Ecological Economics 70 (2010) 434–444

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis

Phetkeo Poumanyvong *, Shinji Kaneko

Graduate School for International Development and Cooperation, Hiroshima University, 1-5-1 Kagamiyama, Higashi-Hiroshima 739-8529, Japan

ARTICLE INFO

Article history:
Received 16 January 2010
Received in revised form 14 July 2010
Accepted 21 September 2010
Available online 20 October 2010

Keywords:
Urbanization
Energy use
CO_2 emissions
Development stages
STIRPAT model

ABSTRACT

Despite the relationship between urbanization, energy use and CO_2 emissions has been extensively studied in recent years, little attention has been paid to differences in development stages or income levels. Most previous studies have implicitly assumed that the impact of urbanization is homogenous for all countries. This assumption can be questionable as there are many characteristic differences among countries of different levels of affluence. This paper investigates empirically the effects of urbanization on energy use and CO_2 emissions with consideration of the different development stages. Using the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model and a balanced panel dataset of 99 countries over the period 1975–2005, the findings suggest that the impact of urbanization on energy use and emissions varies across the stages of development. Surprisingly, urbanization decreases energy use in the low-income group, while it increases energy use in the middle- and high-income groups. The impact of urbanization on emissions is positive for all the income groups, but it is more pronounced in the middle-income group than in the other income groups. These novel findings not only help advance the existing literature, but also can be of special interest to policy makers and urban planners.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Urbanization is a phenomenon of economic and social modernization. It is not only the process of transferring rural labor from an agricultural-based economy to urban areas where industrial and service sectors predominate, but also the process of the structural transformation of rural areas into urban areas. Through these processes, the world has undergone rapid urbanization in recent decades, with the world urban population increasing from 1.52 billion in 1975 to 3.29 billion in 2007 (UN, 2008). Further, the urban population is projected to double to about 6.4 billion by 2050. To support such unprecedented growth, additional urban infrastructure will inevitably be called for. This possibly causes more resource consumption, exerting additional pressure on the already fragile ecosystem. In 2006, cities consumed about two-thirds of global energy and produced over 70% of global carbon dioxide (CO_2) emissions (hereafter emissions), even though only around half the world's population lived there (IEA, 2008).

The relationship between urbanization and various environmental issues, including energy use and emissions, has been studied extensively in recent years. Some researchers show that urbanization increases energy demand, generating more emissions (Cole and Neumayer, 2004; Jones, 1991; Parikh and Shukla, 1995; York, 2007). Conversely, other scholars argue that urbanization and urban density improve the efficient use of public infrastructure (e.g., public transport and other utilities), lowering energy use and emissions (Chen et al., 2008; Liddle, 2004; Newman and Kenworthy, 1989).

Previous research has shown conflicting results, suggesting that the relationship between urbanization, energy use and emissions is complex. The disagreement in the extant literature can be attributed to differences in methodologies and data. In all likelihood, the failure to consider differences in the stage of development could also be one of these factors. Most previous studies have implicitly assumed that the impact of urbanization on energy use and/or emissions is homogeneous for all countries. Such an assumption can be questionable as there are many characteristic differences (e.g., energy structure and levels of urban public service provision) among countries of different levels of wealth. It also conflicts with the arguments of ecological modernization and urban environmental transition theories that urbanization pressure on the environment may vary across the different levels of development. For instance, Ehrhardt-Martinez et al. (2002) found a curvilinear relationship between urbanization and deforestation rates. The effects of population growth on energy use and emissions are greater in developing than developed countries (Mackellar et al., 1995; Shi, 2003). However, it remains unclear whether the impact of urbanization on energy use and CO_2 emissions varies across the different levels of development or income. Further study with careful consideration of the different development stages is imperative.

The objective of this study is to investigate the effects of urbanization on energy use and CO_2 emissions, while considering

* Corresponding author. Tel.: +81 82 424 5975; fax: +81 82 424 6904.
E-mail address: poumanyvong@hiroshima-u.ac.jp (P. Poumanyvong).

0921-8009/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2010.09.029

the differences in development. Using a balanced panel dataset of 99 countries over the period 1975–2005, the findings show that the impact of urbanization on energy use and emissions varies across the different levels of development. These novel empirical findings not only help advance the existing literature, but also deserve greater attention from policy makers.

The paper is organized as follows. Section 2 presents the theoretical background, literature review and hypotheses. Section 3 details the empirical model and methodology. Section 4 describes and discusses the results. Section 5 offers conclusions and policy implications.

2. Theoretical Background, Literature Review and Hypotheses

2.1. Theoretical Background

Although urbanization is often discussed in the context of economic modernization, it is a demographic indicator that increases urban density and transforms the organization of human behavior, thereby influencing household energy use patterns (Barnes et al., 2005). However, the extent to which urbanization affects national energy use and CO_2 emissions has not been fully and clearly explained in a single theory. Instead, some possible impacts of urbanization on the environment are partially and separately discussed in three relevant theories: ecological modernization, urban environmental transition and compact city theories. The first theory focuses on impacts at the national level, while the others discuss impacts at the city level.

Ecological modernization theory emphasizes not only economic modernization but also social and institutional transformations in explaining the effects of modernization on the environment. In this theory, urbanization is the process of social transformation regarded as one important indicator of modernization. It is argued that environmental problems may increase from low to intermediate stages of development. However, further modernization can minimize such problems, as societies come to realize the importance of environmental sustainability, seeking to decouple environmental impact from economic growth through technological innovation, urban agglomeration, and the shift toward knowledge and service based industries (Crenshaw and Jenkins, 1996; Gouldson and Murphy, 1997; Mol and Spaargaren, 2000).

The urban environmental transition theory mainly discusses the types of urban environmental issues and their evolution. It suggests that urban environmental problems vary with respect to stages of economic development (McGranahan et al., 2001). Because of limited resources, low stages of development often face poverty-related environmental problems (lack of safe water supply and inadequate sanitation). However, as income levels rise, these problems gradually subside. The increasing wealth of cities is often accompanied by an increase in manufacturing activities, causing substantial industrial pollution-related issues (water and air pollution). Nonetheless, such problems decrease in wealthy cities as the result of improved environmental regulations, technological progress and structural change in the economy.

However, wealthy cities are often associated with consumption-related environmental issues. Consumption patterns and lifestyles of the wealthy cities tend to be more resource intensive than those of lower-income cities. As cities become affluent, demands for urban infrastructure, transportation and individual resource consumption rise. Consequently, consumption-related issues such as energy consumption and CO_2 emissions become more prominent. The three types of urban environmental issues could occur simultaneously at the same development stage (Bai and Imura, 2000; Marcotullio et al., 2003). However, the dominant issues of each stage described by this theory seem plausible.

The compact city theory mainly discusses the environmental benefits of urban compaction. The theory argues that high urban density allows cities to exploit economies of scale for urban public infrastructure (e.g., public transport, schools and water supply), and reduces car dependency, travel distance, the transmission and distribution losses of electricity supply, decreasing energy consumption and CO_2 emissions (Burton, 2000; Capello and Camagni, 2000; Jenks et al., 1996; Newman and Kenworthy, 1989). However, some critics argue that increasing urban density is likely to cause traffic congestion, overcrowding and greater air pollution, which will outweigh the claimed benefits of compact cities (Breheny, 2001; Rudlin and Falk, 1999). In turn, this may increase energy use and emissions. Without adequate urban infrastructure support, greater urban density can cause substantial urban environmental issues (Burgess, 2000).

2.2. Literature Review

The relationship between urbanization and various forms of environmental pressure, including energy consumption and CO_2 emissions, has been extensively investigated in recent decades using various types of data and models at the national, city and household level. To start with, using a national level analysis with cross-sectional data, Jones (1991) derived a positive correlation between urbanization and energy use per capita, noting that while urbanization enabled cities to benefit from economies of scale in production, it increased transport energy use and energy use per unit of output. Using a STIRPAT model, York et al. (2003a,b) also found that urbanization positively affects national energy footprints and emissions. Ehrhardt-Martinez et al. (2002) examined the relationship between urbanization and deforestation rates in developing nations using the environmental Kuznets curve (EKC) model. The results suggested that deforestation rates increase at the early stage of urbanization, but decline as urbanization advances. This curvilinear relationship was attributed to the effects of urban agglomeration and growing service sector dominance in urban areas.

