The Heterogeneity of Urbanization Patterns and Carbon Emissions

Leiwen Jiang

National Center for Atmospheric Research

Abstract

Studies on the impacts of urbanization on carbon emissions across countries, even adopting the same research methods, often reach discrete conclusions. This is largely due to the distinct datasets used by individual studies that represent countries across various socioeconomic conditions and under different forms of urban growth. This paper investigates the heterogeneity of urbanization patterns and its associated carbon emissions through energy consumption. We compare the per capita energy consumption and energy intensity of cities to the national averages in different regions, and analyzes the within-region variations and their causes based on a case study of Chinese cities. It reveals that cities in the developing region has higher than national average energy intensity, while the opposite result is found in most developed regions; the large variations across cities within a country are mainly caused by urban sizes and forms, population density, income levels, and other geographic and climate factors.

Extended Abstract

Urbanization is a process of transferring population from the rural areas to the urban ones, and labor force from agricultural pursuits to industrial and service occupations (Jones 2004). Many authors indicate that urbanization, accompanying by the changes in industrial structure and economic development, increases fuel consumption, particularly fossil fuels, per worker and per unit of output. However, studies based on across-nation historical records, even adopting the same method, often reach discrete conclusions (Table 1). The discrepancies are largely due to fact that those studies use the different datasets which includes time series vs. cross-sectional data, and data from all countries vs. data from countries distinguished by development and urbanization levels.

Table 1 Effects of urbanization on energy consumption by studies in developed and developing countries over different time periods

Study	***Countries***	***Time period***	***Urbanization elasticity of***	
			Energy use	***Carbon emissions***
Jones 1991	59 developing countries	1980	+0.48	
Parikh and Shukla 1995	78 developed &developing countries	1965-1987	+0.28	
York 2007a	14 developed countries	1960-2000	+0.53	
York 2007b	14 Asian developing countries	1971-2002	-0.22	
Mishra et al. 2009	9 Pacific Island countries	1980-2005	+2.41	
Jorgenson et al. 2010	57 developing countries	1990-2005	+0.22	
Liddle and Lung 2010	17 developed countries	1960-2005	+0.61	
Poumanyvong and Kaneko 2010	33 high income countries	1975-2005	+0.91	+0.36
	43 middle income	1975-2005	+0.51	+0.51
	23 low income	1975-2005	-0.13	+0.43
	All 99 countries	1975-2005	NS	+0.45
York et al. 2002	137 developed and developing countries	1991		+0.72
York et al. 2003	146 developed and developing countries	1996		+0.62
Cole and Neumayer, 2004	86 developed and developing countries	1975-1998		+0.70
Jorgenson and Clark 2010	86 developed and developing countries	1960-2005		+0.02
Martinez-Zarzoso 2008	26 upper middle income countries	1975-2003		-0.25
	38 lower middle income countries	1975-2003		+0.73
	31 low income countries	1975-2003		+2.83
Martinez-Zarzoso and Maruotti 2011	88 developing countries	1975-2003		+0.76

Note: NS – not significant.

Table 1 shows that the majority of the studies points out a positive net impact of urbanization on per capita energy consumption, after controlling for industrialization, income growth and population density (Table 1). However, urbanization elasticity vary considerably across studies, ranging from -0.22 (York 2007b) to +2.41 (Mishra et al. 2009). All the studies, except the one of

9 small Pacific Island Countries by Mishra et al. (2009), suggest that urbanization in the more urbanized developed countries contribute more to the increase of energy use than in the developing countries; negative effect of urbanization generally occurs in less urbanized low income countries. While almost all studies reveal a positive urbanization elasticity of carbon emissions in all regions ranging from +0.02 to 0.76, the extents of urbanization effect vary significantly across regions. The study by Martinez-Zarzoso (2008) shows that the positive effect of urbanization on carbon emissions is the strongest in the low income countries, even though urbanization may play a negative role in energy consumption in those countries. It suggests that the urbanization elasticity for carbon emissions is larger than 1 for the low income group, 0.72 for the middle income group, and negative for the upper income group. On the other hand, Poumanyvong and Kaneko (2010) found an inverted-U shaped curve between urbanization and carbon emissions: the urbanization elasticity for carbon emissions increase from low income countries to middle income countries, but decline among high income countries. The study by Martinez-Zarzoso and Maruotti (2011) reaches a similar conclusion.

