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Research Project

Megacities: comparative analysis of urban macrosystems

Comparative analysis of energy and material flows in megacities

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Research project

Megacities: comparative analysis of urban macrosystems

By 2020, there will be an estimated 38 megacities on this planet, with a combined population of approximately 685 million people. Compared to 2010, this constitutes an addition of 11 urban agglomeration with populations over 10 million, and a 50% increase in the total population of such megacities. The majority of the world's current and future megacities are in developing regions of the world, particularly in Asia. The development challenges that these megacities face in an era of climate change are immense.

In spite of their huge populations, the multi-jurisdictional governance structures of megacities have thwarted comparative study and understanding of these urban regions. The resource flows into megacities, and the wastes produced, likely have environmental impacts on a planetary scale. Unlike nations, however, the quantification of resource and waste flows associated with these massive urban regions is rarely undertaken. Lack of such data on the world's megacities may significantly hamper policy development; therefore, research seeking to understand the sustainable development of megacities is critical.

The research project has two main objectives, to be addressed in two phases:

1. Conduct urban metabolism (UM) studies of a selected number of the world's current megacities, collecting data on a small number of UM parameters, specifically energy (all sources), water, materials and waste flows. From such data it will be possible to identify a set of general biophysical characteristics that are independent of the specific urban system, and that can be used to compare megacities (one example of a biophysical characteristic is population density, which is known to impact among others, transportation energy use). In conducting the UM studies, particular focus will be given to the role of utilities (electricity, natural gas, water, etc.), and how they can affect the urban metabolism.

2. Conduct more detailed analysis of the UM of 3–5 megacities, including extension to appropriate socio-economic sustainability indicators. For these more detailed UM studies, the research can then develop scenarios of sustainable urban evolution, as well as outlining a more general roadmap to sustainable urban development. In this second phase, the objective is to extend the analysis beyond the biophysical UM to include measures of quality of life and other social indicators. The scenarios will then assess the future role of utilities in megacities looking, for example, at how integrated infrastructure solutions, electric mobility and energy efficiency can impact the UM and quality of life in megacities.

Table of Contents

Abstract

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 due to their sheer size and complexity. In this working paper we determine and compare the energy and material flows through 27 of the world's megacities, i.e., the urban areas with populations over 10 million as of 2010. In particular, we focus on flows of energy, water, and waste, as well as considering the access to basic resources and services.

In addition, a set of correlations are established for electricity consumption, heating and industrial fuel use, water consumption, waste generation and steel production in terms of climate, urban form, economic activity and population growth. Our finding that per capita electricity use increases for lower density cities is particularly important, adding support to policies that encourage compact city development. We also make a first quantification of the impacts of urban growth rates on water consumption, solid waste production, and electricity consumption.

The results help to identify megacities exhibiting high and low levels of consumption, those making efficient use of resources, and the global impact of megacities on the main global energy, economic, and material flows.

Keywords: urban metabolism, material flow analysis, megacities, sustainable cities

JEL Codes: Q4,L94,L95,L98

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1 Introduction

The remarkable growth of cities on our planet over the past century has provoked a range of scientific inquiries. From 1900 to 2011, the world's urban population grew from just 220 million (13% of population) to 3,530 million (52% of population)[1]. Such a rapid increase of urbanization has prompted the development of a science of cities, including contributions on scaling laws[2], networks[3] and the thermodynamics of cities[4]. The growth of cities has also been strongly linked to global challenges of environmental sustainability[5], placing an importance on the study of urban energy and material flows – and urban resource efficiency. This is important because cities use about 70% of the global primary energy and produce over 60% of the global greenhouse gas emissions[6].

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. As depicted in Figure 1, in 1970, there were just 8 megacities on the planet. By 2010, the number had grown to 27, and a further 11 megacities will likely exist by 2020[7], and by 2030 a total of 41 megacities is expected[8] As depicted in Figure 2, as of 2010, 7 of the 27 megacities considered have more than 20 million inhabitants, with Tokyo having more than 34 million. These figures together with the sheer size and complexity of megacities gives rise to enormous social challenges. Megacities are often perceived to be areas of high global risk, with extreme levels of poverty leading to the formation of wide shanty towns, vulnerability, and social-spatial fragmentation[9]. Furthermore, to provide adequate water and wastewater services, many megacities require massive technical investment and appropriate institutional development[10]. Many inhabitants of megacities also suffer severe health impacts from air pollution[11]. Yet, this is just one side; the megacities include some of the wealthiest cities in the world (albeit with large disparities between citizens). On the other side, even the poorer megacities are seen by some as potential centers of innovation, centers where high levels of resource efficiency might reduce global environmental burdens[12]. Whether megacities fall into chaos or rise up as sustainable cities[13] also depends to a large extent on how they obtain, share and manage their energy and material resources.

[1] United Nations, 2006, 2012
[2] Bettencourt et al., 2007; Bettencourt,2013
[3] Batty, 2012, 2013; Derrible & Kennedy, 2010
[4] Bristow & Kennedy, 2014, Liu et al., 2012
[5] Baynes & Wiedmann, 2012
[6] Weisz and Steinberger, 2010; Grubler et al., 2012; Kennedy et al., 2007,2009, 2010, 2011, 2014; Kim & Barles, 2012
[7] Kennedy et al. 2014
[8] UN world urbanization prospects, 2014
[9] Kraas, 2007; Sorensen & Okata, 2011
[10] Varis 2006; Varis et al., 2006
[11] Parrish and Zhu, 2009
[12] Kraas, 2007; Mulder & Kraas, 2008; Stratmann, 2011
[13] Canton, 2011

FIGURE 1 - The number of megacities at the start of each decade since 1960, with projection to 2020

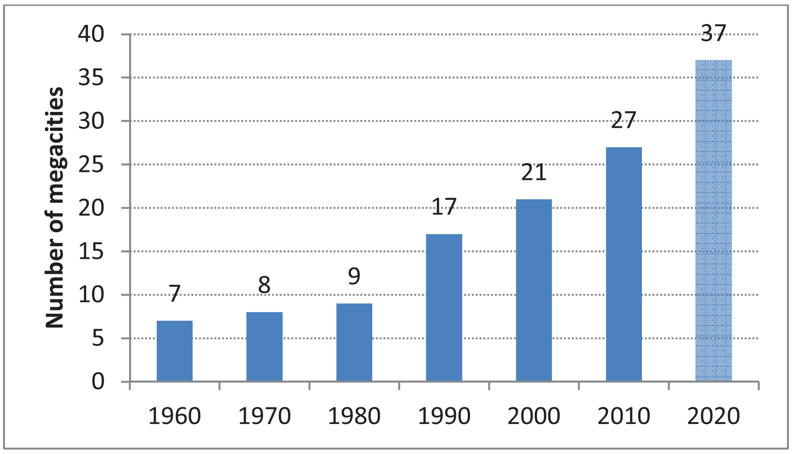

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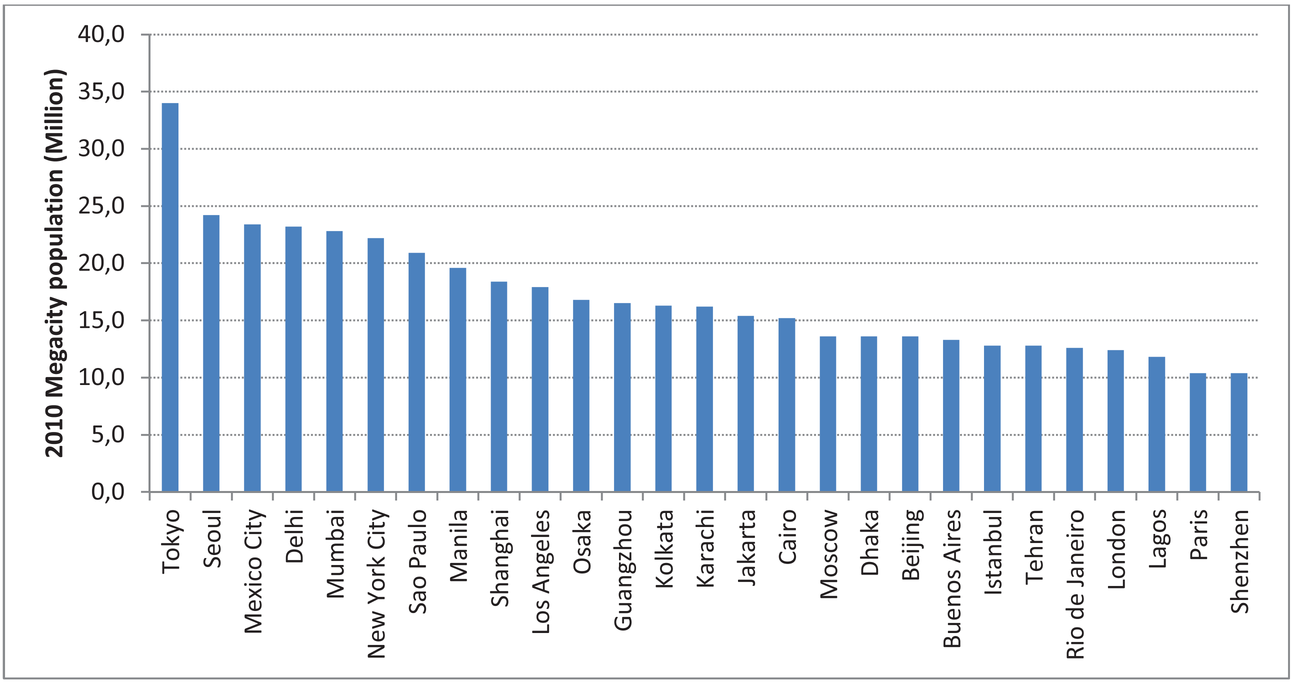
FIGURE 2 - Megacities population as of 2010



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The aim of this working paper is to investigate and firstly determine the quantities of energy and material flows for the world's 27 megacities as of 2010, and, secondly, to shed light on some of the physical and economic characteristics that underlie these resource flows.

Results presented are based on a common database collected by means of a multi-layered survey, that investigates the main aspect of the megacity, namely spatial boundaries, biophysical characteristics, urban metabolism, and role of the utilities14. These 4 mentioned "layers" are all important in order to better understand the results presented in this working paper. By example, megacities are essentially common commuter sheds of over 10 million people, and most of them are contiguous urban regions, but this is not a requirement; for example, the London megacity includes a ring of commuter towns outside of the Greater London area.

This working paper is organized as follows: Section 2 presents the results of the analysis of the urban metabolic flows in megacities, showing figures regarding energy, water, waste, and materials. Section 3 is devoted to the quality of life in megacities, while section 4 illustrates the impact of megacities in the global system. Section 5 states the conclusions and sheds light on future perspectives and investigation.

2 Energy and material flows in megacities

This section presents the analysis and the main results concerning the metabolism components of the urban ecosystem, focusing on energy, water, solid waste, and materials.

2.1 Energy

Figure 3 shows that per capita annual energy consumption in megacities, for 2011, ranges from approximately 127 TJ for New York (population 22.2 million) to ~5.3 TJ for Kolkata (population 16.3 million). While Tokyo is the largest megacity at about 34 million people, its energy consumption is lower with respect to New York because of higher consumption of both transportation fuels and heating/industrial fuels. Regarding the total energy use in megacities (Figure 4), it is worth noting that New York consumes over 2800 PJ per year, while Shanghai, Guangzhou, Los Angeles, Osaka, London, and Tehran consume in excess of 1,000 PJ/year. To put this in perspective, an oil supertanker can hold about 12.2 PJ of oil[15]; New York consumes the energy equivalent to one supertanker approximately every 1.5 days. At the lower end, Kolkata and Mumbai (population 22.8 million) both consume less than 300 PJ/year.

[14] Kennedy, 2014a
[15] UN, 2006.

FIGURE 3 - Per capita energy use in megacities

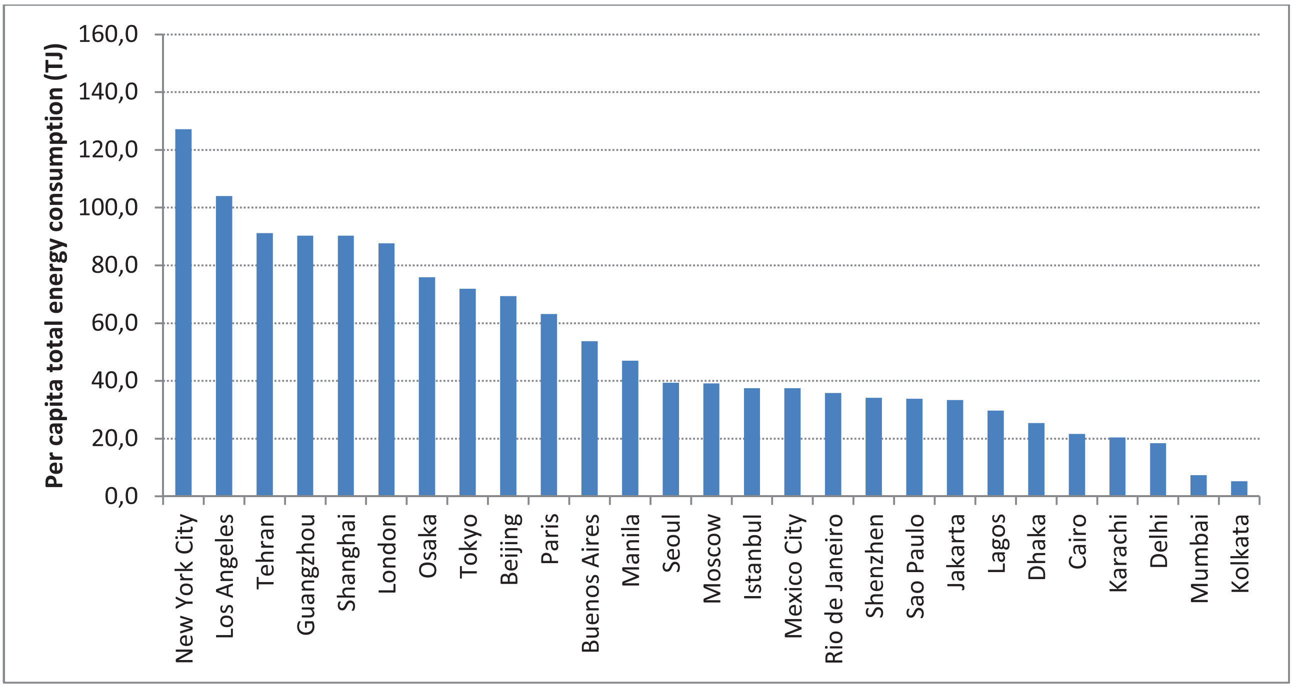

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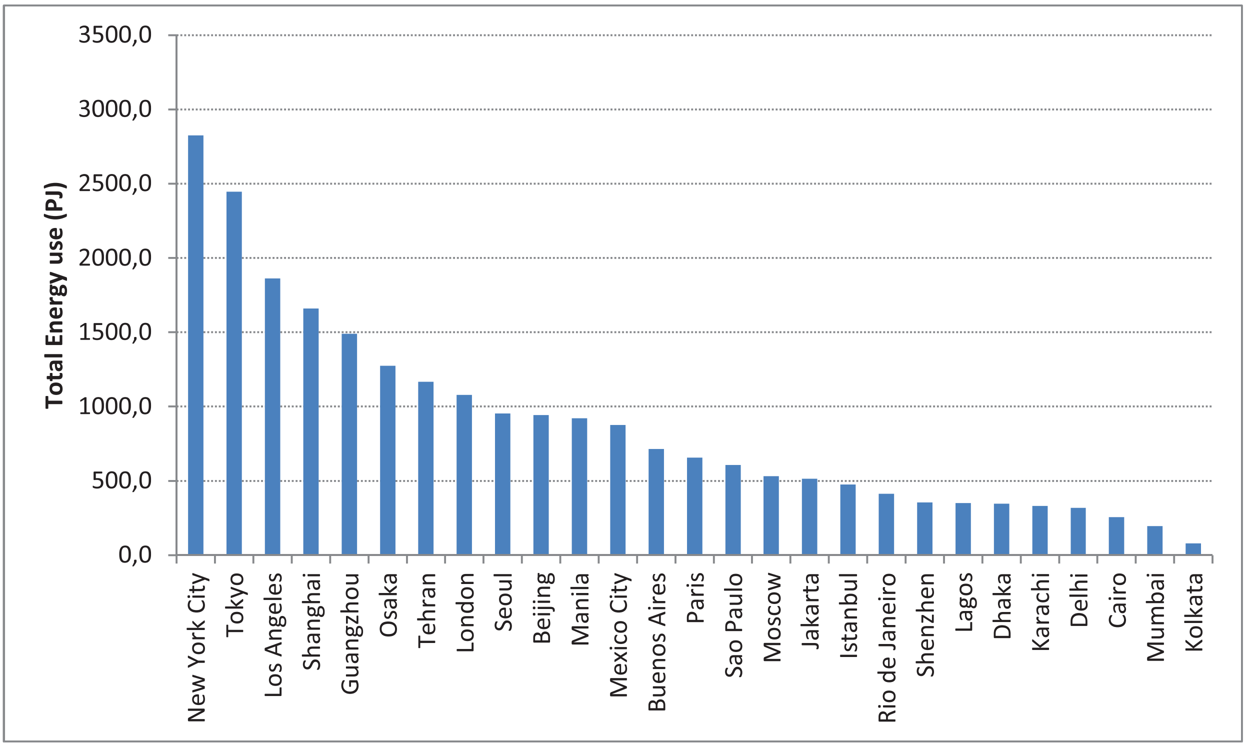
FIGURE 4 - Total energy use in megacities



Source: own elaboration

These amounts of total energy consumption in megacities can be explained in part by their populations and the size of their economies, as shown in figure 5. Other factors influencing the energy consumption are listed in Table 1, where the regression analysis shows influential factors related to climate, urban form and economic activity.