In a time-series data context, Alam et al. (2007) investigated the impact of urbanization on CO_2 emissions in Pakistan with a model similar to the STIRPAT, and found a positive link between urbanization and emissions. Liu (2009) also found that urbanization positively influences energy use, but that the magnitude of the influence is declining. Liu (2009) attributed this decreasing influence to improvements in industrial and technological structure and more efficient utilization of resources. Similarly, Holtedahl and Joutz (2004) suggested that urbanization increases residential energy consumption for two reasons. First, moving to urban areas increases household accessibility to electricity. Second, households that had access to electricity in rural areas may increase their energy consumption after moving to urban areas by using existing electric appliances and after the purchase of new items.

In a panel data context, Parikh and Shukla (1995) showed that urbanization increases per capita energy consumption, noting that urbanization affects energy use in three ways: first, by shifting energy use from traditional fuels to modern fuels, second, by increasing embodied energy consumption through goods and service demands, and third, via direct household and transport consumption. Using the STIRPAT model, similar evidence was obtained by York (2007), who further argued that even in the most modernized nations, urbanization contributes to the growth of energy use. Following a similar model, Cole and Neumayer (2004) found that urbanization increases CO_2 emissions. On the other hand, Mishra et al. (2009) reported that the relationship between urbanization and per capita energy was negative in New Caledonia, but positive in Fiji, French Polynesia, Samoa and Tonga. Using the EKC model and OECD data, Liddle (2004) found that urbanization and population density negatively affect per capita road transport energy use, implying that populous and highly urbanized societies have less demand for personal transport.

In terms of analysis at the city level, Newman and Kenworthy (1989) examined the relationship between urban density and transport energy use using data on 32 cities in high-income countries, and found that high urban density is associated with less per capita transport energy use. Likewise, Chen et al. (2008) investigated the impact of urban compaction on household energy use using Chinese city data, concluding a negative link between urban density and per capita household energy consumption. Moreover, Dodman (2009) found that per capita greenhouse gas emissions of several wealthy cities were significantly lower than their national average for two reasons. The first is that most of these cities have highly dense building forms with small average dwelling sizes. These require less energy to heat, light and cool than those in suburban or rural areas. The second reason is that these cities have extensive public transport systems with lower car ownership levels than the national average. Similarly, Dhakal et al. (2002) reported that per capita CO_2 emissions were lower in cities at a higher development stage (Tokyo and Seoul) than in those at a lower development stage (Beijing and Shanghai).

In terms of analysis at the household level, Pachauri (2004) showed that per capita household energy requirements in urban areas of India were higher than in its rural areas. However, when controlling for effects of household expenditure, household size and dwelling attributes, urban residents had lower energy requirements than rural residents. Pachauri and Jiang (2008) also found similar evidence and proposed two reasons for the difference between urban and rural household energy use. First was the continued reliance on inefficient solid fuels (biomass, charcoal and coal) in rural areas. Second, households shift from inefficient solid fuel use to more efficient commercial fuels and grid sources (kerosene, liquid petroleum gas and electricity) after moving to urban areas. Several studies have confirmed that urbanization plays an important role in energy urban transition processes (Barnes et al., 2005; DeFries and Pandey, 2009; Pachauri and Jiang, 2008). Urbanization increases urban density, resulting in limited space for biomass fuels storage and collection. At the same time, it encourages the substitution of more compact modern energy forms for traditional fuels by providing improved access to kerosene, liquid petroleum gas and electricity grids. These modern fuels are more efficient and produce less indoor air pollution compared with traditional fuels.

2.3. Hypotheses

Despite mixed results in the existing literature, most of the empirical results from cross-sectional, time-series and panel data analyses suggest that urbanization positively influences energy use and emissions. The negative relationship between urban density, energy use and emissions is mainly derived from descriptive studies at the city level. Most of these studies used cross-sectional data from a small sample of wealthy cities in developed nations. Although urban density is closely related to urbanization, their measures are different, suggesting that their influence on energy use and emissions can be different. Moreover, an increase in urbanization rates does not always increase urban density because cities can expand horizontally.

As the stages of development have rarely been considered in most previous studies, the existing literature conveys little information on what the impact of urbanization on energy use and emissions at each stage of development is, and how the impact differs across the different stages of development. However, the ecological modernization theory implies that urbanization's impact on energy use and emissions may increase in low- to middle-income countries, but eventually declines in high-income countries. From the perspective of urban environmental transition theory, the effects of urbanization on energy use and emissions may be greater in high- than in low- and middle-income countries.

Nonetheless, when considering the existing literature on the nature of each stage of development, the argument of the latter theory seems more relevant to the relationship between urbanization and energy use for two main reasons. First, the level of energy consumption is largely influenced by income levels, so the increase in energy consumption by urban residents of low-income countries may not be as large as in middle- and high-income countries. Second, high-income countries provide more urban amenities than low- and middle-income countries. The more urban public services a country provides, the greater the energy resources it is likely to consume.

Concerning the relationship between urbanization and emissions, the argument of the ecological modernization theory seems plausible. First, the impact of urbanization on emissions is conditional on structural change in energy use. As high-income countries shift toward low carbon fuels, the urbanization elasticity of emissions is likely to decline. Second, the urbanization elasticity of emissions is affected by levels of technological efficiency. High levels of technological efficiency in the high-income countries may help lower their emissions per unit of energy use.

3. Empirical Model and Methodology

3.1. Empirical Model

The impact of demographic and economic factors on the environment is largely postulated in the *IPAT* identity ($I = PAT$) proposed by Ehrlich and Holdren (1971). The equation denotes I as environmental impact, which is determined by a multiplicative combination of three factors: population size (P), per capita consumption (usually proxied by per capita affluence) (A) and the level of environmentally damaging technology or the impact per unit of economic activity (T). The value of T is often derived from the known values of I, P and A, and is equal to $I/(PA)$ or I/GDP.

The *IPAT* model is a very simple and useful framework, yet has two limitations (Dietz and Rosa, 1994). First, it is only a mathematical identity and cannot be used directly to test hypotheses on the impact of each factor on the environment. Second, it simply assumes that the elasticities of environmental impact to population, affluence and technology are unitary. For instance, a 1% increase in per capita income increases environmental impact by 1%. This contradicts the EKC hypothesis, which exhibits an inverted U-shape on the income–environment relationship (World Bank, 1992).

The *IPAT* model was later reformulated in the STIRPAT model of Dietz and Rosa (1997), where $I_i = aP_i^bA_i^cT_i^du_i$. Here, a is the constant term of the equation, b, c and d are the parameters of A, P and T, respectively, u denotes the disturbance term and subscript i represents the unit of analysis. Importantly, unlike the original *IPAT* identity, multiple variables other than A and P that influence the impact per unit of economic activity can express T (York et al., 2003b). For instance, Martínez-Zarzoso et al. (2007) proxied T with the share of industry in GDP and energy intensity, while Shi (2003) employed the share of the industrial and service sectors in the economy as a proxy. As urbanization is one of the important factors influencing energy use and emissions, several studies included it in the STIRPAT model and estimated its impact on energy use, emissions and energy footprints (Cole and Neumayer, 2004; York et al., 2003a,b; York, 2007).

3.2. Methodology

We employ the STIRPAT model ($I_i = aP_i^bA_i^cT_i^du_i$) reformulated by Dietz and Rosa (1997), and add urbanization as an additional variable. After taking natural logarithms of both sides of the model and rearranging, we can write the empirical models for the panel data of total energy use and CO_2 emissions as follows.

$$\ln Energy_{it} = a_0 + a_1\ln(P_{it}) + a_2\ln(A_{it}) + a_3\ln(IND_{it}) + a_4\ln(SV_{it}) + a_5\ln(URB_{it}) + Y_t + C_i + u_{1it} \quad (1)$$

$$\ln CO_{2it} = b_0 + b_1\ln(P_{it}) + b_2\ln(A_{it}) + b_3\ln(IND_{it}) + b_4\ln(SV_{it}) + b_5\ln(URB_{it}) + b_6\ln(EI_{it}) + Y_t + C_i + u_{2it} \quad (2)$$

where P denotes population size and A is per capita GDP. As in Shi (2003), in the energy use equation (Eq. (1)), T is proxied with two variables: the share of the industry (IND) and service sectors (SV) in GDP. In addition to these two variables, energy intensity is included in the CO_2 emission equation (Eq. (2)). Note that the energy intensity variable cannot be included in Eq. (1) because it is measured by total energy use divided by GDP, containing part of the dependent variable.

