Energy and material flows of megacities

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Understanding the drivers of energy and material flows of cities is important for addressing global environmental challenges. Accessing, sharing, and managing energy and material resources is particularly critical for megacities, which face enormous social stresses because of their sheer size and complexity. Here we quantify the energy and material flows through the world's 27 megacities with populations greater than 10 million people as of 2010. Collectively the resource flows through megacities are largely consistent with scaling laws established in the emerging science of cities. Correlations are established for electricity consumption, heating and industrial fuel use, ground transportation energy use, water consumption, waste generation, and steel production in terms of heating-degree-days, urban form, economic activity, and population growth. The results help identify megacities exhibiting high and low levels of consumption and those making efficient use of resources. The correlation between per capita electricity use and urbanized area per capita is shown to be a consequence of gross building floor area per capita, which is found to increase for lower-density cities. Many of the megacities are growing rapidly in population but are growing even faster in terms of gross domestic product (GDP) and energy use. In the decade from 2001–2011, electricity use and ground transportation fuel use in megacities grew at approximately half the rate of GDP growth.

sustainability | sustainable development | urbanization | urban metabolism | industrial ecology

The remarkable growth of cities on our planet during the past century has provoked a range of scientific inquires. From 1900–2011, the world's urban population grew from 220 million (13% of the world's population) to 3,530 million (52% of the world's population) (1, 2). This phenomenon of urbanization has prompted the development of a science of cities (3, 4), including interdisciplinary contributions on scaling laws (5, 6), networks (7), and the thermodynamics of cities (8, 9). The growth of cities also has been strongly linked to global challenges of environmental sustainability, making the study of urban energy and material flows, e.g., for determining greenhouse gas emissions from cities and urban resource efficiency (10–19), important.

At the pinnacle of the growth of cities is the formation of megacities, i.e., metropolitan regions with populations in excess of 10 million people. In 1970, there were only eight megacities on the planet (*SI Appendix*, Fig. S1). By 2010, the number had grown to 27, and a further 10 megacities likely will exist by 2020 (20). In 2010, 460 million people (6.7% of the global population) lived in the 27 megacities. The sheer size and complexity of megacities gives rise to enormous social and environmental challenges. Megacities often are perceived to be areas of high global risk (i.e., threatened by economic, environmental, geopolitical, societal, and technological risks with potential impacts across entire countries) with extreme levels of poverty, vulnerability, and social–spatial fragmentation (21–24). To provide adequate water and wastewater services, many megacities require massive technical investment and appropriate institutional development (25, 26). Many inhabitants of megacities also suffer severe health impacts from air pollution (27). However, these factors present only one side; the megacities include some of the wealthiest cities in the world (albeit with large disparities between citizens). Even the poorer megacities are seen by some as potential centers of innovation, where high levels of resource efficiency might reduce global environmental burdens (21, 28, 29). Whether megacities can develop as sustainable cities depends to a large extent on how they obtain, share, and manage their energy and material resources.

Significance

Our quantification of energy and material flows for the world's 27 megacities is a major undertaking, not previously achieved. The sheer magnitude of these flows (e.g., 9% of global electricity, 10% of gasoline; 13% of solid waste) shows the importance of megacities in addressing global environmental challenges. In aggregate the resource flows through megacities are consistent with scaling laws for cities. Statistical relations are established for electricity use, heating/industrial fuels, ground transportation, water consumption, waste generation, and steel production in terms of heating-degree days, urban form, economic activity, and population growth. Analysis at the microscale shows that electricity use is strongly correlated with building floor area, explaining the macroscale correlation between per capita electricity use and urbanized area per capita.

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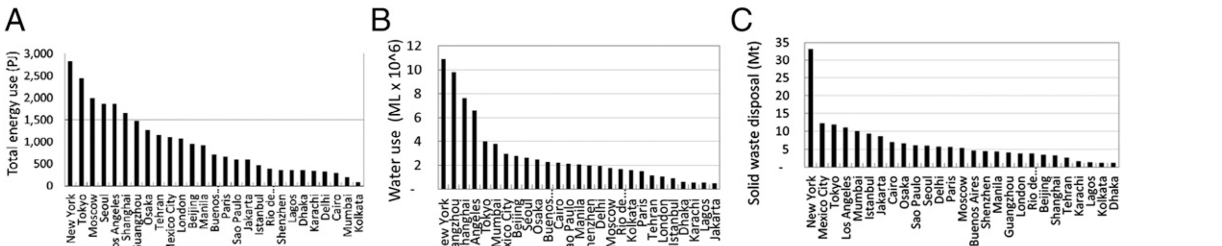

Fig. 1. Resource flows for megacities in 2011. (*A*) Energy use. (*B*) Water use including line losses. (*C*) Municipal solid waste production. Values shown are for the megacity populations scaled on a per capita basis from recorded data for the study area population (*Methods*).

