcityphl-pilot-project-focused-on-loading-zones-in-center-city/*. Last accessed: June 1, 2023.

3. *Solid Waste*

Solid waste contributes between 3 and 5% of total global emissions.[35] The sector stands out because the GHG it emits is primarily methane, which is about 30 times more effective at trapping heat in the atmosphere than carbon dioxide.[36] Methane comes from the decay of organic matter in landfills as well as from its release during waste transportation and processing. In the US, landfills are responsible for 14% of methane emissions, which represents about 18% of the country's GHG emissions.[37] In developing country cities—where final treatment at landfills can be lacking, municipal waste collection services are limited, and where alternative practices can include uncontrolled dumping and the burning of waste—there is an even higher potential for the release of methane and other GHG emissions.

A simple way to identify opportunities to reduce emissions is to break the waste management process into three general steps: collection, processing and sorting, and final disposal. Regarding collection, improving service coverage and quality in developing country cities, including among informal neighborhoods, can alone reduce sector emissions by 21%.[38] Segregation, composting, and recycling could altogether reduce emissions by 84%.[39] Finally, tackling emissions from the disposal of waste is critical, given that landfills bear the largest responsibility for methane production in the sector. Biogas recovery, which involves the decomposing of organic waste in the absence of oxygen, stands out as a proven technology, currently used in cities such as Buenos Aires,

[35] Global Methane Initiative, 2019. *Global Methane Assessment*; World Bank, 2018. *What a Waste 2.0*.
[36] UN Economic Commission for Europe (UNECE). "Methane Management". https://unece.org/sustainable-energy/methane-management.
[37] United States Environmental Protection Agency. "Sources of Greenhouse Gas Emissions". https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[38] World Bank, 2018b. "Improvement of Solid Waste Management to Support Regional and Metropolitan Cities. Project Appraisal Document." World Bank, Washington, DC, cited in World Bank, 2018, *What a Waste 2.0*.
[39] United States Environmental Protection Agency. "Sources of Greenhouse Gas Emissions". https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

Argentina and Indore, India.[40] (Waste-to-energy incineration may help reduce the amount of refuse going to landfills, but is comparatively more expensive; without rigorous environment standards, incineration can result in comparable or even higher CO2 emissions[41]). Finally, waste prevention at the source should be at the core of any waste management system, as it reduces the need for corrective and mitigating measures along the waste management cycle.

Smart city solutions can help mitigate emissions by **optimizing operations** along the waste management cycle, especially during collection and sorting.

Optimization of waste management operations

Like the solutions discussed in the buildings section, optimization for waste management can be achieved using IoT infrastructure—whether by deploying new, data-enabled equipment, such as 'smart' waste bins, or by incorporating connected sensors to generate relevant data from 'legacy' or old equipment, such as old collection trucks. In all cases, the goal is to generate more precise measurements: what, how much, when, and where to collect and sort waste.

Smart waste bins are equipped with sensors that monitor their fill level, weight, and location in real-time. This sensor-based approach can minimize overflowing bins, littering, and illegal dumping, which can indirectly reduce methane release. Additionally, data from smart bins can help management utilities or collection entities optimize the collection schedule and routes. Fleet management can be further optimized using GPS-enabled trucks to track the location and movement of waste collection vehicles in real-time. Mitigation comes from the potential reduction in unnecessary trips, which can limit transportation-related emissions.

Deploying smart waste bins and GPS-enabled trucks requires a robust analytics infrastructure that can collect, process, and analyze large volumes of data in real-time. This infrastructure should include a combination of hardware, such as sensors, GPS devices, and data transmission networks, as well as software platforms for data management, analytics (including machine learning and predictive models), and visualization—and talent to manage the overall system. Additionally, integration with existing city infrastructure, such as traffic management and public safety systems, can improve overall efficiency and coordination.

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[40] Bloomberg CityLab, 2021. "Buenos Aires Landfill Leads Latin America in Turning Methane into Power". https://www.bloomberg.com/news/articles/2021-11-05/ceamse-s-buenos-aires-landfill-leads-latin-america-in-turning-methane-into-power; Smart City Indore, 2019. *Solid Waste Management*. Indore. www.smartcityindore.org/solid-waste/.

[41] Global Alliance for Incinerator Alternatives (GAIA), 2022. *Zero Waste to Zero Emissions*. https://www.no-burn.org/zerowaste-zero-emissions/

Box 3.1 Smart Waste Bin Pilots

Cities around the world are embarking on smart waste bin pilots to set fill-level benchmarks to improve waste collection schedules and to tackle frequent waste collections and overflow issues in popular pedestrian areas. In Buenos Aires, Argentina, the deployment of 4,500 smart ultrasonic bin sensors has allowed for monitoring of fill-levels and data collection to optimize bin placement and transition to dynamic waste collection schedules. The city has used the sensors to guide their decision-making toward future contracting of collection services. In Korea, the Seoul Metropolitan Government addressed waste overflow and inefficiencies by implementing smart waste bins equipped with fill-level sensors in particularly crowded areas of the city center. In Australia, the City of Subiaco recently replaced traditional bins with solar-powered compacting stations in neighborhoods with high pedestrian traffic. These smart waste stations utilize solar energy to automatically compact waste, maximizing capacity and reducing the frequency of waste collections. Overall, these early applications have demonstrated significant improvements in public sanitation and streamlined waste collection schedules – thus indirectly contributing to emissions mitigation.

