A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories

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Greenhouse gas (GHG) accounting for individual cities is confounded by spatial scale and boundary effects that impact the allocation of regional material and energy flows. This paper develops a demand-centered, hybrid life-cycle-based methodology for conducting city-scale GHG inventories that incorporates (1) spatial allocation of surface and airline travel across colocated cities in larger metropolitan regions, and, (2) life-cycle assessment (LCA) to quantify the embodied energy of key urban materials—food, water, fuel, and concrete. The hybrid methodology enables cities to separately report the GHG impact associated with direct end-use of energy by cities (consistent with EPA and IPCC methods), as well as the impact of extra-boundary activities such as air travel and production of key urban materials (consistent with Scope 3 protocols recommended by the World Resources Institute). Application of this hybrid methodology to Denver, Colorado, yielded a more holistic GHG inventory that approaches a GHG footprint computation, with consistency of inclusions across spatial scale as well as convergence of city-scale per capita GHG emissions (∼25 mt CO2e/person/year) with state and national data. The method is shown to have significant policy impacts, and also demonstrates the utility of benchmarks in understanding energy use in various city sectors.

1. Introduction: Greenhouse Gas Mitigation at the City Scale

Recognizing the global reach of GHG pollutants, more than 160 countries have signed the Kyoto protocol, which pledges GHG emissions reductions of at least 5% relative to 1990 levels (1). However, national-level policies are increasingly being supplemented with city-scale actions to mitigate climate change, particularly in the United States which has not ratified the Kyoto Protocol. In the United States, the Mayors of more than 527 cities (as of June 2007) have committed to meet or beat the GHG reduction goals articulated in the Kyoto protocol, viewing this as an opportunity to address global warming at the local level (2).

Because cities contain a large proportion of the global human population (3) and exert huge direct and indirect demands on our natural capital, city-scale climate actions have the opportunity to engage vast segments of human populations as well as ameliorate impacts in large spatial areas across the globe. Therefore, understanding GHG emissions at the spatial scale of the city becomes very important in the context of global efforts to mitigate climate change.

The first step in planning city-scale climate actions is to develop a comprehensive GHG inventory associated with cities. However, city-scale GHG inventory methods have been quite variable. As of March 2006, only about 10 U.S. cities had compiled their GHG inventory and evaluated subsequent actions; inventory methods and inclusions varied widely across the 10 cities (4). For example, the impact of airline travel of city residents is often ignored when airports are located outside city boundaries. Thus, only the cities of Aspen and Seattle had incorporated air travel emissions. Upstream GHG emissions associated with the production of key urban materials such as food, water, fuel, and concrete have also typically been ignored when their production occurs outside city boundaries; prior to this study, only one city (5) had included emissions associated with asphalt use. Most importantly, no standardized benchmarking method has been used to benchmark city-scale GHG inventories through comparisons with state or national data, or with widely reported energy use benchmarks.

As more than 500 U.S. cities embark on local-scale climate actions, developing a more standardized GHG inventory method that is consistent with national-scale and state-level data becomes critically important. The objective of this paper is to develop a more holistic and consistent methodology for conducting GHG inventories for US cities viewing the city as a demand center for both energy and key urban materials. The inventory method is applied to compute community-wide and per capita GHG emissions for the city of Denver, Colorado. Comparisons with national (U.S.) and State of Colorado per capita GHG emissions are used to benchmark the results.

2. Spatial Scales, Inventory Approaches, and Policy Relevance

At the national scale, protocols developed by the Intergovernmental Panel on Climate Change (6) are used to account for all GHG emissions within national boundaries—encompassing energy use in all buildings, transportation, and industrial activities, and emissions from waste disposal (e.g., ref (7) for the U.S.). Similar approaches that focus on direct emissions within geographic boundaries have been used at the scale of individual states such as California (8). The approach of counting only direct emissions (along with upstream electricity production and waste processing emissions) within fixed geographic boundaries has been implemented at the city scale through ICLEI’s Clean Air Climate Protection (CACP) model (9), used by most U.S. cities to date. However, at the much reduced spatial scale of towns and cities (typically of the order of ten to hundred square miles), accounting only for the “direct” GHG emissions occurring strictly within the geographic boundaries of the city raises the following two practical issues.

