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What metrics best reflect the energy and carbon intensity of cities? Insights from theory and modeling of 20 US cities

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Abstract
Three broad approaches have emerged for energy and greenhouse gas (GHG) accounting for individual cities: (a) purely in-boundary source-based accounting (IB); (b) community-wide infrastructure GHG emissions footprinting (CIF) incorporating life cycle GHGs (in-boundary plus trans-boundary) of key infrastructures providing water, energy, food, shelter, mobility–connectivity, waste management/sanitation and public amenities to support community-wide activities in cities—all resident, visitor, commercial and industrial activities; and (c) consumption-based GHG emissions footprints (CBF) incorporating life cycle GHGs associated with activities of a sub-set of the community—its final consumption sector dominated by resident households. The latter two activity-based accounts are recommended in recent GHG reporting standards, to provide production-dominated and consumption perspectives of cities, respectively. Little is known, however, on how to normalize and report the different GHG numbers that arise for the same city. We propose that CIF and IB, since they incorporate production, are best reported per unit GDP, while CBF is best reported per capita. Analysis of input–output models of 20 US cities shows that GHG^{CIF}/GDP is well suited to represent differences in urban energy intensity features across cities, while GHG^{CBF}/capita best represents variation in expenditures across cities. These results advance our understanding of the methods and metrics used to represent the energy and GHG performance of cities.

Keywords: cities, greenhouse gas accounting, infrastructure, consumption, metrics, carbon accounting, energy efficiency

S Online supplementary data available from stacks.iop.org/ERL/8/035011/mmedia

1. Introduction

More than 1000 cities have pledged to reduce greenhouse gas (GHG) emissions (Mayors 2010, WMSC 2010), however, methods to measure the energy use and GHG emissions of cities are still evolving. Cities are porous, embedded in larger infrastructure systems, and engaged in significant trade with other communities—all three factors have significantly complicated GHG emissions accounting at the scale of individual cities (Baynes *et al* 2011, Baynes and Wiedmann 2012, Ramaswami *et al* 2011, 2012). To address these factors, three broad approaches to measure the GHG emissions associated with cities have emerged that are detailed in section 2. A compendium of different research groups and cities applying the three different methods is also provided in Chavez and Ramaswami (2013a).

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Most importantly, multi-city organizations such as ICLEI-USA and the British Standards Institution (BSI)—that have capacity to reach many hundreds of cities—have started to translate the three different methods into guidance documents that suggest cities should report their aggregate GHG emissions in at least two to three different ways (see ICLEI 2012, BSI 2012). The multiple views of cities associated with the different GHG accounting methods—promoted both by the research and by guidance documents—is unprecedented and highly nuanced, and enables cities to be viewed from infrastructure/production and consumption perspectives. However, no guidance is yet provided on how to normalize the aggregate GHG emissions computed by the different methods to help cities compare their local energy intensity and carbon intensity features with other cities.

Since cities intuitively understand that aggregate (total) emissions increase with city population, there is a natural tendency to compare cities using the GHG/capita metric. Indeed, The World Bank and UN have published reports comparing mostly territorial (Scope 1+2)[3] GHG emissions of cities on a per capita basis (Hoornweg *et al* 2011, UN-Habitat 2011), although they indicate highly industrial cities may have disproportionately high per capita GHG emissions. The word consumption has sometimes been used erroneously in the literature (e.g., Hoornweg *et al* 2011), not reflecting final economic consumption, but incorrectly incorporating commercial–industrial electricity *use* for products or services that are exported elsewhere. As a result, it is not readily understood that cities with a high level of commercial activities, e.g., cities with large tourist economies, will also report disproportionately high Scope 1 + 2 GHG emissions on a per capita basis, i.e., per unit of the city's residential population, that has no reflection on the city's energy efficiency features.

Efforts to compare GHG emissions of multiple cities in terms of urban form characteristics have also been confused in terms of what is being compared across cities. For example, some studies have compared Scope 1 + 2 GHG emissions normalized per capita (per resident) across cities with different population densities and found widely varying results (i.e., GHG emissions may be positively or negatively correlated with density (Kennedy *et al* 2009, Hillman *et al* 2011). In contrast, other studies have compared consumption-based GHG emissions per capita across cities with differing densities and found no relationship with local density, given the global reach of households (Heinonen and Junnila 2011). These examples illustrate that the different methods of measuring GHG emissions in cross-city comparisons can make a difference in the results seen.

Recent theoretical work conducted by our research group (Chavez and Ramaswami 2013a) reveals explicit mathematical relationships between the different approaches to measuring GHG emission of cities, defined in detail in section 2. In this paper, we explore what *metrics* best reflect the urban energy intensity and carbon intensity of cities. We posit that not only is it important to understand the different methods of aggregate GHG accounting for cities, but also how these aggregate numbers are normalized (e.g., GHG per capita resident or GHG per unit GDP metrics) can make a difference in exploring relations with urban form, urban efficiency and urban energy intensity features. We explore this not by assessing urban form features (density, shape or other) since these are indirect and uncertain proxies of urban energy and carbon intensity. But rather, we assess the degree to which the different GHG metrics correlate with the actual underlying urban energy intensity features that are most important at the city-scale—i.e., the energy intensity of local housing, of regional surface transportation, and of commercial–industrial activities occurring in a city.

The big picture message of this paper is that the different GHG accounting methods yield different aggregate GHG accounts for cities that have all traditionally been normalized per capita. We suggest exploring both GHG/capita and GHG/GDP metrics—and observe how these correlate with aggregate measures of urban energy intensity (UEI)—to enable cities to better relate their GHG emission to the local characteristics of energy use in cities. The study is conducted with data and models of 20 US cities—hence energy intensity and GHG intensity are closely related.

Section 2 provides an overview of the broad approaches to GHG accounting at the city scale.

2. Overview of different approaches for city GHG accounting

(1) *Purely territorial source-based GHG accounting (IB)*: mirrors national accounting methods by inventorying all direct fuel combustion and GHG emission sources within the city boundary according to the IPCC classification (energy, industrial processes, agricultural, etc (IPCC 2006)). Effectively, the method tracks fuel use and combustion in the buildings and transportation sector, for homes, businesses, and industries within the city, yielding in-boundary GHG emissions (GHG^{IB}), also called Scope 1 GHG emissions. Fuel combustion for electricity generation within the city boundary may be included in this category, as well as any non-energy GHG emissions, i.e., GHGs from calcining in cement production. The Vulcan database (Gurney *et al* 2009) is an example of such a strict source-based approach wherein GHGs are assigned to cities based on the location of the source emissions, accounting for CO_2 emissions from fossil fuel combustion for every US county.

