Greenhouse Gas Emission Footprints and Energy Use Benchmarks for Eight U.S. Cities

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A hybrid life cycle-based trans-boundary greenhouse gas (GHG) emissions footprint is elucidated at the city-scale and evaluated for 8 US cities. The method incorporates end-uses of energy within city boundaries, plus cross-boundary demand for airline/freight transport and embodied energy of four key urban materials [food, water, energy (fuels), and shelter (cement)], essential for life in all cities. These cross-boundary activities contributed 47% on average more than the in-boundary GHG contributions traditionally reported for cities, indicating significant truncation at city boundaries of GHG emissions associated with urban activities. Incorporating cross-boundary contributions created convergence in per capita GHG emissions from the city-scale (average 23.7 mt-CO$_2$e/capita) to the national-scale (24.5 mt-CO$_2$e/capita), suggesting that six key cross-boundary activities may suffice to yield a holistic GHG emission footprint for cities, with important policy ramifications. Average GHG contributions from various human activity sectors include buildings/facilities energy use (47.1%), regional surface transport (20.8%), food production (14.7%), transport fuel production (6.4%), airline transport (4.8%), long-distance freight trucking (2.8%), cement production (2.2%), and water/wastewater/waste processing (1.3%). Energy-, travel-, and key materials-consumption efficiency metrics are elucidated in these sectors; these consumption metrics are observed to be largely similar across the eight U.S. cities and consistent with national/regional averages.

Introduction

With more than a thousand cities worldwide pledging to reduce greenhouse gas (GHG) emissions at the local scale (*1*), of which 956 cities are in the U.S. alone (*2*), the city-scale is becoming increasingly important in global climate action efforts. However, the smaller spatial scale of cities with significant cross-boundary exchange of key goods and services, of surface commuter travel, and of airline travel, has posed a challenge in developing a holistic accounting of GHG emissions associated with human demand for energy and materials in cities. In a previous paper published in *ES&T*, Ramaswami et al. (*3*) introduced a new demand-centered hybrid life cycle-based methodology to overcome some of the spatial boundary challenges described above. In addition to end-uses of energy in cities that are traditionally included in most GHG accounting protocols (*4, 5*), Ramaswami et al.'s demand method incorporates spatial-allocation of cross-boundary transport exerted by cities and incorporates the embodied energy of key urban materials used in cities. Such trans-boundary GHG emissions associated with energy use occurring outside the boundary of the organization of interest are termed Scope 3 emissions (*4*). In contrast, end-uses of energy within an organization's boundaries yield Scope 1, direct GHG emissions from fuel combustion (e.g., burning natural gas in furnaces or gasoline in engines), and Scope 2, indirect GHG emissions at powerplants to provide electricity end-uses within organizational boundaries (*4*).

While Scope 1+2 GHG emissions are required to be reported, inclusion of a small number of relevant Scope 3 items is highly recommended by EPA for corporate GHG accounting to promote win−win life cycle-based strategies for GHG mitigation (*6*). For cities, however, while many cities have been developing GHG inventories, no standardized list of most relevant cross-boundary Scope 3 inclusions had previously been developed for the city-scale.

A few cities had previously included select cross-boundary GHG emission contributions on an ad hoc basis. For example, Aspen and Seattle included emissions from airline travel; Seattle included embodied emissions of asphalt (*7*), and embodied emissions of foods and construction materials (cement, steel) were included by Paris, Delhi, and Calcutta (*8, 9*). In their previous study of Denver, Ramaswami et al. (*3*), for the first time articulated a concise list of key urban materials to be included in Scope 3 GHG accounting for cities and developed an origin−destination allocation methodology for cross-boundary transport demanded by the city, for example, air travel and vehicle commutes to neighboring cities. On the basis of the functionality of cities, the four key urban materials were articulated as food, water, transport fuels (i.e., energy), and cement (shelter) that are essential for life in *all cities*, but often produced outside in hinterland areas*;* life cycle assessment (LCA) was used to capture the upstream trans-boundary GHG emissions associated with producing these materials (*3*). A hybrid demand-centered method was thus developed that coupled cross-boundary demand for travel and for key urban materials with direct end-uses of energy and GHG emissions within city boundaries.

First tested in Denver, CO, the hybrid methodology showed that incorporating these additional cross-boundary activities increased Denver's GHG accounting by 40% of the conventional in-boundary accounting. More importantly, the cross-boundary additions created consistency in GHG accounting across spatial scale, such that per capita demand-based GHG emissions at the city-scale of Denver (~25 mt-CO$_2$e/capita (*3*),) were consistent both in terms of inclusions and numeric value with those at the scale of the State of Colorado (25.2 mt-CO$_2$e/capita (*10*)) and the U.S. (24.5 mt-CO$_2$e/capita (*11*),). In other words, when activities such as airline transport, freight transport, oil refining, cement production, and food production activities that largely occur outside city boundaries but appear in national inventories are now mapped to cities based on demand, challenges associated with truncation at the spatial boundary of cities are mitigated. See Table 1. On the basis of results for Denver, it was hypothesized that the demand-centered LCA-based inventory methodology may approach a GHG emissions footprint computation, which, analogous to water footprints (e.g., ref *12*), includes trans-boundary upstream life cycle GHG emissions from producing both energy and key urban materials for end-use in cities; the demand and outflow of other materials is assumed to be incorporated in the trade/exchange of goods that occurs across cities. The demand-based method was also shown to be policy-relevant, leading

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TABLE 1. U.S. National-Scale GHG Emissions by End-Use Economic Activity Sectors Are Mapped to City-Scale Scope 1, Scope 2, and Scope 3 Activity Sectors[a,b]