1. Surface and Airline Transportation Allocation. Commuting trips in large metropolitan areas typically traverse the boundaries of several cities and counties. Many cities are confounded by how to deal with such vehicular travel since
the current boundary-limited methodology does not count the entire distance of commuting trips that originate outside city boundaries, while significant pass-through trips that occur on large interstate highways are counted that do not pertain to the city of interest. Allocating airline travel poses a similar challenge—many cities have ignored this activity entirely, especially when local airports are situated outside city boundaries. Accounting for the fraction of direct tailpipe emissions from airplanes as they fly across city boundaries presents an absurd picture. To be policy relevant, the entire airline trip needs to be allocated, recognizing that major airports typically serve many cities colocated in the same metropolitan area. Thus, developing a suitable spatial allocation procedure for transportation activities (surface and air) is an important means to effectively quantify direct (tailpipe) transportation emissions at the city scale.

2. Embodied Energy of Key Urban Materials. The present boundary-limited direct emissions methodology for cities ignores the indirect upstream emissions of key urban materials, e.g., cement, water, transportation fuels, and food, which are used intensively in all cities but are typically produced outside city boundaries. Furthermore, cities can presently claim credit for recycling some of these materials even though the embodied energy associated with producing these urban materials is not included in these urban inventories. Such an approach may effectively penalize “producer cities” that produce critical urban materials, while giving credit to “consumer” cities for end of life recycling. Well-developed life-cycle assessment (LCA) tools and regional material flow accounts (MFA) can be used together to allocate the indirect emissions associated with use of key urban materials in cities. Such an approach, consistent with World Resources Institute (WRI) Scope 3 GHG accounting protocols, can offer a more holistic account of a city’s GHG impacts (10).

The above two modifications to current city-scale inventory methods can significantly impact not only the numeric value, but also the scope of climate action policies explored by cities. For example, incorporating key urban materials into city-scale GHG inventories can spur materials recycling and conservation as well as alternative materials policies (e.g., green concrete (11)) in cities. Incorporating airline travel into city GHG inventories raises awareness of this important sector that contributes almost 4% to the U.S. national GHG emissions (7), potentially sparking interest in airline travel offset programs (11). Thus city-scale GHG policy development and analysis can be strongly impacted by the underlying GHG inventory methods and inclusions.

Life Cycle-Based Assessment of Indirect Emissions. Economic input–output LCA (EIO-LCA) is a useful tool at the national scale to account for upstream GHG emissions from all consumer behaviors (12), which links economy-wide monetary exchanges in the United States with energy use and associated GHG emissions calibrated at the national scale (13). A few studies have applied EIO-LCA to quantify GHG emissions associated with household expenditures (e.g., ref (14)). However, applying EIO-LCA at the city scale, exclusively, can be difficult since expenditure data at the level of metropolitan statistical areas (MSAs) are not always available publicly for all economic sectors, e.g., those with too few business entities to maintain confidentiality (such as electric utilities). Also, local features such as a greater investment in renewable energy at the local utility will not be represented when nationally aggregated EIO-LCA emissions factors are applied. Thus in this paper, a hybrid life-cycle-based approach is proposed for developing a more holistic GHG inventory protocol for cities, coupling local-scale direct energy use and emission factors with life-cycle-based embodied (indirect) energy use associated with urban material use. By separately accounting for the direct emissions associated with end-use of energy in cities and the indirect emissions associated with key urban materials, cities will have the flexibility to report both a direct emissions inventory and a more holistic inventory that approaches a GHG footprint computation for the city.

This demand-centered hybrid LCA-based inventory methodology is applied to Denver, CO, as described next. It is important to note that this methodology has stemmed from the impetus for developing a more consistent and holistic GHG inventory method that is appropriate and easy to use by cities in the United States. Consequently, the methodology adds on spatial transportation allocation methods and embodied energy of key urban materials to the well-developed ICL/EI model for direct emissions inventory that is already available in many cities (9). This enhanced methodology is consistent with the WRI Scope 3 GHG emissions inventory protocol recommended as the most holistic and stringent protocol for businesses and corporations (10). This paper is presented as a first step toward development and application of such as Scope 3 protocol to the spatial scale of cities.