The aims of our study are first to quantify the energy and material flows for the world's 27 megacities, based on 2010 population, and second to identify physical and economic characteristics that underlie these resource flows at multiple scales. This goal entailed developing a common data-collection process applied to all the megacities. The cities were identified based on Brinkhoff's database of metropolitan regions (www.citypopulation.de/world/Agglomerations.html; *SI Appendix*, Fig. S2). The megacities are essentially common commuter-sheds of more than 10 million people; most are contiguous urban regions, but a contiguous area is not a requirement; for example, the London megacity includes a ring of commuter towns outside the Greater London area. Megacities can spread across political borders. They include large tracts of suburban regions, which can have higher per capita resource flows than central areas (30, 31). We quantify energy flows for the dominant direct forms of consumption in megacities. A wide and complex range of materials flow through cities; here the focus is on water, concrete, steel, and waste. We show how values of aggregate resource use of all megacities generally are consistent with the scaling laws that have been developed for cities (5, 6). We then analyze factors correlated with energy and material flow at macro- and microscales; discuss megacities with low, high, and efficient use of resources; and examine changes over time.

Results

Total Resource Flows. Annual energy consumption in megacities, for 2011, ranges from ∼78 PJ for Kolkata (population 16.3 million) to ∼2,824 PJ for the New York Metropolitan Area (population 22.2 million) (Fig. 1*A*). Although Tokyo is the largest megacity, with 34.0 million people, its energy consumption is surpassed by New York because of New York's higher consumption of both transportation fuels (47 GJ per capita vs. 18 GJ per capita in Tokyo; *SI Appendix*, Fig. S3) and heating/industrial fuels (56 GJ per capita vs. 29 GJ per capita in Tokyo; *SI Appendix*, Fig. S4); per capita electricity use is approximately equal in the two megacities (*SI Appendix*, Fig. S5). Nine other megacities—Moscow, Seoul, Los Angeles, Shanghai, Guangzhou, Osaka, Tehran, Mexico City, and London—consume in excess of 1,000 PJ/y. To put these figures in perspective, an oil supertanker can hold about 12.2 PJ of oil (32); New York consumes the energy equivalent of one supertanker approximately every 1.5 days.

Total water consumption is notably higher in New York (10.9 million ML), Guangzhou (9.80 million ML), Shanghai (9.75 million ML), and Los Angeles (6.62 million ML) than in the other megacities (Fig. 1*B*). In New York about 54% of the water is used in thermoelectric plants. Water consumption in the remaining megacities ranges from a low of 0.48 million ML in Jakarta to a high of 4.19 million ML in Tokyo.

New York also exceeds other megacities in solid waste production, both in absolute and per capita terms (Fig. 1*C* and *SI Appendix*, Fig. S6). One of the challenges with solid waste data that we have observed in the past (13) is that the construction sector often produces large quantities of waste (not always counted in inventories), and commercial waste production can be difficult to estimate when handled by the private sector.

Aggregate Resource Use and Scaling Laws. Although there is great diversity in the energy and material flows through individual megacities, collectively their resource flows are, with the exception of gasoline, consistent with scaling laws observed for cities over a wide range of populations (6). This consistency can be seen by comparing the total resource flows of the megacities as a percentage of the world's total with the percentage of global population living in megacities (*Methods*). Clearly megacities are at the top of the population scale and should exhibit extreme values for quantities that scale superlinearly or sublinearly. The 27 megacities had a combined population of 460 million in 2010, equal to 6.7% of global population (Fig. 2). Their combined gross domestic product (GDP) was much larger in percentage terms, at 14.6% of global GDP. This result is expected for socioeconomic characteristics, which have been shown to scale superlinearly (6).

