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An Analysis of Urban Environmental Kuznets Curve of CO_2 Emissions: Empirical Analysis of 276 Global Metropolitan Areas

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Abstract

This study analyzed the relationship between urban CO_2 emissions and economic growth applying the environmental Kuznets curve hypothesis. The objective of this study is to investigate how urban CO_2 emissions and their composition have changed with urban economic growth, depending on city characteristics, using a dataset of metropolitan areas. We obtained data for 276 cities in 26 countries for the years 2000, 2005, and 2008. The dataset includes urban CO_2 emissions, GDP, and population. Additionally, data regarding compact city variables are applied to determinants analysis using an econometric approach. The results demonstrate an inverted U-shape relationship between urban CO_2 emissions and urban economic growth. Additionally, an inverted U-shape relationship is observed for the transport and residential & industry sectors. However, the turning points of each inverted U-shape curve varies. This result implies that we can better understand urban policies for reducing urban CO_2 emissions by considering the characteristics of each sector.

Keywords: urban CO_2 emissions, environmental Kuznets curve, compact city, metropolitan area

1. Introduction

Currently, over half of the world's population lives in cities, and more than two-thirds of the population will do so by 2050 (OECD, 2014). The reason for this increase in urbanization appears to be driven by economic development and the bringing together of people, business and other activities within cities (OECD, 2012a). Cities are critical to the economic prosperity and development of nations, accounting for over 60% of gross domestic product (GDP) in most nations, increasing to some 80-90% of GDP for developed nations (UN, 2015a). In addition, urban areas offer the greatest opportunities for skilled employment, with urban characteristics and city size playing a role in the nature of employment opportunities for each locale (UN, 2015b).

While cities are important in terms of their contribution to employment opportunity and economic prosperity, they also consume in excess of three quarters of energy produced around the globe, and urban areas are estimated to account for more than two-thirds of global energy-related greenhouse gas emissions (Seto *et al*., 2014). This share is expected to increase to almost three-quarters of global energy-related emissions by 2030 with the vast majority of urbanizing population to come from developing nations, particularly in emerging Asian economies (OECD, 2014).

Thus, as the majority of global CO_2 emissions originate from urban regions, there is a need to clarify the relationship between CO_2 emissions and economic development in cities (Shi *et al*., 2018). As developing nations continue to both develop and urbanize, it is likely that their CO_2 emissions will also increase, identifying a further need to forecast how urban economic development in developing nations will affect future CO_2 emissions.

Previous studies have focused specifically on the transport sector and investigated the relationship between air pollutants such as nitrous oxides (NO_x) and particulate matter (PM) originating from within the transport sector and economic development in urban areas (Liddle, 2015). It is crucial to reduce CO_2 emissions from urban areas in order to meet global climate change mitigation targets and avoid global temperature increases (below 2 degrees above pre-industrial levels; UNFCCC, 2017). Therefore, this study addresses an important question; whether or not there is an empirical relationship between CO_2 emissions associated with industrial and household activities and urban economic development?

Another important point is that urban characteristics can be diverse within the same country. Therefore, country level data analysis has limited usefulness in terms of investigating the relationship between CO_2 emissions and economic development considering diverse urban characteristics within each country.

According to Fujii et al. (2017), urban characteristics are a key factor to determine the relationship between economic development and CO_2 emissions. Thus, the trend and pattern of the relationship between urban CO_2 emissions and economic development represent useful information to build effective and appropriate urban climate policy. Based on these points, city level data analysis is necessary to thoroughly investigate the relationship between urban CO_2 emissions and economic development considering urban characteristics.

According to country level data analysis between pollution and economic development, sector composition change is the key factor to achieve emission reduction with economic growth (Fujii and Managi, 2016). Thus, this study considers that sectoral composition change is also important for urban areas to reduce CO_2 emissions. To confirm how the composition of CO_2 emissions are different among metropolitan areas, this study describes the scatter plot using Figure 1. Here, we investigate three sectors; which are the energy sector, transport sector, and residential and industry (R&I) sectors as the CO_2 emitters in urban areas. The sum of CO_2 emissions from three sectors equal the total CO_2 emissions in the urban area.

Figure 1 is scatter plot about showing the share of CO_2 emissions from the transport (vertical axis) and energy (horizontal axis) sectors for 276 urban areas of low, middle, and high-income countries. It should be noted that plotted cities located near the origin represents that the share of CO_2 emissions from the R&I sector is high. The figure shows there is not much difference in distribution tendencies among low, middle, and high-income countries. Therefore, economic development at the country level does not have a strong relationship with the share of urban CO_2 emissions in the energy and transport sectors. This finding represents that the characteristics of urban CO_2 emissions are diverse among metropolitan areas at the global scale.

[INSERT FIGURE 1 ABOUT HERE]

Based on the above findings, as shown in Figure 1, this study considers important city characteristics affecting urban CO_2 emissions and estimates an urban environmental Kuznets curve (EKC) which can more comprehensively evaluate the main sources of CO_2 emissions. This approach offers a more holistic evaluation of the relationship between emissions and economic development by considering overall city CO_2 emissions as well as the transport, energy, and residential & industry sectors as described in Figure 2. Using the estimated urban EKC, we address the key policy issues highlighted by the OECD regarding a tailored response to urbanization cognizant of local circumstances and issues such as land use, public transport and population density, among others (OECD, 2012b).

[INSERT FIGURE 2 ABOUT HERE]

Different from previous studies focusing on specific countries or regions, shown in section 2, this study considers both developed and developing nations in the world, in order to deliver a holistic evaluation to guide future city specific development and climate change mitigation policies, improving upon EKC approaches to date, which have been nation or sector/factor specific as described in the literature review.

The remainder of this paper is organized as follows: Section 2 provides a literature review of academic EKC analysis to date; Section 3 details our methodology; Section 4 explains the relevance of the data used in this study; Section 5 presents and discusses the results; and finally, Section 6 provides the conclusions of our study.

2. Literature review and urban EKC hypothesis

The EKC describes the relationship between per-capita income and environmental quality (Dinda, 2004), and is based on the original work of Kuznets (1955), describing an inverted-U relationship between income equality and economic development. Results of EKC analyses have demonstrated that CO_2 emissions are related with economic growth in terms of energy consumption (Kaika and Zervas, 2013), and that economic growth and environmental improvement may be complementary under appropriate policy settings (Dinda, 2004).

To date, very few urban investigations utilizing EKC have been undertaken, except for predominantly single nation case studies and multi-nation, limited factor analyses. For example, in the case of China, the relationship between air pollutants and economic development was investigated, identifying that environmental quality initially declines before improving with income growth, describing an inverted-U, EKC trend (Luo *et al*., 2014). In addition, Liu (2009) investigated the sustainability gap between East, West and 'Model' cities across eight environmental indicators in China concluding that policies should prioritize environmental sustainability over economic growth. Wang and Liu (2017) investigate the EKC hypothesis using 341 city-level CO_2 data in China and confirmed the inverted U shape relationship between CO_2 per capita and urban economic development.