U.S. national GHG emissions by economic activity sectors[b] (% contribution)	Related city-scale activities and scopes	City boundary classification
Residential and commercial energy use and related GHG emissions (33.9%)	Residential and commercial energy use within city boundaries and related GHG emissions [Scope 1 (i.e., direct fossil fuel combustion) + Scope 2 (i.e., electricity generation)]	In-boundary buildings/facilities GHG emissions
Industrial energy use and GHG emissions (28.7%)	Industrial energy use and GHG emissions within city boundaries; larger cities have a balance between industrial-commercial-residential activities [Scope 1 + Scope 2]	In-boundary buildings/facilities GHG emissions
	Industrial energy use and GHG emissions occurring outside city boundaries to meet critical urban materials demand: cement production, petro-fuel production, water/wastewater/waste treatment, etc.[Scope 3]	**Cross-boundary contribution**
Personal road transport (17.8%)	Petro-fuel use for personal transport within regional commutershed, allocated to individual cities based on travel demand [Scope 1]	In-boundary and regional cross-boundary surface transport emissions
Freight transport (7.6%)	Petro-fuel use for commercial trucks within regional commutershed, allocated to individual cities based on travel demand [Scope 1] **Long distance freight trucking outside region[c] [Scope 3]**	In-boundary and regional cross-boundary surface transport emissions **Cross-boundary**
Airline transport (2.3%)	**Jet fuel use for airline travel from regional airport, allocated to individual cities using that airport [Scope 3]**	**Cross-boundary**
Agriculture (8.5%)	**Emissions from food production (excluding freight) to meet food consumption demand in cities [Scope 3]**	**Cross-boundary**
Total: 99% of national GHG emissions[c]	Total: With scope 1+2+3 inclusions, city-scale GHG accounts should include in-boundary and key cross-boundary activities, appropriate for a GHG footprint computation.	

[a] Six Scope 3 items related to cross boundary transport (airline and freight) and embodied energy of materials are shown in bold. [b] National GHG emissions by economic activity sectors from U.S. EPA (11); emissions only (no sinks). [c] Excludes 0.9% contributed by U.S. Territories (11). [d] Long-distance rail transport is not included as economic census data is not reported for this sector, and rail contributes less than 0.7% of national GHG emissions.

to green concrete policies and airline offset programs in Denver (13).

The objective of this paper is to assess the applicability of the demand-centered hybrid LCA-based GHG inventory methodology first developed for Denver, CO (3) to eight U.S. cities. The purpose is to assess consistent availability of data for the model, evaluate the relative contribution of Scope 3 inclusions in an expanded GHG emissions footprint versus a traditional boundary-limited inventory, test the hypothesis of scale convergence of per capita GHG emissions from the city-scale to the national-scale, and, to establish metrics for materials and energy consumption across eight U.S. cities.

The above will provide a more comprehensive understanding of GHG emissions at the city scale and build upon the ongoing work in urban metabolism (14, 15).

Methodology

Cities. The cities in this analysis include Denver, CO, Boulder, CO, Ft. Collins, CO, Arvada, CO, Portland, OR, Seattle, WA, Minneapolis, MN, and Austin, TX. These cities are situated in larger metropolitan regions with surface travel in regional commutersheds modeled by Metropolitan Planning Organizations (MPOs). Major airports that serve the regions, and, the geographic area encompassed by the regional MPO's versus the individual city's legal municipal boundary are displayed in Table 2. The eight cities were selected on the basis of their previous experience with GHG inventories and willingness to gather more data necessary for this study, as well as providing a good cross section of city sizes and climate

throughout the U.S. In addition, four of the eight cities were selected in the same region in Colorado, so that airline and surface travel allocation across cities could be explored in the same region.

City-Scale Hybrid Method Overview. The demand-centered methodology computes communitywide GHG emissions associated with two major categories of activities, in-boundary energy use/emissions and cross-boundary contributions, as shown below.

$$GHG = \left\{ \sum_{Electricity, Natural\ Gas, Petro-fuels} Energy\ Use \times EF + \sum M_{waste} \times EF \right\} + \left\{ \sum_{Producing\ key\ Urbanmails} MFA \times Ef_{LCA} + \sum_{Trans-Boundary\ Transport} M_{Fuel} \times Ef_{WTW} \right\}$$

$\{\leftarrow$In-boundary Energy use and emissions (Scope 1 + 2)

$\rightarrow\} + \{\leftarrow$Trans-boundary Emissions (Scope 3)$\rightarrow\}$

(1)

GHG emissions for a full Scope 1+2+3 GHG accounting (eq 1 above) are computed as the sum of both material and energy flows consumed by the community, each multiplied by a corresponding GHG emissions factor (EF) per unit of consumption. In-boundary energy use includes electricity, natural gas and petro-fuels use for residential, commercial

TABLE 2. Data Sources and GHG Emission Factors (EF) for the Hybrid Demand-Centered GHG Accounting Methodology for Cities

Cities in the study and their bounded area [sq. miles]	Regional Metropolitan Planning Organization (MPO) with regional commutershed area [sq. miles]	Regional airport	Local Water/WW EF (mt-CO_2e/million gallons)[a]	Local waste EF (mt-CO_2e/ton-waste)	Local electricity EF (kg-CO2e/kWh)
Denver, CO (153)	Denver Regional Council of Governments, DRCOG [5,100]	Denver International Airport: serves region including Denver, Boulder, Arvada, Fort Collins	0.71	−0.196	0.80
Boulder, CO (24)			0.77	0.641	0.80
Arvada, CO (32)			1.11	0.150	0.80
Ft Collins, CO (46)	North Front Range [6,593]		0.78	0.290	0.77
Portland, OR (134)	Metro Regional Government [3,655]	Portland International Airport	0.63	0.423	0.41
Seattle, WA (83)	Puget Sound Regional Council [6,290]	Seattle—Tacoma International Airport	0.73	−0.097	0.41
Minneapolis, MN (54)	Metropolitan Council [2,813]	Minneapolis—St. Paul International Airport	1.76	0.056	0.82
Austin, TX (251)	Capital Area (CAMPO) [2,790]	Austin—Bergstrom International Airport	1.54	0.150	0.50

Non-varying emissions factors and data sources[b]

Natural gas	5.4 (kg-CO_2e/therm)	ICLEI
Gasoline tailpipe (P2W)	9.1 (kg-CO_2e/gallon)	TCR
Diesel tailpipe (P2W)	10.2 (kg-CO_2e/gallon)	TCR
Jet fuel tailpipe (P2W)	9.9 (kg-CO_2e/gallon)	TCR
Gasoline processing (W2P)	2.3 (kg-CO_2e/gallon)	GREET
Diesel processing (W2P)	2.3 (kg-CO_2e/gallon)	GREET
Jet fuel processing (W2P)	2.3 (kg-CO_2e/gallon)	GREET
Cement	1 (mt-CO_2e/mt-Cement)	NREL
Food	1.5 (kg-CO_2e/1997-$)	EIO-LCA
Long distance freight	2.1 (kg-CO_2e/1997-$)	EIO-LCA