The impacts of urbanization on energy use and carbon emissions differ not only by the stages of urbanization and economic development levels of the countries under-study, but also by the forms and patterns of urban growth. Urban density and spatial organization are crucial elements that influence energy consumption, particularly in transportation and residential energy use. In responses to increased affluence and growing dependence on automobile, urban sprawl occurs in many parts of the world, particularly in the US (Burchell etc. 1998). A comparison of 10 major cities in the US with 12 European cities shows that while the latter are five times as dense as the former, the US cities consume 3.5 times more energy in transportation than their European counterparts (Steemers 2003). This is mainly because the suburban households in the US drive 31 percent more than the residents in the central cities (Khan 2000). Suburbanization may also contribute to increasing residential fuel consumption and land use (Kalnay and Cai 2003). While a more compact development in the low-latitude regions may induce greater demands for space cooling due to the strong effect of urban heat island (Santamouris et al. 2001; Pitts 2010), urban sprawl increases energy use for housing everywhere that poses a much stronger effect than the possible energy saving from space cooling (Ewing and Rong 2008). Considering the effects of urban form and transportation system, moving households from a city with the characteristics of Atlanta to a city with the characteristics of Boston reduces annual vehicle miles travelled by 25% (Bento et al. 200%).

Comparing to the more developed North America and Europe, an even greater heterogeneity of urbanization patterns is observed in the developing world. Although the urban system of developing countries is generally less mature than in Europe and North America, countries in the developing region has reached all stages of urban transition, and displays various types of urban forms. On the one hand, rapid urbanization in the Sub-Saharan Africa and Middle East over the past half century have been accompanied by excessively high levels of population concentration in the large cities (Henderson 2002); on the other hand, urban sprawl has already been observed in the Latin America and in some Asian countries (Burchell et al. 1998). While the majority of urban population growth occurs in small or medium size urban areas (Martin et al. 2008), the rural poor has consistently been urbanized faster than the nonpoor in Sub-Saharan Africa, Latin America, South and Southeast Asia, which leads to a prominent phenomenon of urbanization of poverty (Haddad and Garrett 1999; Ravallion 2002).

Due to the regional variations in the relationship between urbanization and economic growth and industrialization, the impact of urbanization on carbon emissions differs remarkably across countries. For instance, Latin America has a similar urbanization level but substantially lower per capita energy consumption and CO2 emissions compared to North America and West Europe; the per capita energy use and carbon emissions in Sub-Saharan Africa remained unchanged in the past four decades, even though the urbanization level of the region almost doubled, because the rapid urbanization were not accompanied by significant industrialization and economic growth in Sub-Saharan Africa, which resulted in the so called 'urbanization without growth" (Easterly 1999; Fay & Opal 2000; Haddad et al. 1999; Ravallion 2002; Ravallion et al. 2007).

Therefore, to study the impacts of urbanization on energy consumption and carbon emissions, it is important to consider not only the levels of urbanization, but also the stage, scales and forms of urban growth as well as their relationships with industrialization and economic growth. Unfortunately, in the long-lasting debate on the nexus between urbanization and environment, urbanization and climate change in more recent decade (e.g. Satterthwaite 2009; Jiang et al. 2009; O'Neill et al. 2012; Seto et al. 2012), scholars have paid far from enough attention to the diverse relationships in the heterogeneous urbanization world. This paper aims to systematically investigate the heterogeneity of urbanization patterns and energy use and carbon emissions through regional comparison and in-depth case studies.