Table 1
Description of the variables used in the analysis for the period 1975–2005.

Variable	Definition	Unit of measurement	Data source
Population (*P*)	Mid year population	Number	World Bank (2007)
GDP per capita (*A*)	Gross domestic product divided by mid year population	US$ in PPP (2000 prices)	World Bank (2007)
Energy intensity (*EI*)	Total energy use divided by GDP	Ton of oil equivalent (toe) per thousand US$ in PPP (2000 prices)	Calculated using data from IEA (2009b,c) and World Bank (2007)
Share of industry in GDP (*IND*)	Industrial sector value added expressed as a percentage of GDP	Percent	World Bank (2007) and UN (2009)
Share of services in GDP (*SV*)	Service sector value added expressed as a percentage of GDP	Percent	World Bank (2007) and UN (2009)
Urbanization (*URB*)	The percentage of the urban population in the total population	Percent	World Bank (2007)
Total energy use	Total use of primary energy before transformation to other end-use fuels (indigenous production + imports − exports − international marine bunkers ± stock changes)	Kiloton of oil equivalent (ktoe)	IEA (2009b,c)
Total carbon dioxide emissions (CO_2)	CO_2 emissions stem from fuel combustion	Kiloton	IEA (2009a)
CO_2 intensity (hereafter carbon intensity)	Total CO_2 emissions divided by total energy use	Metric ton per terajoule	Calculated using data from IEA (2009a,b,c)

URB denotes urbanization, a_0 and b_0 are the constant terms, and u_1 and u_2 are the disturbance terms for Eqs. (1) and (2), respectively. *Y* is a year dummy that captures the time-specific effect. This can capture the effects of changes in global energy prices and technological progress not proxied by *T*. It also helps remove possible cross-sectional dependence in the equations (Petersen, 2009). *C* is a country dummy used to capture the unobserved country-specific effect, namely geographic location and resource endowment, as these possibly affect energy consumption and emissions. Adding country and time dummies is a standard treatment for panel data analysis, helping minimize heterogeneity bias and problems with possible spurious regression (Wooldridge, 2007). Therefore, the previously discussed equations are robust against omitted variables, generating reliable estimates.

This paper estimates the impact of urbanization on energy use and emissions using a balanced panel dataset of 99 countries covering the period from 1975 to 2005, yielding 3069 observations. The sample is considerably larger in terms of countries and years when compared with many previous studies. To fully address the concern whether urbanization pressure on energy use and emissions differs across the different levels of income and to empirically test the arguments of the ecological modernization and urban environmental transition theories, we divide our estimation into two parts. First, we estimate the whole sample without consideration of different income levels. Second, we estimate the sample divided into three income groups, low-, middle- and high-income groups, based on country classifications in 2004 (World Bank, 2009).[1] The low-income group consists of 23 countries, while the middle- and high-income groups consist of 43 and 33 countries, respectively (see Table A.1 in Appendix A).

The data on population, urbanization, GDP, the share of the industry and service sectors in GDP are mainly from the World Bank (2007). The GDP information was missing for some countries, but we filled it in with the data from IEA (2009b,c).The data on industry and services were also missing for a number of countries. Fortunately, we found the missing information in the United Nations online database (UN, 2009). The data on CO_2 emissions and energy use are derived from the International Energy Agency (IEA, 2009a,b,c). The energy intensity and carbon intensity information is calculated using data from the World Bank (2007) and IEA (2009a,b,c). Table 1 provides a detailed description of the variables and the data sources used in this study.

[1] In the current literature, there is no scientific criterion for country classifications. However, like most previous studies, we employed the World Bank's country classifications and divided our sample into three different income groups for two reasons. First, the estimated results from the three income groups can directly compare with the predictions of ecological modernization and urban environmental transition theories. Second, the results of this study can easily relate to other studies using a similar classification method.

The research estimates the impact of urbanization on energy use and emissions for the whole sample and for the three income groups using four different estimation methods: the pooled Ordinary Least Squares (OLS), Fixed Effects (FE), Prais–Winsten (PW) and first differenced (FD) estimates, generating 32 models. For comparative purposes, all estimated results are shown in Tables 2, 3, 4, 5, 6, 7, 8 and 9. Given the heterogeneity in the sample, the results from the OLS estimates possibly incur heterogeneity bias as it imposes a common constant term. To tackle this problem, the FE estimation is applied. However, using the Wooldridge test for autocorrelation in panel data (Wooldridge, 2002), we found serial correlation in all the FE models as shown in the third column of Tables 2, 3, 4, 5, 6, 7, 8 and 9. Moreover, the presence of heteroskedasticity is detected in the FE models after applying the modified Wald test for groupwise heteroskedasticity developed by Greene (2000). Consequently, the results of the FE estimation could possibly be biased. To address these two issues, the PW estimation with panel-corrected standard errors is employed.

Table 2
Estimation results for energy use models (*all income groups*).

Variable	OLS (1)	FE (2)	PW (3)	FD (4)
Constant	−12.363***	–	–	–
	(−51.68)			
ln*P*	0.964***	1.735***	1.459***	1.235***
	(148.77)	(52.88)	(20.20)	(9.18)
ln*A*	0.870***	0.644***	0.411***	0.316***
	(63.02)	(35.24)	(13.89)	(5.44)
ln*IND*	0.121***	−0.015	0.060***	0.069**
	(3.45)	(0.67)	(3.12)	(2.51)
ln*SV*	−0.542***	0.096***	0.077***	0.049**
	(−10.12)	(3.76)	(3.00)	(2.00)
ln*URB*	0.070**	−0.198***	−0.130**	0.003
	(2.06)	(−5.46)	(−2.07)	(0.03)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.990	0.801	0.990	0.180
Autocorrelation test		F = 90.05***		
Heteroscedasticity test		χ^2 (99) = 5.3e+04***		
Observations	3069	3069	3069	2970

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

Table 3
Estimation results for energy use models (*low-income group*).

Variable	OLS (5)	FE (6)	PW (7)	FD (8)
Constant	−8.244***	–	–	–
	(−22.15)			
ln*P*	0.968***	0.784***	0.729***	0.601**
	(81.51)	(9.14)	(4.71)	(2.47)
ln*A*	0.060*	0.225***	0.201***	0.180***
	(1.85)	(10.39)	(7.65)	(4.70)
ln*IND*	0.343***	0.065***	0.031**	0.023*
	(8.39)	(3.14)	(2.05)	(1.63)
ln*SV*	−0.188**	0.024	0.023	0.022
	(−2.50)	(0.83)	(1.28)	(1.17)
ln*URB*	0.040	−0.204***	−0.182**	−0.132*
	(0.98)	(−5.70)	(−4.03)	(−1.74)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.922	0.881	0.996	0.122
Autocorrelation test		F = 79.69***		
Heteroscedasticity test		χ^2 (23) = 1.3e + 04***		
Observations	713	713	713	690

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

To check whether the data used in this study are stationary or not, we performed four different but commonly quoted unit root tests in the current empirical literature for panel data. The first test was proposed by Levin et al. (2002) (hereafter LLC). The null hypothesis of this test assumes that there is a common unit root process and the autoregressive coefficient is identical across cross-sections. Conversely, the second test developed by Im et al. (2003) (hereafter IPS) allows the autoregressive coefficient to vary across cross-sections. The third and fourth tests proposed by Maddala and Wu (1999) and Choi (2001) (hereafter ADF and PP) share the same assumption as for the IPS test. Given the heterogeneity in the sample, the IPS, ADF and PP tests are more relevant in this study. However, we put more emphasis on the IPS test as the sample meets its asymptotic requirements (numbers of cross-sections are larger than numbers of years).

The test results show that all the variables are stationary except for GDP and energy intensity. However, the two series became stationary after taking first differences (see Table A.2 in Appendix A). Another benefit from first differencing is that it helps reduce or even remove serial correlation (Wooldridge, 2007). We applied the autocorrelation test proposed by Wooldridge (2002) and the heteroskedasticity test

Table 4
Estimation results for energy use models (*middle-income group*).