(2) *Source-based GHG accounting with allocation of power generation (Scope 1 + 2)*: since most cities (more than 93% in the US) import some share of their electricity (EPA 2011), it was intuitively recognized early-on that power generation emissions should be allocated to cities based on their *use* of electricity rather than the location of the source. GHG emissions associated with electricity imports can be considered Scope 2, using the analogy to WRI's corporate GHG protocol (WRI 2004). Cities that export electricity may subtract the exported GHGs from the in-boundary GHGs; such an approach is now standardized in the Global GHG protocol for cities (GPC 2012). Many US cities as well

[3] This term is defined further in section 2.

used this approach early-on as can be observed in the GHG emission inventories reported to ICLEI-USA (ICLEI 2012).

However, questions arose about other infrastructure sectors such as transportation, fuel production, water supply, food production, etc, that (like electricity) are also essential for basic life functions of cities, and are also often produced outside city boundaries and hence termed trans-boundary (Ramaswami *et al* 2008). Further, applying the same logic, what about the trans-boundary production of other consumer goods, such as furniture and clothing, which may be consumed in one city, but produced elsewhere? To address trans-boundary energy use from a systems perspective, two types of activity-based GHG accounting methods emerged, described in methods 3 and 4 below.

(3) *Community-wide infrastructure-supply chain GHG emission footprints (CIF)*: measure life cycle (in-boundary *plus* trans-boundary) GHG emissions associated with community-wide use of a finite set of key infrastructures that provide energy (electricity and fuels), water, food, mobility/connectivity (i.e., commuter, freight, air and marine travel), construction materials, sanitation, waste management and public spaces to the entire community consisting of homes, businesses and industries co-located in the city (Ramaswami 2013). These infrastructures are essential for basic life functions, and/or are also found to be highly correlated with economic development in all cities while being produced sparsely in only a few cities (Chavez and Ramaswami 2013a). GHGs from these key infrastructures are assigned to cities based on infrastructure use rather than the location where the GHG emissions are produced[4]. Effectively, all in-boundary GHG emissions are accounted as part of use phase of energy infrastructures, and the supply chain GHGs from trans-boundary infrastructure provisions are added/subtracted, based on their import/export from the community.

Thus, method 2 (Scope 1+2 only) can be considered to be the simplest form of the CIF where only Scope 2 (electricity infrastructure net imports) is included. The trans-boundary supply chain GHGs of the other infrastructure sectors can be incorporated in two different ways: (a) $GHG^{CIF,allocated}$: like electricity (Scope 2), the GHGs associated with these trans-boundary infrastructure provisions can be allocated out of communities that produce them to communities that use these infrastructures, (b) $GHG^{CIF\ Scope1+2+3}$: alternatively, these additional infrastructure sectors may be added separately as Scope 3 items, with care being taken to avoid double counting with the same source category within the city boundary (Ramaswami *et al* 2008, Hillman and Ramaswami 2010, Chavez *et al* 2012). CIF is expected to provide a production-based view of cities akin to national accounts (e.g., Peters and Hertwich 2008), by overcoming the artificial truncation of key infrastructures at the city boundary.

[4] In the CIF method, for food, only farm-to-gate GHGs are accounted and allocated to cities based on food used in the community, i.e., food used in homes, restaurants, hotels, etc. In this way, food processed in one city and then exported to another will make no impact (its farm-to-gate GHG in imports and exports will cancel each other). Details are in Chavez and Ramaswami (2013a).

(4) *Consumption-based footprints (CBF)*: CBFs compute life cycle (in-boundary and trans-boundary) GHGs associated with the consumption of both infrastructure and non-infrastructure goods and services by a sub-set of a community—its final economic consumption sector (formally defined as household, government and business capital expenditures within a city), which is dominated by local household expenditures. However, energy use by visitors to the local community, as well as by businesses and industries that serve those visitors or that export goods and services elsewhere are excluded from the CBF of that community. Thus CBF primarily informs local resident households and governments of the global impact of the full suite of goods and services consumed by that sub-set of the city. The distinction between in-boundary and trans-boundary portions (and hence Scopes) is not always easy to make in CBF because, in this method, household and government expenditures are typically multiplied by environmentally-extended input–output (EEIO) models that represent the production GHG intensity of the entire global economy. The extent of local production for local consumption and its unique local efficiency may be captured by multi-region IO (MRIO models); but high quality MRIO data are not readily available for all cities worldwide (Chavez and Ramaswami 2013a).

There is increasing recognition that CIF and CBF inform GHG accounting for cities in complementary ways, focusing on infrastructure/production in the former, and consumption in the latter (Baynes *et al* 2011, Ramaswami *et al* 2011). Thus GHG accounting protocols developed recently by ICLEI (2012) and by the British Standards Institution (BSI) for London (in a Publicly Available Standard, PAS 2070, BSI (2012)) recommend computing a CIF to inform citywide infrastructure planning for GHG mitigation, and a separate CBF to inform household consumption. These protocols enable standardization of the CIF method, which is a new GHG accounting approach developed uniquely to address the scale and function of cities (Ramaswami *et al* 2008, 2011). Note, consumption-based accounting has been better established previously to represent the role of households (e.g., (Weber and Matthews 2008)). ICLEI's protocol provides guidance on computing 'trans-boundary community-wide supply-chains' GHGs (ICLEI 2012). In the BSI PAS 2070, the methodology is termed 'direct plus supply chain' GHG accounting. While the two protocols use different nomenclature, both include the key community-wide infrastructure inclusions described in the CIF.

With multiple methods, and variations within the methods, for measuring GHG emissions associated with cities, a key question that arises is: *what metrics best represent the energy intensity of cities at the local or regional scale*? Section 1 highlighted some of the challenges of using per capita metrics for Scope (1 + 2) GHGs of cities. For example, suburban communities with low commercial–industrial activity reported GHG^{CIF}/capita emissions much lower than the national average, although the city was not more efficient than others based on local transportation or buildings energy intensity benchmarks. Likewise, cities with disproportionately high commercial and industrial activities compared to homes would misleadingly report much higher GHG/capita, not indicative of the efficiency of their housing, production or transportation provisions, but merely an artifact of the disproportionately high commercial–industrial energy use within the boundary (Chavez and Ramaswami 2013a).

However, despite the drawbacks of per capita GHG reporting being alluded to in the literature, the practice remains widespread. Now that dual methods (CIF and a separate CBF) have been proposed in guidance documents for measuring overall city GHG emissions (ICLEI 2012, BSI 2012), a question to ask is whether different normalizing metrics are needed to accompany the different methods for GHG accounting at the city scale? Further, which metric best represents the local urban energy/carbon intensity features of cities, i.e., do lower GHG emissions represented by a certain metric (GHG/GDP or GHG/capita) better reflect the reduced energy intensity features of a city? This paper explores these two questions using insights form theory and from modeling across 20 US cities.