The total waste production for the megacities is estimated to be 12.6% of the global amount. This value suggests that waste production also may exhibit superlinear behavior, likely because of its relation with GDP. Essentially the higher amount of economic activity in larger cities entails importing relatively high quantities of goods and other materials that, apart from those that become bound in the building stock, leave cities relatively rapidly as wastes.

The total energy consumption of the 27 megacities is 26,347 PJ, which is ∼6.7% of global energy consumption. This percentage is about the same as the percentage of global population that lives in megacities. Bettencourt and colleagues (5, 6) found a mixture of energy-related scaling relationships: Residential electricity scales linearly, total electricity scales superlinearly, and gasoline use scales sublinearly. We found megacities consumed 9.3% of global electricity and 9.9% of global gasoline; the former is consistent with superlinear scaling, but the latter is not consistent with sublinear scaling and requires further exploration (This sublinear scaling could reflect the use of other transportation fuels in cities, e.g., the high use of diesel in many European cities).

The observation that megacities consume 6.7% of total global energy use also should be treated cautiously for the following reasons. (*i*) The global energy use total includes energy consumed in global aviation and marine transportation of goods and people;

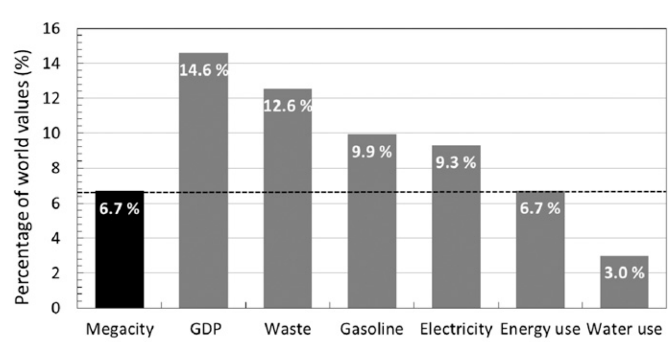

Fig. 2. Megacity resource and waste flows as a percentage of world values.

much of this transportation is between cities but is not reflected in their recorded energy use here. (*ii*) We have reported final energy consumption by cities, not primary energy use. Electrical energy use would be higher if expressed in terms of primary energy input. (*iii*) The extraction and refining of fossil fuels requires an energy premium that necessarily occurs to combust fuels in cities. (*iv*) The majority of megacities are in warm to hot climates where requirements for heating are relatively low [only Moscow, Beijing, Seoul, London, New York, Istanbul, and Paris-Isle-de-France recorded more than 2,000 heating-degree-days (HDD) in 2011]. Whether the distribution of climatic zones for megacities is representative of that for all global inhabitants has not been established.

The final quantity compared in Fig. 2 is water use. The 78 million ML consumed in megacities (including losses) is about 3.0% of global water use, which is estimated to be roughly 2,600 million ML (33). This percentage seems reasonably consistent with expectations, because a large amount of the global water supply is used in agriculture, which is a predominantly rural activity (34).

Macroscale Correlations. Some understanding of the factors that underlie the energy and material flows through megacities can be established by first analyzing per capita rates at the macroscale. There already is a large literature debating the relation between urban transportation energy use and urban form (35). Essentially, the literature shows that density (or, alternatively, urbanized area per capita) displays a significant relation with urban transportation energy if the dataset analyzed includes a wide spectrum of global cities with a wide range of densities. When studies include only cities within the same country or the same continent, for which differences in density are less wide ranging, or examine microscale features within cities, then density is found to be less significant than other variables such as supply of public transit, spikiness, and other characteristics of urban design (e.g., ref. 36). Previous research also has found that per capita use of heating and industrial fuels is significantly correlated with HDD (17). This known relationship, as well as that for transportation energy use, also is found to hold for the megacities, thereby corroborating the dataset (Table 1). For the megacities, however, we also find a significant correlation between heating and industrial fuel use per capita and urbanized area per person.

Little previous research has explored differences in electricity use between global cities. In our stepwise regression analysis we found per capita electricity use in megacities to be significantly correlated with urbanized area per capita (Table 1 and *SI Appendix*, Fig. S5). Electricity use is known to be a strong determinant of economic growth (37), and we also observe significant correlation between per capita GDP and electricity use in the megacities (*SI Appendix*, Fig. S7). Because there is relatively strong correlation between urbanized area per capita and GDP per capita (*SI Appendix*, *Correction for Multiple Inferences*), the latter drops out of the stepwise regression analysis, because it has less explanatory power than area per person. We suspect that lower-density megacities such as Los Angeles and New York have greater building floor space per capita, leading to higher electricity consumption for lighting and other building applications. We explore this possibility further in the microscale correlation analysis that follows.