FIGURE 5 - Total energy consumption in relation to megacity GDP

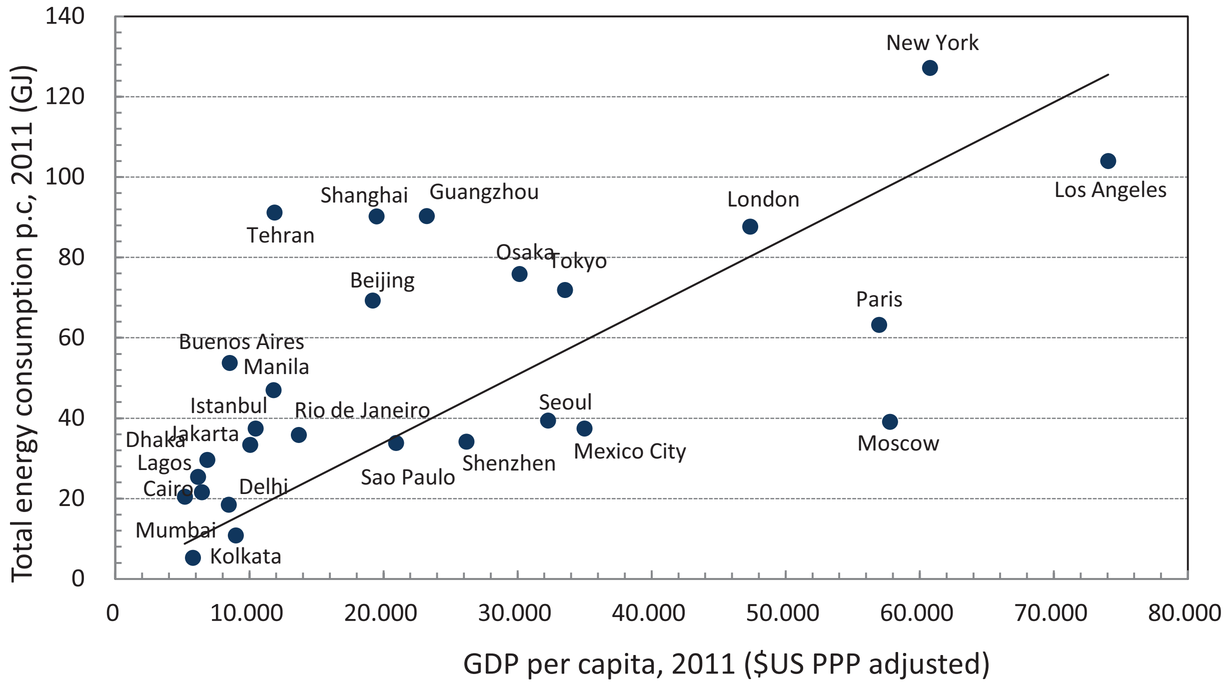


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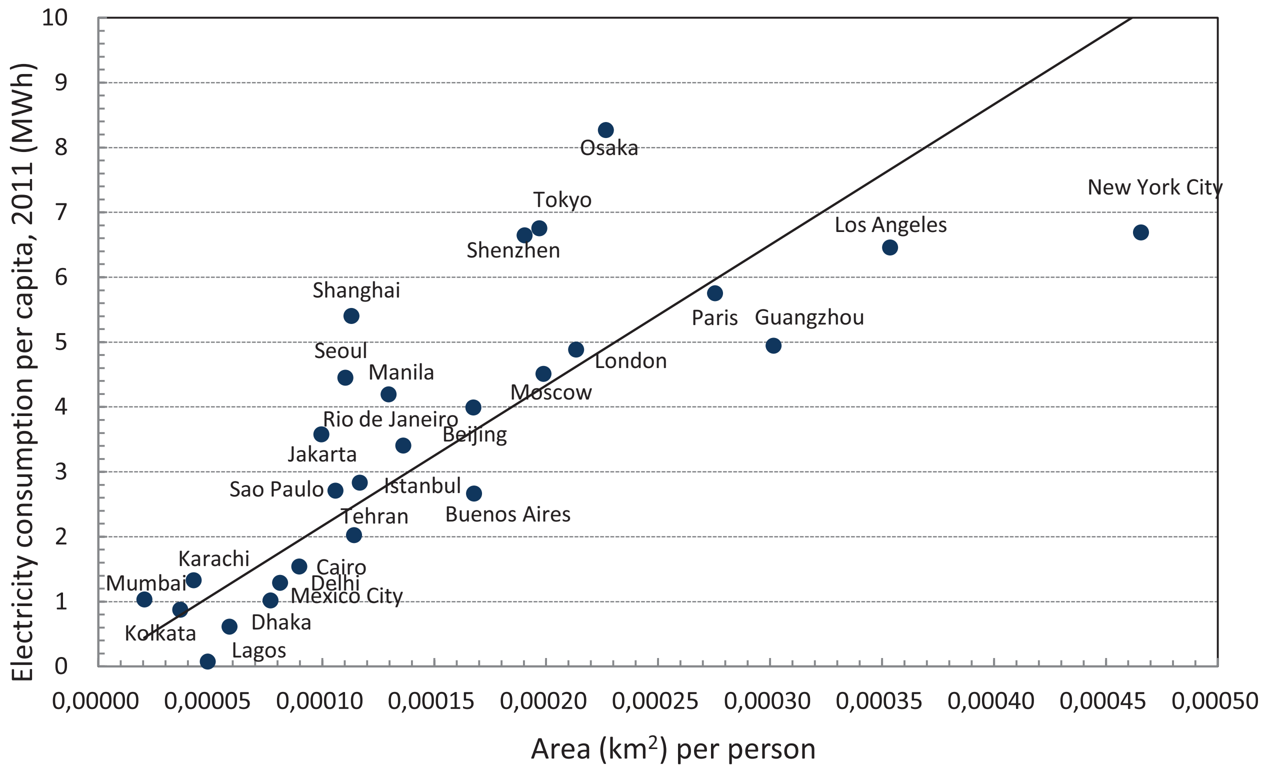
FIGURE 6 - Electricity consumption (excluding line losses) in relation to urban area per person



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From Table 1 it is also worth noting that per capita electricity use in megacities has a significant correlation (t stat = 13.5) with urbanized area per person, while other possible explanatory variables (e.g., heating degree days and GDP) were found to be statistically insignificant. Our hypothesis is that more spread out megacities such as Los Angeles and New York have larger building floor space per capita leading to higher electricity consumption for lighting and other building applications. While relations between transportation energy use and urban form have previously been established, we find, as shown in figure 6, that electricity consumption per capita also increasing with lower density cities is important, adding further substantial support to policies aimed at promoting compact cities.

Table 1 - Statistical analysis for per capita electricity consumption, heating and industrial fuel use, ground transportation fuel use, water consumption, solid waste production and steel consumption in megacities

Variable	t Stat	Coefficient	95% CI
Electricity consumption (R^2 = 0.88; R^2 adjusted = 0.84; n = 27; $t_{0,95}$= 2.479)			
Area per person	13.5	21664	18370 to 24958
Heating and Industrial Fuel Energy Use (R^2 = 0.82; R^2 adjusted = 77; n = 26; $t_{0,95}$= 2.485)			
Heating degree days	2.77	0.0080	0.002 to 0.014
Area per person	4.08	90820	44883 to 136757
Ground transportation fuels (R^2 = 0.85; R^2 adjusted = 0.81; n = 27; $t_{0,95}$= 2.479)			
Area per person	12.1	90376	75028 to 105724
Water Consumption (R^2 = 0.78; R^2 adjusted = 0.74; n = 27; $t_{0,95}$= 2.479)			
Area per person	9.62	953200	749467 to 1156934
Solid Waste Production (R^2 = 0.87; R^2 adjusted = 0.80; n = 20; $t_{0,95}$= 2.539)			
GDP	5.98	7.4×10^{-6}	4.80×10^{-6} to 1.00×10^{-5}
10-yr GDP growth rate (%)	5.17	0.001	0.0006 to 0.0013
Steel Consumption (R^2 = 0.88; R^2 adjusted = 0.76; n = 9; $t_{0,95}$= 2.306)			
10-yr pop growth (# people)	7.67	0.002	0.001 to 0.003

Source: own elaboration

Furthermore, in the analysis of a different dataset of cities is found that per capita electricity consumption was also significantly correlated with heating degree days (a measure of how cold a city is)[16]. Such a correlation was not found with the megacities data, possibly because it is dominated by cities in warm to hot climates. Only 7 of the 27 megacities (Moscow, Beijing, Seoul, London, New York, Istanbul and Paris-Isle-de-France) had over 2000 heating degree days in 2011, while the other dataset included four cities with interior continental climates similar to Moscow.

[16] Singh & Kennedy, 2014

By comparing the 10-year (2001-2011) growth rates of population and electricity consumption, there exists a significant difference between the megacities located in higher income countries and those of lower income countries, mainly in Latin America and Asia. The latter have experienced exceptional growth in the observation period.[17] In Figure 7, excluding London, Paris, Mexico City and Cairo, the growth rates of electricity consumption in the other megacities are larger than the population growth rates.

In order to better understand the differences between the two growth rates, we report in Figure 8 the ratio between electricity consumption growth and population growth. Rio the Janeiro is the megacity in which the ratio of the growth rates is the largest (10.8); lower values are found in Sao Paulo and Buenos Aires in Latin America (4.5 and 3.3, respectively) and in Shenzhen, Delhi and other Asiatic megacities, that are in the range 5.1-1.9. European megacities, excluding Moscow, show lower rates. Paris and London are the only megacities in which the electricity consumption growth has been lower than the population growth, with London showing negative growth rates for electricity. The only non-European megacity showing a lower growth ratio is Cairo.

An explanation for the values reported in Figure 8 is not straightforward and needs further investigation that will be performed in the future.

Working hypotheses are the following:

1. People, especially in developing regions, are moving on the social scale, and as their income increases they consume more electricity.

2. Use and diffusion of low efficient appliances and technologies in developing countries.

3. Low or negative rates in London and Paris may be associated to energy efficiency measures, new technologies, and the economic crisis of the last decade.

[17] From the graphic the following megacities have been excluded because of the lack of data: New York City, Los Angeles, Lagos, Tehran, Mumbai, Kolkata, Seoul, Tokyo, Osaka.

FIGURE 7 - Comparison of 10-year growth rates (2001-2001) of electricity consumption and population