3. Insights from theory

Mathematical relationships have been developed between the three main GHG measurement approaches: IB, CIF and CBF (see Chavez and Ramaswami 2013a). The theoretical relationships show that a community's territorial GHG account plus/minus the GHGs embodied in community-wide *infrastructure* imports/exports yields the CIF. Further adding/subtracting from the CIF the GHGs embodied in imports/exports of *non-infrastructure* goods and services yields CBF. These relationships shown in the following equation represent the simpler single-region IO (SRIO) case; MRIO derivations are also shown in Chavez and Ramaswami (2013a):

$$\begin{aligned}\mathrm{GHG}^{\mathrm{CBF}} &= [B][\mathrm{TLO}] + [\mathrm{EF}^{\mathrm{use}}] \times \{[F] + [M_{\mathrm{F}}]\} \\ &\quad + [B][L][M_Z + M_{\mathrm{F}} - E] \\ &= \underbrace{\underbrace{[B][\mathrm{TLO}] + [\mathrm{EF}^{\mathrm{use}}] \times \{[F] + [M_{\mathrm{F}}]\}}_{\text{Represents geographic (territorial) GHG emissions inventory (GHG}^{\mathrm{IB}})} + [B][L][M_{\mathrm{net}}^{\mathrm{infra}}]}_{\text{Represents CIF GHG emissions footprint (GHG}^{\mathrm{CIF}})} \\ &\quad + \underbrace{[B][L][M_{\mathrm{net}}^{\mathrm{non-infra}}]}_{\text{GHG embodied in net non-infrastructure imports to city}} \qquad (1)\end{aligned}$$

where $[B]$ is the GHG intensity vector (e.g., CMU (2008)); [TLO] is the total local outputs for producing local final demand. $[B]$[TLO] are in-boundary GHG emissions from all local production. $[\mathrm{EF}^{\mathrm{use}}]$ is the use-phase combustion emissions factor for fuels (natural gas, transport fuels) consumed directly by final consumption. $[F]$ is local final consumption met locally, and $[M_{\mathrm{F}}]$ is the portion of local final consumption met by imports. $[L]$ is the total requirements matrix representing total (direct and indirect) inter-industry requirements of domestically produced goods/services which we assume to be equal to the US national L in our model. $[M_Z]$ are imports to local industries, and $[E]$ are city exports. Details on these relationships are in Chavez and Ramaswami (2013a).

A typology of cities emerges from equation (1), with cities identified as net-producers, net-consumers and trade-balanced based on GHG embodied in the *non-infrastructure* imports/exports, infrastructure being considered essential for life functions and economic production in all communities. A community with significant net-exports of non-infrastructure goods/services is considered a net-producer, and in such a community $\mathrm{GHG}^{\mathrm{CIF}}$ is expected to be much larger than $\mathrm{GHG}^{\mathrm{CBF}}$. The reverse is shown for net-consuming communities.

$$\begin{aligned}&\text{In a } \textit{trade-balanced} \text{ city, where } \mathrm{GHG}_{M_{\mathrm{net}}}^{\mathrm{non-infra}} \ll \mathrm{GHG}^{\mathrm{CIF}}, \\ &\quad \mathrm{GHG}^{\mathrm{CIF}} \approx \mathrm{GHG}^{\mathrm{CBF}} \\ &\text{In a net-}\textit{producer} \text{ city, where } \mathrm{GHG}_{M_{\mathrm{net}}}^{\mathrm{non-infra}} \\ &\quad \text{is a large negative, } \mathrm{GHG}^{\mathrm{CIF}} > \mathrm{GHG}^{\mathrm{CBF}} \qquad (2) \\ &\text{In a net-}\textit{consumer} \text{ city, where } \mathrm{GHG}_{M_{\mathrm{net}}}^{\mathrm{non-infra}} \\ &\quad \text{is a large positive, } \mathrm{GHG}^{\mathrm{CIF}} < \mathrm{GHG}^{\mathrm{CBF}}.\end{aligned}$$

Neither $\mathrm{GHG}^{\mathrm{CIF}}$ nor $\mathrm{GHG}^{\mathrm{CBF}}$ is shown to be automatically 'more holistic', both are complementary, they measure different although overlapping flows, and inform different GHG mitigation strategies (Chavez and Ramaswami 2013a).

The theory (equations (1) and (2)) shows that for the same city, two widely different numbers can be obtained. If a city were highly net-producing, its $\mathrm{GHG}^{\mathrm{CIF}}$ would be much larger than $\mathrm{GHG}^{\mathrm{CBF}}$. Normalizing both these numbers by resident population to obtain a GHG/capita metric—a practice of habit—will leave cities with two widely different numbers, both represented as GHG/capita, and creating public communication challenges. This is particularly relevant for the dual perspectives currently being proposed by ICLEI-USA and BSI because two different numbers, both normalized per capita, will not help public understanding.

Instead, here we propose the understanding that $\mathrm{GHG}^{\mathrm{CIF}}$ (like national accounts) largely tracks production activities in a community after overcoming the challenge of infrastructure truncation, and therefore we recommend that all community-wide infrastructure based GHG accounts (i.e., metabolism-based accounting (Baynes and Wiedmann 2012)) be normalized by community GDP. In contrast, since $\mathrm{GHG}^{\mathrm{CBF}}$ represents the full consumption primarily by households, the GHG/capita metric should be reserved for $\mathrm{GHG}^{\mathrm{CBF}}$. But, which of these metrics best represents the energy-use intensity of the city? To explore this we analyze bottom-up field data and associated IO models developed for 20 US cities.

4. Field data and IO modeling of 20 US cities

The dataset of 20 cities: represents all US cities that are also counties and that had reported a bottom-up local GHG inventory to ICLEI (2010) that could then be applied to improve available county-scale IO tables (MIG 2010); provision of a local contact from each city was also critical. The improvements included replacing: household energy and transportation fuel use based on local inventory data that reflect local characteristics, total

Table 1. Energy-use benchmarks for the case-study cities. Comparative state-level benchmark shown in *[bracket]*. (Note: *energy-use data*: local retrieved from bottom-up data (ICLEI 2010), state retrieved from (EIA 2012); *employment statistics*: local retrieved from (MIG 2010), state retrieved from (Census 2011); *population and households*: local retrieved from (MIG 2010), state retrieved from (Census 2011); *vehicles miles traveled (VMT)*: local retrieved from (ICLEI 2010), state retrieved from (FHWA 2008).)