For the United States of America, a city level analysis of sustainability was undertaken by Berry and Portney (2013), who find that the inclusion of environmental groups in policy making tends to improve local economic robustness, and may also provide a link between income growth, the emergence of environmental interest groups and environmental quality, represented by the EKC. Further, a specific study on the waste sector and CO_2 emissions by Lee *et al* (2016) showed no EKC relationship, with no causal relationship between waste generation and GDP per capita using annually based U.S. data from 1990 to 2012. Following these studies, an empirical study of Chinese provincial data was undertaken to verify the existence of an EKC relationship between economic growth and CO_2 emissions between 2000 and 2013 (Wang et al., 2017). Results indicated that EKC type relationships between CO_2 emissions per capita and per capita GDP were established in energy sector but not in mining and manufacturing sectors. Yang et al. (2017) investigated the ECK hypotheses using data in Russia from 1998 to 2013 and results supported EKC relationship under a business as usual scenario.

An investigation of the relationship between energy consumption, CO_2 emissions and economic growth in 19 European nations between 1960 and 2005 was undertaken by Acaravci and Ozturk (2010). This study examined causality between investigated factors and showed that a positive EKC hypothesis exists for Denmark and Italy, suggesting that an increase in real GDP per capita in these nations would likely reduce the carbon emissions per capita. A further study of 90 middle-income countries in Eastern Europe and Central Asia confirmed an EKC relationship between CO_2 emissions and economic growth, identifying turning points for income levels at which the relationship is confirmed (Oh, 2014).

In terms of multi-regional studies, Shahbaz *et al*. (2017) investigate the CO_2-growth nexus for the G7 economies between 1820 and 2015, taking into account structural breaks, reforms, regulations and external shocks. Results show that the EKC hypothesis is substantiated for 6 of the 7 investigated nations, implying improved environmental quality following the achievement of a certain level of income per capita. Japan was the only exception, not displaying an unambiguous inverted-U relationship between variables, however a slight decline was shown with respect to high GDP per capita. The role of renewable energy (RE) is also investigated with regard to the EKC hypothesis in seven regions between 1980-2010 (Al-Mulali *et al*., 2016). This study incorporated multiple factors including CO_2 emissions, GDP, RE consumption, openness, urbanization and financial development. RE consumption was shown to support the EKC hypothesis in Central and Eastern Europe, Western Europe, East Asia and the Pacific, South Asia and the Americas. However, the reverse was true for the Middle East, North Africa and Sub Saharan Africa. These findings may be linked to the low contribution of RE to the energy mix in these regions.

Considering this sample of precedential and recent EKC investigative literature, the authors find that no study exists which considers urban characteristics holistically in order to determine the relationship between economic development and CO_2 emissions, as well as the urban factors which influence these relationships. By considering developed and developing nations, each at varying levels of economic development, this study provides a broader, more comprehensive evaluation, leading to policy implications which can be tailored according to the urban characteristics and level of development in each case considered.

Underpinning this research is an analysis of how urban characteristics impact upon CO_2 per capita (Fujii *et al*., 2017). CO_2 emissions were analyzed across regional groups and four clusters based on emission sources to identify the effect of urban characteristics on CO_2 emissions, and any relationship between these factors. The results of this research showed that the impact of population density and commuting zone share had a different level of impact between city cluster types and region investigated. Based on these findings, the consideration of major sources of emissions in each urban area was identified as an important factor needing further investigation to clarify the linkage between CO_2 emissions and economic development in urban areas (Fujii *et al*, 2017).

Table 1 represents the development stage of urban economic growth and urban CO_2 emissions per capita. At the low GDP per capita stage, people have difficulty in purchasing electronic products and private vehicles because of their low-income level (WorldBank, 2008). Additionally, infrastructure including roads and power generation systems have a low capacity because the infrastructure and energy demands are relatively low (Arto *et al*., 2016). Thus, we hypothesize that the amount of urban CO_2 emissions per capita is smaller at the low urban economic growth stage.

Next, at the middle economic growth stage, income growth promotes the dissemination of electronic products and vehicles in the household sector (Rao and Ummel, 2017). With economic development and increasing electronic product diffusion, electricity demand is rapidly increased (Khanna and Rao, 2009). To supply the large demand for electricity, governments build new power generation systems. Based on this situation, we hypothesize that urban CO_2 emissions are rapidly increasing in locales at the middle economic growth stage.

Finally, we hypothesize that urban CO_2 emissions will be decreased at the high economic growth stage. There are two main reasons. Firstly, people's preference shifts toward more environmentally friendly options which enhance the probability of people purchasing highly energy efficient electronic products and fuel-efficient vehicles (Mizobuchi and Takeuchi, 2016). Secondly, measures to relieve traffic congestion by improvement of public transportation and road construction would be promoted at the high economic growth level. This is because people's opportunity cost increases with economic development (Wang *et al*., 2016). Increased time preference generally has the effecting of increasing people's stress level in times of congestion. Therefore, local governments promote the relief of traffic congestion to increase citizen's satisfaction, a key factor to decide their choice of residence location.

Furthermore, we hypothesize that distributed energy with smart grid and renewable energy systems are diffused at the high economic development level. Distributed energy systems with renewable energy have an advantage in terms of decreasing power transmission losses and creating a low carbon society (Good *et al*., 2016). However, a large amount of initial investment and maintenance costs are required to induce such a system, available for urban centers at the high economic development stage (Zhang, *et al*. 2017). Thus, we consider that the energy sector will decrease urban CO_2 emissions if the city deploys distributed energy systems which incorporate renewable energy.

[INSERT TABLE 1 ABOUT HERE]

3. Methodology

To examine the relationship between urban economic growth and urban CO_2 emissions, we regressed urban CO_2 emissions on GDP per capita, controlling for city characteristics. In the regression, we employed two types of econometric estimation. One is a conventional linear regression model (i.e. a parametric approach). The other is a partial linear regression model (i.e. a semi-parametric approach). We explain these two methodologies here, in order.

We divided the total urban CO_2 emissions into emissions from each of our three assessed sectors (i.e. the energy, transport and residential & industry sectors), mentioned in section 1. We separately conducted four regressions whose dependent variables are total and sectoral CO_2 emissions. Therefore, let $\boldsymbol{CO2PC_{j,t}^{i}}$ represent urban CO_2 emissions from sector $\boldsymbol{i}$ in city $\boldsymbol{j}$ for the year $\boldsymbol{t}$. $\boldsymbol{GDPPC}$ stands for GDP per capita. The quadratic term of GDP per capita ($\boldsymbol{GDPPC^2}$) is incorporated as an explanatory variable because we hypothesize that the relationship between urban CO_2 emissions and economic growth as an inverted-U shape. As mentioned earlier, population density, commuting land share and central population concentration are used as control variables ($\boldsymbol{CONTROL}$) for city characteristics. $\boldsymbol{\delta}$ and $\boldsymbol{\mu}$ denote city and time fixed effects, respectively. The city fixed effect is a time-invariant variable and captures unobserved socio-economic and geographical city characteristics such as culture and altitude. The time fixed effect is cross-sectional invariant but varies across cities. This effect, therefore, captures worldwide effects such as common technology and world business booms. The idiosyncratic error term is expressed as $\boldsymbol{\varepsilon}$. Finally, the specification for estimating the relationship is written according to the following equation.

$$\boldsymbol{CO2PC_{j,t}^{i}} = \boldsymbol{\beta_0^{i} GDPPC_{j,t}^{2}} + \boldsymbol{\beta_1^{i} GDPPC_{j,t}} + \boldsymbol{CONTROL_{j,t} \beta_2^{i}} + \boldsymbol{\delta_j^{i}} + \boldsymbol{\mu_t^{i}} + \boldsymbol{\varepsilon_{j,t}^{i}} \qquad \text{(eq. 1)}$$

where $\boldsymbol{\beta_0}$, $\boldsymbol{\beta_1}$ and vector $\boldsymbol{\beta_2}$ are the coefficients to be estimated. The most important coefficients are $\boldsymbol{\beta_0}$ and $\boldsymbol{\beta_1}$. If the estimated coefficients $\widehat{\boldsymbol{\beta_0}}$ and $\widehat{\boldsymbol{\beta_1}}$ are observed to be negative and positive, then the urban EKC is supported.