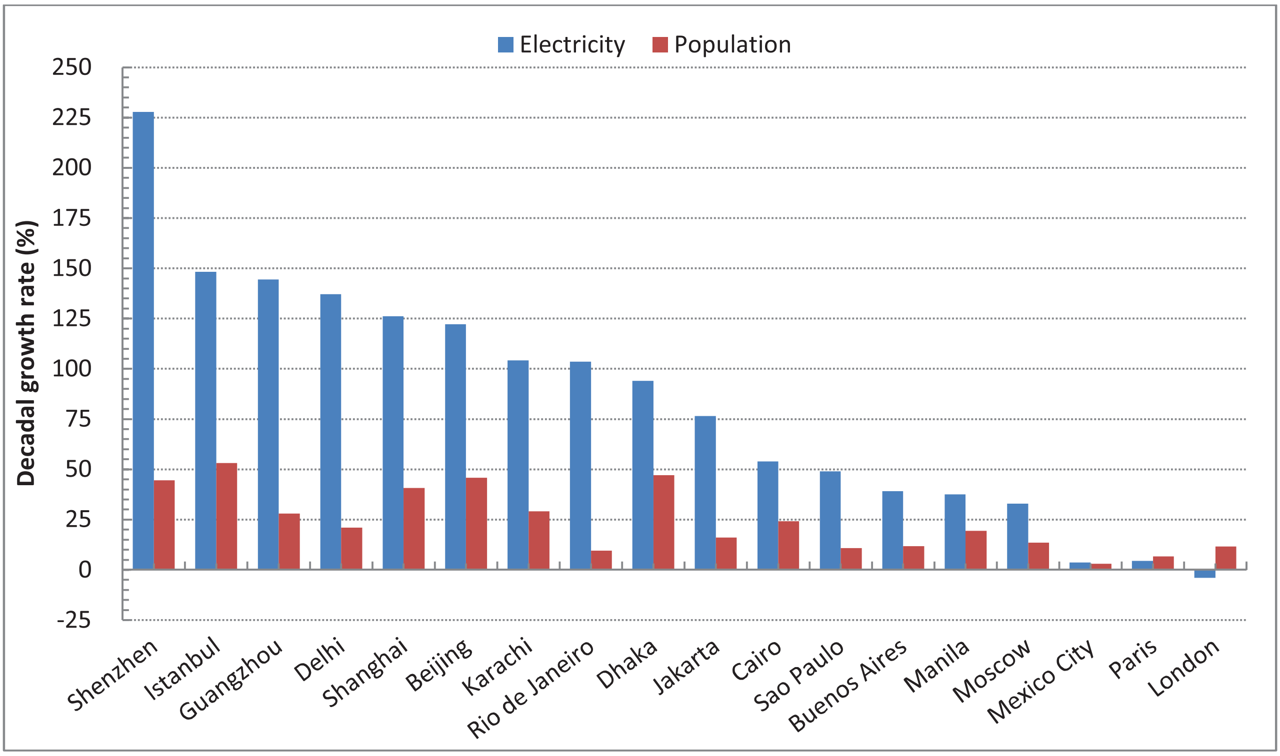

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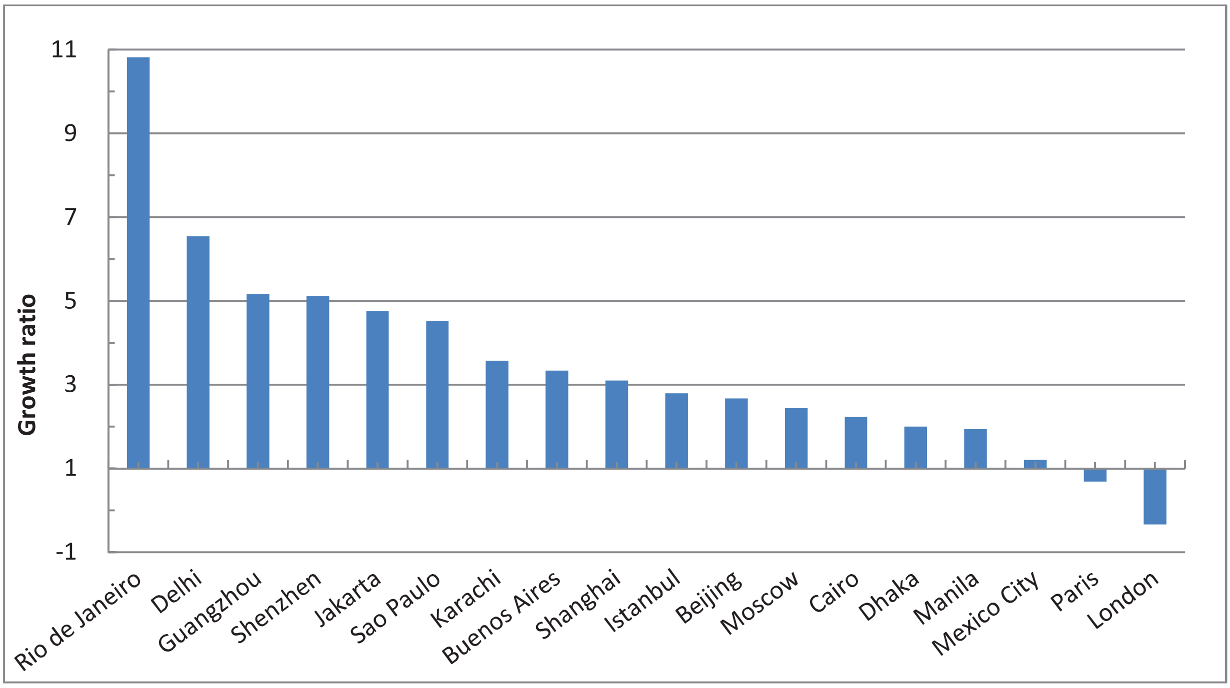
FIGURE 8 - Ratio between growth rates of electricity consumption and population



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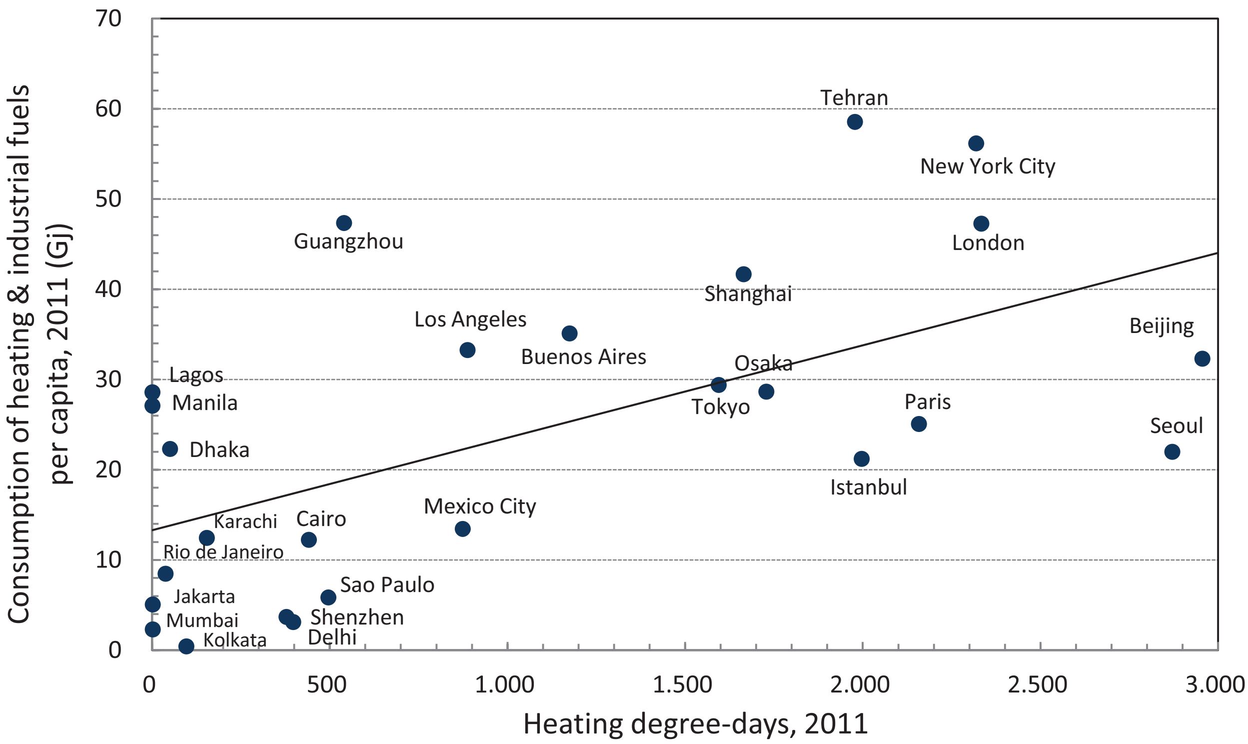
Heating degree days was, however, found to be significantly correlated (t-stat = 3.27) with the per capita use of heating and industrial fuels (Figure 9). This is also consistent with previous findings in the literature[18]. Only for the megacities we additionally found a significant correlation (t stat = 4.57) between heating and industrial fuel use per capita and urbanized area per person.

FIGURE 9 - Heating and industrial fuel consumption in relation to heating degree-days



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The last component of urban energy use is ground transportation. This had previously been found to relate to land area per person[19] but for the megacities we find a stronger correlation (t-value 4.66) with per capita GDP, as shown in Figure 10. The significance of GDP as an explanatory variable to transportation energy use is likely related to high rates of auto-ownership in wealthier cities. There is also a fairly strong cross-correlation (t-value 6.70) between GDP and urbanized area per person (Figure 11).

Figure 12 reports the total consumption for transportation fuels, while Figure 13 shows the 10-year growth ratio for a selected number of megacities. Regarding the total energy use, as expected, New York is at the top of the list, followed by Los Angeles and Shanghai. Despite the

[18] Kennedy et al., 2009; Singh & Kennedy, 2014
[19] Kennedy et al., 2009

lower population (about 17,9 million), Los Angeles shows consumption values larger than Shanghai (18,4 million) and other more populated cities like Seoul (24.2 million), Mexico City (22.2 million), Manila (19.6 million), and Sao Paulo (20.9 million). On the other side, the 10-year growth rates reported in Figure 13 well represent the difference between cities that have experienced rapid growth (e.g., Guangzhou, Shanghai, Beijing, Rio de Janeiro), and cities that have implemented measures for the limitation of traffic congestion and air pollution (e.g., London and Paris). The negative value for London is consistent with the data reported in Figures 7 and 8. These aspects are worth investigating further and will be the subject of a future investigation

FIGURE 10 - Consumption of transportation fuels with increasing per capita GDP.

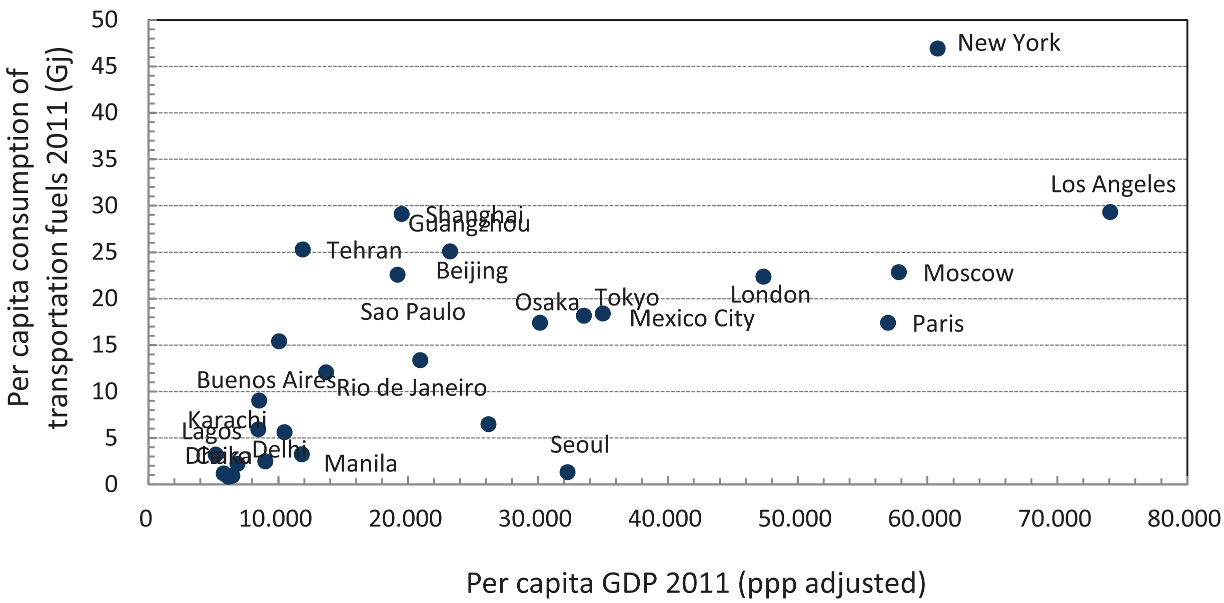

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FIGURE 11 - Correlation between per capita GDP and area per person

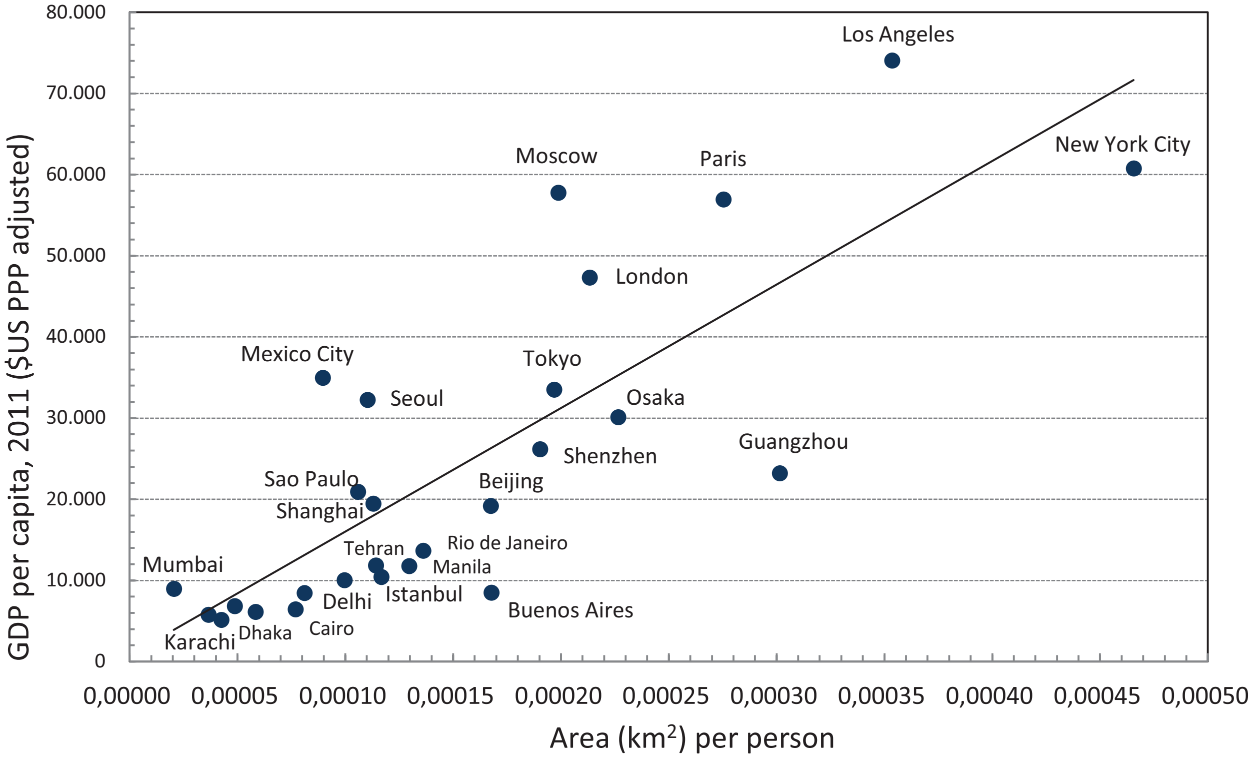

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FIGURE 12 - Per capita energy consumption for transportation