1. Regional Comparisons

We first compare the per capita energy consumption and energy intensity (energy use per unit of GDP) of cities to the national averages in different regions. The data used in this analysis are from the GEA (Global Energy Assessment) City Energy Data Base (Grubler 2014) for the city energy use and from the IEA (International Energy Agency) Energy Balances (IEA 2010) for national average energy use. The result shows that the per capita energy consumptions in the developed regions are significantly higher than the ones in the developing regions, for both their urban areas and the country as whole (Figure 1a). Looking at the energy intensity (Figure 1b), however, it is generally higher in developed regions than in developing regions, for both the cities and the countries as a whole. Because the developed countries have higher economic growth and income levels, and use energy more efficiently by adopting modern technologies.

More importantly, Figure 1a indicates that the per capita energy use of cities in most developing regions are usually higher than that of national average (to the up-left above the oblique line), while the relationship is reversed in developed regions. This is because cities in the developed countries generally have lower energy intensity than the national average, while this is not clear in the developing regions. This phenomenon is also pointed out in other studies (e.g. C. Kennedy et al. 2009; Grubler 2014). The differences is largely due to the fact that most developing countries are experiencing industrialization and their cities are usually the manufacturing centers, comparing to developed regions which have mostly already completed the industrialization process. Moreover urban residents of developing regions usually have higher income and consumption levels than their rural counterparts. This is particularly true in the developing Asia, while many cities in Sub-Saharan Africa and Latin America and Caribbean have lower than national average per capita energy use because of the phenomenon of "urbanization of poverty" (Easterly 1999; Fay & Opal 2000; Haddad et al. 1999; Ravallion 2002; Ravallion et al 2007).

Figure 1 also reveals the large variations in energy consumptions among cities within the regions. While the per capita energy consumption and energy intensity of cities in developed regions is mostly less than that of national average, many city residents in Western Europa consume much more energy per person and use more energy to produce the same amount of products than the average citizens. In the developing world, while most cities have higher per capita energy consumption levels than the country as whole, many cities in Sub-Saharan Africa use less energy per person than the national average. The energy density in Sub-Saharan Africa varies enormously from city to city. In China, almost all cities consume more energy per resident than the national average, due to the large urban-rural disparities in socioeconomic levels. However, compared to the 10 MJ per US$ GDP of national average energy intensity level, to generate the same amount of products, about half of the Chinese cities under study needs more energy and the other half needs less energy.