The above equation is a parametric econometric model, known as a fixed effects model (Wooldridge, 2010). However, the function form must be specified to apply the model. In particular, we assume the relationship between urban CO_2 emissions and urban development is quadratic as shown in equation 1. Although the quadratic function can draw both positive and negative relationships between these factors, there is a strong constraint that it is a symmetrical relationship, centred on a turning point.

Next, to allow more flexibility for the relationship, instead of a quadratic function, we employ a partial regression model developed by Lokshin (2006), where the function form between urban CO_2 emissions and economic growth is not specified but the relationship between urban CO_2 emissions and control variables is specified to be linear. That is, the partial regression model consists of nonparametric and parametric parts. Let $\boldsymbol{f}(\cdot)$ be a smooth unspecified function linking urban CO_2 emissions and economic growth. $\boldsymbol{\theta}$, $\boldsymbol{\rho}$ and $\boldsymbol{\varphi}$ are city, time-specific effects and the error term, respectively, similar to equation 1. Thus, the partial regression model can be expressed as follows:

$$\boldsymbol{CO2PC_{j,t}^{i}} = \boldsymbol{f^{i}(GDPPC_{j,t})} + \boldsymbol{CONTROL_{j,t} \gamma_2^{i}} + \boldsymbol{\theta_j^{i}} + \boldsymbol{\rho_j^{i}} + \boldsymbol{\varphi_{j,t}^{i}} \qquad \text{(eq. 2)}$$

where $\boldsymbol{\gamma_2}$ is a coefficient vector for the control variables.

Different from the fixed effects model, the partial regression model does not provide an explicit coefficient for $\boldsymbol{GDPPC}$. Instead, the relationship between $\boldsymbol{CO2PC}$ and $\boldsymbol{GDPPC}$ is illustrated as a figure, enabling us to visually understand whether the urban EKC is supported or not. As for the other parametric parts (i.e. control variables), coefficients can be obtained as usual.

4. Data

Our dataset includes 276 metropolitan cities in 26 OECD countries, covering the years 2000, 2005, and 2008. The city list is described in Table A1 to A3 in the supplementary materials. We sourced all data variables from the OECD metropolitan database (OECD, 2012b). This database provides a set of economic, environmental and social indicators for 281 metropolitan areas within OECD nations (functional urban areas with 500,000 or more inhabitants). Five metropolitan areas (Oslo, Zurich, Geneva, Basel and Copenhagen) were removed from the data sample due to missing regional GDP data, resulting in 276 metropolitan areas suitable for analysis in this study.

Table 2 shows the variables and their descriptions. CO_2 emissions data are available for three types of variables: [1] CO_2 emissions per capita, [2] CO_2 emissions per capita from the energy sector, and [3] CO_2 emissions per capita from the transport sector. We created the category "CO_2 emissions per capita from residential & industry sectors" incorporating the above three variables (see definition in Table 2).

[INSERT TABLE 2 ABOUT HERE]

Density, Commuting, and Concentration are applied as control variables explaining urban CO_2 emissions. Previous research has attempted to capture regional characteristics using a variety of variables (see Table 1 in Siedentop and Fina (2010) and Table 1 in Bhatta *et al*. (2010) for examples). We follow the theory and framework for urban data specifications constructed through prior scholarship. Below we explain our reasoning behind the choice of determinant variables, referencing precedential literature.

First, this study used the population density variable as the degree of agglomeration in metropolitan areas. According to Melo *et al*. (2009) and Uchida and Nelson (2010), population density is a key factor to evaluate urban agglomeration. Fritsch and Mueller (2008) noted that "one of these variables is population density or degree of agglomeration." Thus, this study applied population density as a proxy variable for urban agglomeration.

Next, this study applied the commuting zone variable as the degree of urban sprawl. Wolman *et al*. (2005) analyzed urban sprawl by focusing on a commuting data variable. Holcombe and Williams (2010) stated that "a most common complaint of sprawling development is that it lengthens commuting times." Thus, strong relationship between commuting time and urban sprawl can be assumed. Based on the above studies, this study used the land share of commuting zone in the metropolitan area as a proxy variable for urban sprawl.

Finally, the concentration of population in the core area was used as the degree of compactness. In contrast to the commuting zone variable, which evaluates urban sprawl by focusing on a specific area, concentration of population in the core area measures the degree of compactness using population distribution. According to the OECD (2012b), the population divided by the surface of urban land within a metropolitan area can be introduced as a proxy variable for urban compactness.

5. Results

The results for the analysis incorporating the city dummy is shown in Table 3. The results utilizing the country dummy are shown in Table A4. The results show that the model utilizing the city dummy produces a higher R-squared value (Table 3). This result implies that the model which controls the characteristics of the city is more effective than the model which controls for country characteristics. This result also confirms the necessity for conducting analysis which controls for the diverse characteristics of cities.

[INSERT TABLE 3 ABOUT HERE]

Based on the results in Table 3, the model incorporating the city dummy variable shows a statistically significant negative relationship between the GDPPC squared value and urban CO_2 emissions per capita ($CO2PC^{total}$). Additionally, the coefficient of single power of GDPPC shows a significantly positive relationship to $CO2PC^{total}$. The combination of a positive coefficient in single power GDPPC and a negative coefficient in the GDPPC squared value represents that an inverted U-shape curve relationship is observed between GDPPC and $CO2PC^{total}$. Another important finding is that the turning point of the inverted U-shape curve exists in the first quadrant. The first quadrant is located at the top right of the graph. There is a threshold of GDPPC which makes the relationship between GDPPC and $CO2PC^{total}$ change from positive to negative if the turning point of the inverted U-shape curve exists within the first quadrant.

In addition to $CO2PC^{total}$, an inverted U-relationship was observed in the urban CO_2 emissions from transport ($CO2PC^{tr}$) and residential & Industry sectors ($CO2PC^{R\&I}$). Thus, the transport and residential & industry sectors play an important role in identifying the urban EKC relationship. However, for the energy sector, although a negative relationship with GDPPC squared was shown, this result is not statistically significant (Table 3).