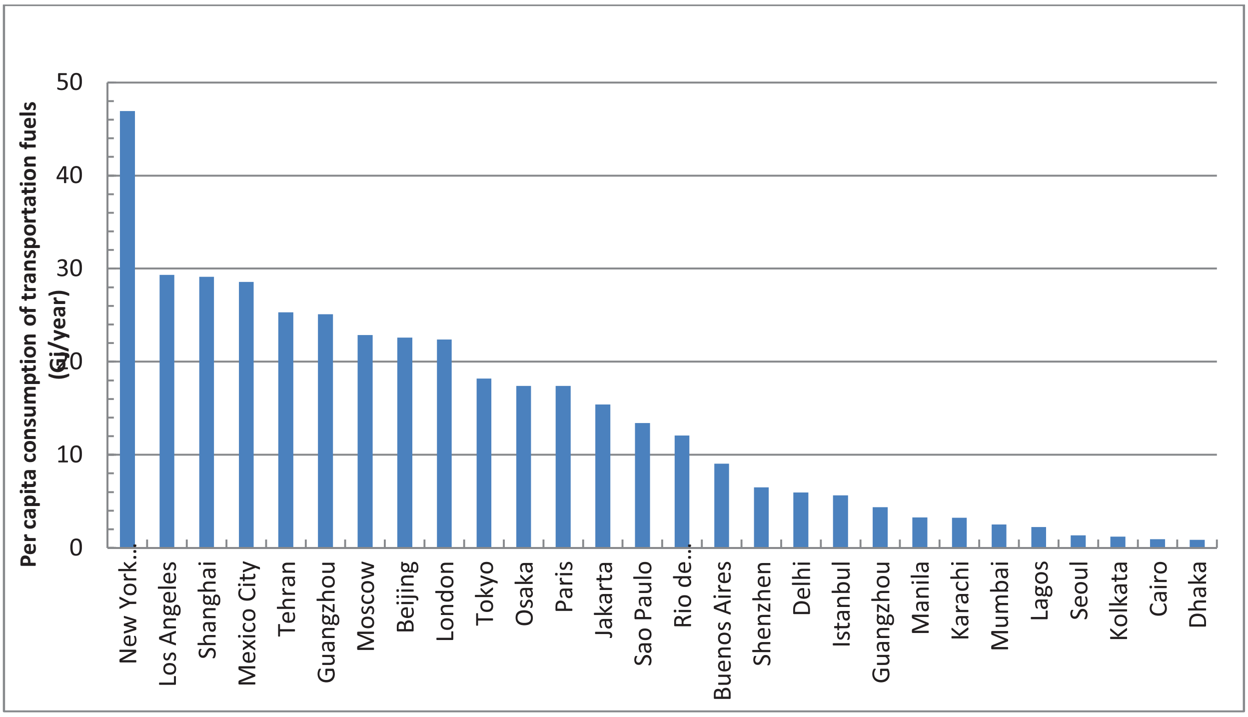

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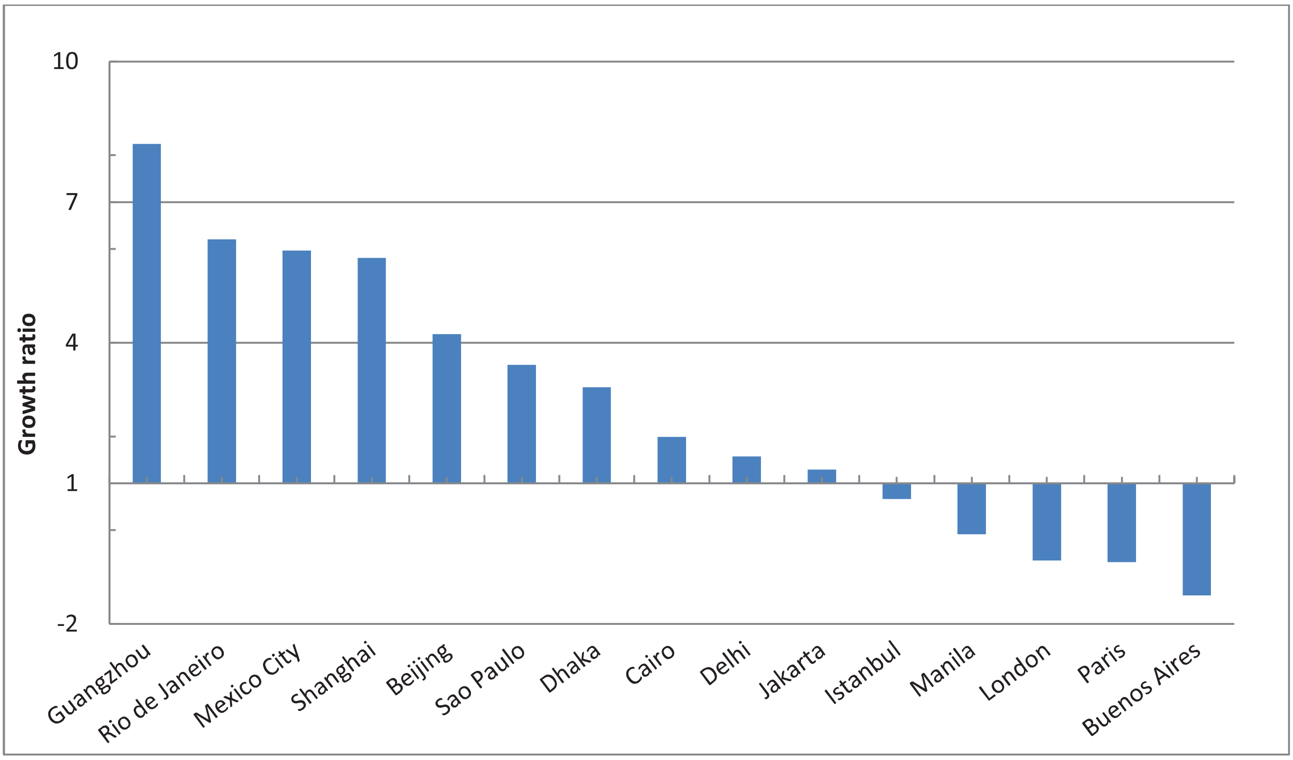
FIGURE 13 - 10-year growth rates (2001-2011) for transportation energy consumption



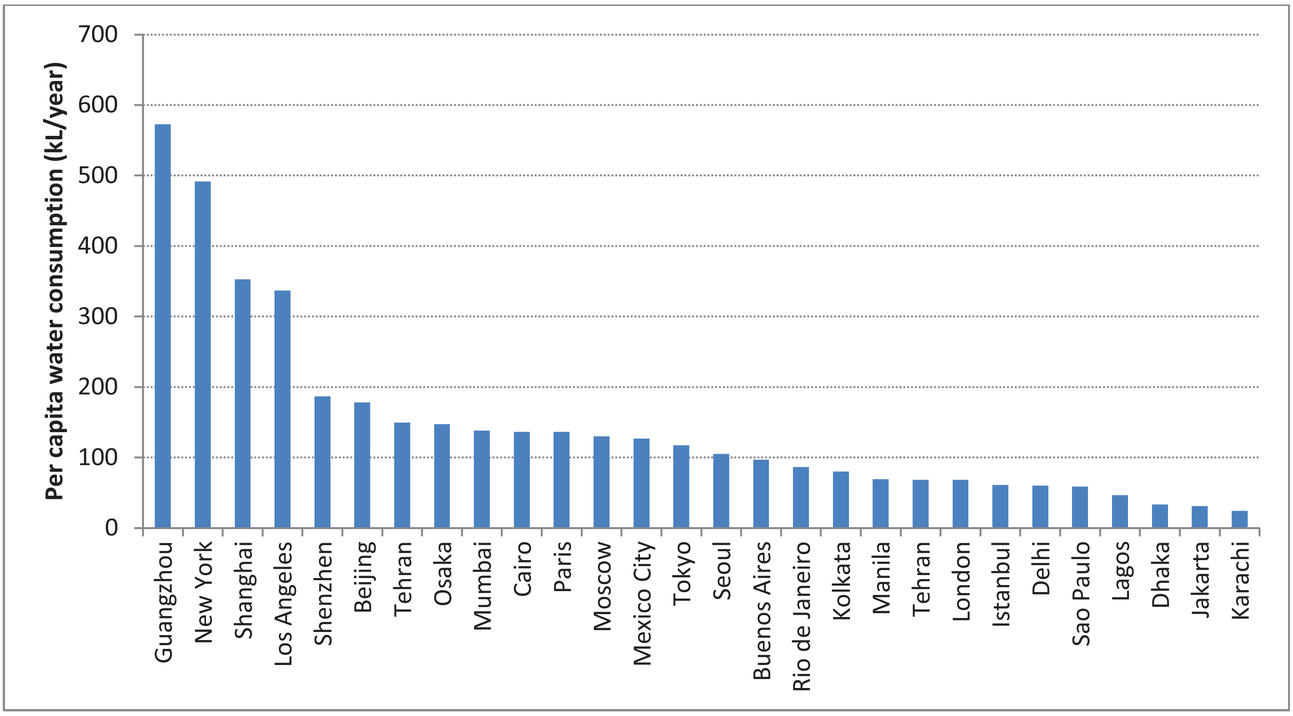
Source: own elaboration

2.2 Water

Total water consumption is notably higher in New York (10.9 million ML), Guangzhou (9.80 million ML), Shanghai (7.6 million ML) and Los Angeles (6.6 million ML) than in all of the other megacities (Figure 15). Despite the highest population, Tokyo ranks lower both in the total consumption (4.0 ML) and in the per capita consumption list (115.5 KL/year - Figure 14). In the case of New York, about 54% of the water was used in thermoelectric plants. Water consumption in the remaining megacities ranged between 0.48 million ML (Jakarta) and 4.19 million ML (Tokyo). Aside from the four high-consuming megacities, differences in per capita water consumption were modest for the other cities (in comparison to energy use). Statistical analysis revealed a correlation between water consumption per capita and area per person (t-value 5.22). A weak correlation was also found with GDP (t-value 2.61), if area per capita was omitted from the model, but no relations with climate (precipitation, cooling degree days) were found. A different study for Chinese and American cities found that urban water use per capita is inversely related to freshwater availability[20].

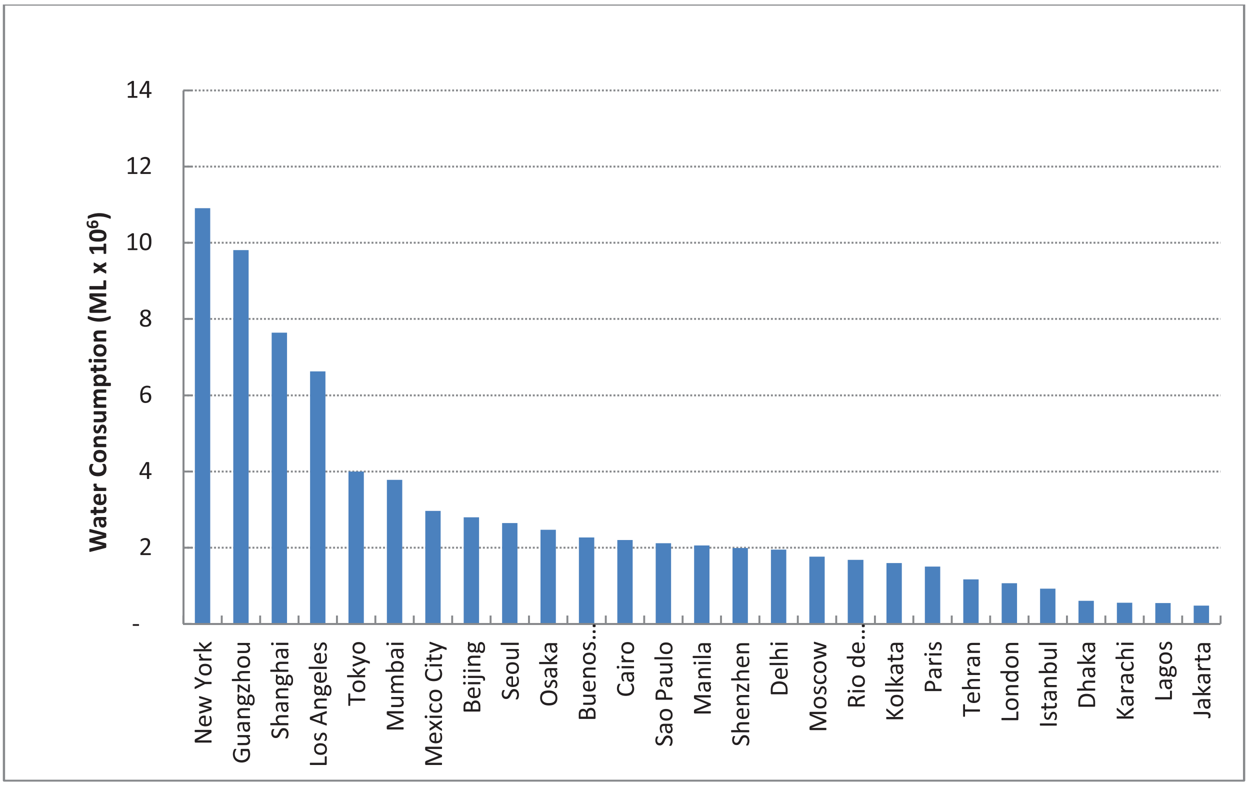
[20] Jenerette et al., 2006

FIGURE 14 - Per capita water consumption



Source: own elaboration

FIGURE 15 - Water consumption (including losses)



Source: own elaboration

Figure 16 shows a comparison between the 10-year growth rate of population and water consumption. Dhaka and Cairo have experienced the highest growth rates, especially when compared with population increases. In general, as already noticed for the case of electricity consumption (Figure 7), megacities in the fast developing countries experience higher growth rates. Tehran and London have similar rates, while Beijing and Guangzhou decreased their water consumption in the last 10 years. A better description of the difference between the population and water consumption growth rates can be found in Figure 17, were the ratio between water consumption and population growth rates is shown. As for the case of electricity, Rio the Janeiro experienced one of the highest increases of water consumption (about 4 times faster than the population growth). On the other side, Cairo has increased its water consumption 5 times faster that its population growth, while its electricity consumption grew slower than population. The cases of Istanbul, Beijing and Guangzhou should be investigated in future work.

In general, results reported in Figures 7 and 16 give evidence that, especially in Asian and Latin American megacities, both water and electricity are growing faster than the population, reinforcing the link/competition between water and electricity.

FIGURE 16 - Comparison between 10-year growth rates of population and water consumption