The macroscale analysis also revealed a correlation between water consumption per capita and area per capita. Again, a weak correlation was found with GDP if area per capita was omitted from the model, but no relationships with precipitation or cooling-degree-days (CDDs) were found. A different study for Chinese and American cities found that urban water use per capita is inversely related to freshwater availability (38).

Based on observation of national solid waste data, we expected per capita waste generation by cities to be strongly correlated with GDP (39, 40); a statistically significant upward trend was observed (Table 1 and *SI Appendix*, Fig. S6), although the pattern of residuals suggests other factors may be at play. Policies can matter; it is interesting to contrast New York's waste production (1.49 tons per capita) with that of London (0.32 tons per capita), where the share of municipal solid waste landfilled in the United Kingdom has fallen from 80% in 2001 to 49% in 2010, encouraged by a landfill tax (41). We also found the percentage growth rate in GDP over 10 y to be correlated significantly with per capita waste production. (Note, however, that this variable is insignificant when correcting for multiple statistical inference; see *Methods* and *SI Appendix*, *Correction for Multiple Inferences*).

Because concrete and steel largely become bound up in the building stock in cities, we expected that their rates of consumption would be higher for faster-growing cities. This expectation was found to be the case for steel consumption (*SI Appendix*, Fig. S8). We obtained data on steel consumption for only nine megacities and found that steel consumption was correlated significantly with the absolute population growth of megacities over 10 y (Table 1). Data on cement consumption in 2011 were obtained for 10 cities; five megacities—Mumbai, Kolkata, Delhi, Dhaka, and Sao Paulo—were the largest consumers at 7.7–9.2 million tons. No significant statistical correlations were found between cement and population growth, GDP, or area per person.

Microscale Correlations. Although urbanized land area per person correlates strongly with energy use in megacities at the macrolevel, it is a less significant factor in microscale analysis, as we demonstrate by focusing on electricity use, for which building floor area is an important underlying factor at the microscale. We analyzed variables correlating with electricity use in subareas of London and Buenos Aires.

Analysis of London boroughs demonstrates the significance of gross floor area in explaining electricity use, with land area per capita and income having weaker influence. Gross floor area data for London's boroughs were available only for industrial and

Table 1. Final regression results for factors correlating with energy and material flows for megacities in 2011, correlations with gross building floor area, and changes in energy use, 2001–2011

Variable	*t*-stat (*P* value); coefficient
Energy and material flows for 2011	
Electricity consumption (R^2 = 0.88; n = 27; $t_{0,95}$ = 2.056)	
Urbanized area per person	13.55 (2.71 E−13); 21614
Heating and industrial fuel use (R^2 = 0.85; n = 27; $t_{0,95}$ = 2.056)	
HDD	5.87 (4.01 E−6); 0.02
Urbanized area per person	2.50 (0.02); 57722
Ground transportation fuels (R^2 = 0.83; n = 27; $t_{0,95}$ = 2.056)	
Urbanized area per person	11.40 (1.30 E−11); 92858
Water consumption (R^2 = 0.78; n = 27; $t_{0,95}$ = 2.056)	
Urbanized area per person	9.62 (4.75 E−10); 953201
Solid waste production (R^2 = 0.87; n = 20; $t_{0,95}$ = 2.093)	
GDP	5.98 (1.19 E−5); 7.41 E−6
10-y GDP growth rate, %	5.17 (6.40 E−5); 0.0002
Steel consumption (R^2 = 0.88; n = 9; $t_{0,95}$ = 2.306)	
10-y pop growth, no. of people	7.67 (5.93 E−5); 0.002
Regressions with gross building floor area	
Urbanized area per person (R^2 = 0.84; n = 13; $t_{0,95}$ = 2.179)	
Total gross floor area	8.09 (3.36 E−6); 4.02 E−6
Urbanized area per person (R^2 = 0.87; n = 16; $t_{0,95}$ = 2.131)	
Residential gross floor area	9.84 (6.2 E−8); 7.47 E−6
Electricity consumption (R^2 = 0.93; n = 16; $t_{0,95}$ = 2.131)	
Residential gross floor area	14.05 (4.86 E−10); 0.19
Electricity consumption (R^2 = 0.95; n = 16; $t_{0,95}$ = 2.131)	
Residential gross floor area	3.66 (0.003); 0.12
Urbanized area per person	2.46 (0.03); 9726
Changes in energy flows, 2001–2011	
Electricity, 10-y growth rate, % (R^2 = 0.80; n = 16; $t_{0,95}$= 2.131)	
GDP, 10-y growth rate, %	7.80 (1.17 E−6); 0.56
Ground transportation, 10-y growth, % (R^2 = 0.67; n = 13; $t_{0,95}$ = 2.179)	
GDP, 10-y growth rate, %	4.89 (0.0004); 0.61

