Environ. Sci. Technol. **2009,** *43,* 7297–7302

Greenhouse Gas Emissions from Global Cities

CHRISTOPHER KENNEDY,[*,†]
JULIA STEINBERGER,[‡] BARRIE GASSON,[§]
YVONNE HANSEN,[||] TIMOTHY HILLMAN,[⊥]
MIROSLAV HAVRÁNEK,[#] DIANE PATAKI,[∇]
AUMNAD PHDUNGSILP,[○]
ANU RAMASWAMI,[◆] AND
GARA VILLALBA MENDEZ[+]

Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto M5S 1A4 Canada, Vienna Institute of Social Ecology, IFF, University of Klagenfurt, Schottenfeldgasse 29, 1070 Vienna, Austria, School of Architecture and Planning, University of Cape Town, 7701 Rondebosch, Cape Town, South Africa, African Centre for Cities, University of Cape Town, 7701 Rondebosch, Cape Town, South Africa, Department of Civil Engineering, University of Colorado Denver, Campus Box 113, P.O. Box 173364, Denver, Colorado 80217-3364, Charles University Environment Center, U Krize8, 15000 Prague, Czech Republic, Department of Earth System Science and Department of Ecology & Evolutionary Biology, University of California, Irvine, Irvine, California 92697-3100, Department of Energy Management, Dhurakij Pundit University, 110/1-4 Prachachuen Road, Laksi, Bangkok 10210, Thailand, Department of Civil Engineering, University of Colorado Denver, Campus Box 113, P.O. Box 173364, Denver, Colorado 80217-3364, and Institut de Ciència i Tecnologia Ambientals, Autonomous University of Barcelona, Edifici Cn 08193 Bellaterra, Barcelona, Spain

Received January 21, 2009. Revised manuscript received August 17, 2009. Accepted August 20, 2009.

The world's population is now over 50% urban, and cities make an important contribution to national greenhouse gas (GHG) emissions. Many cities are developing strategies to reduce their emissions. Here we ask how and why emissions differ between cities. Our study of ten global cities shows how a balance of geophysical factors (climate, access to resources, and gateway status) and technical factors (power generation, urban design, and waste processing) determine the GHGs attributable to cities. Within the overall trends, however, there are differences between cities with more or less public transit; while personal income also impacts heating and industrial fuel use. By including upstream emissions from fuels, GHG emissions attributable to cities exceed those from direct end use by up to 25%. Our findings should help foster intercity learning on reducing GHG emissions.

* Corresponding author phone: 416-978-5978; e-mail: christopher.kennedy@utoronto.ca.
† University of Toronto.
‡ University of Klagenfurt.
§ School of Architecture and Planning, University of Cape Town.
|| African Centre for Cities, University of Cape Town.
⊥ Department of Civil Engineering, University of Colorado Denver.
Charles University Environment Center.
∇ University of California.
○ Dhurakij Pundit University.
◆ Department of Civil Engineering, University of Colorado Denver.
+ Autonomous University of Barcelona.

Introduction

With anthropogenic releases of greenhouse gases (GHG) contributing toward global climate change, many governments and organizations are seeking measures to reduce emissions. Prominent among these are cities. Not only are cities a major driver of GHG emissions, but some perhaps have the knowledge, creativity, and resources to reduce them. Cities may also learn by examining and adapting the strategies of other cities. For such a process to be successful, however, it is necessary for cities to have reliable GHG inventories and to understand how and why their emissions differ.

A central concept in the scientific study of cities is that of urban metabolism (*1, 2*). The metabolism of a city can be interpreted either primarily in terms of energy flows (*3*) or more broadly including a city's flows of water, materials, and nutrients (*2*). Through studies of urban metabolism, scientists have developed an understanding of phenomena such as ecosystem appropriation by cities (*4*); the accumulation of toxic materials in the urban building stock (*5*); historical growth in the transportation of materials (*6*); and economies of scale for urban infrastructure systems (*7*). A key issue for urban ecology, however, is the lack of reliable, published data on comprehensive energy use in cities. Data for some components are available, e.g., for urban transportation (*8*) or electricity (*7*). Reviews by Decker et al. (*9*) and Kennedy et al. (*10*) found a paucity of data on overall urban energy consumption. The first challenge of our work in comparing GHG emissions between cities was to establish consistent data on energy use by cities.

