11

Understanding Urban Infrastructure-Related Greenhouse Gas Emissions and Key Mitigation Strategies

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For the first time in human history, more than half of the world's inhabitants are now living in cities and urban areas. Between 2007 and 2050, the world's population will increase from 6.6 to 9.4 billion people, 70 percent of whom will be living in urban settings (United Nations 2007). Because cities house such a large proportion of the world's people, they are major contributors to global greenhouse gas (GHG) emissions. The International Energy Agency estimates that more than 70 percent of global GHG emissions are attributed to energy use in cities (International Energy Agency 2008). Recognizing this fact, more than 1,200 cities worldwide have taken on the challenge of measuring and mitigating GHG emissions associated with their communities, including more than 1,000 cities that have signed on to the U.S. Mayor's Climate Protection Agreement.

Cities and Global Greenhouse Gas Emissions

MEASUREMENT CHALLENGES

Greenhouse gas accounting at the city scale is confounded by the relatively small spatial size of cities compared to nations, as a result of which two issues arise (Ramaswami et al. 2011). First, essential infrastructures that provide energy, water, wastewater treatment, commuter and airline transport, and other basic services to urban residents often cross city boundaries. Hence, the energy use to provide these infrastructure services often occurs outside the boundary of the cities using them. This results in the phenomenon of energy being embodied in the transboundary provision of various infrastructure services to cities. For example, energy used to produce and pump water to cities over long distances would be termed the energy embodied in water supply. Beyond infrastructures, significant trade of other goods and services that likewise occurs across city boundaries is also associated with embodied energy and GHG emissions. Consequently, human activity in cities—occurring in residential, commercial, and industrial sectors—stimulates both direct in-boundary GHG emissions (occurring within the geopolitical boundary of the community) and transboundary emissions (occurring outside).

Thus, strictly limiting the measurement of energy use and GHG emissions to those occurring within a city's boundary can provide an incorrect and even misleading picture. In some cases, a purely geographic measurement approach may create unintended incentives to simply move GHG emissions outside the boundary. As we discuss new technologies, urban design strategies, and policy levers for low-carbon city development, it is important to develop robust methods for measuring GHG emissions associated with cities, addressing both in-boundary and transboundary emissions.

INFRASTRUCTURE SUPPLY CHAIN GHG EMISSION FOOTPRINTS OF CITIES

Ramaswami et al. (2008), Hillman and Ramaswami (2010), and Chavez and Ramaswami (2012) have articulated a transboundary infrastructure footprint (TBIF) to explicitly incorporate the impact of in-boundary and transboundary infrastructures on the GHG emissions associated with cities. Infrastructures are defined broadly as those that provide basic needs of water, energy, food, mobility and connectivity, shelter (building materials), sanitation/waste disposal, and public spaces in cities, and are also important for economic activity in all cities (Chavez and Ramaswami 2012). The TBIF methodology combines urban material and energy flows associated with these key urban infrastructure services in a city with the life cycle energy needed to provide these services, obtained from life cycle assessment.

The energy and materials use in a city associated with the key infrastructure sectors in a TBIF can be detailed as follows:

- *Energy use in buildings and facilities* (residential, commercial, and industrial) and the provision of such energy by electric power plants and natural gas plants, which may be located outside the city boundary.
- *Fuel use for transportation activities by the community* (gasoline, diesel, and jet fuel). Because surface travel occurs regionally and air travel occurs nationally and globally, appropriate methods are needed to allocate road and air travel to communities based on the actual demand for transportation activities.
    - Increasingly, the literature is converging toward allocating surface

  travel based on demand elicited from regional metropolitan transportation models, rather than merely counting all vehicle trips within the city boundary, which often include pass-through and highway trips that have no relationship to the city of interest.
  - Methods for allocating airline travel to communities are also emerging. A full allocation of airline trips to each community requires detailed data on whether the trip was initiated by residents, businesses, or visitors to the community and on the average distance of travel for each category of passenger. Such data are nearly impossible to obtain. Hence, a simpler estimate allocates jet fuel loaded at each airport (i.e., fuel needed for a one-way trip out of the airport) to surrounding cities using that airport. Such allocation can be done either using airline passenger surveys (see Chavez et al. 2012) or using regional surface transport models that provide data on the proportion of all road trips to and from the airport that arise from the surrounding cities, separating out employee trips (see Hillman, Janson, and Ramaswami 2011; Ramaswami et al. 2008).
- The embodied energy of various materials needed to support key infrastructure supply chains to the city*:*
  - The production and refining of transportation fuels to support the transportation activities allocated to cities, as described above.
  - Energy use to provide water supply, wastewater treatment, and waste management services to the community, even if such energy use occurs outside the city boundary.
  - Embodied energy to produce key urban built environment materials, such as cement, iron, and steel.
  - Additional energy embodied in long-distance freight transport to and from the community.
  - Energy embodied in the production of food to support the community's residential and commercial sectors.

While the provision of food is not traditionally considered infrastructure, a food supply is essential to life in cities, just like the provision of water, wastewater, energy, and transportation services. Community-wide use of food includes food for the residents' personal consumption and food for the hospitality/restaurant industry that serves visitors to the community. New methods are emerging that track not only food consumed at home using consumer expenditure surveys (as in Ramaswami et al. 2008), but also food sales data in restaurants that can help track food services to residents and visitors (Chavez and Ramaswami 2012).

All these infrastructure services support the entire community—that is, local homes, businesses, and industries as well as visitors, and provide a production-based view of the city. Indeed, the impact of visitors—can be important both in small resort cities like the ski resort towns of Vail and Aspen, Colorado, and in large tourist destinations like London, New York, and Paris.