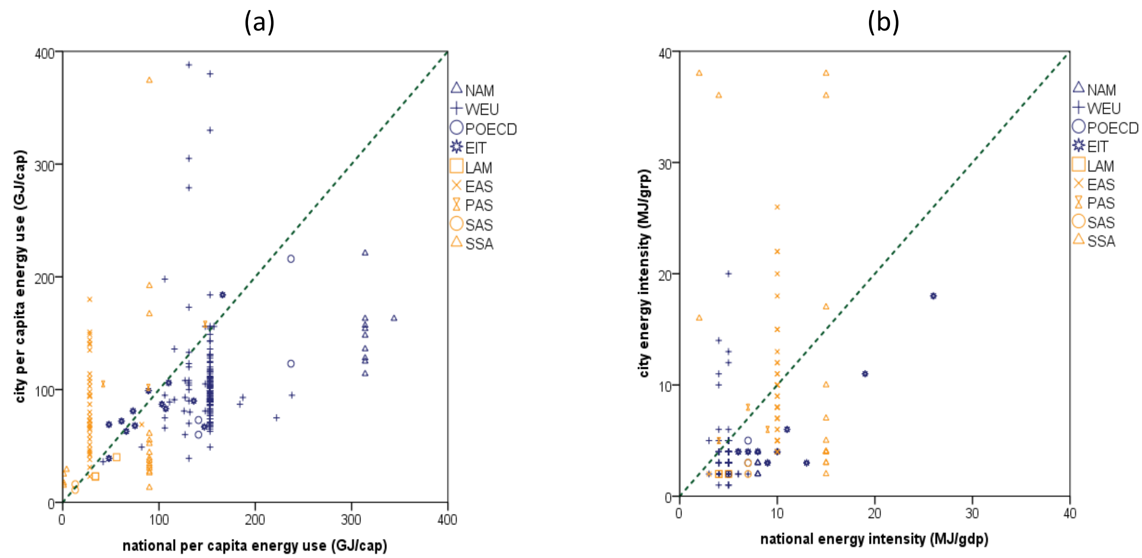


Figure Error! No text of specified style in document.. Per capita energy use (a) and energy intensity (b) in cities compared with the national average by regions, 2000

Note: NAM – North America, WEU-West Europe, POECD-Pacific OECD countries, EIT-economies in transition, LAM-Latin America and the Caribbean, EAS-East Asia, PAS-Southeast Asia and Pacific Islands, SAS-South Asia, SSA-Sub-Saharan Africa.
The per capita energy use of cities represented by dot above the green line is higher than the national average; otherwise, is lower than the national average.
Data sources: (1) city energy data is from Global Energy Assessment database (Grubler 2014); (2) national energy data is from IEA energy balances (International Energy Agency 2010).

To understand the large variations in per capita energy use and energy intensity across the cities, it is important to carefully explore the main features of those cities that contribute to their different energy consumption patterns. In the next section, we use China as an example to conduct the in-depth analysis.

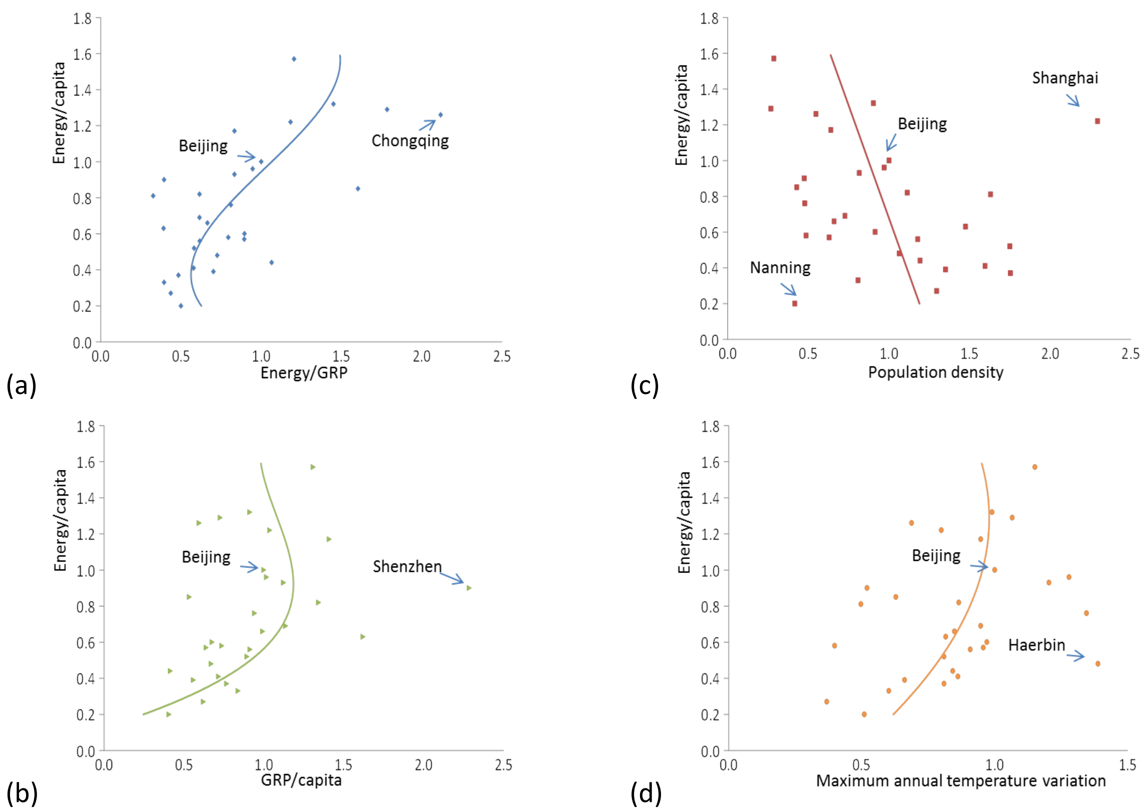
2. Case study of energy use in Chinese cities