	Commercial–industrial		Residential		Road transport
City/county	kWh/job/mo[a]	Therms/job/mo[b]	kWh/hh/mo[c]	Therms/hh/mo	VMT/cap/day[d]
Sacramento, CA	771 *[918]*	16 *[59]*	748 *[580]*	33 *[34]*	25.3 *[25.2]*
Napa, CA	719 *[918]*	16 *[59]*	714 *[1071]*	25 *[24]*	26.0 *[25.2]*
Boulder, CO	1156 *[1214]*	39 *[94]*	852 *[743]*	56 *[58]*	24.2 *[28.2]*
Denver, CO	948 *[1222]*	46 *[88]*	546 *[768]*	47 *[59]*	25.3 *[27.6]*
Routt, CO	1470 *[1214]*	30 *[94]*	1221 *[743]*	52 *[58]*	32.3 *[28.2]*
Collier, FL	1300 *[1187]*	5 *[13]*	1780 *[1354]*	1 *[2]*	32.3 *[30.9]*
Sarasota, FL	981 *[1173]*	8 *[13]*	1403 *[1367]*	2 *[2]*	35.3 *[31.0]*
Broward, FL	1188 *[1187]*	4 *[13]*	1352 *[1354]*	1 *[2]*	28.5 *[30.9]*
Miami-Dade, FL	1194 *[1173]*	3 *[13]*	1267 *[1367]*	9 *[2]*	24.9 *[31.0]*
Washoe, NV	1145 *[1538]*	28 *[29]*	700 *[1022]*	50 *[34]*	23.6 *[21.8]*
Tompkins, NY	799 *[892]*	42 *[37]*	564 *[554]*	33 *[46]*	19.5 *[18.9]*
Westchester, NY	666 *[966]*	29 *[37]*	589 *[575]*	51 *[47]*	28.3 *[19.7]*
Multnomah, OR	1066 *[1423]*	30 *[49]*	793 *[1092]*	30 *[25]*	26.1 *[24.2]*
Philadelphia, PA	1181 *[1390]*	37 *[50]*	507 *[851]*	53 *[35]*	11.0 *[23.8]*
Roanoke, VA	1202 *[1495]*	42 *[33]*	1261 *[1247]*	54 *[23]*	28.9 *[29.1]*
Loudoun, VA	1388 *[1495]*	15 *[33]*	1472 *[1247]*	46 *[23]*	22.3 *[29.1]*
Snohomish, WA	1200 *[1513]*	30 *[36]*	994 *[1114]*	27 *[25]*	22.5 *[24.3]*
Oregon METRO[e]	1212 *[1425]*	34 *[49]*	714 *[1071]*	25 *[24]*	23.9 *[26.4]*
NYC[f]	772 *[892]*	26 *[37]*	374 *[554]*	37 *[46]*	8.4 *[18.9]*
DVRPC[g]	1203 *[1279]*	46 *[52]*	842 *[851]*	48 *[50]*	21.7 *[23.7]*
US	1450	70	982	36	27.0

[a] kWh = kilowatt hours.
[b] mo = month.
[c] hh = households.
[d] VMT = vehicle miles traveled; cap = capita.
[e] The greater Portland regional area comprised of three counties *(Clackamas, Multnomah, and Washington)*.
[f] The New York City (NYC) area comprised of five boroughs *(Bronx, Kings, New York, Queens, Richmond)*.
[g] The Delaware Valley Regional Planning Commission (DVRPC) regional area comprised of five Pennsylvania counties *(Bucks, Chester, Delaware, Montgomery, and Philadelphia)* and four New Jersey counties *(Burlington, Camden, Gloucester, and Mercer)*.

commercial–industrial–residential electricity use using local utility data, total transport and airline fuel use based on regional transportation models and fuel loaded at airport data, and, local energy generation using EPA's eGRID (EPA 2011). In addition, a check of output/employee as well as GDP/capita reported in IMPLAN versus the US Bureau of Economic Analysis (BEA 2009) was conducted to flag economic flows misallocated to a city (e.g., in Denver, oil and gas economic activity arose due to ownership of wells not within Denver's boundary; corporate headquarters may also be flagged in this way). Because not all parts of the IO table can be fully verified, we caution that this dataset does not present an accurate model of each of the cities, but rather, it broadly represents the *economies of different city typologies* that can be used to verify the theoretical equations (1) and (2) (Chavez and Ramaswami 2013b). In this paper we explore these models of the 20 cities to examine whether the per capita or per GDP metric applied to GHGs computed by the different methods (GHG^{IB}, GHG^{CIF}, GHG^{CBF}), most effectively represented the local energy intensity features of cities, drawing upon cities of different trade-typologies. Our data set was found to be composed of 2 net-producers, 10 trade-balanced and 8 net-consuming cities; thus a slight dominance of net-consumers.

Data checks: the local bottom-up energy-use data for the 20 cities were vetted by comparing energy-use metrics such as household electricity use per month, and annual commercial energy-use intensity, to check if they are of the same order of magnitude as those reported in respective state or regional averages (Hillman and Ramaswami 2010). See table 1. In our experience large (order of magnitude) unexplained deviances from regional averages are indicative of data errors. The data checks showed consistency with regional benchmarks. Cities varied widely in energy intensity in the different sectors—thus, there was no significant so-called self-selection bias (note—we did not select the cities, but used data for all cities that were counties and had done a GHG inventory and reported the results to ICLEI-USA).

Comparing with top-down models: a preliminary comparison between bottom-up inventory Scope 1 GHG emissions versus the top-down Vulcan inventory (Gurney *et al* 2009) was also conducted—the latter computes fossil fuel CO_2 emissions by spatially downscaling various data sets to census tract-level geographic units. For example, on-road CO_2 emissions are computed from the National Mobile Inventory Model (NMIM), while commercial–industrial fossil fuel combustion (with electricity generation separated) is reported at the county level through the EPA's National Emissions

Inventory. In contrast, the bottom-up local inventory (ICLEI data) estimates buildings sector fuel use from utility billing data and transportation tail-pipe emissions from regional transportation models. Comparison of bottom-up local inventory Scope 1 data versus Vulcan shows good agreement for road transportation emissions (figure S1 available at stacks.iop.org/ERL/8/035011/mmedia), within the error of ~15% identified by Hillman *et al* (2011) when different methods to estimate transport emissions are applied. However, the city inventory for non-electricity fuel use appears to consistently under-estimate direct GHG emissions by about 50% compared to Vulcan (figure S2 available at stacks.iop.org/ERL/8/035011/mmedia). This could be because, anecdotally, energy utilities do not track large independent natural gas providers to the commercial–industrial sector; further a comparison with State datasets (EIA 2012) shows that while cities are tracking natural gas to some extent, they do not have the ability to track coal and other fuels being used in the commercial–industrial sectors, all of these may account for 25%–50% undercounting of buildings–industrial direct fossil fuel combustion in cities (excluding electricity generation and transportation). The combination of benchmarking studies and the comparison with top-down datasets indicates that cities are likely getting good bottom-up data on community-wide electricity use, as well as reasonable transportation fuel estimates; however, other (non-electricity) fossil fuels use in the commercial–industrial sector is likely lacking.