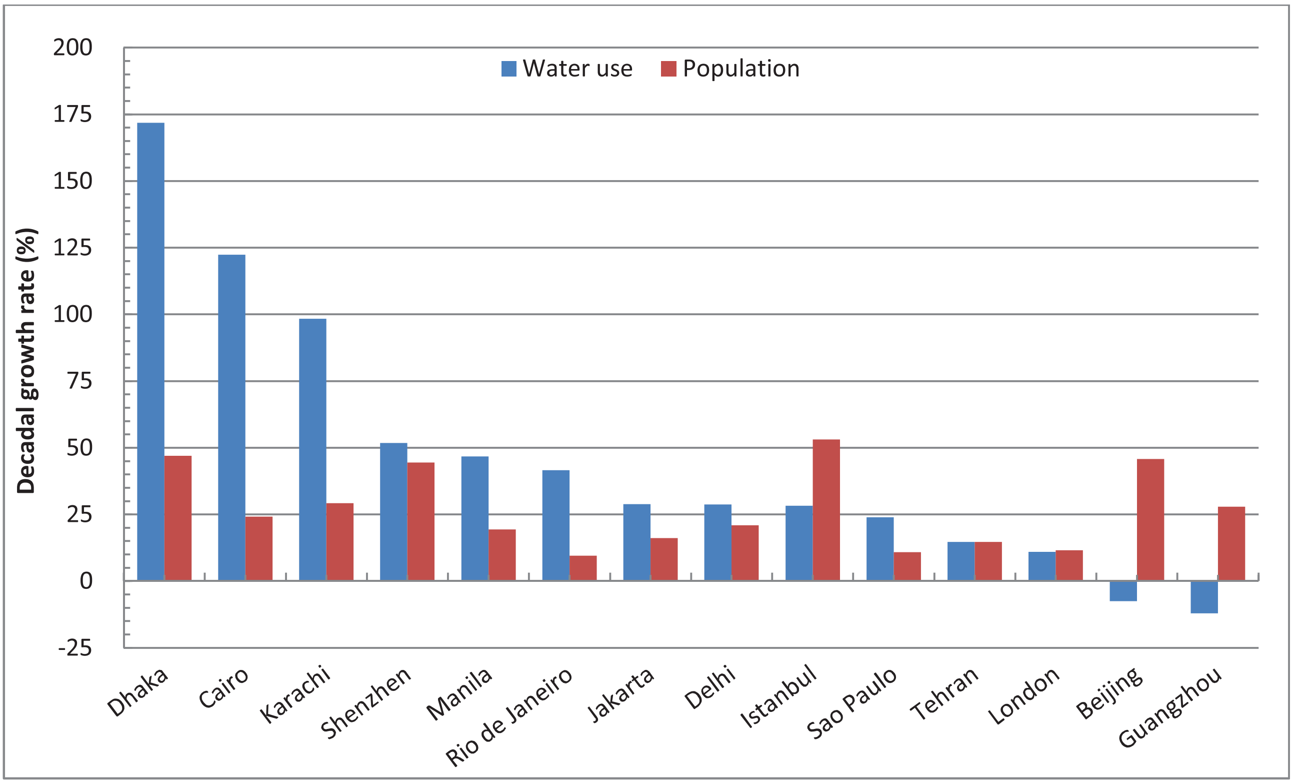


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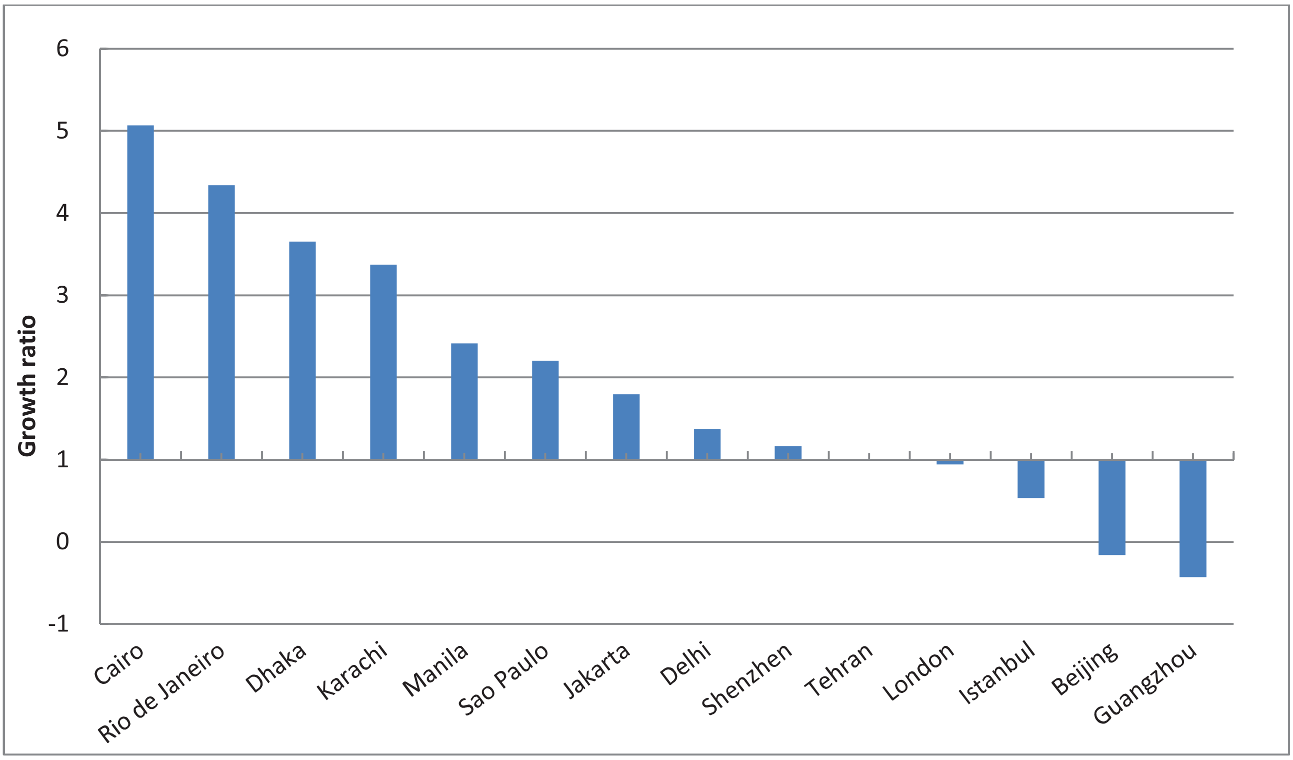
FIGURE 17 - Growth rate ratios between 10-year water consumption and population growth



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2.3 Solid waste

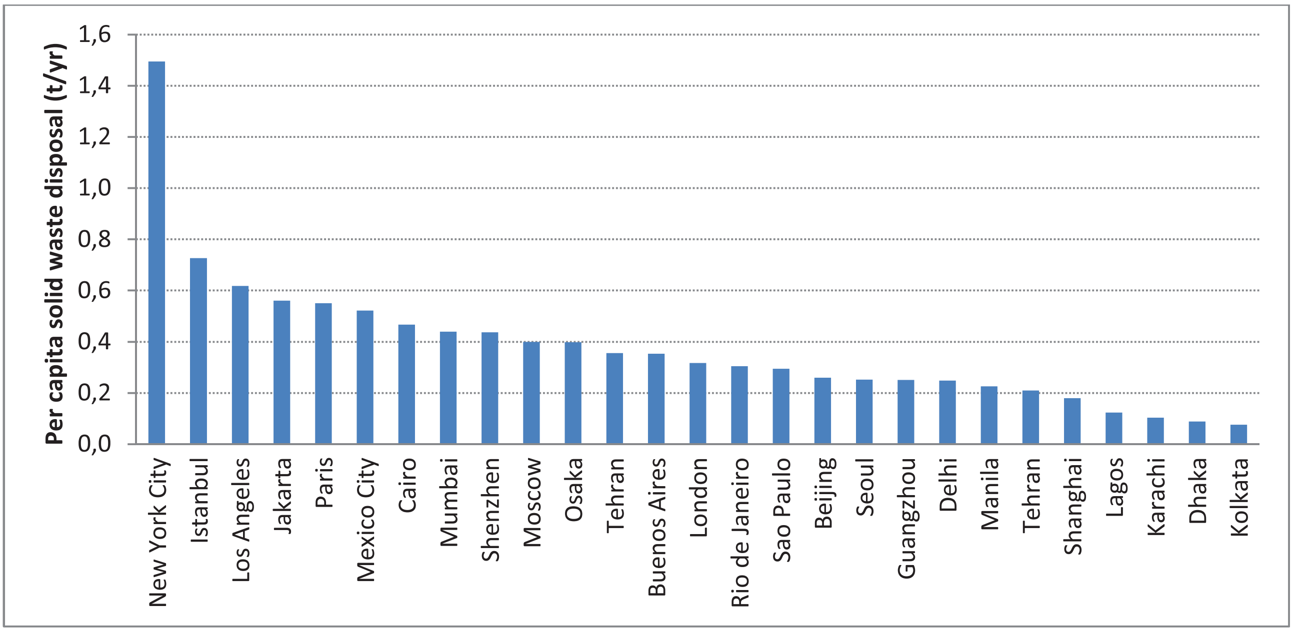
Figures 18 and 19 report per capita and total solid waste production, respectively, in megacities. The largest producers of solid wastes are New York (33.18 Mt/year), Mexico City (12.22 Mt/year), and Los Angeles (11.06 Mt/year). These figures change when considering the per capita values: New York remains the largest producer, but Istanbul, Jakarta, and Paris are ranked higher than Mexico City. The other megacities range in values from 1.21 Mt/year (Dhaka) to 6.7 Mt/year (Osaka). Furthermore, based on observations of national solid waste data, we expected per capita waste generation by cities to be strongly correlated with GDP[21], and a statistically significant (t stat = 5.98) upward trend was observed.

We expect that other factors play an important role. Policies can matter; it is interesting to contrast New York's waste production (1.49 t/cap) with that of London (0.32 t/cap), where the share of municipal solid waste land filled in the UK has fallen from 80% in 2001 to 49% in

[21] Hoornweg, 2014; Hoornweg, 2013.

2010, encouraged by a landfill tax[22]. Suspecting that the growth of cities may be a significant factor in waste generation, we compared in Figure 20 the growth rates of solid waste disposal and population. Karachi, more than any other megacity, has experienced dramatic growth in solid waste disposal (300%), especially when considering the corresponding population growth (29%). The other megacities show much smaller increases, both in comparison with the population growth and with electricity and water consumption (especially in Shenzhen, Buenos Aires, and Istanbul). A better picture of this can be found in Figure 21, where the ratio between the two growth rates is reported. We examined the correlation of solid waste consumption and GDP through regression analysis (Figure 22): our findings show that the percentage growth rate in GDP over 10 years has a significant correlation (t-stat =4.5) with per capita waste production; however, this should be considered as a preliminary result, to be verified by means of a multivariate significance analysis.

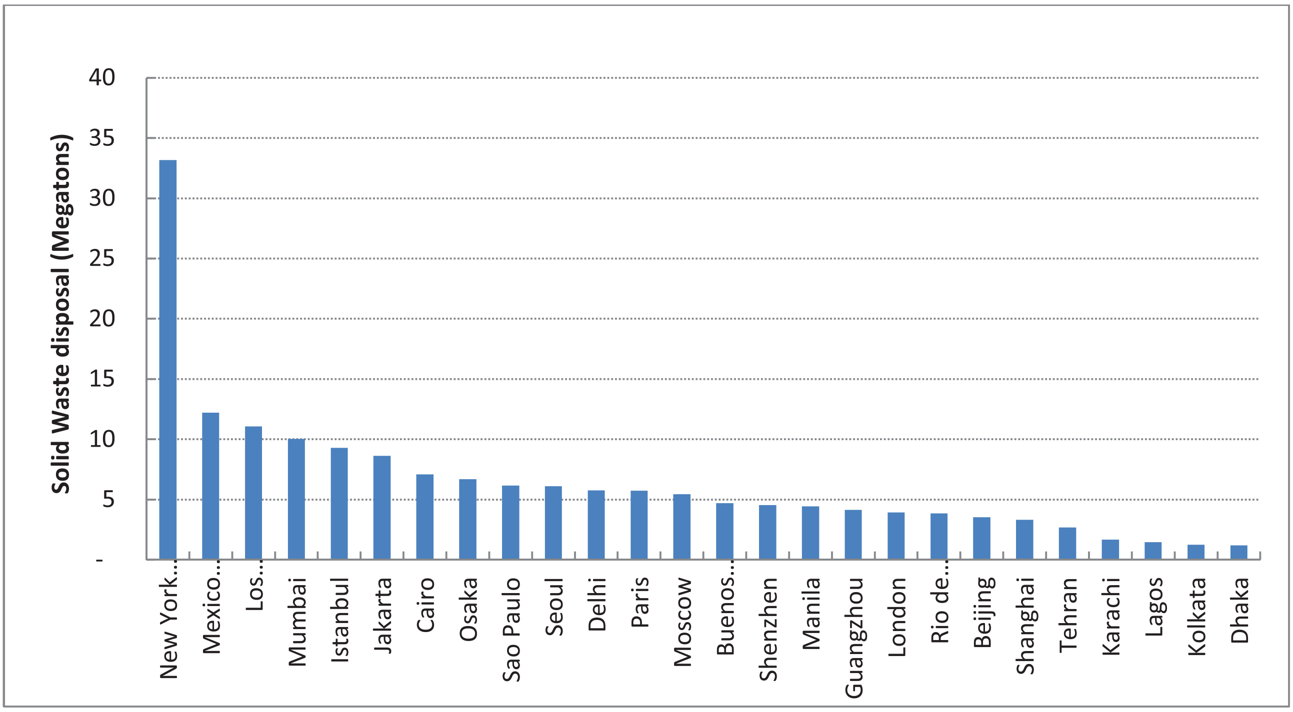
FIGURE 18 - Per capita solid waste disposal in megacities



Source: own elaboration

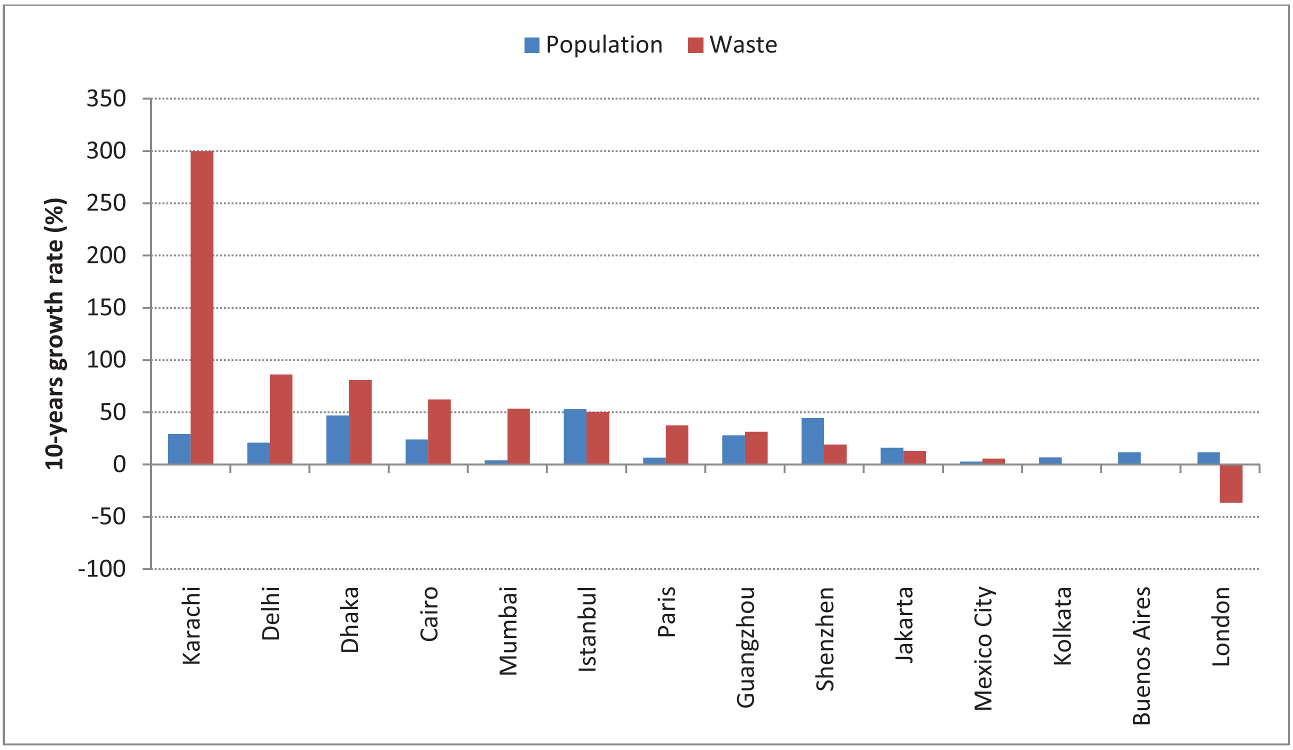
[22] Eurp. Env. Ag., 2013

FIGURE 19 - Total solid waste disposal in megacities.



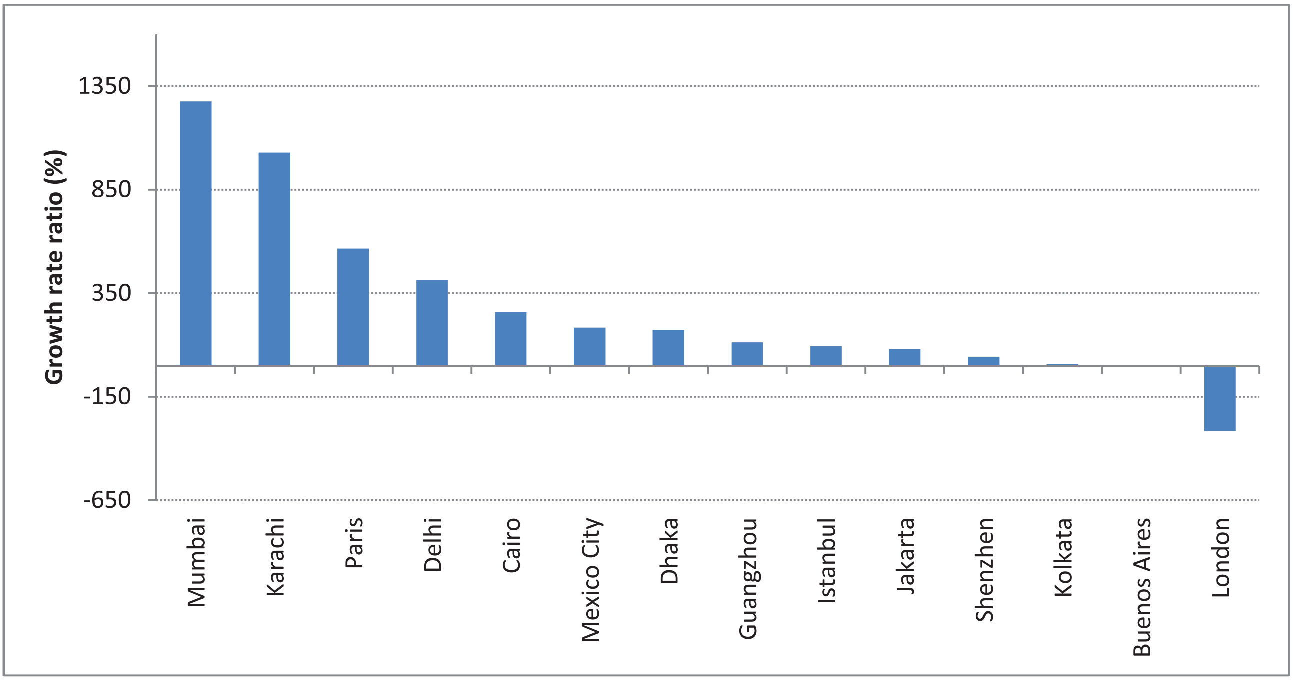
Source: own elaboration

FIGURE 20 - Comparison of 10-year growth rates of population and solid waste disposal in megacities