[a] Average of water and wastewater treatment GHG emissions are shown here in metric tonnes (mt). [b] Pump-to-wheel (P2W) represents tailpipe emissions in transport, while W2P represents fuel processing.

and industrial activities within a city (term 1, eq 1), for which standard EF derived from IPCC (intergovernmental panel for climate change) protocols are used (*4, 5*). The EF for the trans-boundary contribution (term 2, eq 1) incorporates LCA of producing key urban materials outside city boundaries, i.e., producing gasoline, food and cement, from raw material extraction to factory/farm/refinery production, computed using LCA databases. The use-phases of these materials in cities, e.g., tailpipe emissions from driving gasoline-cars or electricity use for cooking food, are included among in-boundary Scope 1+2 energy use. Trans-boundary freight transport includes full fuel cycle (wells-to-wheels, WTW) GHG emissions since both fuel production and tailpipe emissions occur outside city boundaries. Table 1 illustrates how major activities in the U.S. national-scale GHG emission inventory (*11*) map to city-scale activities listed in eq 1, enabling more holistic GHG emissions accounting across boundaries. Note that this paper maps GHG emissions across scale; carbon sinks within or outside city boundaries are not the focus of the methodology.

Materials and Energy Consumption. Annual end-use of electricity and natural gas for residential, commercial and industrial activities within cities was obtained from local utilities' billing data, considered high quality data. Waste generated, M_{waste}, was often estimated and is least reliable as most cities use private haulers who do not disclose this data. Consumption of petro-fuels (diesel and gasoline) for surface transport was obtained by computing annual regional total Vehicle Miles Traveled (VMT) for the entire commut-ershed from MPO models, allocating this regional total VMT to individual cities based on origin-destination of trips, and then dividing the spatially allocated VMT by the fuel economy of the vehicle-mix for that region (see ref *3*).

For key urban materials, annual cement use was tracked via expenditures on cement and concrete products (NAICS 3273) reported in the U.S. Economic Census for Metropolitan Statistical Areas (MSA) in the U.S. (*16*). National expenditures in this sector were normalized against annual national consumption of cement reported by the Portland Cement Authority (*17*) to enable conversion from monetary flow to cement mass flows (e.g., 2.3 kg cement per $ activity in NAICS 3273 reported in 2002). Annual food flows were represented as monetary expenditures on food at home and away from home, reported in Consumer Expenditure Surveys conducted for major metropolitan areas (*18*). Annual water and waste-water flows were obtained from respective regional utilities and allocated to individual cities using billing data.

Cross-Boundary Transport. Annual jet fuel loaded, obtained from regional airports (Table 2), was allocated to surrounding individual cities based on the ratio of road trips to the airport from the city of interest versus all trips to the airport. For Denver, this trip ratio was found to be close to the population percent represented by the city in the region (*3*); the replicability of this relationship was explored for all eight cities. It should be noted that since almost all (>95%) of airplanes refuel at the airports studied, and, since enplaned (departing) passengers represent about half of total passengers (inbound plus outbound), tracking jet fuel loaded at the regional airport implicitly accounts for approximately one-half of air travel to and from the region. In allocating cross-boundary transport, such procedures that consistently count only arrivals, only departures, or 50% of both (i.e., origin−destination allocation, when data are available), are essential to ensure that the same trip is not double-counted at both end-point locations.

An analogous approach was used to track outbound freight from cities, using annual expenditures for long distance truck transport (NAICS 48412 (*16*)), given that trucking is the dominant freight mode in the U.S. and contributes 6% to national GHG emissions (*11, 19*). The long distance speci-fication (NAICS 48412) is separate from truck transport occurring within MSA/MPO boundaries (short distance), already counted within the in-boundary activities. In this paper, we used economic census data for outbound long-distance trucking as a first estimate of cross-boundary freight impacts in cities. More detailed city-scale input-output models are needed to better estimate trucking demand from commodity inflows to cities; however, such methods have only recently been developed and are still being tested (*20*).

Energy/Material Use Efficiency Metrics for Cities. Annual material/energy flows provide data on consumption by residents in the eight U.S. cities. Benchmarking such consumption data on a per person, per household, or other relevant metric (building floor area) provides material-use and energy-use efficiency metrics. To compute efficiency benchmarks, residential and commercial building floor areas were obtained from the County Assessor's database for each of the cities. Population and number of households (HH) were obtained from the U.S. Census (*21*) as a common methodology for all cities. While utility-provided premise counts are more accurate, such data were not readily available for all eight cities.

GHG Emission Factors (EF) used in this study are shown in Table 2. All fuel combustion-related EFs are consistent with IPCC protocols and standardized by The Carbon Registry (TCR (*22*)). National LCA databases such as GREET (*23*), NREL (*24*), and EIO-LCA (*25*) were used to estimate EFs for the Scope 3 items in this study, that is, procurement of transport fuels, cement, and food and freight, respectively. Freight transport of food (*26*) was subtracted from the EF for food to avoid double counting with the general freight sector. As water and wastewater treatment often occurs regionally, GHG emissions were traced to energy use at the respective treatment plants (the major contributors to GHG) and allocated to the city of interest based on billing data; nitrogen-related emissions are negligible in comparison (*5*) and hence were not tracked. Emissions from waste disposal and recycling were estimated from EPA's WARM model (*27*); this EF for waste differed across cities (Table 2) based on differences in methane capture/energy recovery at landfills and varying recycle rates.

In the quantification of both annual material-energy flows and EF, methodological potential for double-counting Scope 3 contributions has been minimized. The EFs avoid overlap, as described above. Likewise, travel and material flow allocations are such that cement, jet fuel (i.e., airline trips), petroleum (i.e., surface VMT), and water use are not double-counted across multiple cities and are calibrated to add up to regional or national consumption totals (*28*). When cement factories, oil refineries, and water treatment plants are operating within city boundaries, GHG emissions from these highly visible industries, just like from jet fuel use at regional airports, should be allocated based on demand in the city of interest. Double counting in the food supply chain is expected to be small given a vast majority of U.S. food is produced outside cites.