Improved IO models: the IMPLAN starting models were checked to ensure that local GDP as estimated by IMPLAN matched BEA. The basic IMPLAN model was then amended with high quality portions of the local inventory data: (a) using household energy and transportation fuel expenditures from local inventory data that reflect local climate and travel characteristics rather than national averages, (b) using total commercial–industrial–residential electricity use from local utility data, (c) applying total transport and airline fuel use based on regional transportation models and fuel loaded at airport data, and, (d) representing local electricity generation using EPA's eGRID. Then the amended IO model was re-generated within the IMPLAN software to integrate the bottom-up amendments and BEA data. The amended and recalibrated IO models were then paired with the energy and GHG intensity vectors of the economy (CMU 2008). Because of the significant undercounting of commercial–industrial non-electricity fuel combustion GHGs (~50%, figure S2) and exclusion of industrial process GHGs in the local inventories, no efforts were made to change the local [*B*] vector for non-electricity sectors in any of the cities. The [*B*] vectors for local electricity use were varied in the 20 cities, as described next.

Local electricity emission factors: i.e., the GHG intensity of electricity used within the city–county boundaries was varied randomly to reflect that cities' electricity supply can be (and often is) different from the national average; some will be higher and some lower than the national average. Because the cities in our dataset showed some self-selection bias, i.e., only one city generated electricity that was more carbon intensive than the national electricity grid, we used a random number generator such that the electricity GHG emission factors (EF) for electricity used in the 20 different cities varied within ±50% of the national electricity EF of 0.65 kg-CO_2e kWh^{-1}. Knowledge of the % local generation from eGRID was then applied to model the local electricity generation EF so as to compute in-boundary (IB) GHGs due to local power plants. Thus, effectively a two-region MRIO model was created with each city using electricity more or less carbon intensive (from ±50%) than the US national average, while the rest of the world was represented by the US average EIO-LCA (CMU 2008). Note, Ahmad and Wyckoff (2003) indicate the GHG intensity of the US economy is a fair representation of the world average. A Scope 1 + 2 GHG comparison was also conducted for local inventory data (corrected with Vulcan for Scope 1) versus IMPLAN-EIOLCA to ensure that the local inventory was generally consistent with IMPLAN outputs (see table S1 available at stacks.iop.org/ERL/8/035011/mmedia).

The general results seen in this study were also verified by conducting simpler single-region IO (SRIO) modeling with all 20 cities being similar in energy/GHG intensity to the US economy.

Different GHG accounting methods and metrics explored: GHGs were computed by the different methods—GHG^{IB}, GHG^{CIF} and GHG^{CBF}—using equation (1). The GHG computed by the different methods (and smaller variants within the methods) were then normalized per unit GDP and per unit capita (resident population) as shown in table 2, and evaluated for correlation with urban energy/carbon intensity features of these cities, described next.

Urban energy/carbon intensity index (UEI): we developed an aggregate urban energy/carbon intensity index (UEI) composed of three key local energy efficiency and carbon intensity characteristics of a city.

(1) *Household carbon intensity (HCI)*, which is represented as residential GHG per resident computed from local inventory energy-use data. Household energy intensity data for 20 cities are reflected in table 1, from which the household carbon (GHG) intensity is computed by applying appropriate GHG emission factors to the different energy carriers used.
(2) *Transportation system energy intensity (TSI)*, which is represented as vehicle miles traveled (VMT) by residents plus workers (employees) in the city computed based on the regional transportation model (see table 1). The fuel use in road transport computed from the transportation model was also incorporated in the amended IO model.
(3) *Commercial–industrial carbon intensity (CICI)* was computed as GHGs computed in the IO model from electricity use (in-boundary plus imported) as well as in-boundary fuel combustion in the commercial–industrial sectors, and normalized by community GDP. Since the bottom-up inventory data were deficient in estimating the non-electricity commercial–industrial fuel use (see figure S2), the direct fuel combustion Scope 1 emissions were taken from the IO model.

Thus, a city's UEI is computed from the sum of these three characteristics, each of which is normalized by the respective

Table 2. Summary of different GHG accounting methods, and the correlation of the resulting GHGs normalized indifferent metrics with an aggregate urban energy/carbon intensity index (UEI) of cities. (a) Results for 20 US cities of diverse types, each modeled as a two-region MRIO with GHG intensity of electricity use modeled to vary randomly from ±50% higher or lower compared to the larger economy. (b) Results for the same 20 US cities in a SRIO; all cities have the same electricity GHG intensity as the larger economy.

GHG accounting method	GHGs	Correlation of GHG per GDP (community GDP) metric with UEI	Correlation of GHG per capita (resident population) metric with UEI
(a)			
Territorial (IB)	Purely territorial (GHG^{IB})	GHG^{IB}/GDP versus UEI: $R^2 = 0.450$	GHG^{IB}/cap versus UEI: $R^2 = 0.171$
Versions of CIF	Purely territorial + electricity allocated ($GHG^{CIF\ Scope\ 1+2}$)	$GHG^{CIF\ Scope\ 1+2/GDP}$ versus UEI: $R^2 = 0.828$	$GHG^{CIF\ Scope\ 1+2}$/cap versus UEI: $R^2 = 0.380$
	Above plus Scope 3 without allocating ($GHG^{CIF\ Scope\ 1+2+3}$)	$GHG^{CIF\ Scope\ 1+2+3}$/GDP versus UEI: $R^2 = 0.781$	$GHG^{CIF\ Scope\ 1+2+3}$/cap versus UEI: $R^2 = 0.380$
	Above with Scope 3 items allocated ($GHG^{CIF\ Scope\ 1+2+3,allocated}$)	$GHG^{CIF\ Scope\ 1+2+3,allocated}$/GDP versus UEI: $R^2 = 0.709$	$GHG^{CIF\ Scope\ 1+2+3,allocated}$/cap versus UEI: $R^2 = 0.418$
CBF	Consumption-based GHGs (GHG^{CBF})	GHG^{CBF}/GDP versus UEI: $R^2 = 0.494$	GHG^{CBF}/cap versus UEI: $R^2 = 0.512$
(b)			
Territorial (IB)	Purely territorial (GHG^{IB})	GHG^{IB}/GDP versus UEI: $R^2 = 0.462$	GHG^{IB}/cap versus UEI: $R^2 = 0.292$
Versions of CIF	Purely territorial + electricity allocated ($GHG^{CIF\ Scope1+2}$)	$GHG^{CIF\ Scope\ 1+2}$/GDP versus UEI: $R^2 = 0.849$	$GHG^{CIF\ Scope1+2}$/cap versus UEI: $R^2 = 0.452$
	Plus Scope 3 without allocating ($GHG^{CIF\ Scope\ 1+2+3}$)	$GHG^{CIF\ Scope\ 1+2+3}$/GDP versus UEI: $R^2 = 0.782$	$GHG^{CIF\ Scope\ 1+2+3}$/cap versus UEI: $R^2 = 0.446$
	Plus Scope 3 with allocating ($GHG^{CIF\ Scope\ 1+2+3,allocated}$)	$GHG^{CIF\ Scope\ 1+2+3,allocated}$/GDP versus UEI: $R^2 = 0.685$	$GHG^{CIF\ Scope\ 1+2+3,allocated}$/cap versus UEI: $R^2 = 0.454$
CBF	Consumption-based GHGs (GHG^{CBF})	GHG^{CBF}/GDP versus UEI: $R^2 = 0.386$	GHG^{CBF}/cap versus UEI: $R^2 = 0.448$