Variable	OLS (9)	FE (10)	PW (11)	FD (12)
Constant	−14.755***	–	–	–
	(−38.13)			
ln*P*	0.989***	2.214***	1.907***	1.696***
	(108.22)	(36.79)	(19.76)	(6.28)
ln*A*	0.786***	0.795***	0.467***	0.300***
	(27.30)	(27.74)	(12.04)	(3.82)
ln*IND*	0.348***	0.133***	0.179***	0.139***
	(6.06)	(2.82)	(4.99)	(3.16)
ln*SV*	−0.283***	0.180***	0.160***	0.126***
	(−3.65)	(3.47)	(3.54)	(2.72)
ln*URB*	0.258***	0.131**	0.476***	0.507*
	(6.43)	(2.02)	(4.73)	(1.86)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.920	0.842	0.998	0.221
Autocorrelation test		F = 41.14***		
Heteroscedasticity test		χ^2 (43) = 2.8e + 04***		
Observations	1333	1333	1333	1290

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

Table 5
Estimation results for energy use models (*high-income group*).

Variable	OLS (13)	FE (14)	PW (15)	FD (16)
Constant	−23.475***	–	–	–
	(−35.97)			
ln*P*	0.962***	1.583***	1.542***	1.196***
	(112.35)	(37.33)	(16.96)	(5.50)
ln*A*	0.848***	0.495***	0.417***	0.376***
	(15.73)	(14.89)	(6.03)	(2.63)
ln*IND*	1.329***	0.117**	0.055	0.170
	(15.84)	(2.40)	(0.71)	(0.94)
ln*SV*	0.585***	0.231***	0.052	0.075
	(5.18)	(4.52)	(0.62)	(0.54)
ln*URB*	0.682***	1.150***	1.032***	0.907**
	(9.11)	(10.18)	(4.23)	(2.01)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.952	0.866	0.998	0.247
Autocorrelation test		F = 37.42***		
Heteroscedasticity test		χ^2 (33) = 1.2e + 04***		
Observations	1023	1023	1023	990

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

Table 6
Estimation results for CO_2 emission models (*all income groups*).

Variable	OLS (17)	FE (18)	PW (19)	FD (20)
Constant	−11.770***	–	–	–
	(−37.64)			
ln*P*	1.066***	1.273***	1.235***	1.125***
	(195.74)	(37.27)	(26.84)	(11.12)
ln*A*	1.117***	1.144***	1.116***	1.078***
	(84.61)	(61.20)	(40.01)	(21.10)
ln*IND*	0.692***	0.371***	0.131***	0.052
	(18.35)	(16.53)	(3.87)	(0.89)
ln*SV*	0.604***	0.288***	0.092***	0.029
	(10.28)	(11.70)	(2.80)	(0.61)
ln*URB*	0.506***	0.350***	0.454***	0.447**
	(17.23)	(9.97)	(5.41)	(2.45)
ln*EI*	0.770***	0.880***	0.897***	0.919***
	(50.70)	(49.60)	(39.12)	(21.58)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.954	0.864	0.990	0.417
Autocorrelation test		F = 32.81***		
Heteroscedasticity test		χ^2 (99) = 1.2e + 05***		
Observations	3069	3069	3069	2970

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *EI* denotes energy intensity, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

Table 7
Estimation results for CO_2 emission models (*low-income group*).

Variable	OLS (21)	FE (22)	PW (23)	FD (24)
Constant	−16.906***	–	–	–
	(−37.58)			
ln*P*	1.258***	0.827***	0.980**	1.749**
	(134.65)	(3.89)	(2.20)	(2.30)
ln*A*	1.375***	1.831***	2.241***	2.498***
	(24.47)	(19.96)	(15.80)	(6.42)
ln*IND*	0.407***	0.294***	0.099*	0.029
	(7.32)	(5.72)	(1.80)	(0.66)
ln*SV*	1.206***	0.318***	0.036	−0.058
	(13.85)	(4.45)	(0.63)	(−0.77)
ln*URB*	0.494***	0.518***	0.615***	0.430**
	(12.21)	(5.71)	(4.69)	(1.93)
ln*EI*	0.859***	1.576***	2.000***	2.325***
	(23.50)	(16.38)	(13.51)	(5.44)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.938	0.739	0.971	0.379
Autocorrelation test		F = 12.87***		
Heteroscedasticity test		χ^2 (23) = 2.3e + 04***		
Observations	713	713	713	690

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *EI* denotes energy intensity, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

Table 9
Estimation results for CO_2 emission models (*high-income group*).

Variable	OLS (29)	FE (30)	PW (31)	FD (32)
Constant	−1.013	–	–	–
	(−1.43)			
ln*P*	1.036***	1.220***	1.225***	1.122***
	(179.81)	(42.82)	(29.92)	(17.36)
ln*A*	0.633***	1.039***	0.961***	0.829***
	(24.64)	(45.67)	(32.44)	(16.79)
ln*IND*	0.176**	0.002	−0.016	0.005
	(2.38)	(0.09)	(0.39)	(0.14)
ln*SV*	−0.102	0.138***	0.072*	0.025
	(−1.43)	(4.34)	(1.81)	(0.55)
ln*URB*	0.300***	0.041	0.176**	0.358*
	(7.80)	(0.57)	(1.92)	(1.73)
ln*EI*	0.781***	0.894***	0.814***	0.785***
	(39.88)	(45.03)	(35.08)	(26.21)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.981	0.943	0.998	0.763
Autocorrelation test		F = 151.92***		
Heteroscedasticity test		χ^2 (33) = 1.0e + 04***		
Observations	1023	1023	1023	990

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *EI* denotes energy intensity, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

developed by Breusch and Pagan (1979) to all the FD models. The test results show that autocorrelation is present only in Models 24 and 28, while heteroskedasticity is found in all the models. To tackle these two problems, we estimate Models 24 and 28 with the Newey–West corrected standard errors proposed by Newey and West (1987). To address only heteroskedasticity, we estimate the remaining FD models with heteroskedasticity-consistent standard errors suggested by White (1980). We further tested for multicollinearity among the explanatory variables in the FD models using variance inflation factors (VIFs). The VIF values are all less than 10 (see Table A.3 in Appendix A), suggesting no multicollinearity (Chatterjee et al., 2000).

Table 8
Estimation results for CO_2 emission models (*middle-income group*).

Variable	OLS (25)	FE (26)	PW (27)	FD (28)
Constant	−1.540**	–	–	–
	(−2.48)			
ln*P*	1.070***	1.281***	1.231***	1.228***
	(114.81)	(26.08)	(16.35)	(6.55)
ln*A*	1.161***	1.070***	1.011***	0.987***
	(37.40)	(51.57)	(36.19)	(17.53)
ln*IND*	0.107	0.343***	0.095***	0.057
	(1.54)	(10.18)	(3.00)	(1.43)
ln*SV*	0.141	0.063*	−0.001	0.026
	(1.63)	(1.72)	(−0.03)	(0.71)
ln*URB*	0.406***	0.210***	0.423***	0.512**
	(10.11)	(4.55)	(4.71)	(2.03)
ln*EI*	1.179***	0.827***	0.828***	0.810***
	(45.62)	(41.29)	(32.21)	(12.54)
Country dummies	–	Yes	Yes	–
Year dummies	Yes	Yes	Yes	Yes
R^2	0.951	0.939	0.998	0.535
Autocorrelation test		F = 81.77***		
Heteroscedasticity test		χ^2 (43) = 4947.66***		
Observations	1333	1333	1333	1290

Notes: ln denotes natural logarithms, *P* denotes total population, *A* denotes GDP per capita, *URB* denotes urbanization, *EI* denotes energy intensity, *IND* and *SV* denote percent GDP from industry and services respectively. Coefficients of country and year dummies are not reported. OLS (Pooled OLS); FE (Fixed Effects); PW (Prais–Winsten); FD (First Difference). *t*-values are shown in parentheses.
*** $P<0.01$.
** $P<0.05$.
* $P<0.1$.

In summary, as the FD estimator properly addresses all important econometric concerns including autocorrelation, heteroskedasticity and nonstationarity, the coefficients of the FD models are preferred. Our main discussions in this study focus only on the FD models.