The TBIF method accounts for key infrastructures serving the city as a whole and is thus analogous to national production-based GHG accounting with the challenge of infrastructure fragmentation by city boundaries being overcome by the transboundary approach. The production-based TBIF accounting method has been related mathematically to consumption-based GHG accounting that incorporates the full supply chains of all goods and services used by resident households and final economic consumption sectors in a city, including global trade (see Chavez and Ramaswami 2012). The consumption account, however, excludes energy used by local businesses that serve visitors or that produce goods and services that are exported. A dual approach is therefore recommended with TBIF to support city infrastructure planning and a separate consumption-based accounting to inform household consumption behaviors. This dual approach has now been adopted in city-scale GHG reporting protocols developed recently by ICLEI-USA and also by the British Standards Institute (PAS 2070; BSI 2012). These protocols enable standardization and institutionalization of the TBIF method described in this chapter.

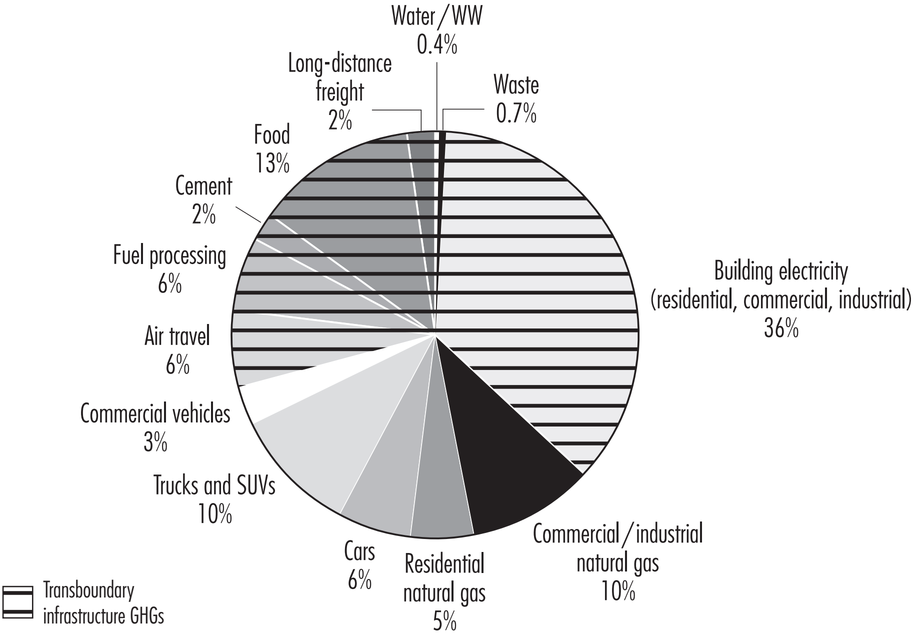
AVOIDING DOUBLE COUNTING IN TBIF

The TBIF for Denver, Colorado, which incorporates all the infrastructure components discussed here, is shown in figure 11.1. Care must be taken in adding the various infrastructure sectors to avoid double counting GHG emissions. (Appropriate methods are described in greater detail in the referenced manuscripts [see Hillman and Ramaswami 2010; Ramaswami et al. 2008].) Future work may also try to separate out the energy use in the buildings energy sector for providing information-communication services, and to track the supply chains that support this infrastructure. At present, however, the emphasis is on tracking the key infrastructure services shown in figure 11.1—the provision of energy, mobility/transportation, water supply, waste treatment, food, fuel, and building materials (e.g., cement) in cities. Indeed, the community-scale GHG accounting protocol of the Local Governments for Sustainability now includes consideration of all the above infrastructure sectors (ICLEI-USA 2012). Some of the services, such as water supply, wastewater treatment, and the embodied energy of construction materials such as cement, contribute less than 2 percent of the total infrastructure footprint (see figure 11.1). Potential future additions to infrastructure sectors in the TBIF, such as the supply chains supporting the information-communication sector, can be compared against these numbers to judge their relative importance.

CONVERGENCE

Developed for Denver in 2008, the TBIF method has since been tested in eight U.S. cities and shows good convergence between the transboundary GHG emission footprints computed at the city scale versus national benchmarks of 25 (mt [metric tons]-CO_2e) per capita per year, suggesting that the transboundary challenge in addressing city-scale GHGs may have been overcome by these transboundary infrastructure supply chain inclusions (see Hillman and Ramaswami

Figure 11.1
Transboundary Infrastructure GHG Emissions Footprint (TBIF) for Denver



Note: Embodied energy and transboundary GHG emissions are hatched.
Source: Adapted from Ramaswami et al. (2008).

2010). Appropriate metrics to represent the resulting GHG emissions are currently being studied. It is proposed that the TBIF GHG emissions be expressed per unit productivity of the community (based on gross domestic product [GDP]), while consumption-based GHG associated with homes be represented per resident (per capita). A meta-analysis across 40 U.S. counties confirms that TBIF GHG emissions expressed per unit GDP track well with measures of local urban efficiency, while consumption-based GHG emissions per capita track most closely with household expenditures (Chavez 2012).

POLICY RELEVANCE AND CONTRIBUTION OF INFRASTRUCTURE SECTORS

The TBIF represents together all the key infrastructure sectors and their supply chains, which support the activities of business, industry, and households in a community. As a result, cross-infrastructure substitutions to reduce GHG emissions are made visible—e.g., the substitution of airline travel in the transportation sector with the typically lower energy usage for teleconferencing in the buildings sector. Because supply chains of infrastructure are incorporated in the TBIF, the method is also effective in informing cross-scale strategies for GHG mitigation (e.g., by greening the supply chain of concrete through suitable substitutes for cement).