To enable comparisons across cities, and to assess consistency of GHG emissions across spatial scale, the community-wide GHG emissions, computed for each city using eq 1, were normalized on a per capita basis and compared with the nationwide per capita emissions reported for the U.S. (*11*).

Results

The demand-centered methodology first tested in Denver was readily adaptable to all seven other U.S. cities. Additional data, such as airport jet fuel use, water and wastewater treatment energy, food and cement flows, and down-scaling from the regional traffic models, were obtained readily. In particular, the methodology for spatial allocation of road and airline transport applied to Denver was effectively replicated in all four other MPOs (*28*). Trip ratios to the airport
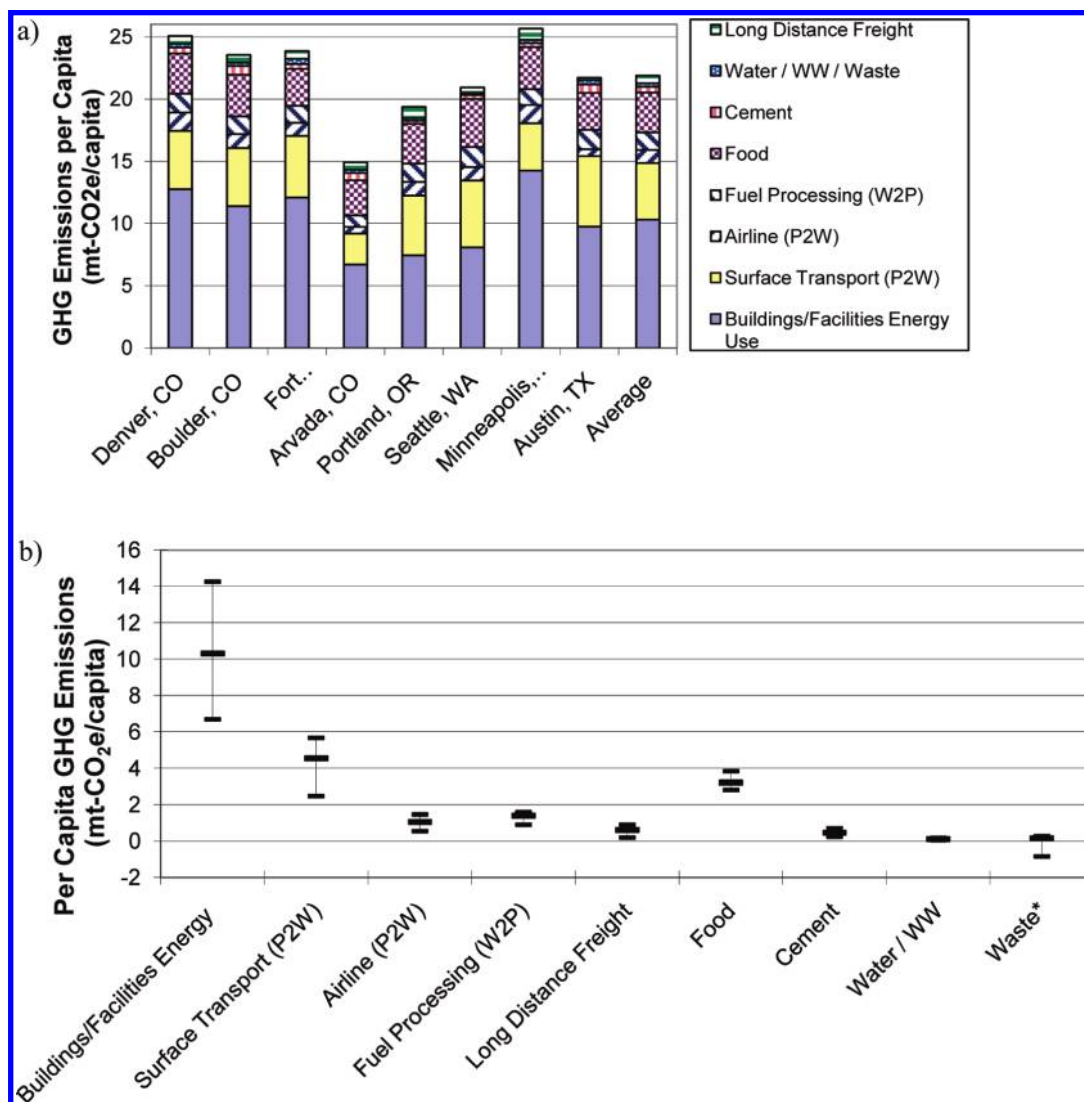
FIGURE 1. Per capita GHG emissions (metric tones CO₂e) by sector for all eight U.S. cities. Note, buildings and facilities energy use includes energy use for residential, commercial, and industrial activity within cities. (A) Individual city data: cross-boundary Scope 3 activities are shown as hatched bars stacked toward the top. (B) Sector contributions (mean and range values) across cities. Pump-to-Wheel (P2W) represents tailpipe emissions in transport, while Well-to-Pump (W2P) represents fuel processing. * Includes recycling credits and carbon sequestration of waste in landfills per WARM model (see ref 27).

correlated nearly one-on-one with population percentages representing each city in the broader region (i.e., $y = 0.98x$, $r^2 = 0.94$), suggesting either approach could be used in a consistent manner to allocate jet fuel use across colocated cities in large metropolitan areas in the U.S. (see Supporting Information).

Total per capita GHG emissions for each of the eight cities, represented as metric tonnes carbon dioxide equivalents (mt-CO₂e), from both in-boundary (Scopes 1 and 2) and cross-boundary (Scope 3) contributions, are shown in Figure 1a. Scope 1+2 emissions (primarily buildings/facilities plus surface transport) averaged about 14.9 mt-CO₂e per person, and these constitute the in-boundary emissions that are required and reported in traditional city-scale inventories (5). The addition of Scope 3, airline and freight transport plus embodied energy of food, fuels, cement, water/wastewater, added an additional 7.0 mt-CO₂e on average. Thus, present boundary-limited methods appear to be underestimating the overall GHG emissions impact of material and energy demand in cities by 47% on average.