Sources:

SENSONEO, "One of the largest smart waste deployments in South America in Buenos Aires". *https://sensoneo.com/reference/smart-waste-deployments-south-america/*. Last accessed: June 1, 2023;

Ecube Labs, "Case Study: City of Seoul" *https://www.ecubelabs.com/references/city-of-seoul/*. Last accessed: June 1, 2023.

Discussion

This primer has profiled a set of smart city solutions that can contribute to GHG mitigation in urban areas. The focus has been on 1) buildings and transportation, which are the top contributing sectors in terms of urban emissions, as well as SWM, and 2) on digital- and software-based solutions capable of accelerating or facilitating broader mitigation actions (i.e., decarbonization and decentralization of electricity; improved equipment and operational efficiency; and reduced demand). While the sections and case studies above illustrate how cities have applied these solutions, there are additional topics that merit additional consideration in the context of climate mitigation.

First, city governments, particularly those who are resource-constrained, need not find it prohibitively expensive to adopt the solutions featured in this primer. It is true that public sector leaders must evaluate investments in vanguard technologies against a diverse of other pressing sectors and needs. And so, all too often, discussions about smart cities focus on the unappealing cost of various technologies, even though previous research has showcased how smart city tools can, in fact, yield important well-being outcomes, especially when applied within well-designed policy frameworks and collaborative, citizen-focused ecosystems.[42] However, we note that the solutions included in this primer do not assume that city governments are the primary 'buyers' of new technologies; indeed, city agencies cannot achieve mitigation targets at scale by behaving as the sole actor.

Some of our case studies illustrate this point. Behind the meter solutions require the right power market design and can benefit from grants or tax incentives for homeowners to install solar at home, but it is not cities who must procure solutions for households or businesses. Similarly, microtransit in the California example benefitted from an initial US$12 million grant, but it is third party operators who must demonstrate results. In short, the focus should not simply be on how to procure solutions for their own assets or fleets, but instead facilitate widespread adoption. This primer's case studies show how cities either *enable* tech-driven climate action, through regulation and incentives, or *demonstrate*, through comparatively small grants or concessions.[43]

Second, we emphasize that while all the solutions featured in this primer are already commercially available and technically feasible, their relative impact in terms of mitigation requires further evaluation. The primer thus takes special care of aligning solutions with broader mitigation actions—e.g., digital solutions that can complement or even jumpstart demand response programs in the buildings sector—and so we recommend cities consider supporting and deploying specific smart city solutions in the context of broader climate actions and plans, subservient to integrated urban planning goals.

Third, the World Bank's knowledge base recommends readers always to evaluate smart city solutions in a way that reflects the realities of cities at different levels of development. While the specific examples included in this primer may not be currently available to every city, our category solutions should still be considered across all contexts. To illustrate, though there may not be a best-in-class provider of IoT solutions in every city, this should not keep cities from cultivating a data ecosystem that relies on open-source alternatives for building automation, or from 'leapfrogging' through policy incentives to help citizens reduce demand.

Overall, these discussion topics should remind readers that "smart city initiatives are not only about technology (...) [The] transition to smart cities requires technology to be contextualized and combined with changes in policy, regulatory, organizational and institutional settings within local governments."[44] Smart city solutions can be narrowly designed to achieve specific results—such as

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[42] See, for instance, UN Habitat 2022 A Global Review of Smart City Governance Practices Nairobi: UN Habitat; OECD (2020) Smart Cities and Inclusive Growth, Paris: OECD; McKinsey Global Institute (2018) Smart cities: Digital solutions for a more livable future, McKinsey and Company.

[43] In all cases, cities can use proven frameworks from climate policy, such as a "energy technology portfolio" approach, to make decisions about which technologies to support. Energy technology portfolios, similar to financial investment portfolios, require careful allocation of resources across assets to maximize outcomes and manage risks. Balancing diversification and concentration, these portfolios aim to achieve sustainability objectives by considering factors such as carbon emissions *alongside* financial returns; for more details, refer to much of the academic work by P. Auerswald at George Mason University and J. Trancik at the Massachusetts Institute of Technology.

[44] UN Habitat (2022) A Global Review of Smart City Governance Practices Nairobi: UN Habitat, p10.

reduced demand for power in buildings—yet they should work within a broader set of climate and urban planning goals.