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commercial buildings, and they show a strong correlation with industrial/commercial electricity use (Fig. 3*A*). Data on residential land area per person (i.e., excluding commercial and industrial land areas) were available for London, but they show a weak correlation with residential electricity use per capita (Fig. 3*B*). Median household income also shows a weak correlation with electricity use per capita (*SI Appendix*, Fig. S9). The correlation between income and land area per capita shown at the macrolevel across megacities (*SI Appendix*, Fig. S10 and *SI Appendix*, *Correction for Multiple Inferences*) does not hold for the boroughs of London (*SI Appendix*, Fig. S11), reflecting spatial variation in wealth and perhaps also classic spatial tradeoffs between living space and disutility of travel.

In Buenos Aires, gross floor area data were not available for the local municipalities; nonetheless, total electricity use (in residential, commercial, and industrial sectors combined) correlates strongly with total building footprint areas for 24 local municipalities in the megacity (Fig. 3*C*). The annual residential electricity use per person shows no relation to urbanized land area per person (Fig. 3*D*).

The overall importance of gross building floor area in explaining electricity use is seen further by linking it to the macroscale analysis. We were able to obtain or estimate values of residential gross floor area and total gross floor area for 16 and 13 of the megacities, respectively. Both measures show relatively strong correlations (R^2 = 0.87 and 0.84; Table 1) with urbanized land area per capita (*SI Appendix*, Figs. S12 and S13). So, although cities can grow upwards, more spread-out cities, with higher urbanized area per person have more building floor area per person. Further statistical analysis shows that residential gross floor area per person is highly correlated with per capita electricity consumption in the megacities (R^2 = 0.93; Table 1). However, there are some nonbuilding uses of electricity in cities, such as street lighting and public transit; hence using both residential gross floor area per person and urbanized land area per person gives a stronger model (R^2 = 0.95; Table 1).

Low Consumption, High Consumption, and Efficient Use of Resources. In addition to the assembled data on energy and material flows, data on access to resources show that many of the megacities are consuming resources at rates below those that support a basic standard of living for all citizens. Substantial proportions of residents in some megacities, particularly in South Asia, have no access to basic services such as clean water, sewerage, electricity, and formal waste disposal (*SI Appendix*, Table S2). For example, *SI Appendix*, Fig. S14 shows that all the megacities with less than 100% access to grid electricity (except Shenzhen) are those with annual electricity consumption below 2 MW per capita. The development challenge for such poorer megacities entails increasing rates of resource use above current low levels of consumption. The challenge is complex, because there also are high rates of resource wastage in some of these cities. For example, nonrevenue water use is high in many megacities, reaching more than 70% of total water consumption in Sao Paulo and Buenos Aires. Some of this loss may be the result of informal/illegal water withdrawals; other losses result from the poor state of infrastructure.

In contrast to the poorer megacities, some of the wealthier megacities may have to decrease their levels of energy and material consumption to reduce associated environmental impacts. This situation is not straightforward, however: Not only do the economies of cities have a bearing on their use of resources; HDD, urban form, and growth rates also affect resource use, as shown by our statistical analysis in Table 1. Nonetheless, the per capita data do suggest opportunities for resource reduction. The two United States megacities, for example, tend to be particularly high in many resource categories, especially electricity, water, and waste. Guangzhou also is a high-resource outlier with respect to water consumption and heating and industrial fuel use. Water efficiency is particularly low in Guangzhou, even compared with the rest of Guangdong province, including Shenzhen. The center of the city contains several industrial sites with outdated technology and high levels of water consumption; also, water prices are very low in Guangzhou (42).