3. Methodology

Background of Study Area. The City and County of Denver (referred to as Denver) covers 155 square miles in the east-central part of the state of Colorado, with Denver serving as the state’s capital. Denver and the local governments of surrounding counties participate in a regional planning entity, the Denver Regional Council of Governments, or DRCOG, which covers a wider area of 5100 square miles and includes 9 counties in addition to Denver. In 2005, the population for Denver and the DRCOG region was 579,744 and 2,641,753, respectively (15). Like most metropolitan areas, Denver is a commerce hub for this much larger area. Significant travel occurs between Denver and the counties in the DRCOG region with 59% of Denver’s workforce commuting in from surrounding counties where they live, and 36% of Denver’s residents working outside of Denver (16). Spatial transportation modeling in the DRCOG region is therefore particularly important in order to understand and allocate GHG impacts of transport activities to Denver and its surrounding counties.

Main Inventory Categories and Inclusions. Both direct GHG emissions (mostly associated with direct energy use in cities) and indirect GHG emissions (associated with key urban materials often produced outside) contribute to global climate change. Therefore, by viewing a city not merely as a bounded plot of land, but as a demand center for energy and materials, city-scale GHG inventories can cover both direct and indirect GHG contributions. The demand-centered, hybrid LCA-based city-scale GHG inventory method developed in this paper incorporates GHG emissions from three main categories: (1) direct (end-use) energy consumed in buildings and facilities, including homes, commercial, industrial, and government buildings and facilities; (2) direct (tailpipe) emissions associated with transportation, including surface and air travel, with a unique spatial allocation procedure applied to allocate such travel within and across city boundaries; and (3) indirect emissions associated with the embodied energy of key urban materials, as well as end-of-life of wastes (e.g., landfill). Based on the functionality of cities, the key urban materials considered are food, water, fuel, and concrete (a dominant construction material). Cement (in concrete) is used as a proxy for construction as it has been noted to be the dominant GHG-emitting residential construction material (17) and the third largest single source of CO₂ emissions in the United States (7).

Methods used to account for GHG emissions in each of these categories are detailed next. The three dominant GHGs (CO₂, CH₄, N₂O) that account for more than 98% of U.S. GHG emissions (7) are inventoried and reported together as carbon
dioxide equivalents (CO₂e); there are no known production facilities in Denver for the three remaining halocarbon GHGs (HFCs, PFCs, and SF6).

**Direct Energy Use in Buildings and Facilities.** Community-wide electricity and natural gas use across all homes, and all commercial and industrial facilities in Denver were obtained from the local utility (Xcel Energy). Community-wide energy use data were normalized and benchmarked against similar data reported from other state and national studies to verify the general range and scale of the numbers. For example, average monthly residential energy uses normalized per home in Denver in 2005 (568 kWh/home-mo; 63 therms/home-mo) were in the same range as those reported for the State of Colorado (683 kWh/home-mo; 65 therms/home-mo; ref [18]). In comparison, the national average monthly residential energy use is reported at 888 kWh/home-mo and 58 therms/home-mo (19).

Local-scale GHG emissions factors for electricity and natural gas supply to Denver were obtained from the local utility, tracing emissions from all generation sources (natural gas supply to Denver were obtained from the local utility). Community-wide energy use data were normalized and benchmarked against similar data reported from other state and national studies to verify the general range and scale of the numbers. For example, average monthly residential energy uses normalized per home in Denver in 2005 (568 kWh/home-mo; 63 therms/home-mo) were in the same range as those reported for the State of Colorado (683 kWh/home-mo; 65 therms/home-mo; ref [18]). In comparison, the national average monthly residential energy use is reported at 888 kWh/home-mo and 58 therms/home-mo (19).