Turning points in the inverted-U relationships were observed in city (TP = \$55,102), residential & industry (TP = \$41,393), transport (TP = \$53,333) and energy sectors (TP = \$67,333) in the parametric estimation model (Table 3). The reasoning behind the *early* turning point shown by the residential & industry sector is easily explained through the relatively easy development process of replacing old facility equipment with lower energy efficiency with new facility equipment with higher energy efficiency. On the other hand, it takes time to secure sufficient tax revenues to improve public transport and roads, suggesting that the transport sector has a *later* turning point occurring only after a certain level of economic growth has been achieved. For the energy sector, which is related not only to the city in which it is located, but also to the consumers of the transmitted power, the turning point of GDP for the replacement of equipment or augmentation of the electricity network is expected to be high.

In addition to the estimation of parametric results, semi-parametric estimation was carried out to verify the robustness of the results. The results of the semi-parametric analysis are shown in Table 4. We can confirm the consistent relationship between semi-parametric and parametric estimations and consider the results presented in this research to be robust. Additionally, we indicate the diagrammatic representation of estimated relationship between urban economic development and urban CO_2 emissions. Figure 3 is described based on parametric estimation (see Table 3) and Figure 4 is described based on the semi-parametric estimation (see Table 4). From Figures 3 and 4, we confirm the similar trend of the estimated relationship between urban economic development and urban CO_2 emissions in each sector, and accumulated urban CO_2 emissions.

[INSERT TABLE 4 ABOUT HERE]

Based on the results presented above, urban CO_2 emissions from the transport, residential & industry sectors proceeded towards turning points as urban economic development progressed, and subsequently suggested a reducing trend. On the other hand, CO_2 emissions due to the energy sector could not be shown to have a clear inverted U-shape trend relative to urban economic development. This analysis result suggests that in order to reduce CO_2 emissions, a decision-making process considering greener urban economic development with regard to the transport and residential & industry sectors, as well as their turning points may be an effective strategy.

This is particularly true for Latin America and Eastern Europe, which contain many cities whose turning points are in the future. Our results show that GDP per capita is below the turning point of the residential & industry sector (i.e. $41,393) in all cities in Chile, Estonia, Hungary, Mexico, Poland, and Portugal. It is important to bring these turning points forward and to promote the reduction of urban CO_2 emissions in metropolitan areas within these countries.

It should be noted that this study uses three breakpoint year’s data to investigate the urban EKC relationship. Three year's data is the minimum necessary in order to isolate city-specific and time-specific effects, implying that our analysis satisfies the minimum conditions. Figures 3 and 4 illustrate the relationships between GDP per capita and sectoral urban CO_2 emissions, removing potential effects on CO_2 emissions from city-specific and time-specific effects and city characteristics. Therefore, a time horizon does not exist in these figures. To consider the long time-series relationship, this study assumes that if cities with low GDP per capita (i.e., their economic level is less than the identified turning point) attain economic growth, that their CO_2 emissions will change averagely along the curve. Although mechanism for economic development is beyond our paper, the assumption that their economy will grow in the future is plausible.

[INSERT FIGURE 3 ABOUT HERE]

[INSERT FIGURE 4 ABOUT HERE]

Finally, comparative analysis with previous studies on EKC is introduced. The inverted U-shaped relationship between CO_2 emissions per capita and economic development is consistent with previous studies introduced in the literature review section. However, the level of turning points is different to those found in previous studies. The turning point of GDP per capita identified in this study is higher than those reported by the previous studies using country data. Heidari et al. (2015) observed an EKC relationship in CO_2 emissions using a 5 ASEAN country dataset from 1980 to 2008 and the turning point of the EKC relationship was identified as 4,686 US$. Hassan and Salim (2015) used 25 OECD nation's data from 1980 to 2010 and observed a turning point for the EKC relationship of 24,657 US$.

These turning points found in the previous studies are considerable lower than the turning point (55,102 US$) of the urban EKC relationship observed in this study. The reason for this difference between this study and the previous studies' results is that this study focuses on large scale metropolitan areas with 500,000 or more inhabitants which are more economically developed when compared with non-urban areas. Previous studies (Heidari et al., 2015; Hassan and Salim, 2015) focused on country level data which includes these non-urban areas, contributing to a decrease in the turning point of the EKC relationship.

The finding that turning point GDP per capita estimated country data is lower than turning point estimated urban level data implies that urban climate policy should refer the turning point information estimated by urban level data as a priority. In other words, turning point estimated by country level data may mislead urban climate policy to be less ambitious, because country level turning points provide easier to achieve targets.

6. Conclusion and policy implication

This study investigated the relationship between urban economic development and urban CO_2 emissions in three sectors including the transport, energy, and residential & industry sectors. We tested the EKC hypothesis using 276 metropolitan area data in the years 2000, 2005, and 2008. From the results, we found that urban CO_2 emissions have an inverted U-shape relationship and turning point toward decline in the transport and residential & industry sectors relative to urban economic development. Another finding is that urban CO_2 emissions from the energy sector did not have an inverted U-shape relationship relative to urban economic development in the parametric estimation model employed.

The turning point of inverted U-shape curves is different among the two sectors. The turning point of regional GDP per capita in the residential & industry sector is approximately \$41,000, while for the transport sector it is approximately \$53,000. Some previous EKC studies concluded that the inverted U-shape relationship between CO_2 emissions and economic development was supported by country or sector level data. However, this study demonstrates that the inverted U-shape relationship is also supported in the transport and residential & industry sectors at the city level. The turning point information has an important role for policy makers to forecast the future urban CO_2 emissions from these two sectors.

Four policy implications were identified through this study. Firstly, the results advocate the development of tailored local urban policy according to the situation of each city, not only in developed countries but also in developing countries, as opposed to a national governmental policy approach. This is in line with the suggestion of the OECD (2012a). Secondly, our study demonstrated that CO_2 reduction strategies should be matched to city development levels and sectors in terms of efficiency, to take advantage of the identified factors and turning points which influence these reductions. The reason being that the appropriate countermeasures against climate change differ according to development levels and specific sectors (see Table 1). Third, due to the differences identified for each city in terms of their individual factors, it may be prudent to develop city specific policies rather than country level policies to reduce emissions. This is particularly true for larger metropolitan areas which are responsible for significant portions of overall national emissions. Towards this end, a number of large cities including New York and Delhi already participate in the C40 Cities Climate Leadership Group and are accelerating their climate actions (Lee and Meene, 2012).

Finally, our study identifies regions in Latin America and Eastern Europe where turning points for reduced emissions in the various sectors are in the future, where GDP per-capita is still below turning point thresholds, identifying policy priority areas to achieve emission reductions while promoting urban economic development. It is urgent to help the developing cites in these regions take climate action. One example for this implication is to establish city networks through joint seminars and workshops designed by international organizations (e.g., The World Mayors Council on Climate Change) to educate urban policy officers about reducing CO_2 emissions effectively without a large investment. Importantly, urban policy officers should consider their city's economic development level and predicted turning point information in order to back cast the optimal carbon reduction strategy, using the climate policies of other cities as a reference. This progressive approach helps low economically developed cities to reduce their emissions without damaging their economic performance. Lee and Jung (2018) demonstrates that such a council as described above can enhance policy cooperation among cities.

There are several limitations in our analysis. The first of these is the analytical period (i.e. 2000, 2005 and 2008). To our knowledge, there is no comprehensive database regarding GHG emissions at the city level which covers the world, except for the OECD metropolitan database. Although a concentrated effort would be necessary to make a new, long-term database, if such database were to be constructed, we could conduct more detailed analysis, resulting in tailored urban policies against global warming. Second, existing urban policies such as tax and regulations are omitted in our analysis. As mentioned earlier, city governments have recently committed to reducing GHG emissions, independent from national governments. To guide a more efficient strategy against climate change, it is necessary to evaluate the urban policies that are actually implemented.