The objective of this work, to understand how and why urban GHG emissions differ, has partially been assisted by the activities of municipal governments. Many cities have used frameworks such as that of the International Council for Local Environmental Initiatives (ICLEI, (*11*)) to quantify their emissions. Comparative studies of cities have shown aggregate urban GHG inventories to vary between 3 and 22 t eCO_2 per capita (*12, 13*). There are, however, several technical issues with attributing GHG emissions to cities, including problems with defining spatial and temporal contexts, and lack of full life-cycle perspective (*14*). Moreover, these previous studies of urban GHG emissions did not compare the components of urban GHG inventories by a consistent methodology. We aim to understand how components such as heating, transportation, waste, etc. contribute to urban GHG emissions.

The methodology for this study has been reported elsewhere (*15*), so only salient details are given here. The global warming potential, expressed in carbon dioxide equivalents (t e CO_2), is determined for seven components of urban inventories: electricity, heating and industrial fuels, industrial processes, ground transportation, aviation, marine, and waste. (Note that energy consumption is generally accounted by fuel type, rather than by sector.) Emissions are calculated for ten cities (or metropolitan regions), which vary in population from 432,000 to 9,519,000 (Table 1); hence they are compared in per capita terms. Some are cities which have been the subject of urban metabolism studies: Los Angeles County (*16*), Greater Toronto (*17*), Geneva Canton (*18*), Greater Prague (*19*), and Cape Town (*20*). Others have had their urban energy use or GHG emissions previously quantified: Denver City and County (*21*), New York City (*22*), Greater London (*23*), Barcelona (*13*), and Bangkok (*24*). Results are first given for GHG emissions from an end-use perspective, which include those that occur outside the boundaries of the cities (e.g., from power generation, air and

10.1021/es900213p CCC: $40.75
Published on Web 09/02/2009

TABLE 1. Definition and Characteristics of the Ten Cities or City—Regions of This Study[a]

	year	population	total land area (km^2)	density of urbanized area (persons/km^2)	heating degree days	per capita income (PPP $U.S. in the study year)
Bangkok (city)	2005	5,658,953	1569	8084	0	7560
Barcelona (city)	2006	1,605,602	100	19,509	1295	27,403
Cape Town (city)	2005	3,497,097	2454	12,059	1013	9035
Denver (city and county)	2005	579,744	397	1558	3425	42,476
Geneva (Canton)	2005	432,058	282	10,829	2902	32,110
London (GLA)	2003	7,364,100	1579	10,505	2559	38,066
Los Angeles (county)	2000	9,519,338	10,518	1616	691	31,049
New York City	2005	8,170,000	789	10,350	2372	46,221
Prague (GPR)	2005	1,181,610	496	9741	3550	21,595
Toronto (GTA)	2005	5,555,912	7195	3677	3722	33,529

[a] Density of urbanized area is calculated using urbanized areas from the Millennium Cities Database (*8*), except for Barcelona, Denver, LA, NYC, and GTA, which are from local sources. Heating degree days are from http://www.degreedays.net/. Except for London and Geneva, which are calculated from ref *8*, pretax per capita income are from national statistical agencies with conversion to PPP $U.S. from http://www.econstats.com/weo/V013.htm.

marine). In totalling the emissions for each city, two further measures are also given: the emissions that only occur within the borders of the cities and a broader measure including the upstream lifecycle emission for fuels used in the cities.

Electricity

GHG emissions from electricity depend on the amount consumed and the GHG intensity of the supply. Electricity consumption for seven of the ten cities is within a range of 4.5 to 7 MWh/cap. (Table S1). This electricity consumption is for all types of end-use: residential (including resistive heating), commercial, industrial and transportation, but excluding that from combined heat and power plants in the city. Denver (11.49 MWh/cap.) and Toronto (10.04 MWh/cap.) have substantially higher per capita consumption, while Cape Town has the lowest at 3.49 MWh/cap., possibly related to lower average household income. The higher consumption in Denver and Toronto may possibly be due to high commercial and industrial contributions, as well as climate. For example, Denver's residential electricity use per capita is 40% lower than the U.S. national average. Residential electricity use represents 34% and 21% of the total electricity used in Denver and the City of Toronto, respectively.

A more important determinant of GHG emissions from electricity is the GHG intensity, or emissions factor, of the supply mix. Some cities rely on their national, state, or provincial grids; while others have some control over their local supply or purchase electricity on international markets (see ref *15*, for references to GHG intensity of supply). With 92% of South Africa's electricity generated from combustion of coal, Cape Town has the highest intensity of 969 t e CO_2/GWh (Table S1). At the opposite end, Geneva's supply mix, based primarily on hydropower, has an intensity of just 54 t e CO_2/GWh, including line losses. In some respects, Geneva might be considered to have almost zero emissions from electricity; it exports hydro power, but has small emissions from the purchase of 380 GWh of electricity from a combined cycle natural generating facility in Luxembourg.