In this case study, we use the data from the GEA City Energy Data Base for the Chinese cities. The 36 cities contained in the dataset are the capital cities of 29 provinces, 4 provincial level municipalities (Beijing, Shanghai, Tianjin and Chongqiong), and other 5 cities (Shenzhen, Xiamen, Ningbo, Qingdao, Dalian) at semi-provincial level. Those cities are distributed spatially across all climate zones and various types of geographic condition, and vary significantly in land territory, population size, economic scale, and economic development level.

According to economic theories and existing empirical studies, among many possible factors that may contribute to differentiated energy consumption behaviour, we specifically focus on the variables related to urban size, form, income level, industrial structure, infrastructure and facility, and climate condition. From the China 2001 City Statistics Yearbook (NSB 20001), we use the following variables to represent these urban features:

- urban size: land area, population size, Gross Regional Products (GRP)
- urban form: population density (population per square kilometre), economic density (GRP per square kilometre)
- income level: per capita GRP
- industrial structure: proportion of GRP and labor force in agricultural, manufacture, and service sector
- infrastructure and facility: road intensity, number of bus per 10,000 residents, percentage built-up area
- climate condition: average monthly temperature in January, July, and temperature differences between July and January.

Figure 2 Comparisons of per capita energy consumption, energy intensity of Chinese cities, by income, population density, and average temperature



Note: The numbers of all variables here are relative values to the level of Beijing (the values of Beijing = 1).

To explore among the cities the general relationships between per capita energy use, energy intensity, and their income level, population density and average temperature, we set the values of all the variables of Beijing to be 1 and derive the relative values for other cities. Figure 2a shows that the per capita energy consumption levels of the cities are generally positively associated with their energy intensities. Although greater per capita energy use is mostly associated with higher per capita income, the relationship is not linear: the cities with the highest income level (e.g. Shenzhen) is at the middle range of per capita energy consumption (Figure 2b). The relationship between per capita energy use and population density is basically negative and linear, with an exception for Shanghai which has much higher population density than the other cities (Figure 2c). This may hints that while higher population density leads to efficiency due to the economy of scale, extremely high density may lose its advantage of low transaction rates due to excessive congestion (Jiang 2014). Figure 2d displays a positive relationship between per capita consumption and extreme weather conditions (hot in the summer and cold in the winter).

A correlation analysis suggests that the per capita energy consumption and energy intensity of Chinese cities are associated with different urban features (Table 2). Per capita energy consumption is positively correlated with city land area, annual maximum temperature difference, income levels, but negatively correlated with January temperature, population density and economic density. On the other hand, energy intensity is positively correlated with city land size and proportion of agriculture products, but negatively correlated with economic density, income level, population density, temperature of both January and July, and road intensity.

Table 2. Correlation coefficients between energy use and city characteristics

variable	Variable label	GJcap (per capita energy use)		MJdollar (energy intensity)	
GJcap	Per capita energy use	1.00		.673	***
cityland	Land area	.481	**	.512	**
population	Population size	-.084	-	-.115	-
GRP	Gross Regional Product	.120	-	-.364	*
popden	Population density	-.313	*	-.301	*
GRPden	Economic density	-.272	*	-.474	**
GRPcap	Per capita income	.262	*	-.435	**
GRP1stind	% of GRP in agriculture	.148	-	.310	*
GRP2nd ind	% of GRP in manufacture	-.036	-	-.133	-
GRP3rdind	% of GRP in service sector	-.157	-	-.263	-
lab1st	% of labor in agriculture	.022	-	.108	-
lab2nd	% of labor in manufacture	.149	-	.049	-
lab3rd	% of labor in service sector	-.163	-	-.174	-
builtuparea	Built-up area	.247	-	.132	-
roadarea	Road density	-.064	-	-.290	*
bus10kpop	# busies per 10,000 population	-.093	-	-.097	-
tem_jan	January average temperature	-.320	*	-.352	*
tem_jul	July average temperature	-.223	-	-.394	*
tem_dmm	Temperature difference between July and January	.302	*	.277	-