4. Results and Discussion

4.1. Descriptive Analysis of the Main Variables

Fig. 1(a) and (b) illustrates urbanization levels, per capita energy use and emissions for the three income groups in 1975 and 2005. As shown, these vary across the income groups: the higher the per capita income of a country, the greater its urbanization level, per capita energy use and emissions. In 1975, the degree of urbanization was 72% in high-income countries, only 24% in low-income countries and 48% in middle-income countries. In addition, per capita energy use and emissions of the high-income group in 1975 and 2005 were also significantly higher than for the other income groups. In 1975, each person in the high-income group on average consumed about 3.6 tons of oil equivalents (toe) and generated over 9 metric tons of CO_2, significantly greater than each person in the low-income group consumed (0.43 toe) and emitted (0.30 ton).

The figure also shows differential changes in urbanization levels, per capita energy use and emissions between 1975 and 2005 among the three income groups. Compared with the other groups, the middle-income group experienced a greater increase in its urbanization level, rising from 48% in 1975 to 65% in 2005. The growth in its per capita emissions was around 40%, slightly lower than the growth in its energy consumption (45%). Similarly, between 1975 and 2005, the per capita energy use of the high-income group increased by about 58%, while its per capita CO_2 emissions grew only 37%. In contrast, in the low-income group, per capita energy use was nearly unchanged, whereas its per capita CO_2 emissions increased approximately 23%.

Fig. 2 details the relative percentage changes in urbanization, population, energy intensity, CO_2 emissions, energy use and CO_2 intensity compared with the base year (1975 = 0). Note that the

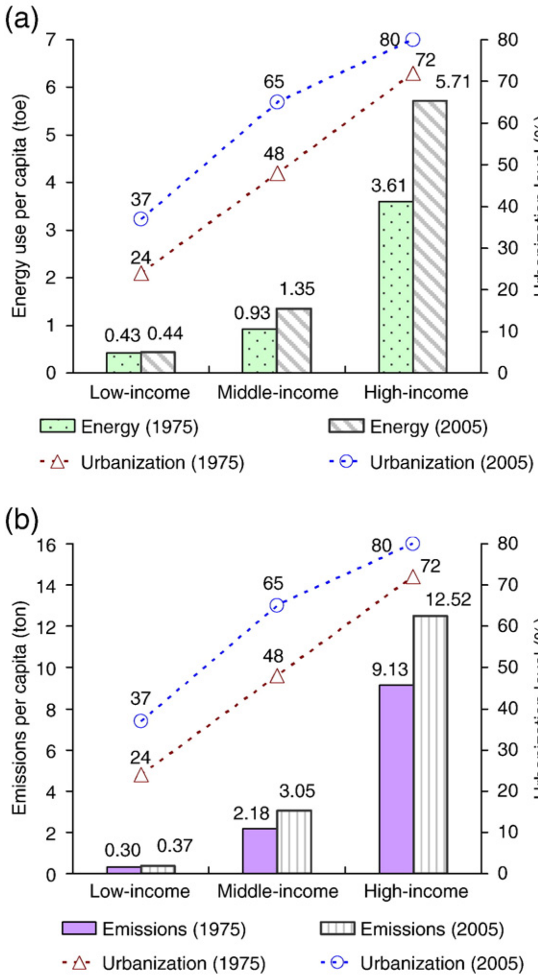

Fig. 1. The level of urbanization, per capita energy use and emissions by income group in 1975 and 2003 (calculated using data from the World Bank (2007) and IEA (2008a,b,c)).

changes in energy use and CO_2 emissions plotted in Figs. 2 and 1 are different as the former employs aggregate data, while the latter uses per capita data. When compared with the base year, the most significant change in urbanization in 2005 was in the low-income group, while the least change occurred in the high-income group because of its high degree of urbanization.

Similarly, the changes in the energy use and CO_2 emissions of the low-income group in 2005 were significantly larger than those of the middle- and high-income groups. The change in the energy use of the low-income group was nearly 180%, while in the middle- and high-income groups, it was about 147% and 58%, respectively. Between 1975 and 2005, the emissions growth of the low-income group was nearly 357%, whereas it was about 132% in the middle-income group and only 38% in the high-income group.

Over the period 1975–2003, while the energy intensity of the low-income group steadily declined below the year 1975 level, in the middle-income group, it fluctuated over time and then fell. Surprisingly, in the high-income group, it increased until 1988 and then started declining. However, it was still above the base year level. This is mainly due to the fact that this income group consists of several major oil exporting countries, largely influencing the group's average energy intensity.

Between 1975 and 2005, the carbon intensity of the high-income group steadily decreased, while in the low- and middle-income groups, it fluctuated before increasing. It should be noted that the change in the emissions of the low-income group was faster than the changes in its energy use, while the opposite held in the other income groups. The figure indicates that the growth in population of the low-

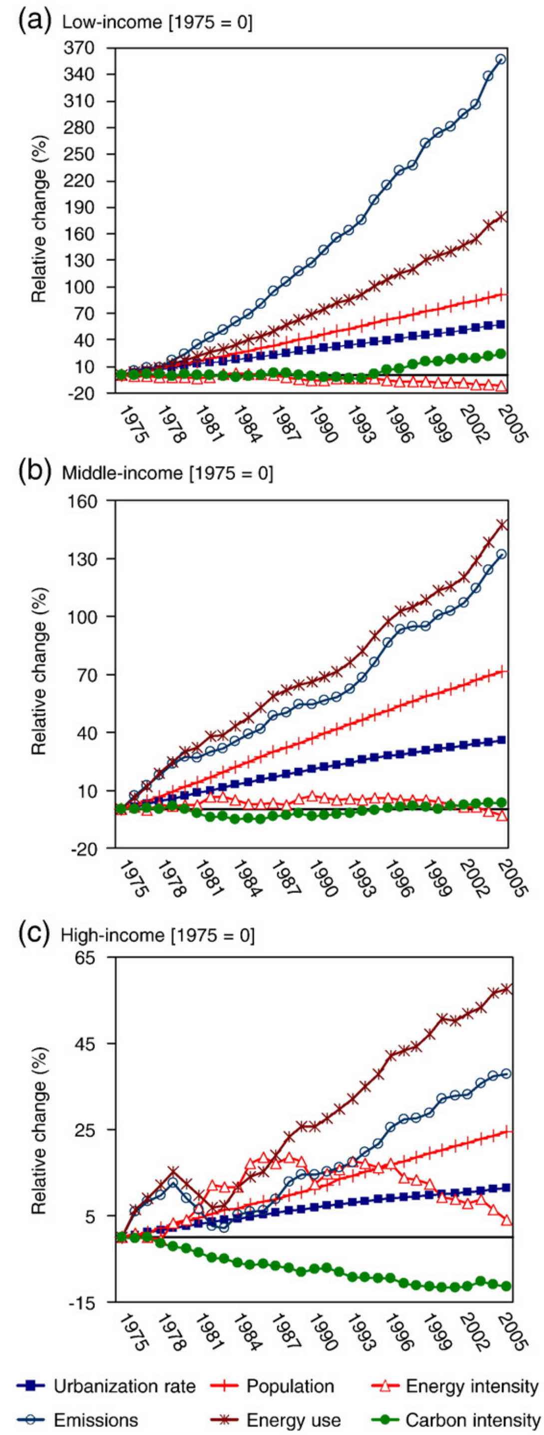

Fig. 2. Relative percentage changes in urbanization, population, energy intensity, CO_2 emissions, energy use and carbon intensity by income groups compared with their 1975 level (calculated using data from the World Bank (2007) and IEA (2008a,b,c)).

and middle-income groups was greater than that of the high-income countries.

4.2. Empirical Results and Discussion

Table 2 reports the estimated results for the whole sample, while Tables 3, 4 and 5 show the results of the low-, middle- and high-income groups, respectively. As the FD models (Models 4, 8, 12 and 16) are the preferred models, our main interpretations focus only on these models.

The estimated coefficients in the FD model (Model 4 listed in Table 2) are all statistically significant at the 5% level or lower, except for the coefficient of urbanization. The relationship between urbanization and energy use is positive but insignificant, whereas population size, GDP per capita and economic structure positively affect energy use. The elasticity of energy use to population growth is 1.23, while the elasticity to GDP per capita is 0.316. A 1% increase in the share of the industrial and service sector in the economy raises energy use by 0.069% and 0.049%, respectively.