The TBIF also supports effective, sustainable urban planning that addresses infrastructure needs to support the future growth of the city as a whole—its homes, visitors, businesses, and industries considered together. Using the information in the TBIF, planners and policy makers can examine the different infrastructure sectors that contribute to GHG emissions. While cities differ vastly in how each sector contributes to GHG emissions, in general a study of eight U.S. cities shows that large cities tend to exhibit these general characteristics (Hillman and Ramaswami 2010):

- Energy use in buildings and facilities contributes a large proportion (greater than 40 percent) of TBIF GHG emissions. As our electricity supply includes more renewables, this contribution is likely to decrease.
- Transportation sector emissions follow closely (between 30 and 40 percent of the overall TBIF emissions) when all modes of travel are included and fuel refining is incorporated. Emission reductions in this sector are most challenging and likely to decrease slowly with smart growth and transit-oriented policies and with the penetration of new vehicle-fuel technologies.
- The GHGs embodied in food use in the community are significant and exceed 10 percent of the TBIF GHG emissions. Cities can lower these emissions by altering the nature of demand for food in communities—for example, by encouraging a healthy diet with less red meat.
- Other infrastructure sectors such as water, wastewater treatment, waste disposal, and the GHG embodied in urban materials, together, total between 5 and 10 percent, depending on the characteristics of different cities. Cities in the developing world have higher GHG contributions from these sectors due to the release of untreated wastewater as well as a high level of construction activities using cement (e.g., see the discussion of GHG emissions in Delhi in Chavez et al. 2012).

The TBIF thus presents a unique view of cities connecting community-wide activities that use infrastructure services with the life cycle energy and materials needed to provide these services. Strategies that reduce or alter the use of energy, water, infrastructure-related materials, and food in cities, as well as those that encourage the cleaner production of these material-energy flows or that promote symbiotic exchanges between municipal and industry sectors (e.g., Van Berkel 2010), can reduce the transboundary infrastructure GHG footprint of cities.

Buildings and Land Use Patterns

Buildings and land use patterns significantly affect the use of energy and materials in urban infrastructure. Energy use in buildings is shown to be highly correlated first with weather, represented by heating and cooling degree days, i.e., the number of days in a year and the extent to which these days exceed a comfortable ambient temperature of 65 degrees Fahrenheit. Cities in cold regions will have a large number for heating degree days, while those in very hot regions have large cooling degree days. Energy use in buildings—which is needed for both heating and cooling—is shown to be strongly correlated with the heating and cooling degree days representing the regional climate. Indeed, the average energy use in homes in different U.S. cities is observed to be close to the state average reported in the residential energy consumption surveys, and representative of climate conditions (Hillman and Ramaswami 2010).

When comparing cities, building occupants and the square footage of homes are also emerging as an important factor, along with the age of homes and the incomes of the home dwellers. Improved data sets are emerging that help uncover these various influences. However, there are many confounding studies on the effect of densification on energy use in buildings. While, in general, more compact buildings with shared walls reduce both direct and indirect energy use (embodied in materials), a decreasing trend in building occupancy levels in more compact buildings can offset these gains. When the income levels and consumption behaviors of occupants are further considered, the results can be mixed.

Energy use in transportation has shown different types of correlations with population density. In a study of global cities (Newman and Kenworthy 1999), this relationship follows the classic exponentially decreasing curve when comparing global cities with large orders of magnitude differences in population density. The cities included Denver, Los Angeles, and New York City (in the United States) versus Geneva, Bangkok, and other international cities. However, it should be emphasized that for several cities, such as New York City, the contribution of mass transit and rail was not included.

In a study of road travel GHG emissions across 40 U.S. cities, per capita surface transportation emissions showed little or no correlation with population density; the population density across U.S. cities does not range as widely as across global cities. Indeed, when regional commuter travel was apportioned based on origin-destination allocation, increases in activity density (i.e., the sum of homes plus businesses per acre) correlated with an increase in per capita transportation sector emissions, reflecting the importance of workplaces and businesses in generating travel demand (Hillman et al. 2011). For five of the eight larger U.S. cities studied—Boulder, Denver, Portland, Seattle, and Austin—the average per capita vehicle miles traveled (VMT) was very similar and hovered around 22 to 25 VMT per person per day, consistent with national benchmarks (Hillman and Ramaswami 2010). For these cities, despite differences in bicycle or transit ridership in the central city, regional patterns of travel changed very little. Since transportation activities are generally regional, the impact of small local changes (e.g., bicycling or walking) is not very apparent at the scale of regional transport.

These examples illustrate that the relationships between land use and travel behaviors are complex (National Research Council 2009). Organizations like the Federal Highway Administration have posited a threshold density of 7 to 10 dwelling units per acre, above which increases in density start yielding decreases in travel demand, with transit, car sharing, and other alternative modes becoming viable. A vast majority of U.S. cities and counties exhibit population densities well below this threshold, with exceptions such as New York City. The relationship between travel demand and land use density is made more complex by many different phenomena, including how travel demand is measured and potential self-selection biases for reduced motorized travel among urban versus suburban residents.

Furthermore, as the well-known adage notes, correlation does not imply causality. Thus, strategies that only focus on densification rarely succeed in reducing per capita VMT. In addition to density, other variables such as diversity, design, access to transit, and regional access to jobs have significant impacts (National Research Council 2009). The elasticity of travel demand with respect to each of these variables, independently, is quite small; however, in the long term, a doubling of density with improvements in design, diversity, and distance to transit and regional accessibility to jobs is estimated to yield about a 25 percent reduction in per capita VMT in U.S. cities (National Research Council 2009).