Average contributions from each of individual sectors to the full Scope 1+2+3 GHG accounting, and the ranges observed for each sector, are shown in Figure 1b. GHG emissions from buildings and facilities represented the largest source of GHG (averaging 10.3 mt-CO₂e/capita) and also exhibited the greatest variation across cities, followed closely by transport sector emissions which total to an average of 7.0 mt-CO₂e/capita when surface travel (4.6 mtCO₂e), airline travel (1.1 mt-CO₂e) and fuel refining (1.4 mt-CO₂e) are aggregated; long distance freight trucking added an additional 0.6 mt-CO₂e on average. The third largest contributor is the food sector at 3.2 mt-CO₂e/capita, followed by cement at 0.5 mt-CO₂e/capita. Water/wastewater and wastes together contributed about 0.3 mt-CO₂e/capita. Thus a full Scope 1+2+3 accounting represents all infrastructure sectors necessary for human life, while only buildings/facilities energy use and tailpipe vehicular emissions are accounted in conventional boundary-limited inventories.

The large variation in GHG emissions in the buildings/facilities sector in Figure 1b is explored further. Seven of the eight cities showed balanced residential-commercial-industrial electricity use, with commercial-industrial use more than twice residential energy use, typical of U.S. national data (11), except for the city of Arvada, which was the only city in which residential electricity use exceeded combined commercial-industrial electricity use. Arvada is a small
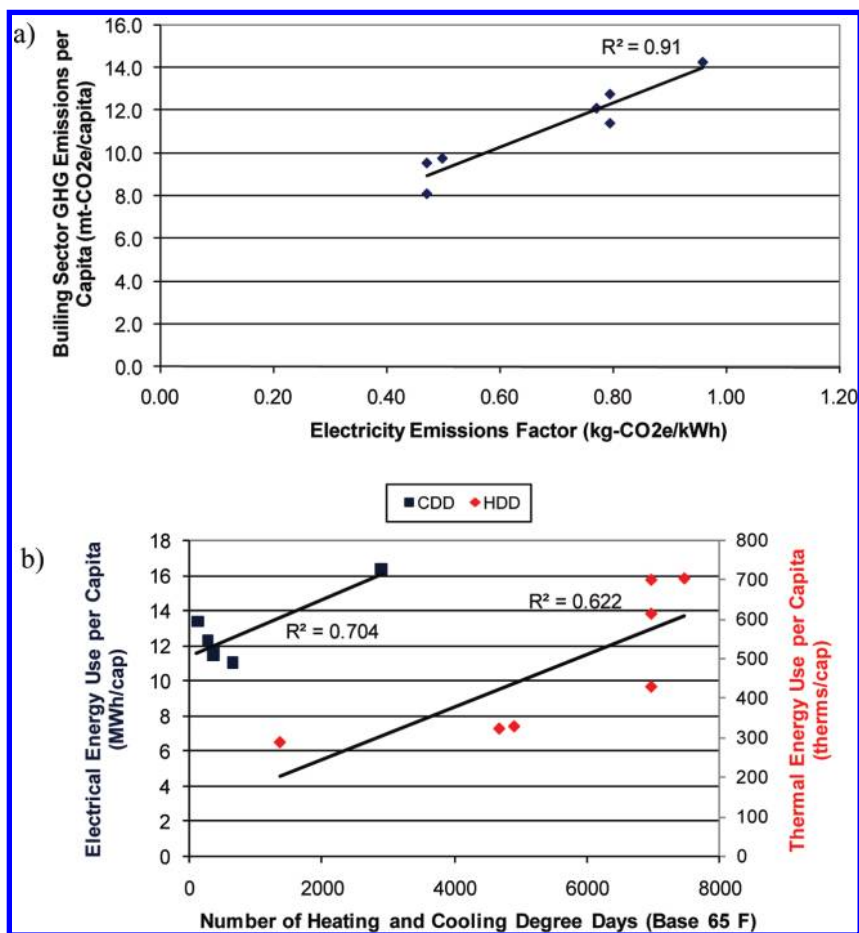
FIGURE 2. Correlations in per capita building sector GHG emissions: Arvada (outlier) has been removed from the sample. (A) Building GHG emissions per capita versus the electricity emissions factor. (B) Building energy use per capita versus heating and cooling degree days.

bedroom community located in the suburbs of Denver, dominated by residences; the city has only one industrial account and is thus considered an outlier with disproportionately low commercial-industrial impact. Excluding this outlier, per capita building sector GHG emission from the seven U.S. cities were highly correlated with the GHG EF for electricity in these cities ($r^2 = 0.91$; Figure 2a); correlations were also seen between per capita electricity and natural gas use and the regional climate represented by heating and cooling degree days (Figure 2b, r^2 of 0.62 and 0.7, respectively). Weak to no correlations were observed between per capita energy use versus floor area per person ($r^2 = 0.09$) and versus income per capita ($r^2 = 0.02$).

Given that the buildings sector comprises about half of the full Scope 1+2+3 GHG footprint and that emissions from this sector are directly proportional to the electricity EF that varies significantly (Table 2), the per capita GHG footprint was recomputed for all eight cities applying the U.S. average electricity EF (0.68 kg CO_2e/kWh) to all cities. The city-scale per capita Scope 1+2+3 GHG emissions, recomputed with the U.S. average electricity EF, showed remarkable consistency with the U.S. average per capita GHG emissions computed at the national scale (Figure 3). Indeed, excluding Arvada as outlier, with the full accounting of Scope 1+2+3 inclusions, the seven cities (average 23.7 mt-CO2e/capita; st. dev. 0.78 mt-CO$_2$e) were within 10% of the national average U.S. per capita emissions of 24.5 mt-CO$_2$e/cap (*11*).

Discussion

Figure 3 shows that carefully allocating the six key transboundary (Scope 3) activities identified in this paper yields

scale-convergence in per capita GHG emissions from the city- to the national-scale, indicating the expanded Scope 1+2+3 method may suffice to capture the vast majority of human activities occurring in the U.S. (Table 1), yielding a city-scale GHG emissions footprint. The method appears to be effective for larger U.S. cities with balanced in-boundary commercial-industrial activity relative to residential energy use, that is, these cities produce goods and services for consumption by their residents and for trade balance between cities, while their Scope 3 inclusions incorporate cross-boundary travel and consumption of key high embodied-GHG materials like gasoline, cement and food, essential for life in all cities, and often produced in hinterland areas. The de minimis rule (*29*) can be applied yielding a stopping rule, that is, no further Scope 3 activities need be included unless they show more than a small (e.g., 2%) increase in the GHG accounting of a city.