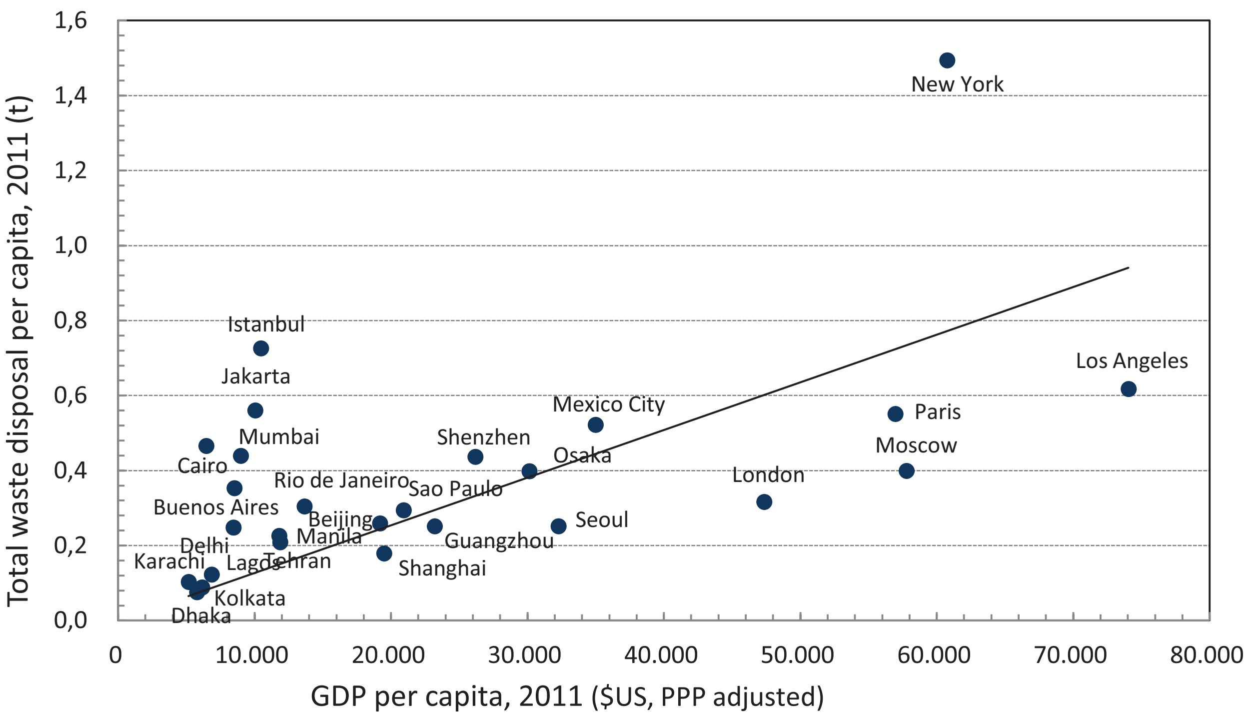
Source: own elaboration

FIGURE 21 - Ratios between 10-year solid waste disposal and population growth



Source: own elaboration

FIGURE 22 - Waste consumption in relation to megacity GDP

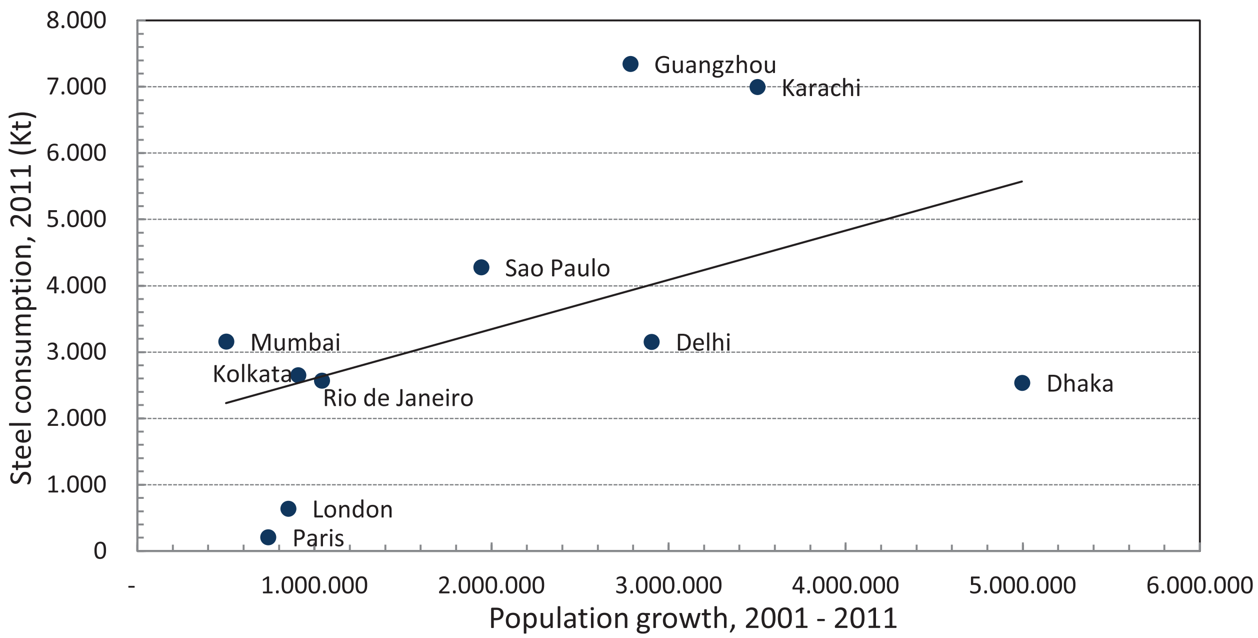


Source: own elaboration

2.4 Materials

As 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 was found to be the case for steel consumption (Figure 23). We obtained data on steel consumption for only 10 megacities and we found that steel consumption was significantly correlated (t-stat = 7.6) with the absolute population growth of megacities over 10 years. Data on cement consumption were obtained for 10 cities, with five megacities - Mumbai, Kolkata, Delhi, Dhaka and Sao Paulo - being the largest consumers at 7.7 - 9.2 million tones, respectively, for 2011.

FIGURE 23 - Steel consumption versus 10-year population growth



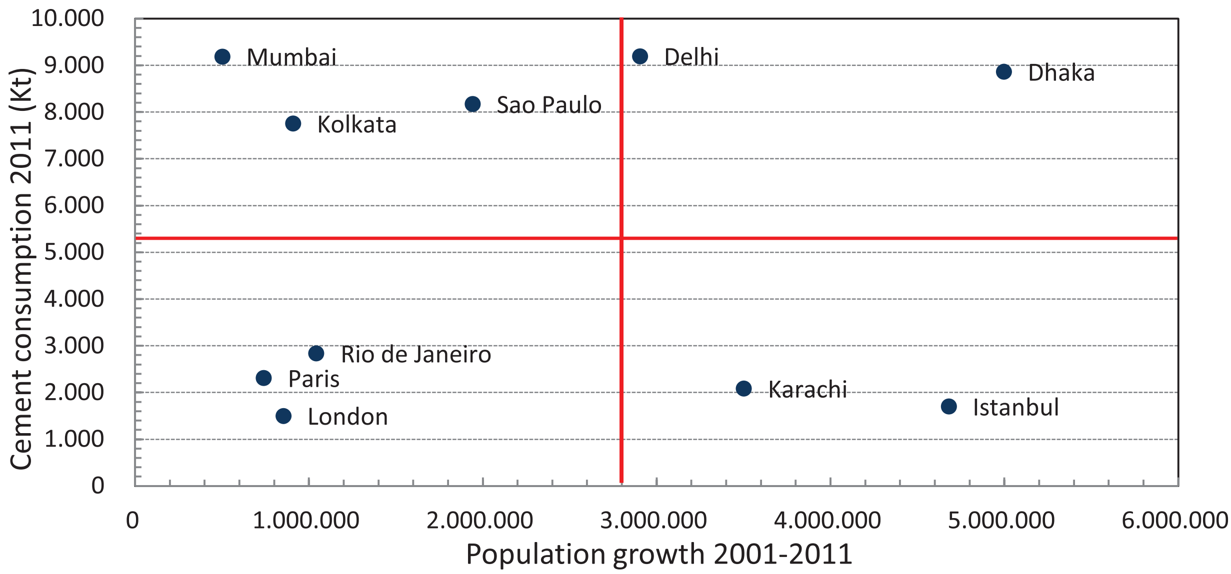
Source: own elaboration

Figure 24 shows that no significant statistical correlations were found for cement. It is worth noting, however, that the megacities can be organized in 4 clusters, separated by red lines. In this case, the plot is divided into four regions:

1. *low increase-high consumption*: in the upper left, we find Mumbai, Kolkata and Sao Paulo;
2. *low increase-low consumption*: in the lower left, we find Rio de Janeiro, Paris, and London;
3. *high increase-high consumption*: in the upper right, we find Delhi and Dhaka;
4. *high increase-low consumption*: in the lower right, we find Karachi and Istanbul.

Because of low data availability, it is hard to reach conclusions, and better investigation must be performed. In any case, also considering Figures 7, 16, and 20, we note that the position of some cities is consistent with the growth rates (i.e., London and Paris in sector 2 and Dhaka and Delhi in sector 3), while some other cities are not consistent with the above mentioned findings (i.e., Rio de Janeiro in sector 1).

FIGURE 24 - Cement consumption vs. 10-year population growth



Source: own elaboration

3 Quality of life in megacities

In addition to the assembled data on energy, water and solid waste, further data on the access to resources show that many of the megacities are consuming resources at rates below those which support a high quality of life. 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 (Table 3). The under-consumption of resources in these cities is, however, complex and needs further investigation. There are also high rates of resource wastage in some of these cities. For example, non-revenue water is high in many megacities, reaching over 70% in Sao Paulo and Buenos Aires. Some of this may be due to informal/illegal water withdrawals, while other losses are due to the poor state of infrastructure. In contrast to the poorer megacities, it may be hypothesized that some of the wealthier cities are over-consuming resources. However, this is not straightforward, as the economies of cities have a bearing on their use of resources, but climate, urban form and growth rates also influence resource use (as shown previously). Nonetheless, the two U.S. megacities tend to be particularly high in many resource categories, especially electricity, water and waste. Guangzhou is also observed to be a high-resource outlier with respect to water and heating and industrial fuel use. Water efficiency is particularly low in Guangzhou, even compared to 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[23]. Water prices are also very low in Guangzhou. There are also examples amongst the wealthier cities of practices that have improved resource efficiency. For example, Moscow is serviced by a combined heat and power system, by which waste heat from electricity generation is used to provide heating to most buildings in the city; Seoul has a wastewater reuse system, which saves on the input of water supplies; while Tokyo has managed to reduce its water leakage rate down to just 3%[24]. Amongst the wealthier cities, overall, Paris appears to be below the average on many of the measures of resource flows.

TABLE 2 - Access to services in megacities (all values are percentages)

Megacity	*Households without direct access to water*	*Households without direct access to drinkable water*	*Water line losses as a share of total water consumption*	*Households without sewerage*	*Wastewater subject to treatment*	*Households without public waste collection*	*Households without grid electricity connection*
Mumbai	21	21	3.7	64	94	48	18
Delhi	20	22	40	64	56	n.d.	0.9
Dhaka	7	31	33.1	65	65	10	67
Kolkata	n.d.	39	22	37	24	n.d.	5
Karachi	40	60	40	43	22	40	35
Jakarta	8	24	n.d.	12	n.d.	n.d.	0.3
Cairo	8	19	6.1	23	6	n.d.	n.d.
Tehran	0	0	33.3	55	n.d.	0	0.1
Rio de	1	11	54.2	26	32	9	0
São Paulo	2	2	71.4	8	43	5	0
Buenos	11	11	76.1	14	42	5	0
Mexico City	4	n.d.	n.d.	0.5	15	n.d.	5
Guangzhou	0.3	2	n.d.	15	4	1	15
Shenzhen	5	6	n.d.	30	20	1	15
Shanghai	0	0.6	15	10	14	1	0
Beijing	0	0.3	15.3	5	5	0	0
Lagos	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

***** n.d. = no data

Source: own elaboration

[23] Nanfang ribao, 2008

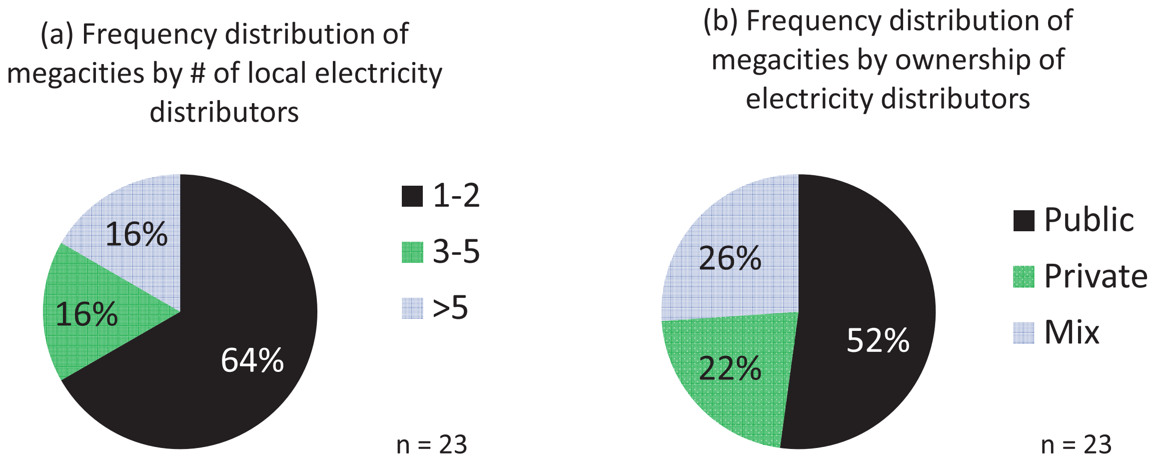
[24] Tokyo Metropolitan Government, 2010

As seen before, London was notably the only megacity to reduce its per capita electricity consumption over the period 2001-2011. This may be due to several factors: electricity prices rose by 66%; 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.

3.1 Utilities and technology

Together with standard data on material and energy flows, a further layer on utilities and technology has been investigated. This additional layer is important when considering the city from an integrated view that encompasses the transformative action that utilities, policy makers, and regulators apply on the urban systems. Panel (a) of Figure 25 shows that in 64% of the investigated megacities, only 1-2 companies operate the electricity distribution network, and that 52% are public owned companies.