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**Direct Surface Transportation Energy Use.** Direct tailpipe (pump-to-wheels, PTW) GHG emissions from the road transport sector were estimated from daily vehicle miles traveled (VMT) obtained from DRCOG’s regional transportation model (20). The DRCOG road network model comprises 16,450 roadway links connecting 2,664 traffic analysis zones (TAZs). DRCOG estimates VMT within each of the TAZs to be used for local air quality modeling; measured traffic volume counts at various links in the network are used to refine and calibrate model parameters. The total VMT generated in all the TAZs for the DRCOG region is 22.4 billion VMT, normalized to yield 25 VMT/person/day, in line with what is seen nationally (∼27 VMT/person/day; [26]). Note, this normalized metric represents all VMT (commercial and personal) normalized over the entire population (including children), and therefore does not correlate exactly with miles traveled per vehicle.

In the GHG inventory method developed in this paper, because of significant intercounty traffic that occurs in the DRCOG region, the interest is in capturing not only the VMT within the TAZ’s located within Denver boundaries, but also the VMT associated with commuting trips originating or ending outside of Denver. The full VMT associated with commuting trips in Denver is found by multiplying the number of trips beginning and/or ending within Denver’s boundaries by the distance of the shortest travel time path between TAZ pairs as reported at the end of the DRCOG model run. Alternate paths between TAZ pairs have similar travel times at the end of the model run due to the equilibration of the assignment procedure, although some paths can be shorter or longer than others. These effects tend to balance out such that using final shortest travel time paths from the model run to compute total VMT between subregions does not introduce significant differences. Indeed, comparing the total VMT computed by the shortest travel time path across the whole DRCOG region with the aggregated VMT reported for all the TAZs yielded a difference of only 2%.

The analysis led to a VMT matrix for surface travel between Denver (city and county, CCD), Denver International Airport (DIA), and the rest of the world (ROW). The jet fuel use per enplaned passenger at DIA in 2005 was 19.5 gallons of jet fuel per passenger (27). The jet fuel use per enplaned passenger at DIA in 2005 was 19.5 gallons of jet fuel per passenger (27). Annual airline transportation statistics (28) indicate that Denver’s annual VMT computed in this manner (see Table 1), was distributed across vehicle types (cars, SUVs, light trucks, etc.) through on-road vehicle counts obtained from the Colorado Department of Public Health and Environment (28). Colorado’s vehicle fleet is dominated by SUVs (53%), and has a weighted average fuel economy of 15 miles per gallon. Direct pump-to-wheels (PTW) emissions from the various vehicles types were computed from PTW emissions constants and national average fuel economies representing the various vehicle types (9).

**Direct Airline Transportation Energy Use.** Annual airline fuel use data at DIA was provided by the airport (29) along with the total number of enplaned passengers at DIA (20.2 million in 2005) as reported by the U.S. Bureau of Transportation Statistics (30). The jet fuel use per enplaned passenger at DIA in 2005 was 19.5 gallons of jet fuel per enplaned passenger, a little lower than the national statistic of 21 gallons of jet fuel per passenger (31). The tailpipe GHG emissions (32) from jet fuel use at DIA was proportionally

|TABLE 1. Matrix of Vehicle Miles Traveled (VMT), in Million Miles, a_ij between City and County of Denver (CCD), Denver International Airport (DIA), and the Rest of the World (ROW) |
|---|---|---|---|
|From (i) | ROW | CCD | DIA |
|ROW | 13,893 | 3,248 | 311 |
|CCD | 3,165 | 3,136 | 87 |
|DIA | 307 | 74 | 7 |
|Total | 17,369 | 6,667 | 386 |
|Total VMT Allocated to Denver^v = (0.5 x ∑aij) + (0.5 x ∑aij) |
|Total VMT Allocated to Denver^v = (0.5 x 13,893 + 3,248) + (0.5 x (3,165 + 3,136 + 87) |

^v Note: Denver includes CCD and DIA.
allocated to Denver based on the ratio of the total surface vehicle trips made from Denver to the airport versus from the entire DRCOG region to the airport. The ratio of annual vehicle trips from Denver to DIA versus from the entire region to DIA is about 0.22, very much in line with the population ratio of Denver versus the entire DRCOG region (also 0.22), suggesting the validity of this method for allocating air line travel among several cities and counties colocated in a metropolitan area.