However, the results of Models 8, 12 and 16 show that the impact of urbanization on energy use is statistically significant at the 10% level or lower, and differs across the various development stages. Surprisingly, a 1% increase in urbanization decreases energy use in the low-income group by 0.132%, while it increases energy use in the middle- and high-income groups by 0.507% and 0.907%, respectively. The positive link between urbanization and energy use is evident in several previous studies (Jones, 1991; Parikh and Shukla, 1995; York, 2007).

The effects of population growth, GDP per capita and economic structure on energy consumption are also heterogeneous across the different income groups. The elasticity of energy use to population change in the middle-income group is about 1.7, significantly greater than in the low- (0.601) and high-income groups (1.196). Similarly, the elasticity of energy use to changes in income in the middle-income group is 0.30, notably greater than in the low-income group (0.18), but slightly smaller than in the high-income group (0.376). The impact of the share of industrial activity in the economy on energy consumption is positive, but statistically significant for only the low- and middle-income groups. The contribution of the share of services in GDP to energy consumption is positive, but statistically significant for only the middle-income group.

The negative urbanization elasticity of energy use in the low-income group seems to support the argument of urban compaction. However, as many cities of this income group still lack basic public services, the negative elasticity is unlikely to be the result of economies of scale for public infrastructure. Rather, it could possibly be due to the effects of modernization, particularly the effect of improved access to modern forms of energy use. The findings are supported by Pachauri (2004) and Pachauri and Jiang (2008), who found that fuel switching from inefficient solid fuels to modern forms of energy use causes per capita household energy use in urban areas to be lower than in rural areas. It is evident that the share of biomass in total energy use in the low-income group significantly decreased from around 75% in 1975 to 66% in 2005 (see Fig. B(b) in Appendix B).

As described previously, further urbanization in the high-income group seems to increase rather than to decrease energy use. This supports the argument of the urban environmental transition theory that consumption-related issues are most pronounced in high-income countries. Unlike the other income groups, the high-income group uses much private and public infrastructure in supporting their urban population and urban economies. Constructing, maintaining and operating the infrastructure involve significant amounts of energy resources. Moreover, consumption patterns and lifestyles in cities of developed countries tend to be more resource intensive than in the cities of developing countries. High levels of energy use in the high-income group also reflect in Fig. 1(a).

Table 6 reports the results for the whole sample, whereas Tables 7, 8 and 9 show the results for the low-, middle- and high-income groups, respectively. As the FD models (Models 20, 24, 28 and 32) address all important econometric concerns, our main interpretations focus only on these models.

The estimated results of Model 20 (Table 6) are all statistically significant at the 5% level or lower, except for the coefficients of economic structure. The results show that population size, GDP per capita, urbanization and energy intensity positively influence emissions. A 1% increase in urbanization raises emissions by 0.447%, all other factors being equal. The elasticity of emissions to population growth is 1.125, indicating a moderately elastic relationship, while the elasticities of emissions to GDP per capita and energy intensity are approximately one, suggesting a unit elastic relationship. The coefficients for industry as percent of GDP and services as percent of GDP appear positive but statistically insignificant.

However, the results of Models 24, 28 and 32 indicate that the relationship between urbanization and emissions varies across the different stages of development. The urbanization elasticity of emissions in the middle-income group is 0.512, greater than in both the low- (0.43) and the high-income group (0.358). The effects of population growth, GDP per capita, economic structure and energy intensity are also heterogeneous across the different income groups. The elasticity of emissions to population change in the low-income group is about 1.75, significantly greater than in the middle-income group (1.228) and in the high-income group (1.122). Similarly, the impact of income and energy intensity on emissions in the low- and middle-income groups is larger than in the high-income group. These results are consistent with the findings by Martínez-Zarzoso et al. (2007) and Shi (2003). Like Model 20, none of the coefficients for economic structure in Models 24, 28 and 32 is statistically significant.

It should be noted that in the low-income group, the relationship between urbanization and energy use is negative, while the relationship between urbanization and emissions is positive. This phenomenon could occur as this income group shifts from traditional fuels (biomass) to fossil fuels (coal, oil and gas), which are more efficient but may have more CO_2 emissions. The share of coal and oil in their total energy use increased from 21% in 1975 to 24% in 2005 (see Fig. B(a) in Appendix B). Over the same period, their carbon intensity exhibited an upward trend as illustrated in Fig. 2.

Another point worth noting is that the impact of urbanization on energy use of the high-income group is greater than that of the middle-income group, whereas its urbanization elasticity of emissions is smaller than that of the middle-income group. This can possibly be attributed to structural change in energy use. The high-income group significantly decreased the share of coal and oil in their total energy use from around 71% in 1975 to only 56% in 2005 (see Fig. B(a) in Appendix B). The tendency of fuel usage switching toward low carbon intensive fuels (e.g., natural gas and nuclear energy) is shown in Fig. 2(c). The carbon intensity of the high-income group significantly declined over the period 1975–2005. The share of coal and oil in the total energy use of the middle-income group also declined. However, its carbon intensity did not decline as steadily as that of the high-income group. This could possibly relate to differences in their technological efficiency.

The impact of urbanization on emissions not only varies across the three income groups, but also appears greater in the middle-income group. This trend conforms to the argument of the ecological modernization theory that the process of modernization may cause substantial environmental issues. However, further modernization can reduce these problems. Despite different environmental indicators, the findings are in line with previous research by Ehrhardt-Martinez et al. (2002), who found an inverted U-shaped relationship between urbanization and deforestation rates. Fig. 3 summarizes the urbanization elasticities of energy use and CO_2 emissions (derived from Tables 2, 3, 4, 5, 6, 7, 8 and 9).

5. Conclusion

Unlike previous studies, this paper investigated empirically the impact of urbanization on total energy use and CO_2 emissions with consideration of different levels of development using the STIRPAT model and a balanced panel dataset of 99 countries over the period 1975–2005. The sample was divided into three different groups (low-, middle- and high-income groups), and they were separately analyzed. The results suggest that the effects of urbanization on energy use and

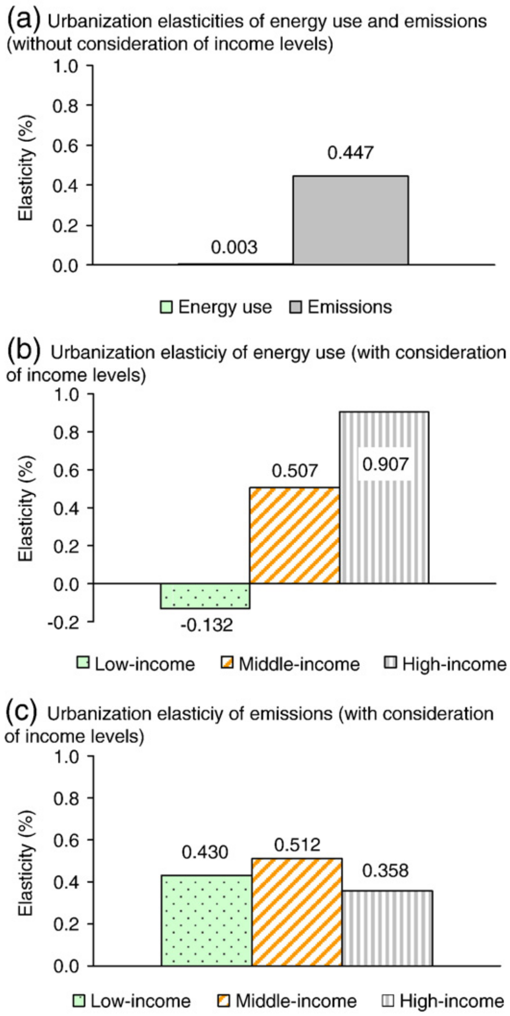

Fig. 3. A summary of the urbanization elasticities of energy use and CO_2 emissions.

emissions vary across the different stages of development. The findings oppose the assumption of previous studies that urbanization impacts are homogeneous for all countries.

Surprisingly, in low-income countries, urbanization contributes to the reduction in energy use. This could possibly be attributed to the effects of fuel switching from inefficient traditional fuels to efficient modern fuels. Conversely, urbanization in middle- and high-income countries positively influences energy use, and the influence is greater in high- than in middle-income countries. This phenomenon generally supports the view of the urban environmental transition theory that consumption-related environmental issues are dominant in high-income countries.