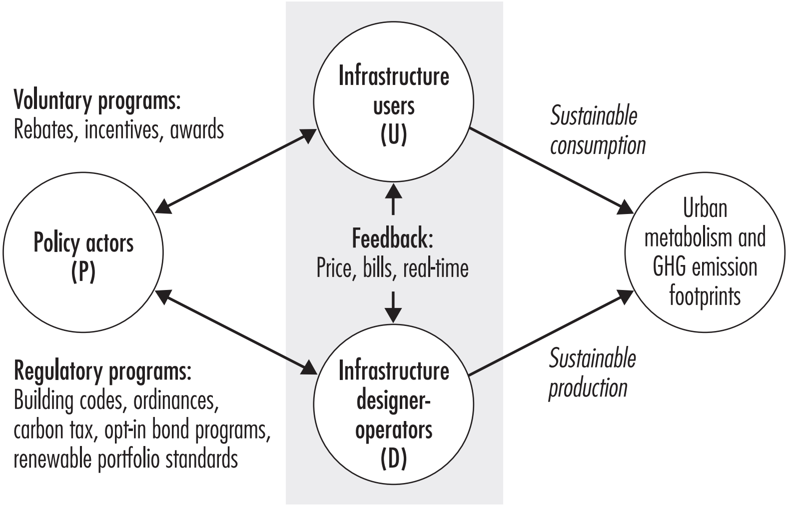
This does not mean, however, that land use change and improvements in building energy efficiency are not effective. The relative inelastic nature of travel demand with respect to land use variables merely indicates that there is significant momentum (inertia) and path dependency in urban systems. Thus, changing current GHG emission trajectories in the transportation sector will take a long time. Also needed are innovative community programs supporting behavioral change and strategic policy interventions, which are described next.

Key Mitigation Strategies

Ramaswami et al. (2012) conducted a first-order analysis of key mitigation strategies in the buildings and transportation sector in typical U.S. cities, addressing the potential for near-term GHG mitigation over four to five years. Greenhouse gas mitigation is computed against a backdrop of an increasing trend in per capita electricity use as well as increased population, and key strategies are explored that will "bend the curve" of increasing community-wide TBIF-GHG emissions in the next five years.

Strategies were organized according to the primary agency among three broad categories of social actors: individual users (e.g., individual homes and businesses), infrastructure designer-operators, and policy actors (government officials, lawmakers, nongovernmental actors, media, scientists, and others involved

Figure 11.2
Typical Strategies for GHG Mitigation Initiated by the Three Actor Categories



Source: Ramaswami et al. (2012). Reprinted by permission of *Environmental Science and Technology*. Copyright © 2012 American Chemical Society.

in the policy process). Typical strategies for GHG footprint mitigation are shown in figure 11.2 and include the following (Ramaswami et al. 2012):

- Voluntary adoption of energy conservation behaviors and efficiency measures by individual users (U), often incentivized by rebates, awards, and other incentives provided by policy actors at local, state, or federal government agencies (U, P). These measures may include both energy conservation and efficiency in homes, as well as efforts to change travel behaviors.
- Voluntary actions among infrastructure designer-operators, such as adoption of green building practices, increased use of renewables in the electric grid, and adoption of higher-efficiency vehicles in bus fleet upgrades (D).
- Regulatory approaches are defined as those that need a mayoral decree or a vote by city council or other legislative bodies. Regulatory approaches institutionalize voluntary strategies aimed at sustainable consumption or sustainable production. Not all regulatory approaches have to be mandates. The following are examples of innovative regulations developed at the city scale:
  - *Time-of-sale ordinances*. Residential and commercial energy conservation ordinances in effect in Berkeley and San Francisco since the 1980s

require that all homes and commercial properties be renovated to basic energy efficiency standards at the time of sale (e.g., minimum Department of Energy–specified attic insulation, weather stripping, pipe insulation around hot and cold water pipes).

- *Climate Smart Loan Program*. The city of Boulder's Climate Smart Loan Program provides loans for more expensive energy efficiency improvements (e.g., windows, solar panels, solar hot water heaters). The loan is repaid through special tax assessments associated with that specific property even if it is subsequently sold. This overcomes one of the main barriers to investing in large home energy projects with payback periods longer than seven years, the average period of home ownership in the United States.
- *Date-certain and Smart Regulations*. Date-certain regulations require that buildings be retrofitted to basic energy efficiency standards by a fixed date. Boulder's Smart Regulations (as referred to in Boulder) require that all rental property be upgraded by 2014 to basic energy efficiency standards; properties will be reviewed at the time of renewal of rental licenses.
- *Behavioral feedback*. Cities and utilities are also experimenting with different forms of energy feedback devices. A few utilities have implemented price feedback via monthly energy bills; this strategy is showing energy savings of 2 percent on average across the community (O-Power). Instantaneous behavioral feedback can be achieved using real-time energy meters that display energy use continuously. These meters have been shown to stimulate 6 to 15 percent savings in electricity use in pilot studies. A few utilities are contemplating requiring such low-cost devices in all homes, such as SoCal Edison in California.

In addition to the city-scale regulations described above, several state-scale regulations can also reduce GHG emissions from buildings' energy use. For example, Colorado's Renewable Portfolio Standard currently requires 30 percent of the state's electricity-generation portfolio to consist of renewable resources by the year 2020. The Clean Air, Clean Jobs Bill (HB 1361) requires that aging coal plants be phased out and replaced with cleaner-burning natural gas power plants that emit about half the CO_2 for generating electricity. The federal renewable fuels policy shapes the penetration of biofuels in the fuel mix.

Strategy Analysis and Policy Implications

The quantitative study of Ramaswami et al. (2012) reveals the following key findings comparing the effectiveness of voluntary, market-based, and regulatory strategies for GHG mitigation in the buildings and transportation sectors.