Outliers can occur on both ends of the spectrum, e.g., in the Denver region, cities like Arvada with disproportionately low in-boundary industrial-commercial activity yield a smaller per capita GHG footprint (15 mt-CO$_2$e/capita), while mountain resort towns with disproportionately high commercial energy use (relative to residents) yield per capita emissions in excess of 80 mt-CO$_2$e/capita, compared with the Denver- and the national average of ∼25 mt-CO$_2$e/capita. Analysis of city regions (commutersheds) rather than individual cities is likely to even out the differences caused by these smaller towns.

Ideally, detailed accounting of all material-energy inflows and outflows to a city, combined with upstream LCA, would be the most accurate method for computing a city's GHG
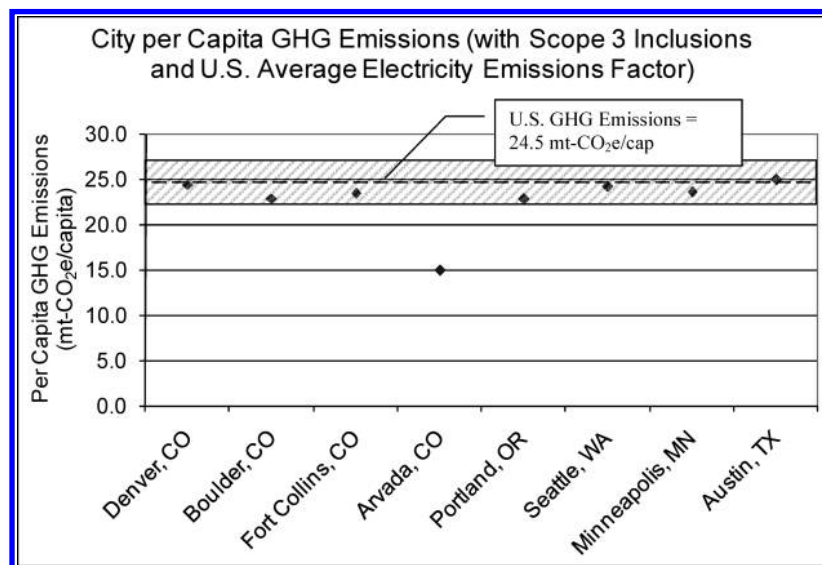
FIGURE 3. Per capita GHG emissions (metric tonnes CO₂e) for eight U.S. cities incorporating Scope 3 inclusions and the U.S. average electricity emissions factor, compared with national U.S. average per capita emissions. The hatched area represents ±10% of the national per capita GHG emissions.

emission footprint. However, complete input-output data is rarely available at the city-scale, and even less so for cities of the developing world. Thus, the hybrid approach developed in this paper makes a useful approximation by combining in-boundary residential-commercial-industrial activity within cities with consumption demand for six key cross-boundary activities essential for urban life in *all cities,* namely, airline and freight transport allocated across cities, and demand allocation for food, fuel, cement (construction materials), and water/wastewater. Results in this paper indicate the method to be effective for U.S. cities where almost 80% of the population lives. In developing countries, however, cities may represent concentrated areas of industrial production, while housing a much smaller percentage of their population. Therefore, in studying global cities, it may be useful to consider a three-way typology of cities as producer-, consumer-, and balanced-cities based on their proportion of commercial-industrial energy use relative to residential energy use; most large cities in the U.S. appear to fall in the last category, based on results in this paper.

Further research on more cities and city regions, in the U.S. and internationally, comparing the hybrid approach with full input−output analysis, will add to the growing literature on urban metabolism and GHG emission footprints of cities. Other model refinements include improved analysis of food and freight and inclusion of fugitive methane emissions into the EF for buildings' energy, because this contributes 2% nationally (*11*).

Policy Implications. While refinements will be ongoing, the expanded Scope 1+2+3 GHG emissions footprint in this paper shows promise in its results for US cities (Figure 3), and has immediate policy relevance. First, consistent inclusion of activities, such as food and airline travel, across scale, from the home to the city to the nation, can help in public communication about GHG emissions. Second, including Scope 3 activities in a city's GHG footprint can facilitate innovative cross-boundary and cross-sector strategies for GHG mitigation. For example, changes in diet can significantly reduce GHG emission from food consumption (*29*); such material shifts would be invisible in traditional Scope 1+2 GHG accounting in cities. Likewise, green materials policies would be invisible in a boundary-limited Scope 1+2 accounting. Lastly, innovative information-communication technologies such as teleconferencing, would only record increases in electricity use in buildings within city boundaries,

without being able to account for associated decreases in cross-boundary airline travel. A strict boundary-limited Scope 1+2 method may also unintentionally credit GHG emissions shifts outside city boundaries, for example, zero-emission hydrogen fuel use within city boundaries, while GHG from hydrogen production from coal or natural gas shifts outside the city.

Present carbon trading programs focus largely on the production-side (e.g., cleaner electric powerplants, cement factories and oil refineries), and do not provide credit for innovative city-scale policies that change *the nature of materials demand in cities,* illustrated in the examples above. To promote holistic GHG mitigation strategies in cities, including cross-sector (e.g., teleconferencing), supply chain (e.g., green concrete), and lifestyle change (e.g., healthy diets) strategies, we propose that both the required existing Scope 1+2 GHG emissions inventory for a city (*5*) and the expanded Scope 1+2+3 emissions footprint developed in this paper, be applied together with two logic rules:

a) Credit GHG reduction strategies that reduce a city's Scope 1+2 GHG inventory only if they also reduce the city's broader Scope 1+2+3 GHG emissions footprint; credit is recommended for the smaller of the two reductions. This prevents unintended incentives to shift GHG emissions across city boundaries.

b) Incorporate flexibility to award cities credit for innovative strategies that demonstrate *additionality* and can quantifiably reduce their Scope 1+2+3 GHG footprint, even if the Scope 1+2 emissions inventory does not show reductions. For example, GHG mitigation credit could be distributed between fly ash suppliers and a city, if the latter's green concrete policy explicitly demonstrates additional fly ash use to displace cement in concrete, when compared to business-as-usual.