The urbanization-emissions relationship is positive and different across the three income groups. The urbanization elasticity of emissions in the middle-income group is larger than in the other groups. This could possibly relate to structural change in energy use and technological differences among the three income groups. The weaker relationship between urbanization and emissions in the low- and high-income groups supports the prediction of the ecological modernization theory that the process of modernization may increase environmental issues, although further modernization can diminish such problems.

This study does not find evidence in support of the urban compaction theory. This does not necessarily mean that increasing urban density does not have positive impacts on the environment. For some sectors, some cities may be more energy efficient than their national average. However, what happens on a micro level cannot be directly compared with the findings of this research obtained from a macro-level analysis using 31-year longitudinal data. Rather, these findings are about societies as a whole. For instance, the urbanization elasticity of energy use is greater in high- than in middle-income countries, suggesting that with a 1% increase in urbanization, the increase in energy use of high-income societies is greater than in middle-income societies.

The findings of the study not only help to advance the existing literature, but also deserve special attention from policy makers and urban planners, particularly those in developing nations where rapid urbanization and industrialization are occurring. To support their rapid urbanization and industrialization, additional urban infrastructure will inevitably be required. This possibly creates additional demand for energy resources. To curb their long-term demand, it is greatly important that developing nations build energy efficient and sustainable urban infrastructure systems and improve their efficient use. It is also critical for all nations to formulate appropriate energy policies to promote energy efficiency and to accelerate the switch to low carbon energy, decoupling environmental impact from economic growth in the longer-run.

Nonetheless, the paper provides only preliminary results derived from a macro-level analysis. The form of urban expansion, urban density, urban population structure and the country's position in the global economy are yet to be included. While these may also potentially influence energy use and emissions, their inclusion is beyond the scope of the current paper. Future research considering these and other factors would then help advance the knowledge of urbanization impacts.

Acknowledgements

We thank two anonymous reviewers for very helpful comments. We are also grateful to the staff of the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), particularly Masakazu Ichimura and Kohji Iwakami for their assistance with data collection. This research is partially supported by the MEXT Special Coordination Funds for Promotion of Science and Technology “Global Environmental Leader Education Program for Designing a Low Carbon Society”, and the Global Environment Research Fund “Establishing of Methodology to Evaluate Middle to Long Term Environmental Policy Options toward Asian Low-Carbon Society (S-6)” from the Ministry of Environment, Japan. All remaining errors are ours.

Appendix A

Table A.1
List of 99 countries in the sample over the period 1975–2005.

1. *Low income group (23 countries with per capita GNP ≤ US$765 in 2004)*
   Bangladesh, Benin, Cameroon, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Ghana, Haiti, India, Kenya, Mozambique, Myanmar, Nepal, Nicaragua, Nigeria, Pakistan, Senegal, Sudan, Tanzania, Togo, Vietnam, Zambia, Zimbabwe
2. *Middle income group (43 countries with per capita GNP between US$766 and US$9385 in 2004)*
   Albania, Algeria, Angola, Argentina, Bolivia, Brazil, Bulgaria, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Egypt, El Salvador, Gabon, Guatemala, Honduras, Hungary, Indonesia, Iran, Jamaica, Jordan, Lebanon, Libya, Malaysia, Mexico, Morocco, Oman, Panama, Paraguay, Peru,
   Philippines, Poland, Romania, South Africa, Sri Lanka, Syria, Thailand, Tunisia, Turkey, Uruguay, Venezuela
3. *High income group (33 countries with per capita GNP > US$9385 in 2004)*
   Australia, Austria, Bahrain, Belgium, Brunei, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Hong Kong (China), Iceland, Ireland, Israel, Italy, Japan, Korea, Kuwait, Malta, Netherlands, New Zealand, Norway, Portugal, Qatar, Saudi Arabia, Spain, Sweden, Switzerland, United Arab Emirates, United Kingdom, United States

Table A.2
Panel unit root tests.

Variable	Levels				First differences			
	LLC	IPS	ADF	PP	LLC	IPS	ADF	PP
ln*Energy*	−3.47***	−3.29***	300.18***	415.75***	−36.48***	−39.12***	1529.64***	1247.12***
lnCO_2	−2.86 ***	−1.65**	245.87 **	476.17***	−30.53***	−33.59***	1286.82***	2648.86***
ln*P*	−11.94***	−3.03***	419.63***	1096.69***	−1.67**	−3.17***	386.30***	313.36***
ln*A*	−0.69	0.89	216.06	152.64	−22.05***	−23.69***	904.68***	1103.78***
ln*IND*	−2.93***	−3.84***	291.21***	252.57***	−34.58***	−35.50***	1495.50***	2935.66***
ln*SRV*	−3.00***	−1.91**	245.81**	191.53	−38.01***	−38.29***	1574.09***	3397.87***
ln*URB*	−6.87***	−5.15***	406.62***	2118***	−33.83***	−24.70***	765.58***	390.27***
ln*EI*	−3.87***	−0.45	251.59***	277.21***	−36.54***	−39.36***	1620.68***	1932.97***

Notes: Exogenous variables: Individual effects and individual linear trends. Automatic selection of lags based upon SIC: 0 to 6 (maximum lags). Newey–West bandwidth selection using Bartlett Kernel. *** and ** denote rejection of the null hypothesis of nonstationary at 1% and 5% significance level, respectively.

Table A.3
VIF tests for multicollinearity.

Variable	Model 4	Model 8	Model 12	Model 16	Model 20	Model 24	Model 28	Model 32
ln*P*	1.10	1.06	1.24	1.26	1.10	1.07	1.26	1.27
ln*A*	1.05	1.10	1.01	1.34	1.44	2.34	1.55	1.49
ln*EI*	–	–	–	–	1.40	2.18	1.61	1.16
ln*IND*	1.44	1.12	1.78	2.91	1.45	1.13	1.81	2.92
ln*SV*	1.40	1.08	1.78	2.62	1.40	1.09	1.80	2.63
ln*URB*	1.06	1.01	1.23	1.03	1.06	1.01	1.24	1.04
Mean VIF	1.21	1.07	1.41	1.83	1.31	1.47	1.54	1.75

Appendix B

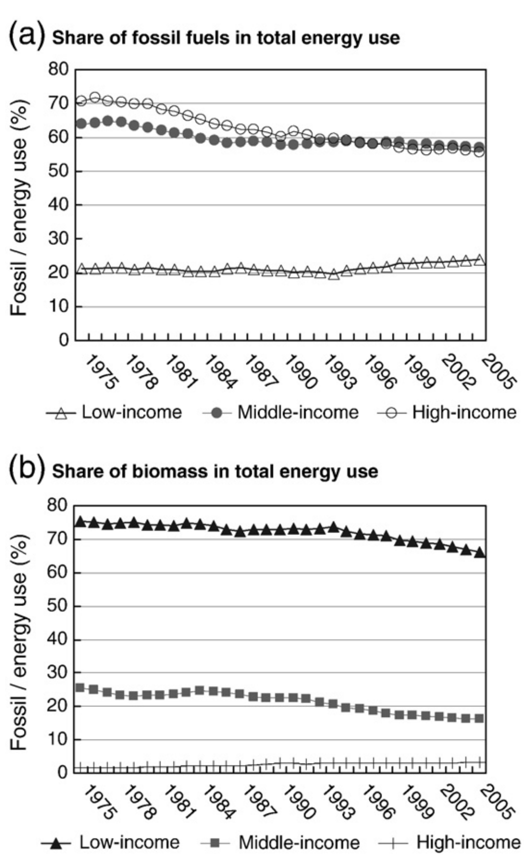

Fig. B. The share of fossil fuels (coal and oil) and solid biomass in total energy use (calculated using data from IEA (2009a,b,c)).

References

Alam, S., Fatima, A., Butt, M.S., 2007. Sustainable development in Pakistan in the context of energy consumption demand and environmental degradation. Journal of Asian Economics 18, 825–837.

Bai, X., Imura, H., 2000. A comparative study of urban environment in East Asia: stage model of urban environmental evolution. International Review for Environmental Strategies 1 (1), 135–158.

Barnes, D.F., Krutilla, K., Hyde, W.F., 2005. The Urban Household Energy Transition: Social and Environmental Impacts in the Developing World. Resources for the Future, Washington, DC.