Embodied Energy of Key Urban Materials and End-of-Life. Based on the functionality of cities, indirect energy use and associated GHG emissions were computed for the critical urban materials: water, fuel, food, and cement. For the most part, the above four materials are produced in hinterland areas with no significant overlap with industrial energy use in Denver. A small number of materials for inclusion in Scope 3 is consistent with WRI recommendations (10). Other materials and consumer goods/services used by Denver residents, e.g., TVs, cell phones, furnishings, etc., are assumed to be included in the commercial–industrial exchanges occurring within and between cities.

The embodied energy and GHG emissions associated with key urban materials were computed by coupling a material flow analysis (MFA) of these materials through the city with an emissions factor (EF) obtained from environmental life cycle assessment (LCA) of these materials, as shown in Table 2. Annual transportation fuel flows demanded by the community were derived from vehicle miles driven computations described above; the Argonne National Laboratory’s GREET model (33) was used to model upstream wells-to-pump (WTP) emissions associated with production of these fuels. Water use within Denver’s boundaries was tracked from billing data provided by Denver Water; the energy needed to produce water upstream from Denver was determined from Denver Water’s Annual reports (34). Cement and food material flows were estimated from county-wide (35) and household consumer economic expenditures (36) reported for the Denver-Aurora Metropolitan Statistical Area (MSA). For cement, a GHG emissions factor of 1 ton of CO2e per metric ton of cement was used, in line with those reported nationally by U.S. EPA and the Portland Cement Authority (PCA) that ranged from 0.97 to 1.05 mt CO2e per metric ton of cement (37, 38). There is little comprehensive process-based information for GHG emissions from food production, packaging, storage, and transport in the United States. Hence, EIO-LCA estimates of this emissions factor were applied (12). End-of-life GHG emissions from municipal solid wastes were generated with ICLEI’s CACP software (9).

4. Results

Material and energy flows, and associated LCA-based emission factors for all flows computed for Denver are shown in Table 2. Important metrics for comparing these flows on a per-person or per-household basis, also shown in Table 2, are very useful to benchmark the data.

Community-Wide Summary. Utilizing the demand-centered LCA hybrid approach, Denver’s community-wide GHG emissions totaled 14.6 million metric tons CO2e in 2005, distributed among the following three sectors: (1) comm-

TABLE 2. Annual Community-Wide Material and Energy Flows with Associated Benchmarks and GHG Emission Factors (EF) for Various Sectors in the City of Denver, CO (GHG Emissions Are Reported in Metric Tons CO2 Equivalents (mt-CO2e))

<table>
<thead>
<tr>
<th>sector/use</th>
<th>community-wide annual urban material/energy flows (MFA) (benchmarks)</th>
<th>data source for MFA [data type]</th>
<th>GHG emission factor (EF)</th>
<th>EF data source [data type]</th>
<th>total GHG emitted = MFA x EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. “direct” emissions in conventional city-scale GHG inventory [WRI Scope 1,2]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>buildings electricity use</td>
<td>6,659 GWh (568 kWh/hm²) (27 kWh/sf/yr)</td>
<td>Xcel Energy [L, MD]</td>
<td>0.8 kg CO2e/kWh</td>
<td>Xcel (29) [L, ME]</td>
<td>5.3 million mt-CO2e</td>
</tr>
<tr>
<td>buildings natural gas use</td>
<td>404 million therms (63 therms/hm²)</td>
<td>Xcel Energy [L, MD]</td>
<td>5.6 kg CO2e/therm</td>
<td>ICLEI (9) [N, ME]</td>
<td>2.3 million mt-CO2e</td>
</tr>
<tr>
<td>surface vehicle miles traveled, VMT</td>
<td>5 billion VMT (25 miles/person/day) average fuel econ. = 15 mpg</td>
<td>DRCOG (25) [L, ME]</td>
<td>9.3 kg CO2e/gal</td>
<td>ICLEI (9) [N, ME]</td>
<td>3.5 million mt-CO2e</td>
</tr>
<tr>
<td>B: “indirect” or out-of-boundary emissions to supplement “direct” GHG inventory [WRI Scope 3]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cement use</td>
<td>total flow: 301,000 mnt cement (0.52 mnt/capita)</td>
<td>Denver-Aurora economic census (35)</td>
<td>0.97 - 1.05 mt CO2e per tonne cement</td>
<td>EPA (37) [N, ME]</td>
<td>0.3 million mt-CO2e</td>
</tr>
<tr>
<td>food purchases at home</td>
<td>$3,000/home/yr (1997-$) (240,000 homes)</td>
<td>Denver-Aurora consumer expenditure (36)</td>
<td>2 kg CO2e/gal (1997-$)</td>
<td>EIO-LCA (12) [N, ME]</td>
<td>1.4 million mt-CO2e</td>
</tr>
</tbody>
</table>