average for the 20 cities in our sample. Namely,

Urban energy/Carbon intensity index for city i

$$= \mathrm{UEI}_i = \frac{\mathrm{HCI}_i}{\mathrm{HCI}_{\mathrm{avg,\ 20\ cities}}} + \frac{\mathrm{TSI}_i}{\mathrm{TSI}_{\mathrm{avg,\ 20\ cities}}} + \frac{\mathrm{CICI}_i}{\mathrm{CICI}_{\mathrm{avg,\ 20\ cities}}}.$$

Note that the urban energy/carbon intensity parameters are derived from parameters used widely in the literature, e.g., residential energy-use intensity is often represented in energy-use units per household or per capita (kWh/hh; kBTU/hh; see US RECS (EIA 2005a)). Transportation system efficiency is often measured based on motorized VMT normalized to all the people using the system (residents and others) (e.g., (SACOG 2012). Commercial energy intensity is often represented in energy-use intensity (EUI)—annual kBTU of gas and electricity per floor area (see commercial buildings energy consumption surveys, CBECS, (EIA 2005b)). In this paper, since commercial floor area is not reported consistently by all cities nor is industrial electricity use always separated from commercial, the energy and GHGs in both industrial and commercial sectors were summed and then normalized to community GDP.

Each UEI attribute was normalized to the in-sample (20-city) average for that attribute, thus lower attribute values signal the city is more efficient (less energy/carbon intensive) than others in the sample. The composite index (UEI) for a given city was computed as the sum of its three normalized attributes. For simplicity, all three attributes were weighted equally given the approximate split of about 30% between energy use in transportation, buildings and industrial sectors in the US (EIA 2011). Thus, a lower UEI represents a less energy intensive (more efficient) city overall (among the 20-city sample), considering all three attributes together.

In-sample correlations between the GHG metrics and the UEI were evaluated to ask a basic question—which GHG metric (measured in whatever manner) best reflects the local energy/carbon intensity features of cities as represented in the underlying model? In other words, *does a city with lower normalized GHGs reported using a certain metric indeed represent lower urban energy/carbon intensity features of the local area?*

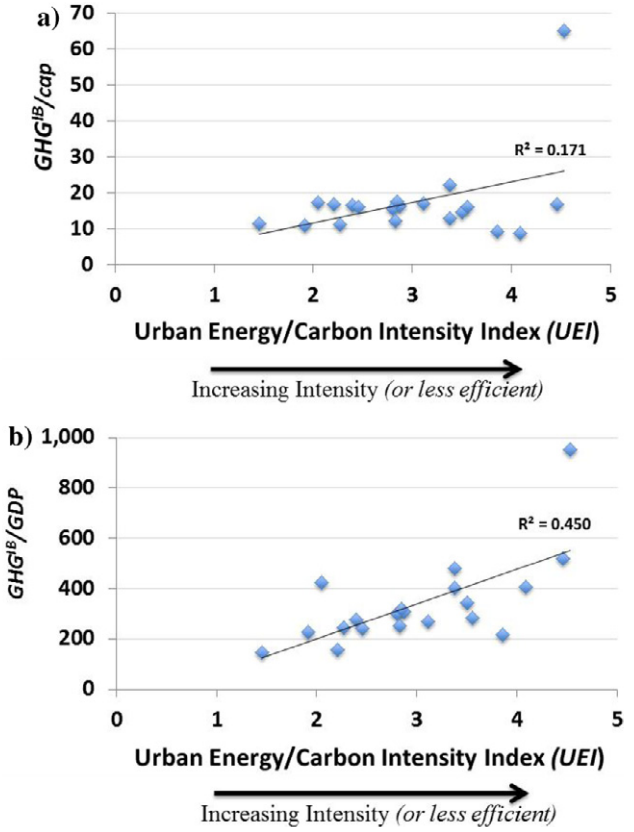

Figure 1. Correlation between in-boundary (IB) GHGs expressed in different metrics versus an aggregate urban *energy/carbon intensity* index (UEI) of cities: (a) GHG^{IB}/resident (capita) versus UEI, and, (b) GHG^{IB}/GDP versus UEI. An increasing UEI index indicates higher intensity of energy use (or carbon use) in residential, transportation and commercial–industrial activities within a city, relative to other cities. The data are from models of 20 US cities of diverse economies, each modeled in a two-region MRIO with GHG intensity of electricity use in the different cities ranging from ±50% higher or lower compared to the larger economy.

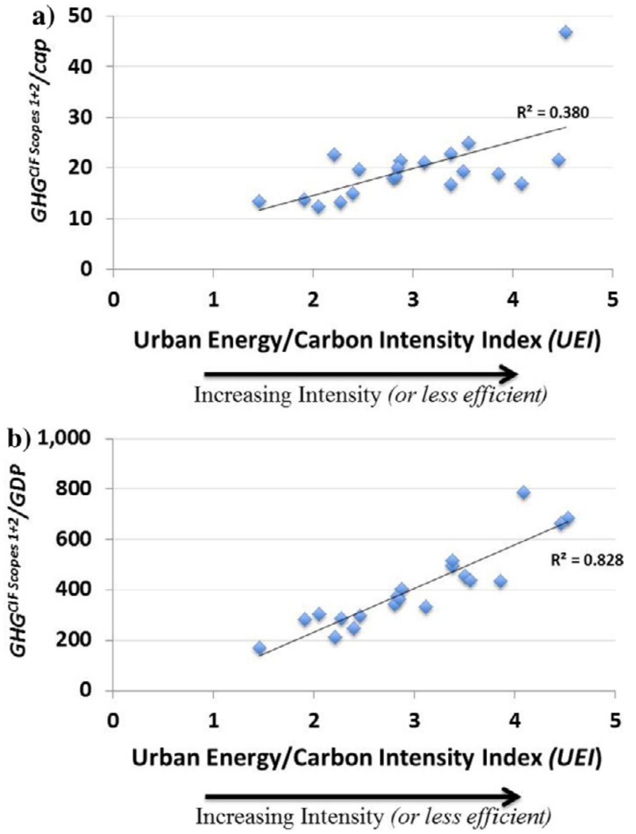

Figure 2. Correlation between community-wide infrastructure footprint (CIF) GHGs covering Scopes 1 + 2, expressed in different metrics versus an aggregate urban *energy/carbon intensity* index (UEI) of cities: (a) GHG$^{CIF\ Scopes1+2}$/resident (capita) versus UEI, and, (b) GHG$^{CIF\ Scopes1+2}$/GDP versus UEI. An increasing UEI index indicates higher intensity of energy use (or carbon use) in residential, transportation and commercial–industrial activities within a city, relative to other cities. The data are from models of 20 US cities of diverse economies, each modeled in a two-region MRIO with GHG intensity of electricity use in the different cities ranging from ±50% higher or lower compared to the larger economy.