Note: *** = 99% confidence, ** = 95% confidence, * = 90% confidence, - = not significant

Based on the correlation analysis, we constructed multivariate regression models to study the net contribution of urban features to energy consumption of the Chinese cities. The regression analysis is displayed in Table 3.

When per capita energy use is used as the dependent variable, city size, population density, income level, and temperature are the significant contributors, while the economic structure, economic density, facilities and infrastructures in the city do not play a significant role. In terms of city size, the bigger the city territory, the more energy use per resident. However, the population size of the city generate negative effects, while the total economy scale does not significantly affect per capita energy use. In addition to the impact of city territory and population size, population density independently and negatively contribute to per capita energy consumption: a 1% increase in population density causes 1% decrease in per capita energy use. However, square of population density positively contributes to per capita energy use, which indicates the negative effects of congestions on energy efficiency in extremely dense conditions. In addition, both income level and annual temperature range of cities have a positive impacts on energy consumption: the higher the income level and the bigger temperature range, the more energy use per resident.

Table 3 Multivariate regression analysis of per capita energy use and energy intensity of Chinese cities (standardized coefficients)

	Per capita energy use			Energy intensity		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Gross Regional Product	-.32			.05		
Land area	.67 *	.51 *	.55 **	.89 **	.81 ***	.79 ***
Population size	-.34	-.55 *	-.32 *	-.81 *	-.75 ***	-.71 ***
Population density	-1.24 *	-1.47 *	-1.09 *	-.89	-.91 *	-.94 *
Square population density	1.36 *	1.45 *	1.17 *	1.08 *	1.06 *	1.09 *
Economic density	.33	.22		.58 *	.55 **	.51 **
Per capita income	.45	.20	.35 *	-.67 *	-.62 ***	-.59 ***
% of GRP in service sector	-.04			.06		
% of labor in service sector	-.08			-.43 *	-.39 *	-.23 *
Built-up area	.27	.34		.35	.37 *	.33 *
Road density	.04			.01		
# busies per 10,000 population	.10			.26	.23	
Temperature difference between July and January	.32 *	.40 **	.36 **	.83	.14	
January average temperature	-.25			.87		
July average temperature	-.26			-.56	-.27 *	-.32 *
Adjusted R^2	.41	.49	.48	.59	.65	.64

Note: independent variables are entered by Backward Elimination method; *** = 99% confidence, ** = 95% confidence, * = 90% confidence.

Comparing to the regression model for per capita energy use, when energy intensity becomes the dependent variable, city territory and population size have the same type but stronger effects; again economy scale is not important; population density plays quite the same role;

economic density becomes important, and make a positive contribution to energy intensity. In contrast to its positive contribution to per capita energy use, income level drives energy intensity low. Moreover, economic structure also play a significant role in changing energy intensity: a higher proportion of workers engaged in service industries reduces energy intensity in the cities. Interestingly, July average temperature plays a negative role in city energy intensity, considering the fact that air conditioning had not yet been very commonly used in Chinese cities in year 2000.

3. Tentative conclusion:

The impact of urbanization on energy consumption and carbon emissions vary considerably across regions in different stages of economic growth and urban transitions. The heterogeneity of urbanization patterns should be carefully accounted for in order to better understand the long-lasting discussion on the urbanization-environment/climate change nexus. Urban size, density, economic structure, and geographic condition are all important factors to be considered.