Outliers Reflecting Leadership in Sustainability. As cities implement sustainability policies over many years, their GHG emissions may diverge from the national per capita average shown in Figure 3; GHG emissions can also decrease as electricity EFs changes over time with federal utility regulations. As a result, per capita Scope 1+2+3 GHG emissions may not be the sole effective metric in demonstrating outcomes of city-scale climate actions. Hence, we propose that cities also report on midpoint energy and materials use efficiency (intensity) benchmarks that enable comparison of a city's material-energy flows

TABLE 3. Proposed Metrics and Benchmarks for Long-Term Tracking of Energy Efficiency and Materials Use Efficiency in Eight U.S. Cities[a]

type	city-scale metric	national bench-mark	Denver, CO	Boulder, CO	Fort Collins, CO	Arvada, CO	Portland, OR	Seattle, WA	Minneapolis, MN	Austin, TX
Demographic	Population (capita)	n/a	579,744	101,547	125,740	104,830	682,835	575,732	387,711	672,011
	Population density (capita/sq mile)		3,789	4,231	2,733	3,276	5,096	6,937	7,180	2,677
	Number of homes (HH)		256,524	45,949	54,908	41,110	294,325	276,794	172,316	281,176
	Square feet per home (sf/HH)		1,107	1,458	1,684	1,442	1,278	1,321	1,683	1,321
	Total commercial floor area (million sf)		229	35	30	23.4	153	269	210	314
	Total floor area per capita (sf/cap)		802	1,004	975	789	992	1102	1,289	1,020
Buildings and facilities energy use[c]	Residential (kWh/HH/mo)	(888)	545 [667]	444 [667]	689 [667]	687 [667]	765 [981]	740 [1,043]	478 [805]	1,108 [1,170]
	Residential (therms/HH/mo)	(58)	45 [57]	38 [57]	51 [57]	55 [57]	30 [26]	28 [29]	60 [59]	26 [21]
	Residential (kBtu/HH)	(8,830)	6,377 [7,965]	5,283 [7,965]	7,423 [7,965]	7,881 [7,965]	5,629 [5,946]	5,316 [6,410]	7,585 [8,663]	6,423 [6,054]
	Commercial-industrial electricity (kWh/sf)	(14)	15	22.6	16	12	20	16	16	18
	Commercial-industrial thermal (kBtu/sf)	(90)	69	47	45	44	43	43	71	20
	Commercial-industrial total (kBtu/sf)	(138)	122 {104}	125 {104}	100 {104}	85 {104}	110 {69}	97 {69}	124 {80}	81 [73]
Transport	Road (VMT/ capita/day)	(27)	24 [28]	24 [28]	25 [28]	13 [28]	22 [26]	25 [24]	17 [30]	26 [28]
	Airline (enplaned passenger/ capita)	(2.3)	8	6	6	3	4	4	7	3
	Jet fuel (gallons/enplaned passenger)	(22)	19	19	19	19	26	30	23	17
	Long distance freight truck ($-1997/cap)	($288)	$295	$295	$295	$295	$424	$203	$432	$94
Key urban materials	Municipal solid waste (tons/capita)	(0.82)	1.25	1.07	1.89	1.14	1.02	0.77	0.97	1.07
	Self-reported waste diversion	(33%)	2%	n/a	n/a	n/a	54%	41%	37%	17%
	Gasoline gallons/ capita/yr	(464)	435	433	459	231	400	446	315	447
	Diesel gallons/ capita/yr	(148)	69[b]	71[b]	73[b]	37[b]	115[b]	128[b]	90[b]	158[b]
	Jet fuel gallons/ capita/yr	(65)	149	112	107	56	112	111	148	56
	Cement mt/ capita/yr	(0.36)	0.50	0.72	0.46	0.50	0.25	0.32	0.32	0.67
	Food ($-1997/ HH/yr)	($4,841)	5,463	5,463	5,463	5,463	5,474	5,979	5,713	5,331
	Treated water/ WW in 1,000 gal/capita/yr		148	129	108	91	97	96	104	122

[a] Corresponding state benchmarks are shown as in brackets, []; multi-state regional benchmarks are shown in braces, {}; national benchmarks are shown in parentheses, (). [b] Does not include long distance freight, which is included as economic activity. [c] Estimation error up to 10% because of differences in residential−commercial designations between cities, census, and utilities, as well as reported building floor area. National/State Data Sources: cement (17), VMT (30), commercial energy (31), residential energy (32), jet fuel use and enplaned passengers (33), state energy data (34), and MSW (35).

relative to peers located in similar climate and energy service regions (Table 3). The metrics in Table 3 show that the hybrid methodology successfully captures unique features of individual cities, while the ranges observed across 8 cities are generally in-line with national or statewide/regional benchmarks for energy/materials demand. For example, Arvada with low commercial-industrial activity is not a travel destination, as reflected by its lower VMT/capita and lower airline trips/capita; its home energy use is close to Colorado's average. VMT per capita is fairly similar across most states and cities

studied, ranging from 25−30 VMT per person-day. The cities studied here (population density 2,700−7,200 people/square mile) are representative of the vast majority of U.S. cities (>97% in year 2000 (36)) that have overall population densities below the threshold of 7−10 dwelling units per acre (∼14,500 people/ square mile). Only above this threshold is densification accompanied by smart growth programs expected to significantly modulate VMT demand (37). Thus, VMT/capita can be expected to be similar across most U.S. regions and to change slowly with sustained smart growth policies over the long-term. In

contrast, electricity use per home varies significantly across cities, even those colocated in the same climate (Colorado), examining underlying causes for which may promote learning across cities.

This paper has provided a first view of metrics for average energy, water, material use, travel demand, and associated GHG emissions across a few different U.S. cities, as well as a snapshot of variation in these parameters across cities. More work is needed to accurately compute building sector metrics, e.g., differences up to 10% arise due to differences in how cities and utilities define commercial versus residential properties. Improved databases with floor area and energy data reported by the same entity can resolve such differences and help assess outcomes of city-wide climate actions. Thus, in tandem with a holistic Scope 1+2+3 GHG footprint, we recommend that cities also track core metrics on end-use energy- and materials-efficiency to understand and model their current and future carbon emissions. With more than half of the world's people and 75% of the U.S. population living in cities, developing benchmarks for energy/material use and more holistic accounting of GHG emission caused by urban activities can have a large impact on climate action plans worldwide.

