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Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: The case of Beijing, Tianjin, Shanghai and Chongqing

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ABSTRACT

With China's rapid economic development and urbanization process, cities are facing great challenges for tackling anthropogenic climate change. In this paper we present features, trajectories and driving forces for energy-related greenhouse gas (GHG) emissions from four Chinese mega-cities (Beijing, Tianjin, Shanghai and Chongqing) during 1995–2009. First, top-down GHG inventories of these four cities, including direct emissions (scope 1) and emissions from imported electricity (scope 2) are presented. Then, the driving forces for the GHG emission changes are uncovered by adopting a time serial LMDI decomposition analysis. Results indicate that annual GHG emission in these four cities exceeds more than 500 million tons and such an amount is still rapidly growing. GHG emissions are mainly generated from energy use in industrial sector and coal-burning thermal power plants. The growth of GHG emissions in four mega-cities during 1995–2009 is mainly due to economic activity effect, partially offset by improvements in carbon intensity. Besides, the proportion of indirect GHG emission from imported energy use (scope 2) keeps growing, implying that big cities are further dependent on energy/material supplies from neighboring regions. Therefore, a comprehensive consideration on various perspectives is needed so that different stakeholders can better understand their responsibilities on reducing total GHG emissions.

1. Introduction

Cities with less than one percent of global surface, where half of the global population lives [1], are responsible for more than 60 percent of global energy consumption and three-fourth of world Greenhouse gas emissions [2]. Therefore, cities play a significant role in curbing anthropogenic climate changes. Besides, with high population density, complicated infrastructure and various municipal services, cities are vulnerable for abrupt climate interference and also sensitive to energy conservation and GHG reduction actions [3].

Currently, more than a thousand cities worldwide have pledged to reduce GHG emissions at local scale. Actions such as "Cities for Climate Protection" (CCP) campaign and C40 group are becoming popular [4]. To date, more sophisticated studies on cities' GHG footprints have been undertaken at different sizes [5–8]. In order to raise appropriate policies for addressing climate change, GHG emission benchmarks and inventories have been considered as the first step for further analysis [8]. Nevertheless, there are three challenges in the holistic analysis of GHG status at city level.

First, it's difficult to define a city's boundary for GHG footprint accounting due to a large amount of cross-boundary GHG emissions caused by urban metabolism [9,10]. Cross-boundary exchange of goods, services, commuter travel and aviation has posed a "challenge in developing a holistic accounting of GHG emissions associated with human demands for energy and materials in cities" [6]. Direct use of primary energy through industrial activity leads to the direct GHG emissions within territorial boundary, and these emissions are usually defined as scope 1 [11–13]. Cities consume a large amount of purchased electricity generated by upstream power plant, and the corresponding emissions are defined as scope 2. The consumption of products leads to the emissions from

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upstream production through supply chain, which is defined as scope 3. Previous studies indicate that emissions among different scopes are significantly different [14,15]. Various boundary definitions have resulted in uncertainties of cities' GHG inventories and then become barriers for the comparable study of cities' GHG emission status at global scale.

Second, appropriate methodologies for the different scopes are still lacking, or having data limitations. To provide a holistic analysis on city's GHG emission can provide incentives to various stakeholders so that they can raise their emission reduction plans. Thus, a comparative study among scope 1, scope 2 and scope 3 emissions is necessary. However, it is difficult to calculate exact emission for each of scope due to several uncertainties, such as embodied emissions of foods and construction materials. For instance, in order to calculate scope 3 emission, a hybrid IO-LCA (input–output life cycle assessment) methodology should be adopted so as to track the supply chain emissions [16]. But both data collection and model development are challenging missions.

Third, due to data availability, boundary and method uncertainties, a comprehensive perspective on urban GHG emission including spatial-temporal features and their underling drivers is missing [8]. Typically, different cities have different features, such as historical development, industrial structure, climate and culture perspectives [17], but little is known on the evolution of urban GHG emission especially with different scope perspectives. In order to raise appropriate mitigation policies, it is also necessary to identify the key factors driving city's emission. Therefore, it is critical to conduct more comprehensive analysis from both special and temporal perspectives. However, challenges exist. For example, the accounting of emissions from purchased electricity requires the grid emission factor, which is influenced by energy structure for power generation and may vary significantly over time. Scope 3 inventories require detailed information on materials and energy flux, and should be calculated through the use of national and regional input–output (IO) models. But in reality such models always appear late. In addition, with the temporal change of GHG emissions, driving forces also change, therefore, mitigation actions should respond to such changes. Academically, several studies focus on historical change of GHG from different scope and their policy implication at global and national levels [18,19], but few studies at city level have been conducted.