Further research could complement our study by investigating the relationship between urban economic development and urban air pollutant emissions including PM and nitrogen dioxide in developing countries. Such analysis could clarify the relationship between urban economic development and urban air pollutant emissions, critical to understanding air quality management and also pertinent to public health policy development.

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Table 1. Development stage of urban economic growth and urban CO_2 emissions

Sector	Lower economic growth stage	Middle economic growth stage	High economic growth stage
Household & business office	Low diffusion rate of electric products (-)	Diffusion of electric products (+)	Diffusion of energy efficient electric products (-)
Industry	Growth of energy intensive sector due to low labor and energy cost (+)	Growth of energy intensive sector due to low labor and energy cost (+)	Plant relocation in energy intensive sector due to high energy and labor cost, and strict environmental regulation (-)
Energy	Electrification with centralized generation (+)	Electrification with centralized generation (+)	Renewable energy with Dispersed power system (-)
Transportation	Less vehicles owned (-) Traffic gridlock due to less road capacity (+)	Traffic gridlock (+) Increase the number of vehicles owned (+)	New infrastructure for road capacity and public transportation (-) Diffusion of fuel efficient vehicle (-)

Table 2. Data description

Data category	Variable (code)	Definition	unit	Mean value	Std. dev.
Urban economic development	GDP per capita (*GDPPC*)	GDP of metropolitan area divided by population	US $	37,226	15,389
Urban CO_2 emissions	CO_2 emissions per capita ($CO2PC^{total}$)	CO_2 emissions (CO_2) divided by population	Tons CO_2/ person	10.63	7.60
	CO_2 emissions per capita from energy sector ($CO2PC^{energy}$)	CO_2 emissions from energy sector divided by population	Tons CO_2/ person	3.36	5.43
	CO_2 emissions from transport sector ($CO2PC^{tr}$)	CO_2 emissions from transport sector divided by population	Tons CO_2/ person	2.64	1.82
	CO_2 emissions from residential & industry sector ($CO2PC^{R\&I}$)	$CO2PC^{total} – (CO2PC^{energy} + CO2PC^{tr})$	Tons CO_2/ person	4.63	2.82
Control variables	Population density of metropolitan area (Density)	Population / metropolitan area	persons / km^2	670.94	740.27
	Commuting zone share (Commuting)	Commuting zone area / metropolitan area	%	60.38	29.25
	Concentration of population in the core (Concentration)	Population living in the core area / total metropolitan population	%	75.40	17.58

Source: Created by authors using metropolitan area data from OECD.stat (OECD, 2013)

Note 1: Monetary data are deflated to 2010 prices.

Note 2: The energy sector includes public electricity, heat production and other energy industries. The transport sector includes road, rail and ground transportation. The "residential & industry" sector includes agriculture, manufacturing, services and residential sectors (OECD, 2013).

Note 3: The core area and commuting zone are defined by the OECD (2013). The identification flow and detailed explanation are provided in "Annex A: Defining regions and functional urban areas" and Figure A.5. in OECD (2013).

Table 3. Results of parametric estimation using city dummy variables

	(1)	(2)	(3)	(4)
Dependent variables	$CO2PC^{energy}$	$CO2PC^{tr}$	$CO2PC^{R\&I}$	$CO2PC^{total}$
$GDPPC^2$	-1.50×10^{-9}	-1.20×10^{-9}***	-1.22×10^{-9}***	-3.92×10^{-9}***
	(1.00×10^{-9})	(1.29×10^{-10})	(3.09×10^{-10})	(1.05×10^{-9})
GDPPC	2.02×10^{-4}**	1.28×10^{-4}***	1.01×10^{-4}***	4.32×10^{-4}***
	(7.81×10^{-5})	(1.31×10^{-5})	(3.27×10^{-5})	(8.64×10^{-5})
Density	-7.38×10^{-4}	6.05×10^{-4}**	5.14×10^{-4}	3.80×10^{-4}
	(4.09×10^{-3})	(2.96×10^{-4})	(4.95×10^{-4})	(4.32×10^{-3})
Commuting	0.347***	-0.0592***	-0.0801***	0.208**
	(0.0849)	(0.0115)	(0.0159)	(0.0917)
Concentration	0.0416	-0.0171	-0.0117	0.0129
	(0.0927)	(0.0142)	(0.0201)	(0.102)
2005 year dummy	0.00339	-0.193***	-0.271***	-0.460***
	(0.144)	(0.0239)	(0.0461)	(0.159)
2008 year dummy	-0.314	-0.377***	-0.506***	-1.198***
	(0.215)	(0.0362)	(0.0587)	(0.240)
Constant	-10.43	4.127***	7.925***	1.622
	(10.92)	(1.560)	(2.142)	(11.84)
turning point	67,333	53,333	41,393	55,102
F-value	104.1***	302.2***	203.0***	160.7***
Adjusted R-squared	0.972	0.990	0.986	0.982

Note: the number of observations is 828 for all estimations. Standard errors clustered by city are presented in parenthesis. ***, **, and * indicate significance levels at the 1, 5, 10% levels, respectively.

Table 4. Results of partial linear regression model

	(1)	(2)	(3)	(4)
Dependent variables	$CO2PC^{energy}$	$CO2PC^{tr}$	$CO2PC^{R\&I}$	$CO2PC^{total}$
Density	-0.00157 (0.00117)	0.000280 (0.000228)	0.000391 (0.000422)	-0.000898 (0.00132)
Commuting	0.325*** (0.0390)	-0.0541*** (0.00761)	-0.0400*** (0.0141)	0.231*** (0.0441)
Concentration	0.0490 (0.0500)	-0.0153 (0.00975)	-0.00726 (0.0180)	0.0264 (0.0565)
2005 year dummy	0.0285 (0.102)	-0.179*** (0.0200)	-0.278*** (0.0369)	-0.428*** (0.116)
2008 year dummy	-0.164 (0.122)	-0.366*** (0.0237)	-0.522*** (0.0439)	-1.052*** (0.138)
Turning point of *GDPPC*	60,000	56,000	41,000	55,000
F-value	125.5***	181.6***	169.4***	138.4***
Significance test for *GDPPC*	8.96***	20.90***	14.25***	11.70***
Adjusted R-squared	0.977	0.984	0.983	0.979

Note 1: the number of observations is 827 for all estimations. In the partial regression, based on observation with lowest GDP per capita, the fitting curve in the Figure 4 is illustrated. Therefore, the number of observations used here decrease by 1. ***, **, and * indicate significance levels at the 1, 5, 10% levels, respectively.

Note 2: Squared GDP per capita and GDP per capita are estimated by a non-parametric approach. Other variables are estimated using a parametric approach, providing coefficient scores and p-values.