a Data type: L = local, N = national, MD = measured data, ME = model estimate. WTP = pump to wheels (tailpipe) GHG emissions. WTP = wells-to-pump GHG emissions. Note: GHG emissions for water delivery into Denver are negligible as it gets water from the mountains. b Residential energy use per household per month. c Combined commercial–industrial energy use per square feet per year. d Incorporates a credit of 0.2 million mt-CO2e for recycling and end of life landfilling (with residual methane capture) in Denver, computed from ICLEI methods (9).
Community-wide energy use in residential buildings and industrial/commercial facilities (52%); (2) community-wide tailpipe GHG emissions from transportation (30%); (3) community-wide use of key materials and waste disposal (18%).

Denver’s 2005 GHG contributions by activity are shown in Figure 1. It is striking to note that the estimated embodied energy of transportation fuels and food contribute more than 15% of the inventory, while the embodied energy of urban cement use alone contributes of the order of 2%, similar to the impact of end-use of energy in all City Government buildings in Denver (including Airport Buildings). Normalized to the population of Denver, the community-wide emissions inventory yielded per capita GHG emissions of 25.3 mt CO2e/person.

The annual per capita GHG emission computed for Denver is sensitive to the parameter inputs to the model. Measured parameters, such as community-wide energy and water uses obtained from local utility billing data, and, airport jet fuel use reported for DIA, are considered to be high-quality data with a high degree of certainty. Modeled parameters such as the various emissions factors or the VMT computations are considered more variable. Sensitivity of the per capita GHG computation to a 10% variation in the key modeled parameters is shown in Figure 2. The magnitude of the community-wide emissions (and hence the per capita) is most sensitive to changes in the emissions factor for electricity and surface transport VMT calculations. Because of the linear additive nature of the GHG emissions from various sectors shown in eq 1 below, a 10% variation in the modeled parameters yields a 10% overall range in our estimate of Denver’s community-wide and per capita GHG emissions.

Community GHG Emissions = \[ \sum \text{Energy Use} \times EF + \sum \text{MFA} \times EF_{LCA} \] (1)

Per Capita Greenhouse Gas Emissions and Benchmarks. The nominal value of Denver’s per capita GHG emissions is benchmarked against state and national data in Table 3. When emissions associated with key urban materials and airline travel are included, Denver’s annual per capita GHG emissions for 2005 (25.3 mt CO2e/person) coincide closely with the U.S. national average (24.5 mt CO2e/person; (7)) and with the average per capita GHG emissions computed for the state of Colorado (25.2 mt CO2e/person; (39)), suggesting effectiveness of the methodology in attaining consistency across spatial scale. Given that more than 80% of the U.S. population resides in urban areas (40), consistency of per capita GHG emissions from the city scale to the state scale is particularly important in benchmarking GHG inventories conducted in similar regional conditions.

In contrast, Denver’s per capita GHG emissions, without the inclusion of airline travel and key urban materials, were about 25% lower at 18.9 mt CO2e per person for 2005, comparable with the direct per capita emissions reported for other cities in Colorado’s Front Range region (Table 3). These inclusions typically do not appear in conventional city-scale inventories conducted to-date wherein per capita GHG computations appear much lower than the national or state averages. Thus, our results for Denver indicate that a
more holistic and scale-consistent GHG inventory can be developed for U.S. cities using the demand-centered hybrid LCA-based method presented in this paper.