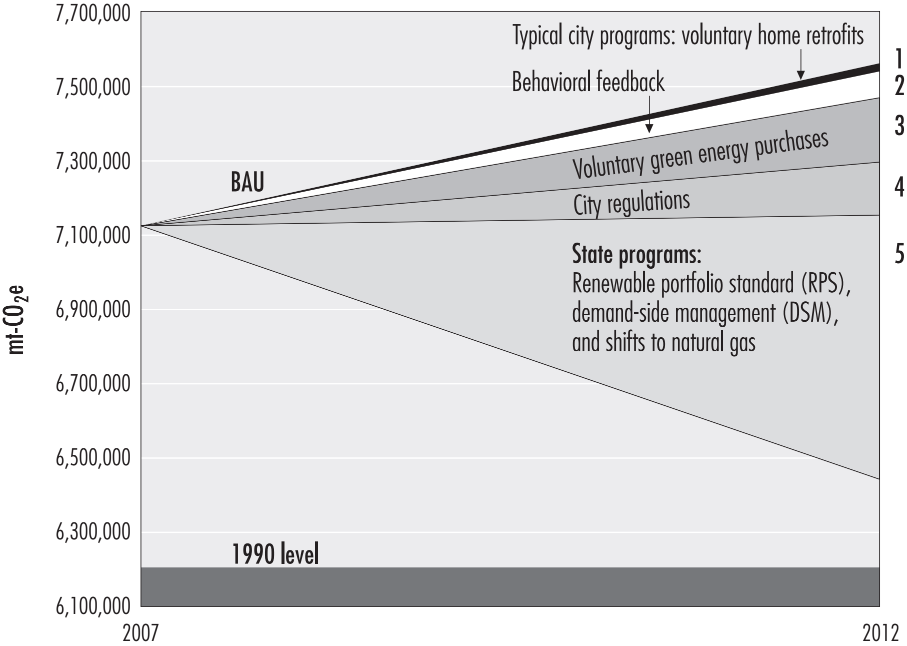
REDUCING GHG EMISSIONS IN THE BUILDINGS SECTOR

To reduce GHG emissions related to energy use in the buildings sector, three broad types of strategies are commonly suggested and adopted by many cities:

- *Voluntary upgrades for home energy efficiency*. Voluntary participation rates of home dwellers in typical home efficiency upgrade programs offered by cities are quite low, decreasing from a high of 50 percent for free giveaways of CFLs to less than 4 percent for modestly higher-cost items like attic insulation. Typical voluntary retrofit programs that hand out free CFLs or employ traditional random door-to-door neighborhood campaigns appear to be ineffective. Given the low participation rates, it is proposed that cities either explore innovative new ways of engaging the community in energy conservation or consider strategic city-scale regulations, such as the date-certain and time-of-sale ordinances that have been successful in some pioneering cities, as described in the previous section.
- *Voluntary changes in green energy purchases*. More consumers are making green energy purchases, not only in Denver, but throughout the United States. One electric utility reported 15 percent green electricity purchases. A stronger marketing campaign in this area may have significant impact in most U.S. cities, where green energy purchases are often less than 1 percent of the total use of electricity.
- *Behavioral change with feedback devices*. Instantaneous feedback devices (real-time energy information displays) and even monthly feedback via energy bills can have a significant impact on behavior, reducing electricity use by as much as 15 percent in numerous pilot studies. Behavioral change with feedback can be strategically combined with rebate programs that promote efficiency measures to yield higher-impact "hybrid" program designs. Mandates that require all homes or all new homes to have low-cost energy feedback devices can significantly increase the penetration of the devices for maximum impact.

Only a handful of cities are exploring regulatory strategies for GHG mitigation at the city scale, such as the time-of-sale ordinances and rental property regulations described in the previous section. A quantitative assessment of the impact of the different types of building sector GHG mitigation strategies in figure 11.3 shows that cities must have a strategic portfolio mix of voluntary programs along with a select few high-impact key regulatory or policy strategies. Both city-scale regulations that shape demand (see wedge 4) as well as state-scale regulations that shape energy supply, such as a renewable electricity portfolio (wedge 5), can have significant impact on GHG mitigation, as shown in the figure. Without regulatory strategies, little GHG mitigation will be realized, while a robust mix of different strategies can be effective in significantly reducing GHG emissions.

Figure 11.3
Relative Impacts of Key Pathways for Near-Term GHG Mitigation for Cities



Source: Adapted from Ramaswami et al. (2012).

REDUCING GHG EMISSIONS IN THE TRANSPORTATION SECTOR

Mitigating GHG emissions from transportation activities is more challenging in the short term and is likely to remain so in the longer term. The impact of new vehicle-fuel technologies has been evaluated by many researchers (e.g., see Argonne National Lab's GREET[1] model). A life cycle–based wells-to-wheels perspective—that includes improvement in not only tail-pipe emissions, but also energy expended in fuel production—is essential to identify system-wide reductions in GHG emissions. While some new vehicle-fuel technologies are promising (e.g., plug-in hybrids using renewable electricity), their production and penetration rates in society are still so small that they will have little impact in the near term on GHG emissions from the transportation sector.

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[1] Greenhouse gases, Regulated Emissions, and Energy use in Transportation.