The GHG emissions attributable to electricity consumption for the ten cities display a wide range (Figure 1). With relatively high consumption and a high intensity (792 t e CO_2/GWh), Denver has GHG emissions that are almost a factor of 3 higher than the next city. Emissions from seven of the ten cities fall within the narrow range of 2.46 to 3.38 t e CO_2/cap. Toronto's high consumption is mediated by low intensity, while Cape Town's low consumption is mediated by high intensity. With access to nearby hydropower, the lowest electricity emissions are those for Geneva at 0.35 t e CO_2/cap., a factor of 26 less than Denver.

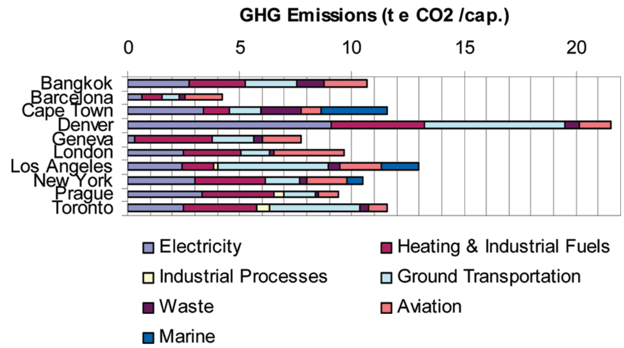

FIGURE 1. Summary of direct GHG emissions attributable to ten global cities.

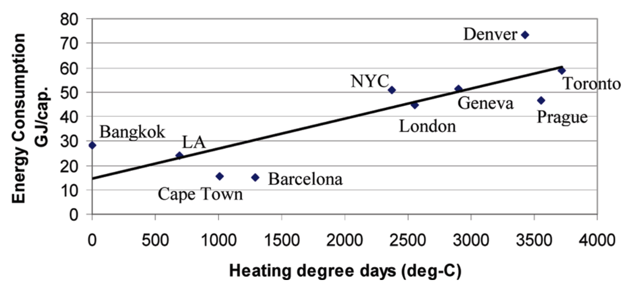

FIGURE 2. Energy consumption from heating and industrial fuels increases with heating degree days (based on an 18 °C base temperature).

Heating and Industrial Fuel Use

The consumption of fuels for heating and industry (i.e., stationary combustion in all sectors excluding electricity) corresponds quite closely to heating degree days (using an 18.0 °C base temperature). This category excludes electricity used for heating. The linear fit in Figure 2 has a statistically significant gradient (t stat = 4.28) and an R^2 of 0.70 (Table 2). Denver and Toronto have the greatest consumption at 73.5 and 58.9 GJ/cap., respectively, while Cape Town and Barcelona each consumes less than 16 GJ/cap. Notably, all three U.S. cities lie above the best-fit line, perhaps due to larger house sizes (discussed further below) or the quality of building envelopes. Also above the line is Bangkok, which has zero heating degree days below 18.0 °C. Its relatively high fuel consumption in this category is primarily for industrial processes; only 5% of Bangkok's 28.4 TJ/cap. is for residential use. Note also that Figure 2 does not include electric resistive heating. While heating degree days largely explain the differences in consumption between cities, there

TABLE 2. Regression Analyses for Heating and Industrial Fuel Energy Use and GHG Emissions from Transportation Fuels

variable	coefficient	t stat	95% CI
Heating and Industrial Fuel Energy Use ($R^2 = 0.74$)			
constant	8.208	0.892	−13.54 to 29.96
heating degree days	0.01005	2.845	0.00170 to 0.0184
av. personal income	0.000384	1.072	−0.000464 to 0.00123
Heating and Industrial Fuel Energy Use ($R^2 = 0.70$)			
constant	14.50	2.030	−1.975 to 30.98
heating degree days	0.0123	4.281	0.00567 to 0.0189
Heating and Industrial Fuel Energy Use Excluding Bangkok ($R^2 = 0.90$)			
constant	−9.721	−1.210	−29.39 to 9.94
heating degree days	0.0129	5.299	0.00693 to 0.0188
av. personal income	0.000681	2.746	7.413×10^{-05} to 0.00129
Log GHGs from Transportation Fuels ($R^2 = 0.94$)			
constant	8.559	5.975	5.172 to 11.95
log urbanized density	−0.769	−10.04	−0.950 to −0.588
log av. personal income	−0.103	−0.969	−0.354 to 0.148
Log GHGs from Transportation Fuels ($R^2 = 0.93$)			
constant	7.321	11.36	5.835 to 8.808
log urbanized density	−0.747	−10.26	−0.914 to −0.579

is some variability, likely associated with differences in industrial fuel consumption and building characteristics.