5. Results

The computed UEIs are shown in table S2 (available at stacks.iop.org/ERL/8/035011/mmedia), with the names of the cities suppressed in accompanying results reported in figures 1–4, to emphasize that these are models of different city trade-typologies, but not perfectly accurate representations of each individual city.

Correlation between each of the metrics and UEI for the 20-city dataset were used to evaluate which metric best represents the energy efficiency of cities. For purely territorial GHGs, both GHG^{IB}/GDP and GHG^{IB}/capita were somewhat weakly correlated with the UEI, although the per GDP metric ($R^2 = 0.45$) was better correlated than the per capita metric ($R^2 = 0.17$) (see figure 1 and table 2). Figure 1 suggests that purely territorial GHG accounting does not correlate very well with city UEI, even when expressed as GHG^{IB}/GDP. This can be expected because GHGs from electricity generation are accounted for in GHG^{IB} even when that electricity is not used within the producing city; likewise other cities that import significant electricity would not show electricity GHGs in their GHG^{IB}.

For community-wide infrastructure-supply chain footprints, CIF, which addresses key infrastructure use by cities, *GHG*^{CIF} *per unit GDP* was highly correlated with UEI for both GHG$^{CIF\ Scope\ 1+2}$ (figure 2; $R^2 = 0.83$) and GHG$^{CIF\ Scopes\ 1+2+3}$ (figure 3; $R^2 = 0.78$); the addition of Scope 3 did not change the correlation significantly. The further allocation of Scope 3 items based on use, i.e., when fuel refining is allocated to the community using the fuel rather than the city where the refinery is situated, reduced the correlation of GHG^{CIF,allocated}/GDP with UEI slightly (table 2; $R^2 = 0.71$). Most importantly, it should be noted that *GHG*^{CIF} *per capita* showed much poorer correlation with UEI for all variations of CIF: GHG$^{CIF\ Scopes\ 1+2}$; GHG$^{CIF\ Scopes\ 1+2+3}$, and GHG^{CIF,allocated} ($R^2 = 0.38$; $R^2 = 0.38$; $R^2 = 0.42$, respectively). See table 2.

For consumption-based footprints (CBF), GHG^{CBF} per unit GDP, showed relatively modest correlation the UEI

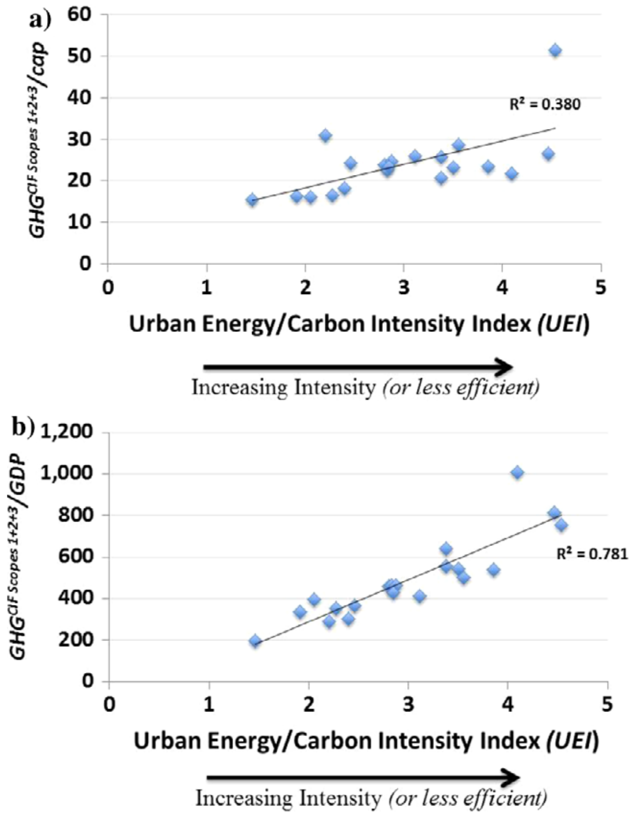

Figure 3. Correlation between community-wide infrastructure footprint (CIF) GHGs covering Scopes 1 + 2 + 3, expressed in different metrics versus an aggregate urban *energy/carbon intensity* index (UEI) of cities: (a) $GHG^{CIF\ Scopes1+2+3}$/resident (capita) versus UEI, and, (b) $GHG^{CIF\ Scopes1+2+3}$/GDP versus UEI. An increasing UEI index indicates higher intensity of energy use (or carbon use) in residential, transportation and commercial–industrial activities within a city, relative to other cities. The data are from models of 20 US cities of diverse economies, each modeled in a two-region MRIO with GHG intensity of electricity use in the different cities ranging from ±50% higher or lower compared to the larger economy.