Table 11.1
Impact of Different Strategies on Near-Term Transport Sector GHG Mitigation Over Five Years

Strategy Type	Description and Assumptions	Percent (%) Reduction in Transport GHG (est. over 5 years)
Voluntary changes in vehicles or travel modes among individuals/businesses	50% fleet upgrades for police, bus, and school fleets (only 2% VMT impacted)	0.2
	Offer community-wide individualized travel marketing program, assuming 10% Denver residents working outside Denver participate	0.6
	Double the number of Denver employees in employer-based commuter programs (carpool, vanpool, telecommuting, bus pass, etc.)	0.6
	Quadruple bike travel (Denver Bike Share Program)	0.01
Voluntary changes in travel services demanded, using innovative technologies/markets	Adoption of telepresence among 3.3% of air travelers	0.7
	Airline offsets purchased by 5% of air travelers	1
Regulatory or policy strategies	Smart growth planning: 75% of new population in Denver (or its equivalent) living in higher-density (double-density) areas, with all other favorable factors (access, design, diversity, distance to transit)	0.9
	Low-rolling-resistance tires mandated for all; tire change assumed every 5–6 years	1.8
	Pay-as-you-drive (PAYD) auto insurance offered community-wide, equivalent to a 40% gasoline tax	2.3

GHG = greenhouse gas; VMT = vehicle miles traveled
Source: Ramaswami et al. (2012).

For the near-term analysis, the following broad strategy types had the most impact, all of which were very small. (See details and computations provided in Ramaswami et al. 2012.)

Cities are trying several voluntary strategies, such as those listed below:

- *Fleet upgrades*. School buses, transit buses, and government fleets contribute only 1.2 percent of VMT in the Denver region, and hence even when 50 percent of the vehicles are upgraded, the impact is small (less than a 1 percent reduction in GHGs), as shown in table 11.1.
- *Employer-based commuter programs*. The impact of employer-based incentives has been quantified in many U.S. metro area case studies, with

a reported average savings of 0.5 mt-CO_2e annually per employee participating in the National Best Workplace for Commuters Program. A similar range of GHG mitigation (0.5 to 1 mt-CO_2e per commuter) emerges in detailed studies of the Denver Regional Council of Governments' RideArrangers program, in which 1,429 employers offered car pools, van pools, transit, and telecommuting during the 2009 program launch year. Doubling the number of employees participating in employer-based programs by 2012, which experts considered to be an aggressive goal, yielded 60,000 additional participants over five years and was estimated to mitigate 0.6 percent of the transportation-related GHG emissions compared to the base year.

- *Individualized travel marketing (ITM)*. Additional mode shifts toward nonautomobile travel (e.g., transit) can be promoted through ITM programs that provide personalized information about existing mass transit routes and safe bike paths to promote switching to these alternative modes. Results from such interventions designed to change travel behavior are often in the gray literature and need to be verified. A recent review reports VMT reductions of 2 to 12 percent as a result of ITM programs across U.S. cities (Dill and Mohr 2010). Such a program implemented in Denver would target those who work outside the city (since Denver workers are covered in the RideArrangers program). If we assume 10 percent of these workers will respond, the GHG mitigation is of the order of only 0.6 percent in the best-case scenario. Quantifying the impact of shifts toward transit can be difficult. The above represents a best-case scenario where increased transit ridership is achieved with existing levels of service. In practice, the efficiency of transit depends on the ability to achieve a high loading of people in buses and trains, which in turn depends on population density and other factors, such as the state of the economy. Under current ridership conditions, energy use per person per mile traveled by bus is only slightly better than by automobile (BTS 2006). Shared automobile trips may yield a larger improvement than transit ridership. Furthermore, life cycle analysis can reveal useful insights about transit. For example, savings in transportation energy in an elevated bus rapid transit system in Xiamen City, China, were partially offset by the increase in energy needed to operate the elevators and other building-related aspects of the system (Cui et al. 2011).
- *Bicycle programs*. Bike share and other popular programs may also yield much less GHG mitigation than commonly understood. Indeed, studies of bicycle travel from several U.S. cities report average bicycle trip distances of about two miles (Krizek, Handy, and Piatkowski 2010). Returning to the Denver case study, if bicycle mode share in the city increases from 2 percent in 2009 to 10 percent in 2018, near the potential maximum observed in U.S. cities, it would result in a quadrupling of the current 100,000 annual bike trips logged in Denver. However, the resulting automobile displacement is computed to be very small, at about 1 million VMT

> annually, compared to total motorized VMT exceeding 5 billion per year (Ramaswami et al. 2008). This is a combination of relatively short bicycle trips (2 miles on average) and the fact that only 22 to 66 percent of bicycle trips displaced automobile trips. Thus, the impact of bike share is very small (less than 0.01 percent), as seen in table 11.1.

Thus, not all popular voluntary programs have high GHG impact, although employer-based and individual travel marketing may hold some promise. In contrast, as shown in table 11.1, innovative market-based strategies that model only a small percentage of airline travelers replacing air travel with teleconferencing or purchasing travel offsets can have the same magnitude of impact. In terms of policies, smart growth planning and innovative state-scale policies such as pay-as-you-drive insurance can also have a larger impact than the purely voluntary programs—the latter because it impacts all vehicles simultaneously. The analysis summarized in table 11.1 shows that rates of adoption of new technologies and policies are very important in shaping GHG mitigation in the transportation sector.

A combination of technological change (vehicle-fuel technologies as well as information technologies that promote telecommuting and teleconferencing) along with land use policies are needed to reduce transportation sector GHG emissions in the long term. Careful field studies and life cycle analyses are needed to ensure that GHG savings in the transportation sector are not lost by related increases in energy use in other sectors (e.g., in providing telework, teleconference, or transit services).

Conclusions

Based on the results shown in figure 11.3 and table 11.1, this chapter recommends that cities develop and analyze their transboundary infrastructure GHG emission footprints and conduct a simple strategy analysis addressing a key variable: the participation rates of people expected in various programs. Based on such data and with a portfolio mix of voluntary and regulatory strategies, cities can achieve significant reductions in GHG emissions in the buildings sector, while only small GHG reductions can be expected in the transportation sector. In general, this study shows that cities could target, in the near term, at best a 1 percent reduction per year in GHG emissions associated with buildings and transportation and will find this to be a challenging but achievable goal.