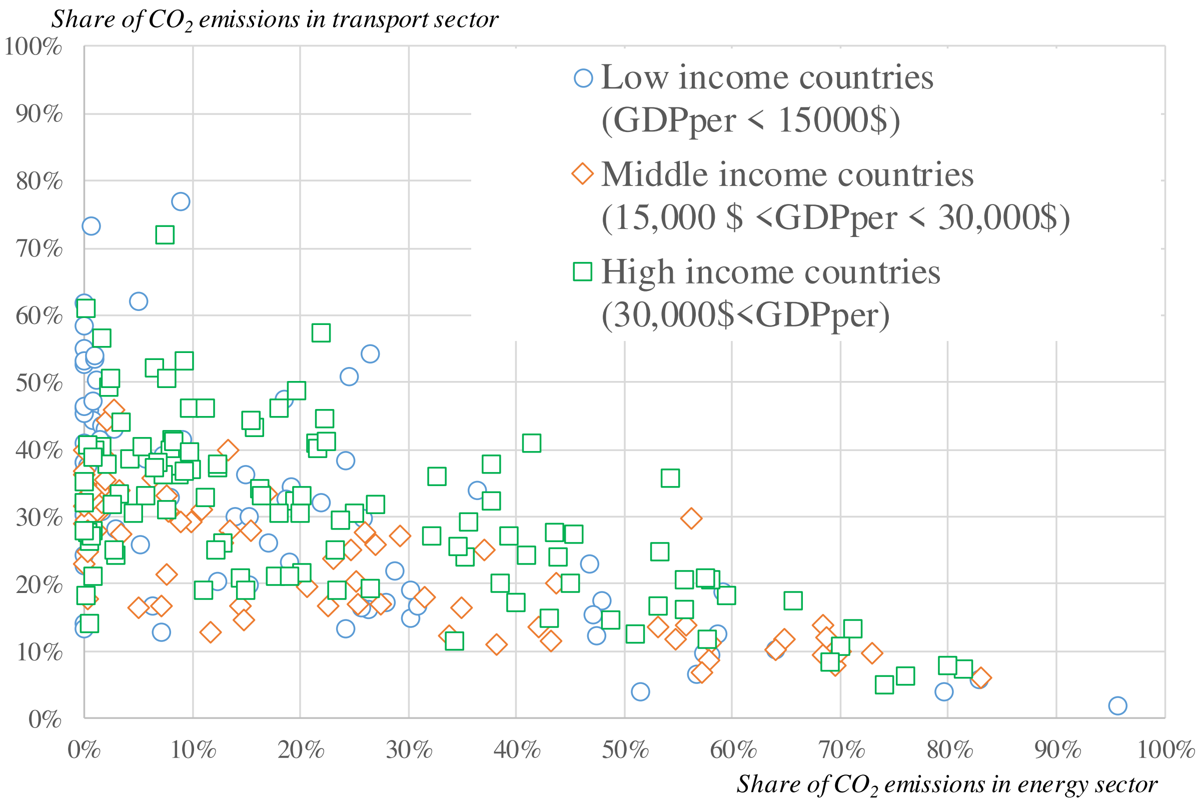

Figure 1. Scatter plot of urban CO_2 emissions share in the energy and transport sectors in 2008

Note: GDP per capita data is deflated according to prices in the year 2010.

Source: Authors made this figure using metropolitan area data from OECD. stat.