Further regression analysis was also conducted to establish whether average per capita income influenced fuel consumption for heating and industry. Per capita income expressed in purchasing power parity dollars (Table 1) was included in a regression with heating degree days but was statistically insignificant (t stat = 1.07). Removing Bangkok from the regression, however, due to its lack of heating degree days and low residential consumption, produced a better fit ($R^2 = 0.90$, Table 2). In this improved model, per capita income was significant (t stat = 2.75), though still secondary to heating degree days.

Other socioeconomic factors, such as the price of energy, might also impact heating/industry fuel use; however, this would require further study, including construction of a suitable price index reflecting all energy sources and differential prices between end-users.

The GHG emissions for heating and industrial fuel use largely follow the same pattern as energy consumption (Table S2), the main exception being with Prague. The Czech capital gets 15% of its heating directly from coal, and a further 17% from a heat pipe that is powered by coal. So while Prague uses less heating fuel energy per capita than New York City, it jumps above in terms of emissions per capita, due to the higher emissions intensity of coal. To a lesser extent Cape Town and Geneva also have slightly elevated emissions due to their predominant use of oil heating, relative to the other cities that primarily use natural gas.

Note that the industrial emissions considered so far are only those associated with end use of energy. Direct emissions from industrial processes, especially cement manufacture, were determined for Los Angeles, Prague, and Toronto. These add between 0.22 and 0.57 t eCO_2/cap. to the cities inventories (Table S5).

Transportation

Ground transportation emissions were determined for combustion by vehicles within the area boundaries, thus excluding electrical forms of transportation. The GHG emissions were calculated based on fuel sales data, vehicle kilometers traveled, or by scaling from a regional level; these three approaches were found to differ by less than 5% (*15*).

Inverse relationships between urban transportation energy use and population density have been empirically established (*8, 25*), although they continue to be critiqued

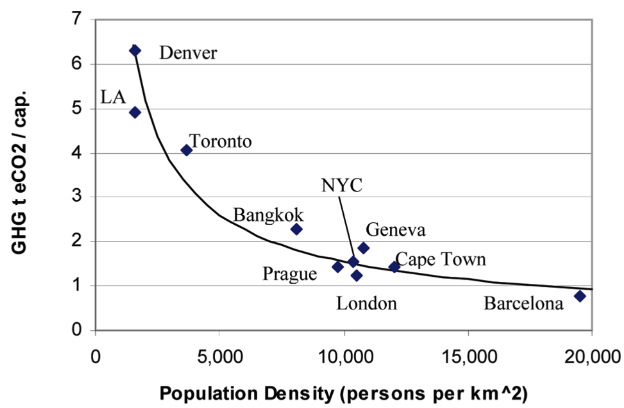

FIGURE 3. GHG emissions from ground transportation fuels are inversely related to population density.

(see refs *26 and 27* among others). Since GHG emissions from ground transportation are highly dependent on the use of fossil fuels, earlier conclusions on the density dependence of transportation energy on urban density carry across to GHG emissions (Figure 3). The logarithm of urbanized density has a statistically significant fit (t stat = −10.26) against the logarithm of GHG emissions from transportation fuels with an R^2 of 0.93 (Table 2). The logarithm of average personal income is statistically insignificant (t stat = −0.35). The findings in Figure 3 are quite familiar, with the three lower density North American cities (excluding New York City) having substantially higher GHG emissions than the other cities. Denver's per capita emission from ground transportation fuels of 6.31 t e CO_2 are a factor of 8 higher than those of Barcelona at 0.77 t e CO_2 (Table S3).

In the long-run, over several decades, the North American cities might ideally reduce per-capita emissions by pursuing smart growth policies that increase population density in tandem with design and diversity of transport options. The line of best fit in Figure 3 shows that a doubling of density from 2500 to 5000 persons per sq km corresponds with a 40% decrease in GHG emissions (from 4.4 to 2.6 t e CO_2). This 40% reduction in GHGs is consistent with the U.S. DOT's (2004) observation on the impacts of land use density on vehicle miles traveled (*28*).

Of course, there is also variation in GHG emissions between cities of similar densities. Denver's ground transportation emissions are 2.26 t eCO_2/cap. higher than those

TABLE 3. Total GHG Emissions, Including End-Use, Life Cycle, and within City Measures

	emissions within city t e CO_2/cap.	emissions from end-use activities t e CO_2/cap.	end-use emissions including life-cycle emissions for fuels t e CO_2/cap.
Bangkok	4.8	10.7	not determined
Barcelona	2.4	4.2	4.6
Cape Town	not determined	11.6	not determined
Denver	not determined	21.5	24.3
Geneva	7.4	7.8	8.7
London	not determined	9.6	10.5
Los Angeles	not determined	13.0	15.5
New York City	not determined	10.5	12.2
Prague	4.3	9.4	10.1
Toronto	8.2	11.6	14.4

of Toronto; Geneva's are 0.63 t eCO_2/cap. higher than those of London (Table S3). Some of this variation may be due to differences in vehicle fuel economy. Much will also depend on the extent of automobile use, which reflects the quality of public transit, land-use planning, and government policy (*29*). Toronto's automobile mode share (percentage of all trips by motorized private mode) is 79% compared to 92% in Denver; Geneva's is 55% compared to 49% for London (*8*).