There are also examples among the wealthier cities of practices that have produced relatively high levels of resource efficiency. For example, most of Moscow is serviced by a large district heating system, which uses waste heat from electricity generation to provide heating to most buildings in the city (see Moscow United Energy Co., www.oaomoek.ru/ru/); Seoul has a wastewater reuse system that saves on the input of water supplies; and Tokyo has managed to reduce its water leakage rate to only 3% (43). Among the wealthier cities overall, Paris is below the average trend on many of the measures of resource flows.

Growth over Time. Rapid growth makes accessing resources challenging in many megacities. Over the 10-y period ending in 2011, all the megacity populations in our study areas grew, and more than half of them grew by more than 10% (*SI Appendix*, Fig. S15). The fastest growth rates were in Istanbul, Dhaka, Beijing, Shenzhen, and Shanghai, all of which grew by more than 40%. Most of the slower-growing populations were in high-income

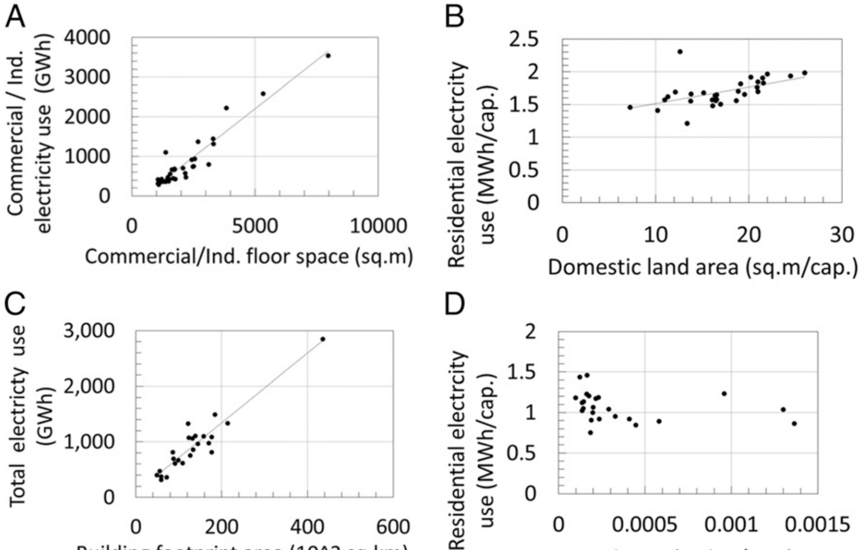

Fig. 3. Microscale analysis of electricity use in London and Buenos Aires. (*A*) Commercial electricity use in local London boroughs is correlated with gross commercial floor area (*t*-stat = 18.85; *P* value = 3.69 E−17; R^2 = 0.90). (*B*) Residential electricity use in London boroughs is weakly correlated with residential land area per person (*t*-stat = 3.34; *P* value = 0.0023; R^2 = 0.28). (*C*) Total electricity use in the local municipalities of Buenos Aires is correlated with building footprint area (*t*-stat = 27.9; *P* value = 3.14E−19; R^2 = 0.97). Data are for 2011, excluding the central area, Ciudad de Buenos Aires. (*D*) Annual residential electricity use per person within the local municipalities of Buenos Aires has no relation to urbanized land area per capita.

megacities, such as New York City, Los Angeles, Paris, Tokyo, and Osaka.

The resource flows for many of the megacities grew faster than the rates of population growth. This difference is shown in Fig. 4 for electricity and transportation fuel use in the megacities for which we were able to determine 10-y growth rates. Six of the megacities had increases in electricity consumption of 100% over the decade, and in nine of them electricity use grew at more than three times the population growth rate. Growth in transportation fuel use also was three times the population growth in 7 of 15 megacities; growth in transportation energy use was particularly high in the Chinese cities.

Further regression analysis shows that growth in electricity use and transportation fuel use are significantly correlated with growth in GDP (Table 1). Both of these energy flows are growing on average at about a half the rate of economic growth in megacities. However, the rates of change in water use (*SI Appendix*, Fig. S16) and solid waste production (*SI Appendix*, Fig. S17) are not correlated significantly with GDP growth (Table 1). Also, one megacity, London, notably managed to reduce its per capita electricity consumption during the period 2001–2011 while growing its GDP. Several factors may be responsible: a 66% rise in electricity prices, improved energy efficiency in buildings and appliances, energy labeling and increases in public awareness of the environmental impacts of energy consumption, and a decline in manufacturing. London is an exception, however. As the economies of megacities continue to grow, the expectation under current trends is that their energy use will continue to increase rapidly.