5. Discussion

Reporting Direct and Indirect Emissions. This paper has developed a demand-centered, hybrid GHG inventory method for U.S. cities that includes direct GHG emissions associated with end-use of energy by cities, as well as the indirect GHG emissions associated with the embodied energy of producing key urban materials. The direct end-use emissions inventory protocols are consistent with IPCC, EPA, WRI, and ICLEI protocols (see Table 2a), with two important modifications to address city-scale spatial boundary effects. (a) Based on a recent evaluation for California (11, 42), the electricity emissions factor was computed including imports to the local utility. (b) Spatial allocation procedures, based on regional VMT matrices (Table 1) and trip/population ratios, were applied to allocate surface and air travel, respectively, across cities colocated within large metropolitan areas. Indirect emissions associated with the embodied energy of key urban materials were computed by coupling an LCA for these materials with a local MFA. By including both direct and indirect emissions, cities have the flexibility to report direct emissions consistent with IPCC and WRI Scope 1–2 protocols, while also reporting additional impact of materials use, consistent with WRI Scope 3 protocols (10).

Inventories, Footprints, and Inclusions. Results obtained for Denver (Figure 1 and Table 3) suggest that the demand-centered hybrid LCA-based approach developed in this paper enabled a more holistic estimate of Denver’s greenhouse gas inventory that tracked well with both national- and state-level per capita benchmarks, possibly approaching a city-scale GHG footprint computation, never before developed for U.S. cities. Through this methodology, sectors such as food, airline travel, and cement which appear in personal GHG footprint calculations (e.g., ref (43)) and in national (7) and global GHG computations (44), now also appear in city-scale greenhouse gas inventories thereby creating consistency of inclusions across spatial scales. For example, food (agriculture), airline travel, and cement contribute 9%, 4%, and 1% nationally in the United States, respectively (7) in line with Denver’s city-scale contributions shown in Figure 1. The numeric values of the per capita GHG emission (≈25 mt CO2e) were also consistent for Denver from the city to the state and national scales.

Policy Relevance. The inclusion of the airline and materials sectors can initiate city-scale GHG mitigation policies such as green concrete and airline offsets (11) that would otherwise be ignored by cities. Indeed both these policies are now part of Denver’s climate action plan (11), the first for any U.S. city. Lastly, fuel-vehicle systems of the future, e.g., bioethanol or hydrogen-powered vehicles, will require full well-to-wheel life-cycle accounting to accurately reflect their GHG impact. Incorporating LCA-based methods, as shown in this paper, will be important in quantitative modeling of such urban transportation futures. Furthermore, the spatial VMT allocation procedure is particularly useful in representing the impact of future regional (cross-city) mass transit expansions in metropolitan areas.

Material Inclusions. In this paper, based on the functionality of cities, we are proposing a few key urban materials for which processing facilities (e.g., oil refineries, cement plants, water treatment facilities) are easily recognized; production of these key materials within city boundaries can be readily identified to avoid double counting across direct and indirect categories. If such large production facilities are present, allocation based on local demand would be applied (as in the case of large regional airports). To achieve consistency, cities must agree on a common list of key urban materials. Local-scale versus national-scale LCA-based GHG emissions factors for materials may also be an important consideration, although the major materials—food and fuel—are typically drawn from large distances.

Importance of Benchmarking. This paper has demonstrated the importance of using benchmarks to assess the quality of information captured in a city-scale GHG inventory. In addition to overall per capita GHG emission benchmarks (Table 3), we have found that sector-specific per capita or per household metrics (see Table 2) are equally important in characterizing energy use and GHG emissions in cities, for comparison with regional and national data. We recommend cities report not only aggregate and per capita GHG emissions, but also sector specific benchmarks shown in Table 2 to aid in understanding and in outcomes assessment. We are currently replicating the inventory methodology developed in this paper to seven other cities in the United States to compare and contrast energy use patterns under different climate conditions, and to verify applicability of the hybrid methodology and scalability of the outcomes seen in Table 3.

Acknowledgments

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