By including emissions from air and marine travel, this study goes beyond the activities that occur in the cities and considers travel between urban centers that happens on a global scale. The calculated emissions are those from combustion of fuels loaded onto the airplanes and ships at the cities' airports and harbors (Table S5). Only airports within the city boundaries are included (e.g., Heathrow and City airport are included for London but not Gatwick and Stansted). In the case of Denver, Ramaswami et al. (*21*) have determined that 22% of the fuel loaded at Denver International Airport is associated with trips made to or from the central city. It is possible that the GHG emissions determined for the other nine cities exceed those that could be attributable to residents of the cities, as the airports also serve wider regions and connecting passengers. There again, the gateway function of a city does contribute to its economy, providing jobs and contributing to agglomeration effects.

The GHG emissions for air and marine generally reflect each city's gateway status. London has the highest emissions for air transportation at 3.12 t e CO_2/cap., with New York City also high. The relatively high emissions for Geneva (1.72 t e CO_2/cap.) might reflect its role as an international organizational center. Of the port cities, Cape Town has the highest GHG emissions for freight, at 2.92 t e CO_2/cap. This likely reflects its key location at the Cape of Good Hope for refuelling of ships passing between the Atlantic and Indian Oceans.

Waste

Methane emissions from landfill waste for all cities were established using a total yield gas (TYG) approach, similar to that recommended by the IPCC in 1996 (*30*). Where data are available, a first order decay (FOD) approach may be preferable (*28*). Using the former approach, the degradable organic content (DOC) for wastes in most cities was calculated to be around 0.2 t C/t waste (Table S4). The exceptions were London (0.07 t C/t waste), which incorporated a large fraction of construction waste, and Cape Town (0.28 t C/t waste) which included a high content of waste paper. In the case of Prague, the calculated DOC value (0.19 t C/t waste) is high relative to a measured value of 0.08 t C/t waste (*32*). This suggests that the approach taken may overestimate emissions.

The most significant determinant of the landfill GHG emissions is, however, the methane recovery factor. For Bangkok and Cape Town, which currently have no methane capture, GHG emissions are over 1 t e CO_2/cap. (Table S4). For the other eight cities, for which methane recovery factors of around 75% are expected, the emissions from waste are all below 1 t e CO_2/cap. As discussed in the methodology paper, however, there is uncertainty as to what levels of methane recovery are achieved (*15*). From a pragmatic perspective, this means that not much is gained by using an FOD approach, until better measurement of methane recovery is achieved.

There is also some scientific debate as to the extent that landfills sequester carbon that would otherwise be emitted to the atmosphere (*31*). Using ICLEI's approach, which accounts for a greater amount of carbon sequestration, Denver's GHG emissions from waste have alternatively been calculated as -0.3 t e CO_2/cap., i.e., the landfill is seen as a sink. This is in contrast to a value of $+0.59$ t e CO_2/cap. by the method in this study (Table S4). The contribution of waste is thus uncertain in a city's GHG inventory, although as the following totals show, waste is a minor contributor to the emissions from most cities.

Total Emissions

The total end use emissions for the ten cities range between 4.2 and 21.5 t e CO_2/cap. (Table 3). With high population density, low heating requirements, and relatively clean electricity, Barcelona has the lowest per capita emissions. Whereas Denver, having the highest per capita emissions for electricity, heating/industrial fuels, and ground transportation is, not surprisingly, the top emitter. The next two highest cities are also both North American: Los Angeles (13.0 t e CO_2/cap.) and Toronto (11.6 t e CO_2/cap.). Other than Geneva at 7.8 t e CO_2/cap., the other cities all have emissions fairly close to 10 t e CO_2/cap. These values for end use emissions are typical of those reported by municipal governments.

The actual physical emissions that occur within city boundaries are lower than the emissions attributable to end-use in cities. In most cases the GHG emissions associated with electricity used in cities occur outside; the main exception is Barcelona which has natural gas power plants within its borders (as well as importing). In the case of Prague, a heat pipe provides 17% of the city's heating requirements, with the GHG emissions from the combustion of coal occurring some 60 km away. The GHG emissions from landfill waste also occur outside of city boundaries in some cases; part of Toronto's landfill waste is currently trucked to Michigan. For the five cities for which we determined the emissions within city boundaries, these were found to be between 45% and 95% of end-use emissions (Table 3). Nevertheless, it is appropriate to attribute more than just the within-boundary emissions to cities, as the consumption activities located in the cities cause the emissions.