Conclusion

Overall energy and material flows vary considerably among megacities. Rates between the lowest- and highest-consuming megacities differ by a factor of 28 for energy per capita, 23 for water per capita, 19 for waste production per capita, 35 for total steel consumption, and 6 for total cement. Some megacities may need to increase such resource flows to provide access to basic services for all citizens, whereas others may aim to decrease energy and material flows to reduce associated environmental impacts. Policies that aim at resource efficiency can be successful, but the energy and material flows of megacities also are influenced by HDD, urban form, economic activity, and scale effects.

Our analysis has provided previously unidentified insights into the relation between electricity consumption and urban form. The close correlation between per capita electricity use and urbanized area per capita at the macroscale is a consequence of the microscale relationship between electricity use and building gross floor area. Cities that have higher urbanized area per person have more building floor area per person.

Methods

Data Collection and Quality Control. Use of the term "flow" in this study is consistent with the stock and flows terminology used in national environmental accounting [see Eurostat (44) or Brunner and Rechberger (45)]. In this study "flows" refers to annual inputs or outputs of energy or material.

Energy and material flow data were collected for the 27 megacities using a standard data-collection form described in ref. 20. After the data forms had been returned by the network of researchers in the megacities, several steps were taken to prepare the data for statistical analysis. First, all data were entered systematically into a spreadsheet (see *SI Appendix* and Dataset S1 for data). Attempts then were made to fill gaps in the reported data, especially where the gaps were crucial to the analysis of resource and waste flows in megacities. The number of data gaps was small; assumptions made to address these gaps are detailed by each megacity in the *SI Appendix* (Part 3). Areas deemed most critical were GDP, population density, HDD/CDD, stationary energy use, transportation energy use, and solid waste disposal (for 2011).

The surveyed GDP data were cross-checked and supplemented with values from The World Bank (46). All GDP values then were adjusted by a purchasing power parity (PPP) conversion factor, defined as the number of local currency units required to buy the same amounts of goods and services in the local market that a US dollar would buy in the United States. PPP-adjusted GDPs are standardized to an international dollar and therefore are amenable to intercity comparison.

Population densities for most megacities in the analysis were acquired from the World Bank (46). The exceptions were cases where the populations considered in our study areas did not correspond well with those in the World Bank's data tables or for which data were missing; these were Cairo, Dhaka, Lagos, Mexico City, Mumbai, Tehran, and the four Chinese megacities. For these megacities we calculated the population density based on data collected on our data forms.

HDD and CDD for each megacity were computed with online degree-day calculators (www.degreedays.net) commonly used by building scientists. For most megacities, the degree-day calculations were derived from standard air temperature data observed at international airports. Given the rural or semirural location of most airport observatories, the temperature data are not representative of thermal conditions inside the city. In all cities, the surface energy and radiation balances have been modified from the natural state, and thus regional airport data are likely to underestimate the true climatic differences that exist within and among megacities. However, because it is difficult to obtain air temperature data that are representative of local climate conditions in megacities, regional airport data were used to approximate urban-based temperatures.

All 27 climate stations in the megacities meet World Meteorological Organization (WMO) standards and are qualified for use as synoptic-level observatories. The online HDD calculator lists the airport and personal weather stations near a particular city. For each of our 27 megacities, we selected major international airport locations, because their data generally are considered superior in quality to data from personal weather stations. Each of the 27 airport stations has an International Civil Aviation Organization identifier code given by the International Civil Aviation Organization and listed by the online calculator. We cross-checked these codes with the WMO station index numbers listed in the National Oceanic and Atmospheric Administration climate database. In all 27 cases, our selected stations had corresponding WMO index numbers. We verified the station authenticity further for a few select stations in WMO Report No. 9 ("Observing Stations") and found the stations are listed there too, with associated metadata for station elevation, latitude and longitude coordinates, observation schedules, and so forth.