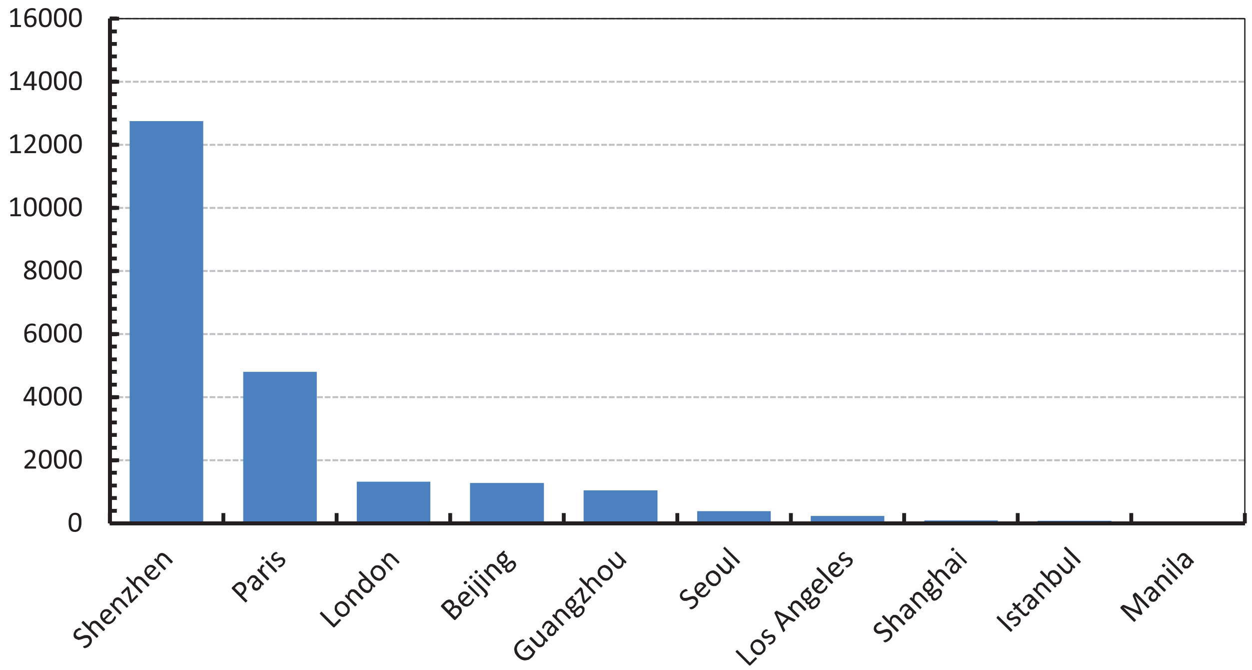
FIGURE 25 - Percentage of local electricity distributors by number and ownership in 23 selected megacities



Source: own elaboration

From the point of view of electric mobility, in Figure 26 it is worth noting that the Chinese megacities are leading the way towards the diffusion of electric mobility, with Shenzhen Counting over 12,000 charging points, followed by Paris and London (4800 and about 1300, respectively). Other cities counting a relevant charging point number are Beijing and Guangzhou.

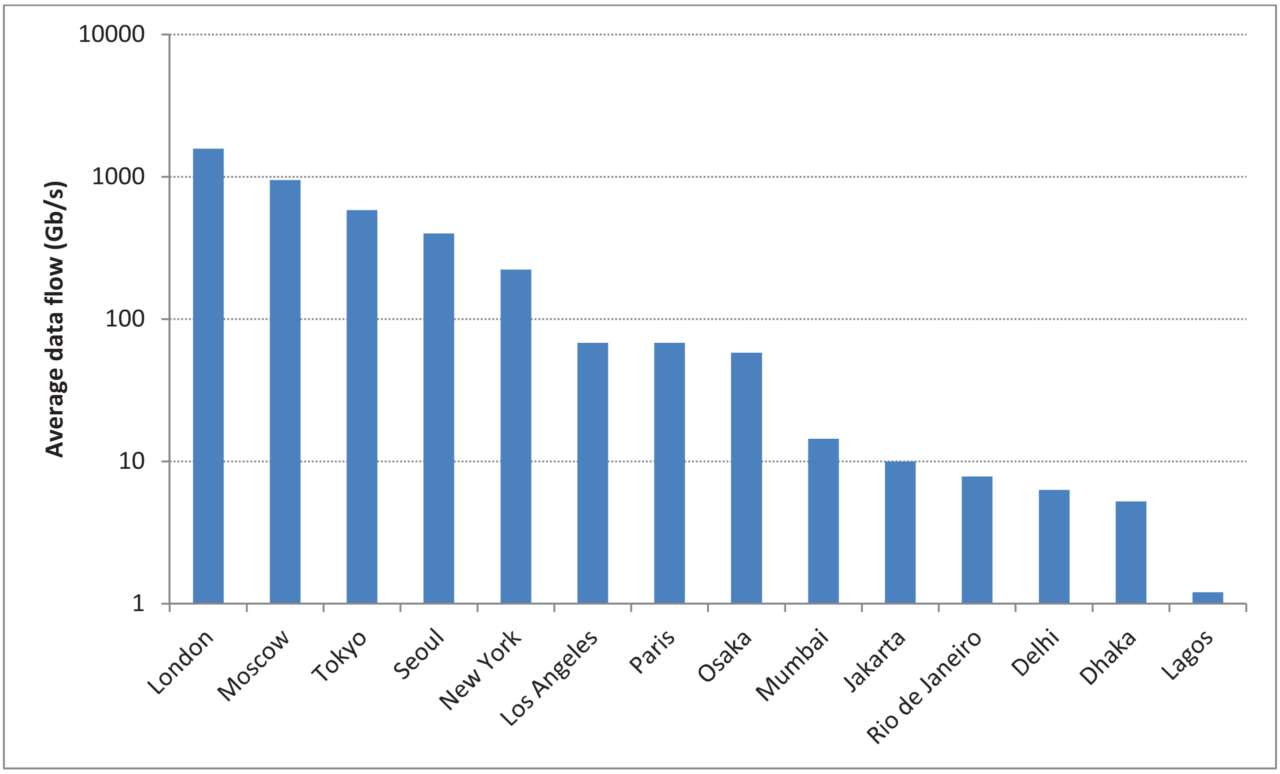
FIGURE 26 - Number of EV charging points in selected megacities



Source: own elaboration

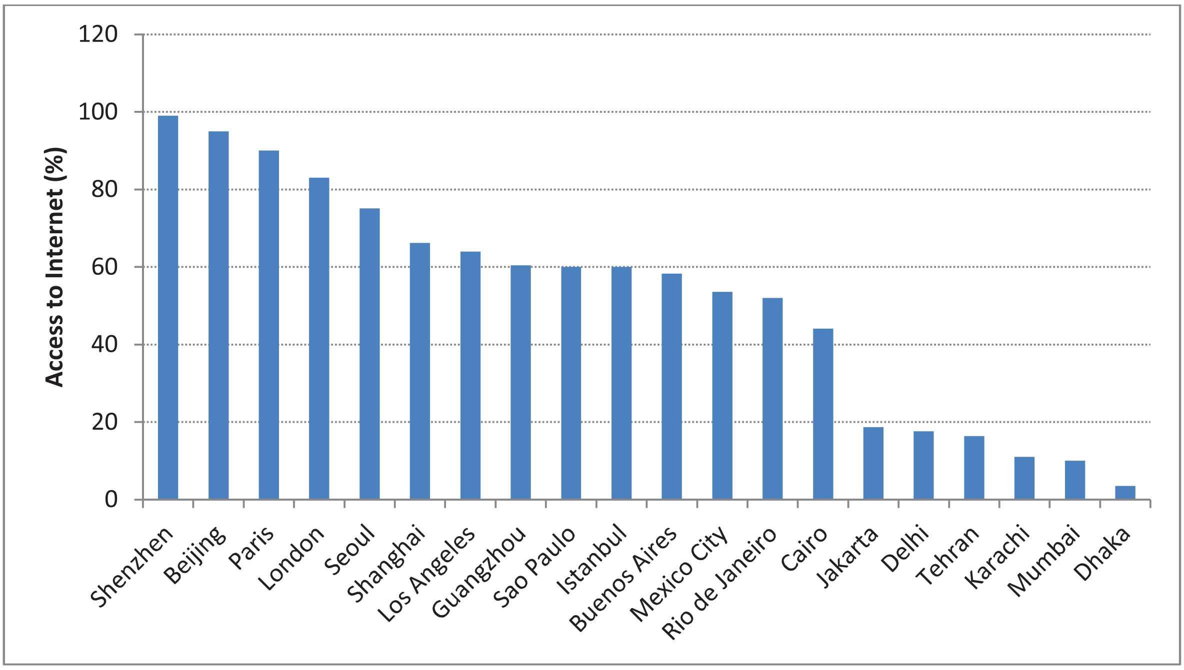
Another important aspect impacting the role of utilities and technology is the flow of information. These data, as of today, are not considered in the standard method of urban metabolism, and data collection does not follow an established standard. Data reported in Figure 27 have been collected from the Internet Exchange Directory (https://prefix.pch.net/applications/ixpdir/index.php) and should be considered as indicative measures of how data flows in cities. This is because, even if located in a specific city, the IXP also collect data flows from other cities in the country. Figure 27 shows the average data flow for 14 out of 27 megacities investigated. The most important megacity from the perspective of data flows is London, with an average of more than 1.5 TB; Moscow, Tokyo and Seoul follow with flows in the bracket 400-900 Gb/sec. Surprisingly, New York, Los Angeles, and Tokyo, the first three cities according to GDP, do not rank highest when considering data flows. This fact should be better investigated and may depend on data source. Another significant aspect to be investigated is the fraction of people connected to the internet. Figure 28 shows that internet access is very high for Chinese megacities, and in some cases confirms the data reported in Figure 27, while in other cases gives different indications.

Figure 27 - Average data flow (Gb/s) in selected megacities (data flow axis displayed in logarithmic scale)



Source: own elaboration based on Internet Exchange data

FIGURE 28 - Percentage of population connected to the internet



Source: own elaboration

3.2 Green areas

Closely connected with the quality of life in urban areas, public green areas receive much attention in the scientific community[25]. Benefits of urban green spaces are the following:

1. improved mental and physical health of urban residents;
2. enhanced social interaction and integration;
3. urban heat mitigation in the form of cooling through shade and evapotranspiration;
4. noise reduction and air filtration of pollutants;
5. promotion of urban biodiversity.

Population growth is challenging urban green space development because of the focus on re-densification policies in inner city areas.

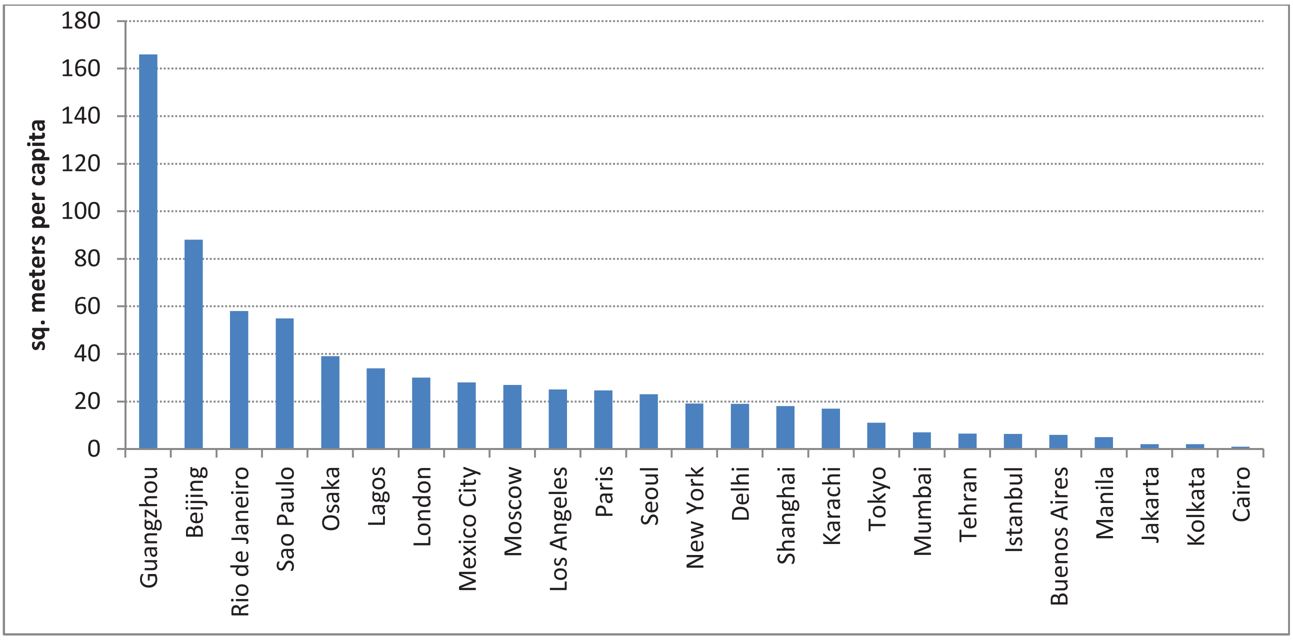
However, in developing countries, the pressure from population growth is far higher, and ongoing and future urbanization will lead to the spread of physical infrastructure and the conversion of open land to residential areas, not always considering green space development. As a result, many residents will succumb to inequalities in access to green spaces and the environmental and social benefits that such spaces provide.

According to the WHO, the minimum area per person in urban areas should be 9 sq meters; Figure 29 shows those megacities that are above and below this critical value.

Among the investigated megacities, about one third are below 9 m^2 of public green space. Surprisingly, Tokyo is near the threshold, while the other megacities are above or well above.

[25] Kabisch et Al., 2015

FIGURE 29 - Sq. meters of public green areas per capita.



Source: own elaboration based on Siemens Green City index data

4 The global impact of megacities

While there is great diversity in the energy and material flows through individual megacities, collectively their resource flows appear to be consistent with scaling laws observed for cities over a wide range of populations. Clearly megacities are at the top of the population scale and should exhibit extreme values for quantities that scale super-linearly or sub-linearly. The 27 megacities had a combined population of 460 million in 2010, equal to 6.7% of global population (Figure 30).

Their combined GDP was much larger in percentage terms, at 15.2% of global GDP. This is expected for socio-economic characteristics, which have been shown to scale with an exponent of $\beta \approx 1.15$ [26]. Furthermore, the economic power of megacities is well represented in Figures 26 to 28. In particular, Figure 31 shows that the GDP of New York, Los Angeles and Tokyo is well above the other megacities, with a GDP over 1000 billion dollars. The other megacities are in the range of 80.6 (Lagos) to 818.4 (Mexico City).

Figure 32 gives evidence of the large growth that Asian and Latin American megacities experienced in the period 2001-2010. In fact, excluding Moscow, all the megacities that grew at rates over 100% are located in these regions. At the pinnacle, we find Chinese megacities (Shenzhen, Beijing, Guangzhou, and Shanghai) with growth rates well over 200%. On the other side, when considering the ratio between the growth rates of GDP and population, the figures change slightly, as reported in Figure 33: Mumbai and Mexico City are the megacities in which the ratio of the growth rates is larger (29 and 21 times faster, respectively).

Regarding energy and material flows, the total waste production for megacities is estimated to be 9.8% of the global amount. This value suggests that waste flows may also exhibit super-linear behavior, because of their relation with GDP. Essentially the higher amount of economic activity in larger cities entails importing relatively high quantities of goods and other materials, which apart from those that become bound in the building stock, exit cities relatively rapidly as wastes.

The total energy consumption of the 27 megacities is about 21,621 PJ, which is approximately 6.0% of global energy consumption. This percentage is close to, but under, the 6.7% of global population that lives in megacities. A mixture of energy related scaling relationships were found by Bettencourt and colleagues[27]: residential electricity scales linearly, total electricity scales super-linearly and gasoline use scales sub-linearly.

We also found that megacities consumed 9.3% of global electricity and 9.1% of global gasoline; the former is consistent with super-linear scaling, but the latter is not consistent with sub-linear scaling and requires further exploration (however, this could be due to the use of other transportation fuels in cities, e.g., high use of diesel in many European cities). The

[26] Bettencourt, 2013
[27] Bettencourt 2007; Bettencourt, 2009.

observation that megacities consume 6% of total global energy use should also be treated cautiously for the following reasons.

i) The global energy use total includes energy consumed in global transportation of goods and people, much of which actually occurs between cities.

ii) We have reported energy consumption by cities, not primary energy use. Electrical energy use is higher if primary energy is determined.