If emissions are to be attributed to cities based on consumption activities, however, then a fuller lifecycle perspective should be taken. Beyond the GHGs emitted during the combustion of fossil fuels, for example, there are emissions produced from the extraction, processing, and transportation of these fuels to cities. Table 3 shows the impact of adding these upstream emissions for heating, industrial, and all transportation fuels used for eight of the cities. The life-cycle emissions are between 7% and 24% higher than the direct emissions for the cities. The greatest changes in life-cycle emissions are observed for the North American cities, since they have higher upstream GHG intensity factors (*15*). Emissions for Denver increase by 2.8 t e CO_2/cap. to 24.3 t e CO_2/cap. Moreover, Ramaswami et al. (*21*) found that Denver's life-cycle emissions increase by a further 2.9 t e CO_2/cap., when upstream embodied emissions for food and cement are included. What this life-cycle analysis shows is that the GHG emissions attributable to cities are higher than recognized in public debate.

Discussion

This study of ten global cities has shown how the metabolism and GHG emissions of a city are strongly dependent upon its location. Climate, in particular heating degree days, is currently an important determinant of the amount of energy required to heat urban buildings (although this could change with tighter building envelopes). Moreover, the location of a city often determines its status as a gateway, thereby explaining emissions arising from airplanes and shipping. Others have shown that household electricity use in U.S. cities rises sharply with average July temperature (*33*). A more significant determinant of GHGs from electricity, however, is the means of power generation — and this too can be influenced by location. Access to hydropower, as in the cases of Geneva and Toronto, substantially reduces the intensity of emissions from these cities. Prague, on the other hand, lies close to some of the thickest coal seams in Europe.

Urban form also has a strong bearing on urban metabolism. As previous researchers have shown, transportation energy use is inversely correlated with urban population density. The analysis of the ten cities here shows that such a relationship also holds for GHG emissions. The density of a city can, of course, itself be a result of other factors, such as the age of the city, fuel prices, or simply the availability of land upon which to grow.

Another major determinant of urban GHG emissions is technology. Emissions from waste disposal may be a minor contribution to the inventories of most of the cities studied here, but for Bangkok and Cape Town, for which methane capture technology is absent, waste emission are over 1 t e CO_2 per capita. Several of the cities, including Barcelona, New York City, and Toronto, also consume electricity from local or regional nuclear power, thereby decreasing their potential emissions. Given that the locations of cities are fixed and that increased population density may take many years, technology may have to play a major role in reducing the GHG emissions from cities.

There are also economic factors at play as well. Personal income was found to influence heating and industrial fuel use (when Bangkok was excluded from the model). Higher income may translate into larger house sizes or impact the temperature threshold at which heating is switched on. Income is also closely tied to metropolitan product; thus the increase in heating and industrial fuel use with income may also reflect activity in the commercial sector. More broadly though, the GHG emissions from aviation and marine fuels are also largely tied to economic activity. The emissions from combustion of fuels loaded onto planes and ships are, to some extent, measures of a city's status as a global service center or its participation in the global trading network.

The policy implications of this study are potentially numerous but can only be briefly addressed here. First the inventorying procedure itself is useful. For example, to support California's Global Warming Solutions Act (AB32), the state and local governments, such as Los Angeles, require methods for estimating emissions, information about the major sources, and comparative data across different cities and regions. By developing an inventorying procedure broadly based on a city's metabolism, we include components such as aviation and marine that are beyond the control of local governments. This may cause debate in the City of Cape Town, as our emissions value is much higher than the city's current estimate. Our inventorying procedure encourages cities to recognize more broadly the impacts of their activities on GHG emissions.

As cities seek to reduce emissions by learning from the best practices of other cities, the understanding that this analysis provides may be of benefit. What this comparison of cities perhaps suggests is that cities may learn best from cohorts with similar geophysical environments. With a warm Mediterranean climate and a dense urban form, Barcelona has the lowest emissions of the ten cities. A high-emitting city like Denver, however, might learn more by comparing its metabolism with a city such as Toronto, which has a more similar climate and is closer in terms of population density than Barcelona. Other potential partner cities can also be identified. London and New York City also have similar densities and heating degree days; they should be comparing each others building codes and other policies to attract alternative energy technologies and sustainable transportation.