Afterword

The TBIF method is now being standardized for use by a large number of cities. It is represented as basic plus community-wide supply chains in ICLEI-USA's recently released protocol for reporting community-scale GHG emissions (ICLEI-USA 2012), available to more than 600 U.S. cities. The TBIF methodology—represented as Direct-Plus-Supply Chain—is also incorporated in a publicly available standard (PAS 2070) for GHG accounting for cities being developed by the British Standards Institute.

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COMMENTARY

W. Ross Morrow

Anu Ramaswami's chapter, and the broader literature associated with it, concerns independent action by city authorities to reduce greenhouse gas (GHG) emissions associated with activities in the city. Cities are, and will continue to be, a key driver both as an immediate source of emissions and as a source of demand for goods and services that cause GHG emissions. However, emissions due to activities within a city boundary do not necessarily *occur* within that boundary or within any particular metro area boundary. These emissions must nonetheless be included if the city's independent policy action is to result in reductions in GHG emissions.

The issue of transboundary emissions is essentially not mathematical, but rather sociopolitical. As Ramaswami states, "A purely geographic measurement approach may create unintended incentives to simply move GHG emissions outside the boundary." That is, what is important is the independent reactions of businesses and households to policy, and these actions are influenced by the ways in which behaviors are measured, regulated, and incentivized. Appropriate measurement of city GHG emissions for policy application has a "self-similarity" property familiar to the complex systems literature: measurement of a city's emissions in the context of state emissions is similar to the measurement of state emissions within the nation, or national emissions in the context of global emissions. Here is an analogy directly related to the work that Ramaswami describes: the United States currently measures its own GHG emissions as a function of geographic boundaries; it does not include emissions occurring in other parts of the world associated with the demand for goods and services consumed within the United States.

The remainder of this commentary addresses in more detail the two key themes in Ramaswami's chapter: measurement and policy.

Measurement

For the last few years, Ramaswami and her colleagues have successfully introduced and applied concepts for activity-based measurement of emissions associated with essential infrastructure services on which cities rely, but that may create emissions outside a city's boundary. The central figure is the transboundary infrastructure footprint (TBIF), which allocates to the city the emissions associated with services located outside its boundaries that are essential to the city's functioning. Not including emissions created outside city boundaries for activities within city boundaries certainly risks undercounting GHG emissions in the absence of a national policy that covers all aspects of the economy regardless of location. The risk presented by including such activities in estimates is just the opposite:

overcounting. Ramaswami and her colleagues have considered this issue in detail in references given in her chapter. Broadly speaking, it seems plausible that the activity-based allocation of GHG emissions (or other environmental stressors) to specific cities is feasible, reasonably practical, and important for effective regulation of GHG emissions by largely noncooperative entities like U.S. cities.

To be effective within a noncooperative network, city-based policy approaches must consider the effects of actions taken by other cities. Using TBIF or another activity-based metric as a measure for motivating and measuring city policies to reduce GHG emissions is maximally beneficial only if the specific techniques for allocating activities from different geographical areas, city or otherwise, are standardized across cities implementing measurement. Speaking in purely mathematical terms, it is possible for collections of cities applying heterogeneous measurement techniques to result in either over- or undercounting of emissions. It would seem, however, that as long as rural[1] emissions are significant sources of emissions associated with cities, as suggested in the research by Ramaswami and her colleagues, then emissions are undercounted if any city uses a geographic basis for measurement.

Established institutions like the U.S. Conference of Mayors' Climate Protection Center,[2] which currently has 1,054 mayors joined under a single climate protection agreement, offer an opportunity to catalyze such standardization in measurement methodology. The agreement primarily identifies specific practices that should be prioritized or promoted, several of which Ramaswami identifies as being rather low-impact paths toward emissions reductions. Moreover, the current agreement only mentions a single *optional* inventory of city emissions, with no specific methodology required and no requirement to continually track emissions reductions toward goals defined by this inventory. Clear, standardized measurement using activity-based principles should also play a role in state and national policies that concern activities associated with cities.

While cities certainly have a significant amount of local authority, specific policy actions will also overlap with state and national policies motivated to reduce GHG emissions. Current policies at higher levels of government are limited, relative to the scale of the climate change problem. In fact, under the Climate Protection Agreement, U.S. mayors agreed to urge state and federal governments to enact broad policies to reduce GHG emissions. When strong policies arrive, however, actions to reduce emissions over all scales in the hierarchical regulatory network that exists in the United States must be considered as a whole to ensure that social, economic, and environmental interests are balanced. Researchers in the physical sciences and engineering are becoming increasingly interested in such "multiscale" phenomena in which microscopic details of physical systems

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[1] Here, "rural" simply means locations not within the geographic boundaries of a city implementing measurement. This may, in fact, include rather developed areas.

[2] The Climate Protection Center's website is www.usmayors.org/climateprotection/revised.

are important for resolving macroscopic properties. One analysis paradigm in engineering, analytical target cascading, uses a hierarchical enterprise paradigm to enable multidisciplinary system optimization (Cooper et al. 2006). While it is unlikely that mathematical optimization technology can literally be applied to inform complex policy design at the national, state, and city levels, scientific insights from these domains may offer compelling metaphors for qualitative investigation of the balance required for effective overlapping policy actions at the national, state, and city levels.