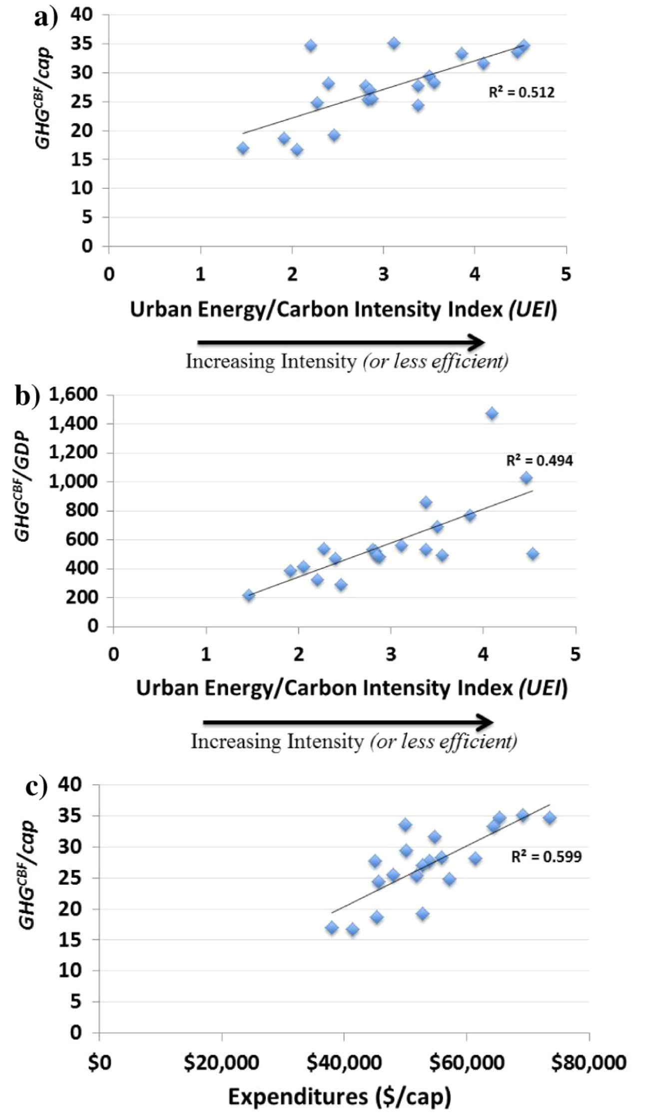

Figure 4. Correlation between consumption-based footprint (CBF) GHGs expressed in different metrics versus different parameters: (a) GHG^{CBF}/resident (capita) versus UEI, (b) GHG^{CBF}/GDP versus UEI, (c) GHG^{CBF}/capita versus expenditures per capita. An increasing UEI index indicates higher intensity of energy use (or carbon use) in residential, transportation and commercial–industrial activities within a city, relative to other cities. The data are from models of 20 US cities of diverse economies, each modeled in a two-region MRIO with GHG intensity of electricity use in the different cities ranging from ±50% higher or lower compared to the larger economy.

($R^2 = 0.49$) while GHG^{CBF} per capita showed a slightly higher $R^2 = 0.51$. However, strongest correlation is observed between GHG^{CBF}/capita and household expenditures ($R^2 = 0.6$), confirming that CBF more directly illustrates the willingness of different city's residents to consume (see figure 4).

All the above results obtained for a two-region MRIO model are summarized in table 2(a). The simpler case of SRIO also shows similar trends, shown in table 2(b). Bottom-up data analyzed—without IO modeling—also showed the same trends (results not shown here). Also, when the one outlier in figures 1–4 was removed—the basic conclusions of table 2 remained the same. We retain the outlier in the paper, since the purpose of the study is to assess if the metrics can be used to compare across widely different cities.

6. Conclusions and discussions

The results seen in figures 1–4 and table 2 are a function of coverage of local UEI features of cities by the different GHG accounting methods. For GHG^{IB}, electricity *use* in buildings and industry is not directly addressed since the focus is on GHGs from electricity generation; thus energy intensity of the housing stock and of the industrial–commercial sectors are not fully reflected in IB source-based GHG accounts. GHG^{CIF} addresses this deficiency by including electricity imports in Scope 1 + 2, thus addressing both household as well as commercial–industrial energy intensity since EUI in buildings always includes both electricity and (other) direct fossil fuel use. Likewise, transportation efficiency is also addressed in CIF, thus all three components of the

UEI are covered. Note, additions to CIF—e.g., cement and food production GHGs—do not improve the correlations significantly, since the efficient use of food or cement by cities is not a feature of the UEI. It is noteworthy that for all variations of CIF (see tables 2(a) and (b)) the GHG^{CIF}/GDP metric consistently shows much better correlation with UEI than the GHG^{CIF}/capita metric. This has important implications for comparing cities—our paper shows that all metabolic type GHG accounts (GHG^{IB}; $GHG^{CIF\ Scope\ 1+2}$; $GHG^{CIF\ Scope\ 1+2+3}$; $GHG^{CIF,\ allocated}$) are best represented as per GDP to facilitate cross-city comparisons.

In contrast, GHG^{CBF} is better represented as per capita—this metric is only modestly correlated with UEI, because of coverage. For our modeled cities, >20% (in consumer cities) to as much as 77% (in producer cities) of local community wide energy use (Scopes 1 + 2), is exported (Chavez and Ramaswami 2013b). Thus GHG^{CBF} covers household efficiency, transportation efficiency mostly related to resident travel, and only a portion of a city's commercial–industrial activities (efficiency of exporting businesses are not covered by GHG^{CBF}). On the other hand, GHG^{CBF} covers imports from the larger economy to serve local resident consumption, which ranges from 29% to 81% in the different cities (Chavez and Ramaswami 2013b). Consequently GHG^{CBF}/capita is more weakly correlated with the city's local UEI features.

The major conclusion of this paper is that a dual approach of GHG accounting for cities, with CIF and a separate CBF, as is being recommended by ICLEI-USA and BSI, demands different metrics. Our modeling of 20 US cities shows the GHG^{CIF} (all metabolic community-wide GHG accounts) are best represented as per unit GDP. Representing metabolic energy flows on a per capita basis is not recommended as it inadvertently portrays each city as an 'unsustainable parasite' assigning all material-energy in-flows to the resident such that the city is not understood to produce anything useful. Furthermore, GHG^{CIF}/GDP much better reflects a city's local or regional energy and carbon intensity features compared to GHG^{CIF}/capita. Thus we conclude the per capita metric is best reserved for GHG^{CBF}.

Our paper suggests that using the appropriate GHG accounting method (CIF) with the suitable normalization (per unit GDP) is important to better uncover relationships with urban form; the per GDP metric has the added advantage that downturns in the economy are readily accounted for. Tracking energy intensity in individual sectors (buildings, transportation) can also be helpful both in cross-city comparisons and in tracking a city's energy performance over time.

While city-scale IO modeling is not an accurate tool for representing each cities' GHG emissions perfectly, we apply it in this paper not for representing each city, but for representing *different city trade-typologies*, and for comparing different methods and metrics with each other for the same set of cities. Such modeling helps understand how much local resident consumption depends on imports, and how much local energy use is exported (Chavez and Ramaswami 2013b). Such IO modeling is also the only way to answer questions such as—is there a benefit of allocating the Scope 3 inclusions based on their use in cities? Our results seem to suggest that $GHG^{CIF\ Scope1+2}$/GDP may suffice for cross-city comparisons, the addition of Scope 3 items is useful to report and can support holistic consideration of a city's infrastructure provisions.

Additional work can further refine the initial explorations presented here. Different weighting of the three main attributes of the UEI can be explored, as well as alternate approaches to represent transportation system efficiency at the finer scale of individual cities within a region. Household consumption expenditures for road transportation must also be explored further to include travel not only regionally but anywhere worldwide. Despite these limitations, we believe this paper offers important overall insights on reporting city GHG emissions—clarifying what is covered and not in the different approaches, and indicating that the choice of per capita and per GDP metrics can be quite significant. Our results suggest cities should use GHG per capita metrics for consumption-based accounts and GHG per GDP metrics for the infrastructure-supply chain accounts. These insights advance our understanding of the methods and metrics used to represent the energy and GHG performance of cities.

Acknowledgments

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