Different cities might learn different things from this study. For instance, it could be concluded that reducing electricity demand in Geneva, with low emissions intensity, would be a waste of resources, but reducing electricity demand in Cape Town, Denver, or Prague, which have high intensities, could yield substantial return in emissions reduced.

For cities such as Denver, Los Angeles, and Toronto, the geography of low density poses a particular challenge. These newer cities may need to evolve over time to support smart growth with the multiple objectives of regional accessibility (to jobs), density (population density), design (multimodal system design), and diversity (land use diversity). Plans for such smart growth now and in the future are in place in many communities in Denver (e.g., Blueprint Denver) and in the wider region. The challenge faced is not simply one of increasing density but one of understanding the complexities of spatial location of homes and work-places (*34*). Denver's situation is shared by other U.S. cities; its emissions, with life-cycle inclusions, are similar to the U.S. average per capita.

Even Barcelona, which does well in comparison with the other cities, still has to stop its emissions from increasing. As a gateway city, Barcelona should pay close attention to its airport, which has the highest percentage of emissions, and its marine port (emissions yet to be established). In the very near future, the city of Barcelona will have two combined cycle power plants of 425 MW each (within city limits), bringing generation closer to the point of consumption and thereby reducing life-cycle emissions for electricity use. This is important since electricity consumption in Barcelona has increased during the last 10 years, in part due to greater use of air conditioning. Future electricity use in Barcelona is expected to rise further because of increased use of air conditioning, especially due to climate change, and because many technologies to substitute petroleum rely on electricity.

Where cities are able to reduce their emissions, a positive finding from this analysis is that they will actually reduce them by more than their current inventorying methods suggest. Upstream emissions such as due to the extraction, processing, and transporting of fossil fuels are not currently counted in the inventories of most cities. The upstream emissions for fuels added between 7% and 24% to the end-use emission totals. If the amounts of fossil fuels combusted in cities are reduced, however, then so will be the upstream emissions.

Overall, we have shown how and why GHG emissions differ for a wide variety of cities. The consistency of our methodology, described elsewhere (*15*), enables us to draw attention to some important factors, which may allow cities to understand and potentially reduce their emissions. We have shown how a balance of geophysical factors (climate, access to resources and gateway status) and technical factors (power generation, urban design, and waste processing) determine the GHGs attributable to cities. Within these overall trends, however, there are differences between cities with more or less public transit as well as in heating (building codes, size of dwelling), which need elucidating with further research.

Acknowledgments

The assistance of Julius Mattai of the Greater London Authority, Jonathan Dickinson of the City of New York, and two reviewers is greatly appreciated. Julia Steinberger was supported by the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement 212034. The GHG accounting for Denver was supported by grants from the U.S. Department of Education GAANN Program and the City and County of Denver.