Breheny, M., 2001. Densities and sustainable cities: the UK experience. In: Echenique, M., Saint, A. (Eds.), Cities for the New Millennium. Spon Press, London, pp. 39–51.

Breusch, T.S., Pagan, A.R., 1979. A simple test for heteroscedasticity and random coefficient variation. Econometrica 47, 1287–1294.

Burgess, R., 2000. The compact city debate: a global perspective. In: Jenks, M., Burgess, R. (Eds.), Compact Cities: Sustainable Urban Forms for Developing Countries. Spon Press, New York, pp. 9–24.

Burton, E., 2000. The compact city: just or just compact? A preliminary analysis. Urban Studies 37 (11), 1969–2001.

Capello, R., Camagni, R., 2000. Beyond optimal city size: an evaluation of alternative urban growth patterns. Urban Studies 37 (9), 1479–1496.

Chatterjee, S., Hadi, A.S., Price, B., 2000. Regression Analysis by Example, third ed. John Wiley & Sons, Inc., New York.

Chen, H., Jia, B., Lau, S.S.Y., 2008. Sustainable urban form for Chinese compact cities: challenges of a rapid urbanized economy. Habitat International 32, 28–40.

Choi, I., 2001. Unit root tests for panel data. Journal of International Money and Finance 20, 249–272.

Cole, M.A., Neumayer, E., 2004. Examining the impact of demographic factors on air pollution. Population and Environment 26 (1), 5–21.

Crenshaw, E.M., Jenkins, J.C., 1996. Social structure and global climate change: sociological propositions concerning the greenhouse effect. Sociological Focus 29 (4), 341–358.

DeFries, R., Pandey, D., 2009. Urbanization, the energy ladder and forest transitions in India's emerging economy. Land Use Policy 27 (2), 130–138.

Dhakal, S., Kaneko, S., Imura, H., 2002. An analysis on driving factors for CO_2 emissions from energy use in Tokyo and Seoul by factor decomposition method. Environmental Systems Research 30, 295–303.

Dietz, T., Rosa, E.A., 1994. Rethinking the environmental impacts of population, affluence and technology. Human Ecology Review 1, 277–300.

Dietz, T., Rosa, E.A., 1997. Effects of population and affluence on CO_2 emissions. Proceedings of the National Academy of Sciences 94, 175–179.

Dodman, D., 2009. Blaming cities for climate change? Analysis of urban greenhouse gas emissions inventories. Environment and Urbanization 21 (1), 185–201.

Ehrhardt-Martinez, K., Crenshaw, E.M., Jenkins, J.C., 2002. Deforestation and the environmental Kuznets curve: a cross-national investigation of intervening mechanism. Social Science Quarterly 83 (1), 226–243.

Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. Science 171, 1212–1217.

Gouldson, A.P., Murphy, J., 1997. Ecological modernization: economic restructuring and the environment. The Political Quarterly 68 (5), 74–86.

Greene, W.H., 2000. Econometric Analysis, fourth ed. Prentice Hall, Upper Saddle River, New Jersey.

Holtedahl, P., Joutz, F.L., 2004. Residential electricity demand in Taiwan. Energy Economics 26, 201–224.

Im, K.S., Pesaran, M.H., Shin, Y., 2003. Testing for unit roots in heterogeneous panels. Journal of Econometrics 115, 53–74.

International Energy Agency (IEA), 2008. World Energy Outlook 2008. IEA, Paris.

International Energy Agency (IEA), 2009a. CO_2 Emissions from Fuel Combustion 2009 CD-ROM. IEA, Paris.

International Energy Agency (IEA), 2009b. Energy Balances of OECD Countries 2009 CD-ROM. IEA, Paris.

International Energy Agency (IEA), 2009c. Energy Balances of Non-OECD Countries 2009 CD-ROM. IEA, Paris.
Jenks, M., Burton, E., Williams, K. (Eds.), 1996. The Compact City: A Sustainable Urban Form? E & FN Spon, New York.
Jones, D.W., 1991. How urbanization affects energy use in developing countries. Energy Policy 19 (7), 621–630.
Levin, A., Lin, C.F., Chu, J.C.S., 2002. Unit root tests in panel data: asymptotic and finite-sample properties. Journal of Econometrics 108, 1–24.
Liddle, B., 2004. Demographic dynamics and per capita environmental impact: using panel regressions and household decompositions to examine population and transport. Population and Environment 26, 23–39.
Liu, Y., 2009. Exploring the relationship between urbanization and energy consumption in China using ARDL (autoregressive distributed lag) and FDM (factor decomposition model). Energy 34 (11), 1846–1854.
Mackellar, L.F., Lutz, W., Prinz, C., Goujon, A., 1995. Population, households, and CO_2 emissions. Population and Development Review 21 (4), 849–865.
Maddala, G.S., Wu, S., 1999. A comparative study of unit root tests with panel data and a new simple test. Oxford Bulletin of Economics and Statistics 61, 631–652.
Marcotullio, P.J., Rothenberg, S., Nakahara, M., 2003. Globalization and urban environmental transitions: comparison of New York's and Tokyo's experiences. The Annals of Regional Science 37 (3), 369–390.
Martínez-Zarzoso, I., Bengochea-Morancho, A., Morales-Lage, R., 2007. The impact of population on CO_2 emissions: evidence from European countries. Environmental & Resource Economics 38, 497–512.
McGranahan, G., Jacobi, P., Songsore, J., Surjadi, C., Kjellen, M., 2001. The Citizen at Risk: From Urban Sanitation to Sustainable Cities. Earthscan, London.
Mishra, V., Smyth, R., Sharma, S., 2009. The energy-GDP nexus: evidence from a panel of Pacific Island countries. Resource and Energy Economics 31 (3), 210–220.
Mol, A.P.J., Spaargaren, G., 2000. Ecological modernization theory in debate: a review. Environmental Politics 9 (1), 17–49.
Newey, W.K., West, K.D., 1987. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 55, 703–708.
Newman, P.W.G., Kenworthy, J.R., 1989. Cities and Automobile Dependence: An International Sourcebook. Gower Technical, Aldershot.
Pachauri, S., 2004. An analysis of cross-sectional variations in total household energy requirements in India using micro survey data. Energy Policy 32 (11), 1723–1735.
Pachauri, S., Jiang, L., 2008. The household energy transition in India and China. Energy Policy 36 (11), 4022–4035.
Parikh, J., Shukla, V., 1995. Urbanization, energy use and greenhouse effects in economic development. Global Environmental Change 5 (2), 87–103.
Petersen, M.A., 2009. Estimating standard errors in financial penal data sets: comparing approaches. Review of Financial Studies 22 (1), 435–480.
Rudlin, D., Falk, N., 1999. Building the 21st Century Home: The Sustainable Urban Neighborhood. Architectural Press, Oxford.
Shi, A., 2003. The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. Ecological Economics 44, 29–42.
United Nations (UN), 2008. World Urbanization Prospects: The 2007 Revision. UN, New York.
United Nations (UN), 2009. UN Data: A World of Information. Available at http://data.un.org/Browse.aspx [Accessed: January 15, 2009].
White, H., 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48, 817–838.
Wooldridge, J.M., 2002. Econometric Analysis of Cross Section and Panel Data. MIT Press, Cambridge, MA.
Wooldridge, J.M., 2007. Introductory Econometrics: A Modern Approach, third ed. Thomson South-Western, Beijing.
World Bank, 1992. World Development Report 1992: Development and the Environment. Oxford University Press, Inc., New York.
World Bank, 2007. World Development Indicators 2007. CD-ROM, World Bank, Washington, DC.
World Bank, 2009. Country Classifications. Available at http://data.worldbank.org/about/country-classifications/a-short-history [Accessed: January 15, 2009].
York, R., Rosa, E.A., Dietz, T., 2003a. Footprints on the earth: the environmental consequences of modernity. American Sociological Review 68 (2), 279–300.
York, R., Rosa, E.A., Dietz, T., 2003b. STIRPAT, IPAT and ImPACT: analytical tools for unpacking the driving forces of environmental impacts. Ecological Economics 46, 351–365.
York, R., 2007. Demographic trends and energy consumption in European Union Nations, 1960–2025. Social Science Research 36 (3), 855–872.