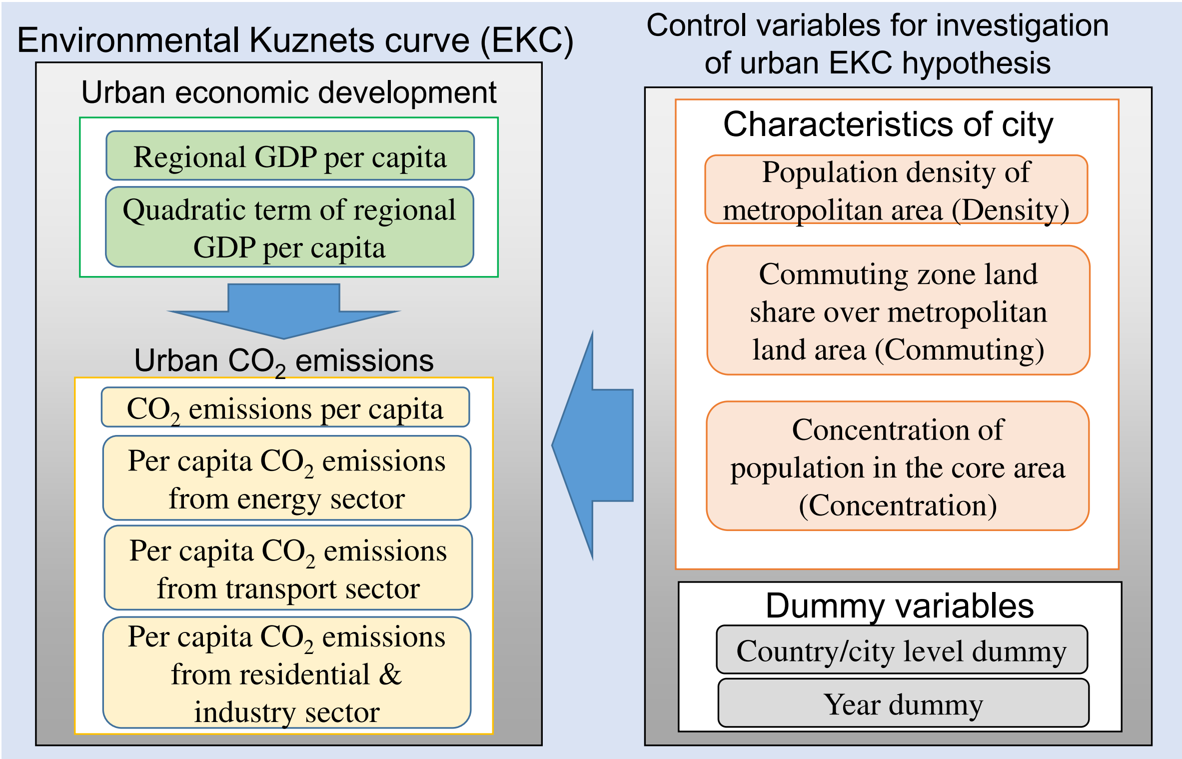

Figure 2. Research framework of this study

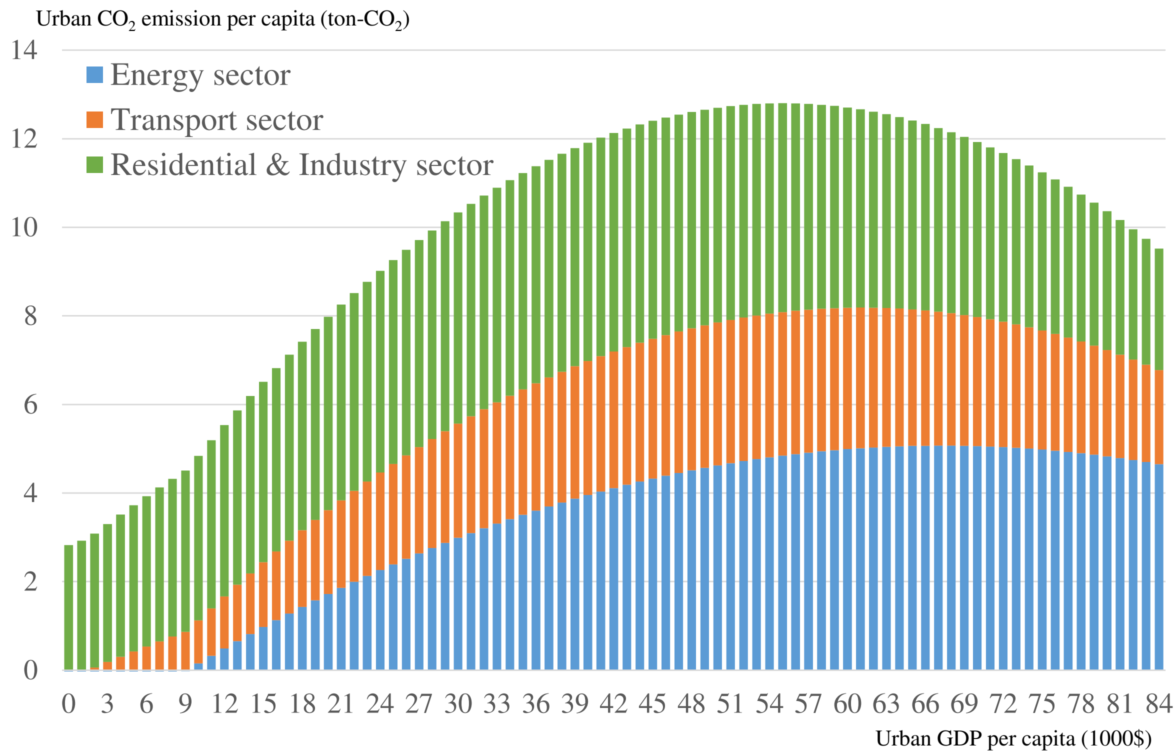

Figure 3. Projection of urban CO_2 emissions in three sectors based on parametric approach

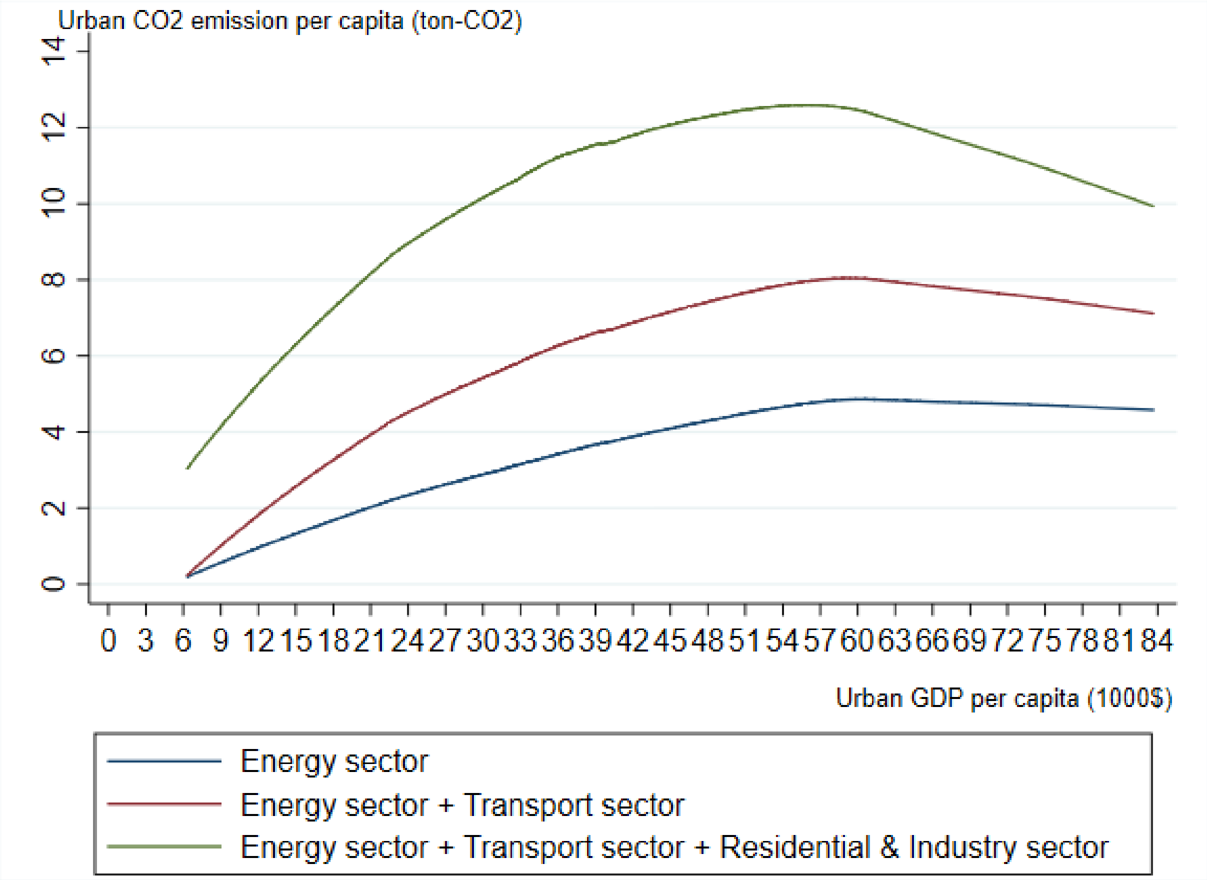

Figure 4. Projection of urban CO_2 emissions in three sectors based on semi-parametric approach

Table A1. Metropolitan city and country names in the American region

City name	Country	City name	Country	City name	Country
Seattle	USA	Tulsa	USA	Mexicali	Mexico
Portland	USA	Raleigh	USA	Tijuana	Mexico
Minneapolis	USA	Oklahoma City	USA	Juárez	Mexico
Milwaukee	USA	Charlotte	USA	Hermosillo	Mexico
Madison	USA	Albuquerque	USA	Chihuahua	Mexico
Buffalo	USA	Memphis	USA	Reynosa	Mexico
Grand Rapids	USA	Little Rock	USA	Monterrey	Mexico
Albany	USA	Los Angeles	USA	Torreón	Mexico
Detroit	USA	Columbia	USA	Saltillo	Mexico
Boston	USA	Atlanta	USA	Culiacán	Mexico
Chicago	USA	Phoenix	USA	Durango	Mexico
Providence	USA	Birmingham	USA	Tampico	Mexico
Toledo	USA	Dallas	USA	San Luis Potosí	Mexico
Cleveland	USA	San Diego	USA	Aguascalientes	Mexico
Des Moines	USA	Fort Worth	USA	Benito Juárez	Mexico
Omaha	USA	Charleston	USA	León	Mexico
Akron	USA	Tucson	USA	Mérida	Mexico
New York	USA	El Paso	USA	Guadalajara	Mexico
Salt Lake City	USA	Baton Rouge	USA	Irapuato	Mexico
Pittsburgh	USA	Austin	USA	Querétaro	Mexico
Harrisburg	USA	Jacksonville	USA	Celaya	Mexico
Philadelphia	USA	New Orleans	USA	Pachuca de Soto	Mexico
Columbus	USA	Houston	USA	Morelia	Mexico
Denver	USA	San Antonio	USA	Mexico City	Mexico
Indianapolis	USA	Orlando	USA	Xalapa	Mexico
Dayton	USA	Clearwater/ Saint Petersburg	USA	Toluca	Mexico
Baltimore	USA	Tampa	USA	Veracruz	Mexico
Cincinnati	USA	Miami	USA	Puebla	Mexico
Washington	USA	Mcallen	USA	Cuernavaca	Mexico
Kansas City	USA	Calgary	Canada	Centro	Mexico
Colorado Springs	USA	Winnipeg	Canada	Oaxaca de Juárez	Mexico
Saint Louis	USA	Vancouver	Canada	Acapulco de Juárez	Mexico
Sacramento/ Roseville	USA	Quebec	Canada	Tuxtla Gutiérrez	Mexico
Louisville	USA	Montreal	Canada	Valparaíso	Chile
San Francisco	USA	Ottawa-Gatineau	Canada	Santiago	Chile
Wichita	USA	Toronto	Canada	Concepción	Chile
Richmond	USA	Hamilton	Canada		
Norfolk-Portsmouth-Chesapeake-Virginia Beach	USA	Edmonton	Canada		
Fresno	USA				
Las Vegas	USA				
Nashville	USA				