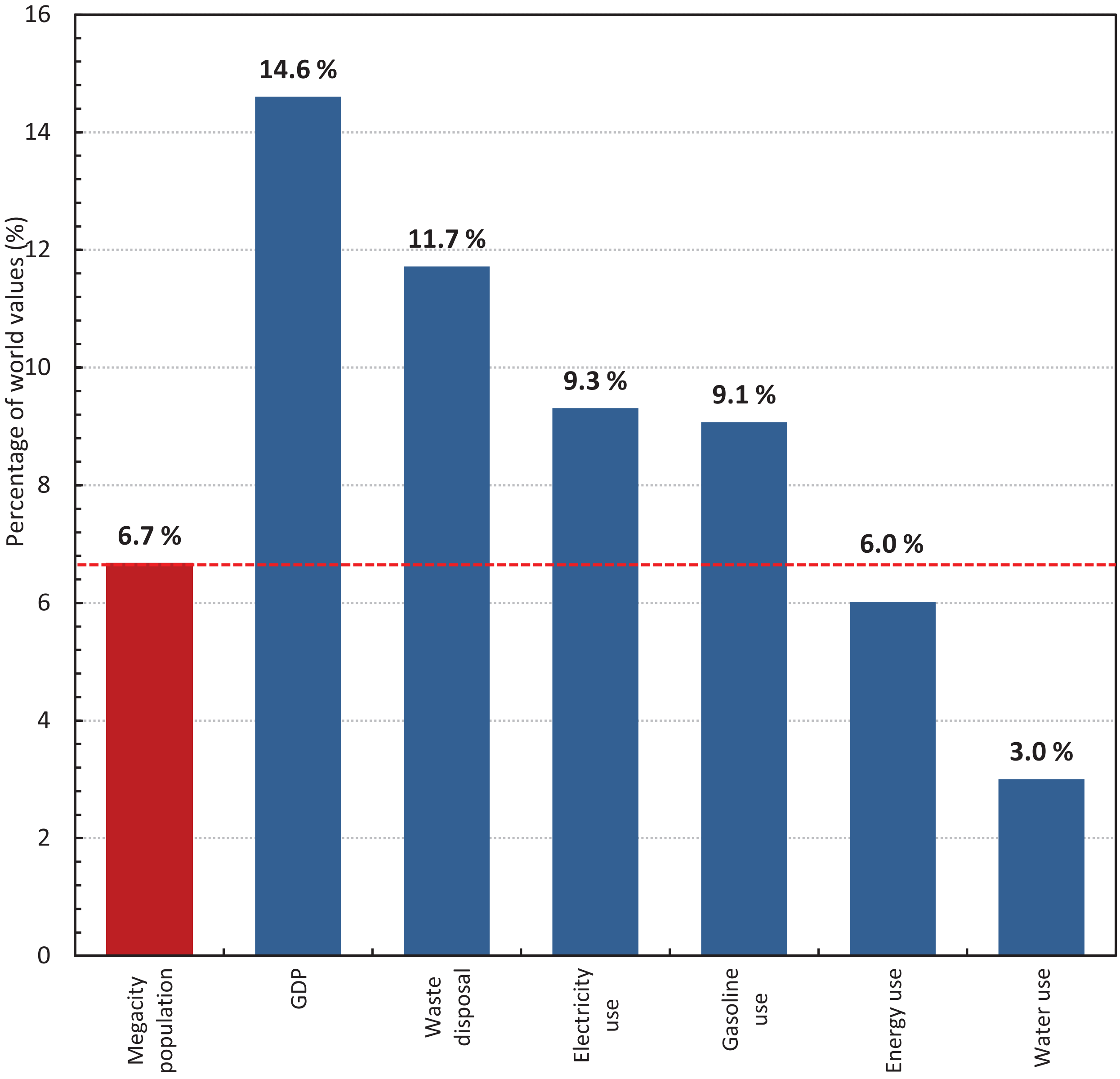
iii) The extraction and refining of fossil fuels requires an energy premium that necessarily occurs in order to combust fuels in cities.

iv) The majority of megacities are located 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 over 2000 heating degree days in 2011). Whether or not the distribution of climatic zones for megacities is representative of that for all global inhabitants has not been determined.

The final quantity compared in Figure 30 is water use. The 51 million ML consumed in megacities (incl. losses) is about 3% of global water use, which is roughly estimated to be 2,600 million ML.[28] This percentage seem reasonably consistent with expectations as a large amount of global water supply is used in agriculture, which is a predominantly rural activity.

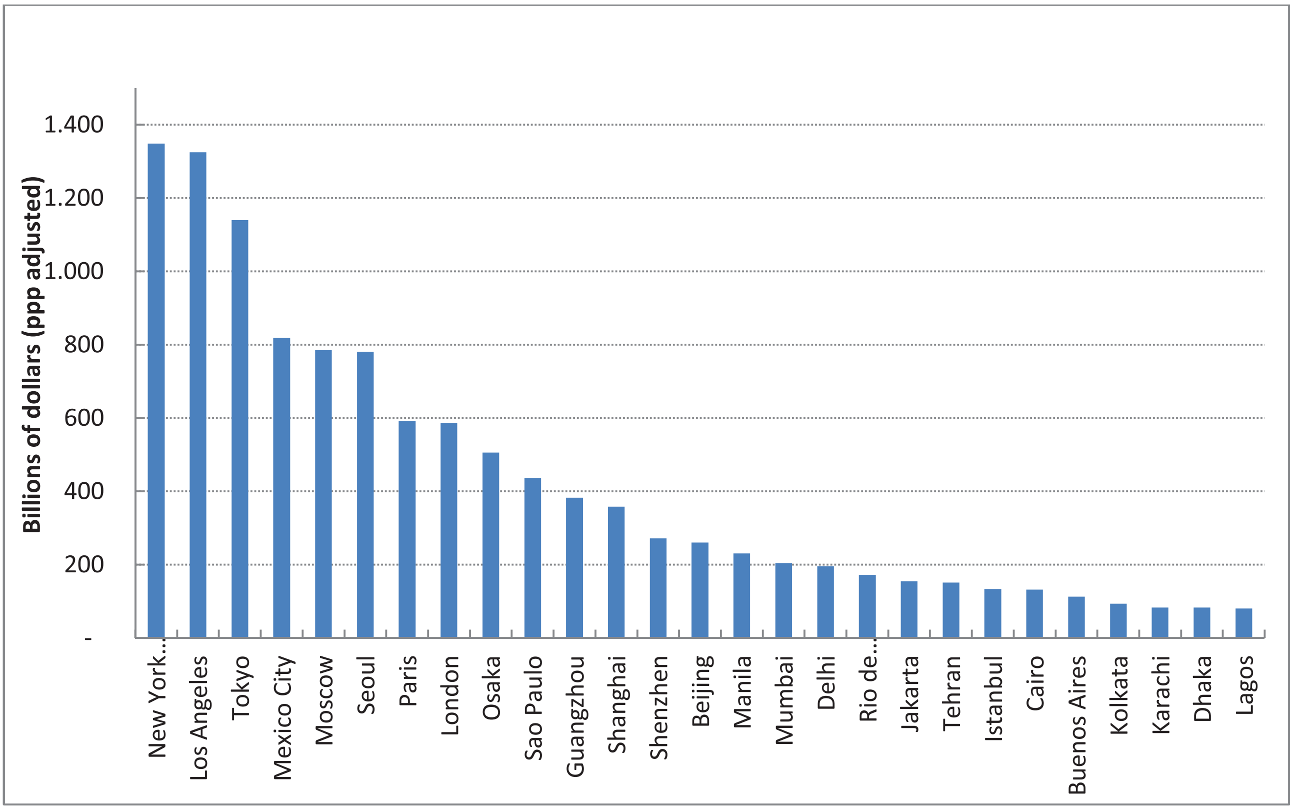
[28] Rockström, 2009.

FIGURA 30 - Megacity resource & waste flows as a percentage of world values



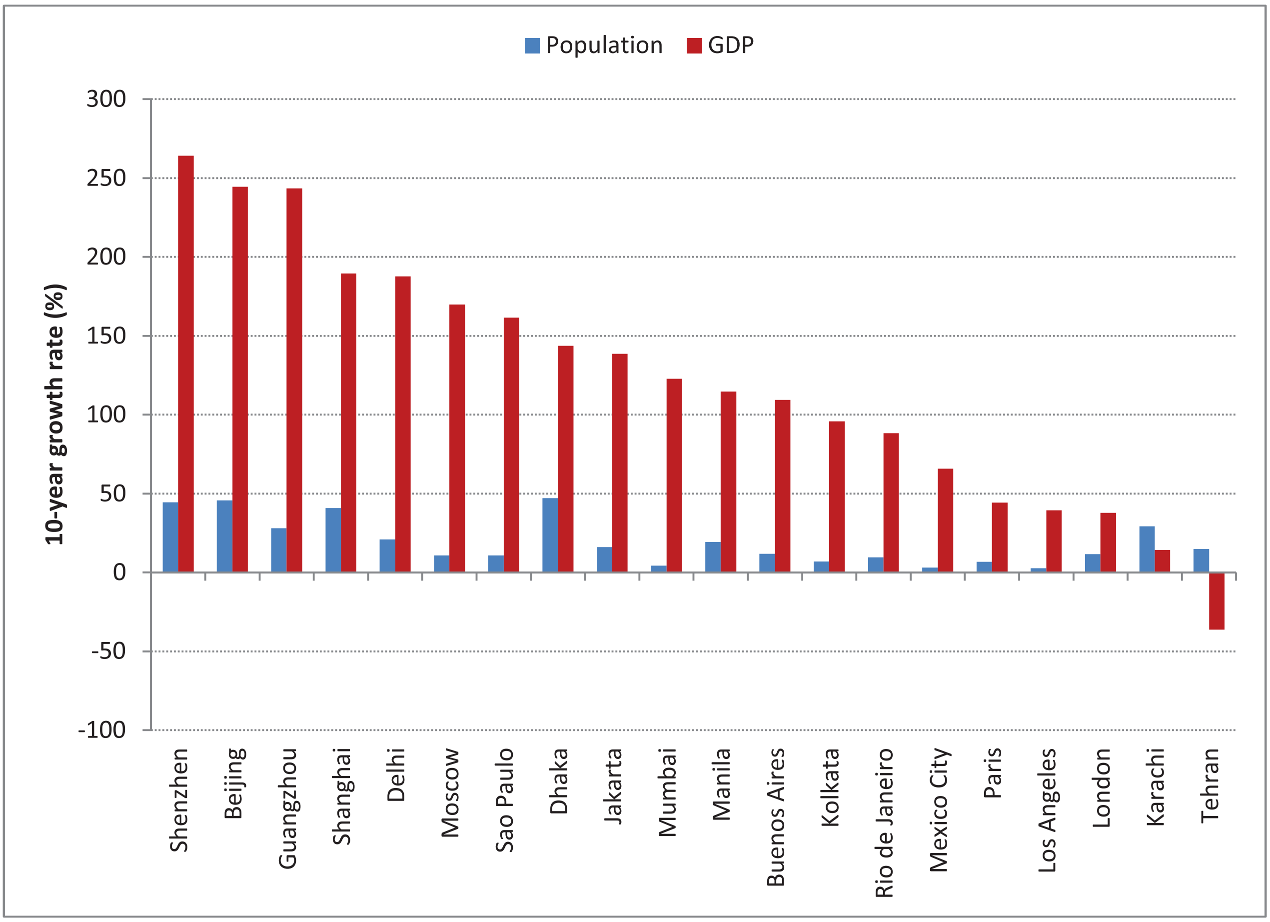
Source: own elaboration

FIGURE 31 - Megacities GDP (2011)



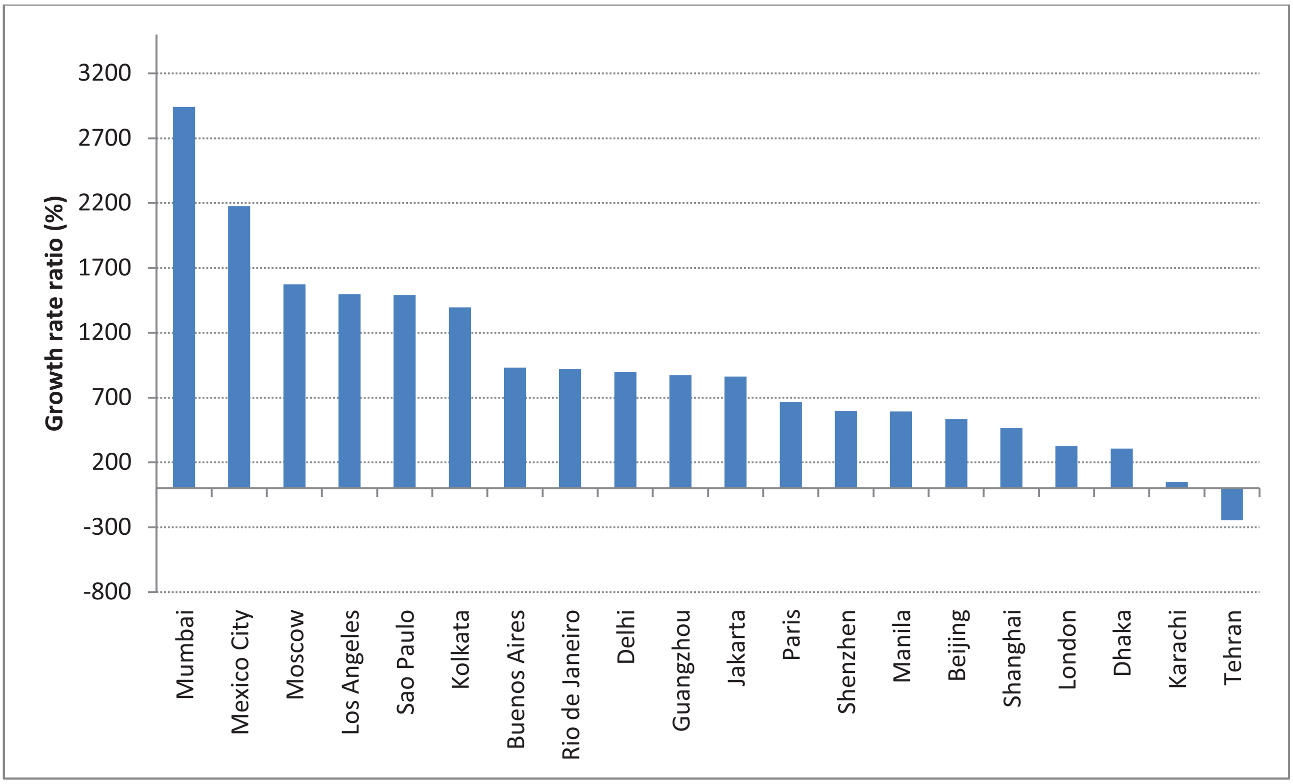
Source: own elaboration

FIGURE 32 - Comparison of 10-year growth rates for GDP and population in megacities



Source: own elaboration

FIGURE 33 - Ratio between growth rates of GDP and population



Source: own elaboration

5 Conclusions

Overall the energy and material flows vary considerably between megacities. Rates between the lowest and highest consuming megacities differ by a factor of 24 for energy per capita, 20 for water per capita, 19 for waste production per capita, 11 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, while 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 are also influenced by climate, urban form, economic activity and scale effects.

Future work will offer a better understanding of all the topics treated in this working paper, and provide further analysis of the role that utilities play in the control of the urban metabolism of megacities.

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