Acknowledgments

Supporting Information Available

Figures showing the spatial alloication of airline travel data for eight U.S. cities. Reprinted with permission from Hillman, T., C. PhD Dissertation, University of Colorado Denver, 2009. This information is available free of charge via the Internet at http://pubs.acs.org/

Literature Cited

(1) ICLEI. Local Governments for Sustainability, Cities for Climate Protection Participants, 2009.

(2) U.S. Mayors Climate Protection Agreement, 2009. http://www.usmayors.org/climateprotection/revised/ (Accessed March 4, 2009).

(3) Ramaswami, A.; Hillman, T.; Janson, B.; Reiner, M.; Thomas, G. A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories. *Environ. Sci. Technol.* **2008**, *42* (17), 6456–6461.

(4) WRI *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*; World Resources Institute and World Business Council for Sustainable Development: Washington, DC, 2004.

(5) ICLEI *Clean Air and Climate Protection Software (CACPS)*; ICLEI: Oakland, CA, 2003.

(6) *EPA: Climate Leaders Program*; U.S. Environmental Protection Agency: Washington, DC, 2007.

(7) Seattle. *2005 Inventory of Seattle Greenhouse Gas Emissions: Community and Corporate*; City of Seattle, Washington Office of Sustainability and Environment: Seattle, WA, 2007.

(8) Hidalgo, A.; Contassot, Y. *Le Bilan Carbone De Paris*: Paris, France, 2007.

(9) Sharma, C.; Dasgupta, A.; Mitra, A. P. *Future Scenarios Of Inventories Of GHG's And Urban Pollutants From Delhi And Calcutta*; Institute for Global Environmental Strategies: Tokyo, Japan, 2002.

(10) Strait, R.; Roe, S.; Bailie, A.; Lindquist, H.; Jamison, A. *DRAFT Colorado Greenhouse Gas Inventory and Reference Case Projections 1990–2020*; Center for Climate Strategies: Harrisburg, PA, 2007.

(11) *EPA: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2005*; U.S. Environmental Protection Agency: Washington, DC, 2007.

(12) Hoekstra, A. Y. Water Neutral: Reducing and Off-setting the Impacts of Water Footprints, Value of Water Research Report Series No. 28, UNESCO-IHE, 2008.

(13) Greenprint *City of Denver Climate Action Plan: Recommendations to Mayor Hickenlooper*; Mayor's Greenprint Denver Advisory Council: Denver, CO, 2007.

(14) Wolman, A. The Metabolism of Cities. *Scientific American Magazine*, **1965**, *179*, 190.

(15) Decker, E. H.; Elliot, S.; Smith, F. A.; Blake, D. R.; Rowland, F. S. Energy and Material Flow Through the Urban Ecosystem. *Annu. Rev. Energy Environ.* **2000**, *685*, 740.

(16) *U.S. Economic Census 2002*; U.S. Census Bureau: Washington, DC, 2004; http://www.census.gov/econ/census02/.

(17) PCA *North American Cement Industry Annual Yearbook*; Portland Cement Association: Stokie, IL, 2005.

(18) BLS *Consumer Expenditure Survey*; Bureau of Labor Statistics: Washington, DC, 2005; http://www.bls.gov/cex/csxmsa.htm.

(19) BTS *Freight in America*; Bureau of Transportation Statistics, Washington D.C., 2009.

(20) Fischer, M.; Ang-Olson, J.; La, A. External Urban Truck Trips Based on Commodity Flows: A Model. *Transportation Research Record* **2007**, *1707* (2000), 73–80.

(21) U.S. Census 2008 (http://www.census.gov/popest/metro/CBSA-est2008-annual.html) (Accessed September 24, 2009).

(22) TRC. *General Reporting Protocol*; The Climate Registry, Los Angeles, CA, May, 2008.

(23) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*; Argonne National Laboratory: Argonne, IL, 2005.

(24) NREL LCA *U.S. Life-Cycle Inventory Database*; National Renewable Energy Laboratory; Golden, CO (http://www.nrel.gov/lci) (Accessed March, 2009).

(25) EIO-LCA *Economic Input-Output Life Cycle Assessment*; Green Design Institute, Carnegie Mellon University: Pittsburgh, PA, 2006; http://www.eiolca.net.

(26) Weber, C. L.; Matthews, H. S. Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *Environ. Sci. Technol.* **2008**, *42* (10), 3508–3513.

(27) EPA WARM *Waste Reduction Model*; U.S. Environmental Protection Agency: Washington, DC (Accessed January 2009).

(28) Hillman, T.; Janson, B.; Ramaswami, A. Spatial Allocation of Transportation Greenhouse Gas Emissions at the City-Scale. *Journal of Transportation Engineering* **2010**, in press.

(29) CCAR: California Climate Action Registry General Reporting Protocols, 2009.

(30) Federal Highway Administration (FHWA) Highway Statistics Series: Functional Travel System–2005. Available Online http://www.fhwa.dot.gov/policyinformation/statistics/vm0.cfm?vm_year=20052 (Accessed May 8, 2009).

(31) Energy Information Administration (EIA). Commercial Buildings Energy Consumption Survey. 2003. Available online http://www.eia.doe.gov/emeu/cbecs/ (Accessed April 20, 2009).

(32) Energy Information Administration (EIA). Residential Energy Consumption Survey. 2001. Available online http://www.eia.doe.gov/emeu/ (Accessed April, 2009).

(33) BTS. *National Transportation Statistics 2006*; Bureau of Transportation Statistics, 2006; Washington D.C., Tables 1−41 and 4−8.

(34) EIA. *Consumption, Price, and Expenditure Estimates−State Energy Data System*; Energy Information Administration, Washington D.C., February 2008.

(35) U.S. EPA. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007*, U. S. Environmental Protection Agency: Washington D.C., 2008.

(36) Demographia. http://www.demographia.com/db-2000city50kdens.htm (Accessed November 2009).

(37) Federal Highway Administration (FHWA). Emissions benefits of land use planning strategies. Appendix D−Land use characteristics and travel variable elasticities. December 2004. Available online http://www.fhwa.dot.gov/environment/conformity/benefits/benefitsd.htm (Accessed November 2009).

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