Previous research (16) has shown that gasoline consumption in cities can be estimated with an accuracy of about 5%, which may be a reasonable estimate of the uncertainty in most of the energy and material flow data collected. However, to provide a complete dataset for 2011, a few parameters (~5%) were estimated based on national scale data. These exceptions are detailed in the notes in *SI Appendix*, *Definition and Notes on Megacities*.

Total Resource Flows for Megacities. To quantify the total energy and material flows for megacities (Figs. 1 and 2), we scaled the collected data by an

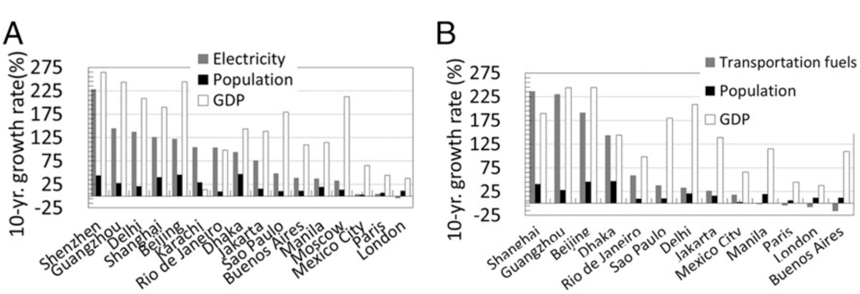

Fig. 4. Growth rates for electricity consumption (excluding line losses) (*A*) and ground transportation fuels (*B*), 2001–2011.

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adjustment factor based on Thomas Brinkhoff's 2010 megacity populations (*SI Appendix*, Fig. S2). Megacities whose study area populations fell below or above those of Brinkhoff's were adjusted by factors greater than or less than unity. The purpose of this global adjustment to the data was to normalize scale inconsistencies and uncertainties in survey reporting and to standardize all flows to the spatial scale of a "megacity." This adjustment is especially pertinent because 77% of the megacities have a formal level of government for the entire metropolitan area and its constituent cities. In some cases, e.g., Seoul and Mexico City, the study area population was smaller than that of the full megacity but still included nearly 10 million people. In other cases, e.g., Cairo and Lagos, the study area population was larger than that of the megacity. For 14 of the 27 cities, the study area population was within 20% of the megacity population defined by Brinkhoff (*SI Appendix*, Fig. S2). The total population of the study areas was 410 million people, compared with 460 million for all megacities.

Note that that there is no single authoritative system for establishing megacity boundaries. We used the Brinkhoff database as the basis for identifying the 27 megacities and establishing the approximate urban populations for data collection, but the Brinkhoff populations are indicative numbers rather than authoritative numbers. The most important consideration for this study was that we obtained data for large metropolitan regions that contain substantial amounts of the suburbs and hence avoided central city bias.

Analysis of Consistency with Scaling Laws. The scaling laws for cities have been established by Bettencourt and colleagues (5, 6) by plotting large datasets on log–log axes. We considered the 27 megacities at the top end of the collection of all cities. Our simpler analysis entails calculating the total resource flows of all of these megacities as a percentage of the world's total for comparison with the percentage of global population living in megacities. Quantities that scale superlinearly should be consumed at disproportionally high rates by the megacities, and quantities that scale sublinearly should be consumed at disproportionally low rates. Our method is intended to check for consistency with the scaling laws but is not a means of fitting parameters to the scaling laws.

The world totals used in the analysis are: populations, 6,892,319,000 (47); global water consumption (~2008), 2,600 km^3/year (32); global waste disposal, 3.93 million tons/day (48); global energy consumption, 393 exa joules (www.iea.org/statistics); gasoline, 42,566,284 TJ (www.iea.org/statistics); electricity, 18,396,735 GWh (www.iea.org/statistics); global GDP (2011), $77,200.00 US billion PPP (49).

Regression Analysis. The statistical analysis of drivers of energy and material flows (Table 1) was conducted using per capita values for the study areas (or total consumption in the study area in the case of steel and cement); i.e., the statistical analysis was conducted on the collected data without scaling. Two related methods of analysis were undertaken. First, multiple regression was undertaken using a stepwise process, starting with trial explanatory variables selected from literature review and knowledge of urban systems and engineering science. The initial models are given in *SI Appendix*, Table S1. Note that in some cases the values of coefficients change substantially between the initial and final models because statistically insignificant constants were eliminated.

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