Supporting Information Available

Detailed GHG emissions by subsectors: S1 electricity; S2 heating and industrial fuels; S3 road transportation; S4 waste; S5 aviation, marine, and industrial processes. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Wolman, A. The metabolism of cities. *Sci. Am.* **1965**, *213*, 179–190.
(2) Baccini, P.; Brunner, P. H. *Metabolism of the Anthroposphere*; Springer-Verlag: Berlin, 1991.
(3) Odum, H. T. *Systems Ecology: An Introduction*; Wiley: New York, 1983.
(4) Folke, C.; Jansson, Å; Larsson, J.; Costanza, R. Ecosystem appropriation by cities. *Ambio* **1997**, *26*, 167–172.
(5) Brunner, P. H.; Rechberger, H. Anthropogenic metabolism and environmental legacies. In *Encyclopedia of Global Environmental Change*; Munn, T., Ed.; Wiley: U.K., 2001; Vol. 3.
(6) Fischer-Kowalski, M.; Krausmann, F.; Smetschka, B. Modelling scenarios of transport across history from a socio-metabolic perspective. *Rev. - Fernand Braudel Center* **2004**, *27*, 307–342.
(7) Bettencourt, L.; Lobo, J.; Helbing, D.; Kuhnert, C.; West, G. B. Growth innovation scaling and the pace of life in cities. *Proc. Natl. Acad. Sci. U.S.A.* **2007**, *104*, 7301–7306.
(8) Kenworthy, J. R.; Laube, F. B.; Vivier, J. *The Millennium Cities Database for Sustainable Transport*; International Union of Public Transport: Brussels, 2001..
(9) Decker, H.; Elliott, S.; Smith, F. A.; Blake, D. R.; Sherwood Rowland, F. Energy and material flow through the urban ecosystem. *Annu. Rev. Energy Environ.* **2000**, *25*, 685–740.
(10) Kennedy, C. A.; Cuddihy, J; Engel Yan, J. The changing metabolism of cities. *J. Ind. Ecol.* **2007**, *11*, 43–59.
(11) ICLEI (2008). Cities for Climate Protection, Toronto, Canada: International Council of Local Environmental Initiatives. Available at http://www.iclei.org/index.php?id=800 (accessed July 22, 2008).
(12) Harvey, L. D. D. Tackling urban CO2 emissions in Toronto. *Environment* **1993**, *35* (7), 16–20, and 33−44.
(13) Baldasano, J. M.; Soriano, C.; Boada, L. Emission inventory for greenhouse gases in the City of Barcelona, 1987−1996. *Atmos. Environ.* **1999**, *33*, 3765–3775.
(14) Kennedy, C. A.; Mohareb, E. Greenhouse Gas Emissions from Cities. Chapter 7 In *Cities in Evolution: Urbanization, Environmental Change and Sustainability*; Bai, X., Graedel, T.,Morishima, A., Eds.; Cambridge University Press:in press, 2009.
(15) Kennedy, C.; Steinberger, J.; Gasson, B.; Hillman, T.; Havránek, M.; Pataki, D.; Phdungsilp, A.; Ramaswami, A.; Villalba Mendez, G. Methodology for inventorying greenhouse gas emissions from global cities. *Energy Policy*, in press.
(16) Ngo, N. S.; Pataki, D. E. The energy and mass balance of Los Angeles County. *Urban Ecosyst.* **2008**, *11*, 121–139.
(17) Sahely, H. R.; Dudding, S.; Kennedy, C. A. Estimating the urban metabolism of Canadian cities: GTA case study. *Can. J. Civ. Eng.* **2003**, *30*, 468–483.
(18) Emmenegger, M. F.; Frischknecht, R.; Cornaglia, L.; Rubli, S. Métabolisme des activités économiques du Canton de Genève −Phase 1, Rapport final, 2003.
(19) CUEC: Charles University Environment Center. Socio-economic Metabolism of Urban Systems and Its Impact on Ecosystems (ongoing project 2B06183, 2008).
(20) Gasson, B. The ecological footprint of Cape Town: Unsustainable resource use and planning implications, paper presented at the SAPI International conference: Planning Africa, Durban, South Africa, 17−20 September, 2002.
(21) Ramaswami, A.; Hillman, T; Janson, B.; Reiner, M.; Thomas, G. A demand-centered, hybrid life cycle methodology for city-scale greenhouse gas emissions. *Environ. Sci. Technol.* **2008**, *42*, 6455–61.
(22) New York City. *Inventory of New York City Greenhouse Gas Emissions*; Mayor's Office of Operations, Office of Long-term Planning and Sustainability, 2007.
(23) Mayor of London. *London Energy and CO2 Emissions Inventory 2003: Methodology Manual*; 2006.
(24) Phdungsilp, A. Energy Analysis for Sustainable Megacities, Licentiate of Engineering Thesis, Department of Energy Technology, Royal Institute of Technology, Sweden, 2006.
(25) Newman, P.; Kenworthy, J. *Cities and Automobile Dependence: An International Source Book*; Avebury: Aldershot, U.K., 1991.
(26) van de Coeveringa, P.; Schwanenb, T. Re-evaluating the impact of urban form on travel patterns in Europe and North-America. *Transp. Policy* **2006**, *13* (3), 229–239.
(27) Rickwood, P.; Glazebrook, G.; Searle, G. Urban Structure and Energy−A Review. *Urban Policy Res.* **2008**, *26* (1), 57–81.
(28) U.S. DOT (United States Department of Transportation), Federal Highway Administration Emissions Benefits of Land Use Planning Strategies, FHWA TOPR 29, 2004..
(29) Kennedy, C. A.; Miller, E.; Shalaby, A.; MacLean, H.; Coleman, J. The four pillars of sustainable urban transportation. *Transp. Rev.* **2005**, *25*, 393–414.
(30) Intergovernmental Panel on Climate Change. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories;* 1997.
(31) IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Japan, 2006.
(32) Straka, F.; Musilová, M.; Crha, J.; Pavlas, M. *Emissions of greenhouse gases from wastes in the territory of CR in 1996* (in Czech); Institute for Research and Use of Fuels, Prague-Běchovice for CHMI: Prague, 1997.
(33) Glaeser, E. L.; Khan, M. E. *The Greenness of Cities: Carbon Dioxide Emissions and Urban Development, National Bureau of Economic Research*; Working Paper 14238. August 2008.
(34) Hillman, T.; Janson, B.; Ramaswami, A. Spatial Allocation of Transportation Greenhouse Gas Emissions at the City Scale. ASCE J. Transp. Eng., in review, submitted March 2009.

ES900213P