Table A2. Metropolitan city and country names in the European region.

City name	Country	City name	Country	City name	Country
Vienna	Austria	Helsinki	Finland	The Hague	The Netherlands
Graz	Austria	Paris	France	Amsterdam	The Netherlands
Linz	Austria	Lyon	France	Rotterdam	The Netherlands
Prague	Czech Republic	Toulouse	France	Utrecht	The Netherlands
Brno	Czech Republic	Strasbourg	France	Eindhoven	The Netherlands
Ostrava	Czech Republic	Bordeaux	France	Warsaw	Poland
Berlin	Germany	Nantes	France	Lódz	Poland
Hamburg	Germany	Lille	France	Kraków	Poland
Munich	Germany	Montpellier	France	Wroclaw	Poland
Cologne	Germany	Saint-Étienne	France	Poznan	Poland
Frankfurt	Germany	Rennes	France	Gdansk	Poland
Essen	Germany	Grenoble	France	Lublin	Poland
Stuttgart	Germany	Toulon	France	Katowice	Poland
Leipzig	Germany	Marseille	France	Lisbon	Portugal
Dresden	Germany	Nice	France	Porto	Portugal
Dortmund	Germany	Rouen	France	Stockholm	Sweden
Düsseldorf	Germany	Brussels	Belgium	Gothenburg	Sweden
Bremen	Germany	Antwerp	Belgium	Malmö	Sweden
Hanover	Germany	Ghent	Belgium	Ljubljana	Slovenia
Nuremberg	Germany	Liege	Belgium	Bratislava	Slovak Republic
Bochum	Germany	Athens	Greece	London	United Kingdom
Freiburg im Breisgau	Germany	Thessalonica	Greece	Birmingham (UK)	United Kingdom
Augsburg	Germany	Budapest	Hungary	Leeds	United Kingdom
Bonn	Germany	Dublin	Ireland	Bradford	United Kingdom
Karlsruhe	Germany	Rome	Italy	Liverpool	United Kingdom
Saarbrücken	Germany	Milan	Italy	Manchester	United Kingdom
Duisburg	Germany	Naples	Italy	Cardiff	United Kingdom
Mannheim	Germany	Turin	Italy	Sheffield	United Kingdom
Münster	Germany	Palermo	Italy	Bristol	United Kingdom
Aachen	Germany	Genova	Italy	Newcastle	United Kingdom
Tallinn	Estonia	Florence	Italy	Leicester	United Kingdom
Madrid	Spain	Bari	Italy	Portsmouth	United Kingdom
Barcelona	Spain	Bologna	Italy	Nottingham	United Kingdom
Valencia	Spain	Catania	Italy	Glasgow	United Kingdom
Seville	Spain	Venice	Italy	Edinburgh	United Kingdom
Zaragoza	Spain				
Málaga	Spain				
Las Palmas	Spain				
Bilbao	Spain				

Table A3. Metropolitan city and country names in the Asian and Oceania region

City name	Country	City name	Country
Sydney	Australia	Sapporo	Japan
Melbourne	Australia	Sendai	Japan
Brisbane	Australia	Niigata	Japan
Perth	Australia	Toyama	Japan
Adelaide	Australia	Nagano	Japan
Gold Coast-Tweed Heads	Australia	Kanazawa	Japan
Seoul Incheon	Korea	Toyohashi	Japan
Cheongju	Korea	Hamamatsu	Japan
Daejeon	Korea	Okayama	Japan
Pohang	Korea	Kurashiki	Japan
Daegu	Korea	Fukuyama	Japan
Jeonju	Korea	Hiroshima	Japan
Ulsan	Korea	Takamatsu	Japan
Busan	Korea	Wakayama	Japan
Changwon	Korea	Tokushima	Japan
Gwangju	Korea	Kitakyushu	Japan
		Matsuyama	Japan
		Fukuoka	Japan
		Kochi	Japan
		Oita	Japan
		Kumamoto	Japan
		Nagasaki	Japan
		Kagoshima	Japan
		Naha	Japan

Table A4. Results of parametric estimation using country dummy variable

	(1)	(2)	(3)	(4)
Dependent variables	$CO2PC^{energy}$	$CO2PC^{tr}$	$CO2PC^{R\&I}$	$CO2PC^{total}$
$GDPPC^2$	-3.57×10^{-9}***	-0.00	-4.05×10^{-10}	-3.98×10^{-9}**
	(1.27×10^{-9})	(2.57×10^{-10})	(5.00×10^{-10})	(1.76×10^{-9})
GDPPC	3.49×10^{-4}**	1.82×10^{-5}	8.19×10^{-5}	4.49×10^{-4}**
	(1.42×10^{-4})	(3.11×10^{-5})	(4.82×10^{-5})	(1.85×10^{-4})
Density	1.07×10^{-4}	2.74×10^{-4}*	3.86×10^{-5}	4.20×10^{-4}
	(5.08×10^{-4})	(1.41×10^{-4})	(1.41×10^{-4})	(5.16×10^{-4})
Commuting	-0.0229	-0.000739	0.00891*	-0.0147
	(0.0286)	(0.00477)	(0.00435)	(0.0254)
Concentration	-0.0578**	-0.00186	0.0352***	-0.0244
	(0.0263)	(0.00424)	(0.00952)	(0.0294)
year 2005 dummy	0.0203	-0.148	-0.382**	-0.510*
	(0.224)	(0.0905)	(0.158)	(0.274)
year 2008 dummy	-0.308	-0.305	-0.660***	-1.273**
	(0.284)	(0.184)	(0.184)	(0.511)
Constant	-0.634	2.344***	-0.773	0.937
	(4.372)	(0.330)	(1.346)	(5.433)
Turning point of *GDPPC* ($)	48,880	n/a	101,111	56,407
individual fixed effects	country level	country level	country level	country level
time fixed effects	yes	yes	yes	yes
Observations	828	828	828	828
R-squared	0.158	0.863	0.622	0.477

Note: the number of observations is 828 for all estimations. Standard errors clustered by country are presented in parenthesis. ***, **, and * indicate significance levels at the 1, 5, 10% levels, respectively.