One technical concern about the language that Ramaswami uses lies in the concept of scale conversion. Here and elsewhere, she claims that the "convergence" of TBIF-based emissions measurements for eight cities to national average emissions suggests that TBIF-based measurement overcomes the transboundary measurement challenge that cities face. This should be a property not of city measurements themselves, but of the average of a group of city measurements. That is, there is no obvious reason each city should have emissions that reflect the national average, even if measured by activities; the combined effects of each city's activities, measured with the TBIF, should reflect the national average as the number of cities measured increases as long as the emissions associated with "rural" activities largely service cities. A small variance in TBIF-based emissions measurement across several different metro areas is a distinct, and interesting, observation.

Policy

Mathematically speaking, it does not matter which cities emissions are allocated to, as long as all emissions are accounted for and regulated. However, this "equivalence" of measurement does not necessarily help define appropriate policy to apply within the boundaries of cities that ultimately exist within a complex hierarchy of regulatory authority and may be heterogeneous in their desire to put in place policies that support reductions in GHG emissions.

TBIF represents an improvement for policy for two reasons. The first concerns measurement alone. Suppose, for the moment, that there is no national policy. If some cities do not account for and regulate their emissions and each city that does account for and regulate emissions measures emissions via its geographic boundaries, then only some fraction of emissions will be accounted for and regulated. Even if every city accounts for and regulates its emissions on the basis of geographic boundaries, emissions from rural entities that drive activities associated with cities will not be accounted for or regulated. If, however, only some cities account for and regulate their emissions, but do so in a TBIF-based fashion, then emissions from other cities and from rural activities can be captured under regulation. Given that it is a (highly visible) minority of cities that are currently attempting to address their GHG emissions, this motivating factor for TBIF-based measurement is important. As soon as all entities are required to measure and reduce emissions, this issue is corrected.

The second reason TBIF represents a potential improvement for policy lies in socioeconomic equity and efficiency and applies even if all emitting entities are covered under some policy. If all cities account for and regulate their emissions and a national policy covers rural emissions not associated with cities, then all emissions can be addressed regardless of accounting based on emissions source or the end-use location of the associated good or service. However, the specific policy measures employed may not be economically efficient or socially equitable if policies are disconnected from the socioeconomic activities that drive emissions. Several useful examples are given in the chapter, including the greening of supply chains and increased use of telepresence in business. Another example might be refining capacity: the Gulf Coast contains a significant proportion of the petroleum- and chemicals-refining capacity for the United States, a capacity that largely exists to serve other major demand centers with transportation fuels and other goods. Direct regulation of metro areas with unusually high direct emissions would seem to disproportionately impact those areas relative to the areas that they serve. This risks market failures similar to the well-known principal-agent problem.

The use of TBIF or other more holistic emissions metrics would thus appear to be an improvement over purely geographic emissions accounting and regulation schemes from the perspective of effective and efficient policy for GHG emissions reduction in cities. However, TBIF-based measurement appears to require that cities accept higher levels of emissions associated with their activities (Hillman and Ramaswami 2010). Purely geographic measurement would seem to have two particularly attractive features for city officials. First, geographic measurement would localize policy activity on the actions that take place only within the city boundaries, offering boundaries for emissions inventory and reduction consistent with other components of city authority. Second, because geographic measurement has the potential unintended side effect of emissions relocation instead of reduction, it offers city officials the potential for relatively easy progress toward publicly stated goals. Accepting TBIF will thus require the "political will" to first accept responsibility for higher proportions of emissions than would likely be measured under a purely geographic measurement approach and then to design and implement policy measures that promote real changes in emissions rather than simply changes in geographically limited measures of emissions. To cities with a large "trade surplus" in goods and services associated with emissions, TBIF accounting may offer an advantage worth capitalizing on. For many cities, the political will to implement holistic measurement may have to be imposed through institutional arrangements or higher-level (state and federal) policy.

As Ramaswami effectively points out, more creative efforts on the part of city officials appear to be required if cities are to participate meaningfully in GHG emissions reductions. Voluntary efforts, in particular, are shown to have extremely limited reductions in GHG emissions associated with city activities. While all improvements are valuable, the conclusion that emissions reductions only on the order of 1 percent per year are possible with current approaches poses a challenge to decision makers who are genuinely interested in confronting the climate challenge. Agreements such as the U.S. Mayors' Climate Protection Agreement, while motivating, lack explicit benchmarks for emissions performance and do not require continued measurement of policy performance. Until policy is closely linked to an initial inventory, specific quantitative targets, and subsequent emissions measurements, progress toward climate change goals will be limited.

Conclusions

Ramaswami and her colleagues have, over the past five years, presented a useful body of research concerning activity-based measurement of GHG emissions for cities. Such measurements are motivated by independent actions currently being taken by cities to improve their GHG emissions profile in the absence of state and federal policies. Ramaswami's chapter succinctly reviews the key challenge facing measurement for city policy: the existence of transboundary emissions produced outside geographic city boundaries that should nonetheless be addressed. The chapter also highlights the difficulties facing existing policy approaches at the city level.

This commentary has tried to highlight several observations brought out by this research. First, the inclusion of transboundary emissions is necessary from a behavioral perspective, concerning the incentives and regulations that can most effectively and efficiently achieve emissions reduction, rather than being purely an accounting concern. Second, standardization of measurement methods is important for honestly addressing emissions from cities in an environment without consistent policies that reach across city boundaries. Such standardization could be executed within formal institutions that already link city officials or within the legislative language employed at higher levels (state or federal) of the policy hierarchy. Third, the results obtained by Ramaswami and her colleagues suggest that, for many cities, accepting activity-based metrics of emissions will more clearly illustrate the difficulty of emissions reduction. This confronts existing incentives for officials in many levels of government to realize short-run results to policy decisions that can be effectively communicated. Many current policy approaches, while often highly visible, may have limited impact on emissions calculated in a holistic fashion.

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