With regard to China, due to rapid industrialization and urbanization in the last three decades, China has become the largest CO_2 emitter in the world, accounting for 25% of global CO_2 emission [20] and 20.3% of global primary energy consumption [21]. Due to the fact that Chinese cities contribute three quarters of national GDP and account for 84% of national commercial energy use [5], to undertake quantitative analysis on GHG emissions from Chinese cities is necessary. Practically, China's regional "low-carbon development" strategy mainly targeted in cities. For example, several cities have already initiated their low-carbon development plans, such as Baoding, Shanghai, Guiyang, Hangzhou, Wuxi, Jilin, Zhuhai, Nanchang and Xiamen [22]. National Reform and Development Commission (NDRC, a ministry leveled agency responsible for national economy planning) initiated national low-carbon demonstration projects in August 2010, in which eight cities were chosen as pilot cities, including Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Guiyang and Baoding. Academically, studies on energy use and GHG emissions in Chinese cities increased quickly, such as Shanghai [23], Shenyang [24], Nanjing [25], Suzhou [10,26,27], etc. Both "top-down" and bottom-up" approaches have been applied and most of the GHG emissions were calculated based on the IPCC method for national GHG inventory [28]. For example, Dhakal estimated energy consumption and CO_2 emission in 35 cities and analyzed historical changes in Beijing, Tianjin, Shanghai and Chongqing by using a "top-down" approach [5]. Xi et al. [24] and Bi et al. [25] developed a bottom up accounting approach with sectoral detailed GHG emissions. These studies created opportunities for global comparison, but a comparison study among different cities from both spatial and temporal perspectives is still missing, especially between different emission scopes.

Hence, this study fills such a gap by employing a case study approach. Four mega-cities, including Beijing, Tianjin, Shanghai and Chongqing, were chosen due to their prominent positions and data availability. Also, these four cities are key targets for implementing China's national policy on "energy saving and emission reduction". The main objective of this paper is to identify the key driving forces on CO_2 emissions in Chinese mega-cities through a spatial-temporal analysis so that policy implications can facilitate decision-makers to prepare appropriate policies on responding anthropogenic climate changes. To achieve our research targets, we first elaborate our methodology, including a brief introduction on four cities, data collection, as well as detailed computation process. We then have a deep analysis on research outcomes and raise our proposals for policy development. We finally make our conclusions.

2. Methodology

2.1. Research areas

Beijing, Tianjin, Shanghai and Chongqing are four municipal cities directly accountable to the central government (politically equal to one province) in China. The definition of the total population of these four cities are 70 million, about 1% of world population, and their total GDP counts for 10% of the whole country in 2009 [29]. Beijing is the capital of China which locates in the northern part of the North China Plain. It covers 16, 410 km^2 area and has a population of 17.6 million and a gross domestic product (GDP) of 1, 215 billion Yuan (RMB) in 2009 (1 USD equals to 6.83 RMB in 2009). Tianjin is east to Beijing, approximately 160 km from Beijing. It covers an area of 11, 917 km^2, with a population of 12.3 million and a GDP of 721 billion Yuan in 2009. Shanghai is an economic center located in Yangtze delta area, with an area of 6340 km^2, a population of 19.2 million and a GDP of 1, 505 billion Yuan in 2009. Chongqing is located along the upper reaches of the Yangtze River, straddling the region that connects the central and western parts of China. It covers an area of 82, 400 km^2 and has a population of 28.6 million and a GDP of 653 billion in 2009. Table 1 lists some basic characteristics of these four cities.

2.2. Direct emission calculation

Cities often involve intensive exchanges of energy and products with their surrounding environment through urban metabolism [9,10]. Inventorying GHG emissions of cities requires a clearly defined boundary to ensure that the results are comparable. In this study boundary definition is based upon ICLEI measure [13]. Scope 1 emissions include all direct GHGs emissions within the terrestrial boundary, such as emissions from fossil fuel combustion; waste;

Table 1
General information of Beijing, Tianjin, Shanghai and Chongqing.

City	Population (million)	GDP (billion Yuan)	Area (km^2)	Urbanization level (%)
Beijing	17.6	1215.3	16,410.5	78.2
Tianjin	12.3	721.2	11,917.3	60.9
Shanghai	19.2	1504.7	6340.5	88.3
Chongqing	28.6	653.0	82,402.9	30.0

Data Source: NBSC 2010 [30].

Table 2
GHG emission factors of various energy types.

	Oxidation rate (%)	Net calorific value (10^{12}J/10^3 ton)	CO_2 emission factor (ton CO_2/10^{12}J)	CH_4 emission factor (ton/10^{15}J)	N_2O emission factor (ton/10^{15}J)	GHG emission (ton CO_2e/ton)
Raw Coal	100	20.91	94.60	1.00	1.50	1.99
Cleaned Coal	100	26.34	98.30	1.00	1.50	2.60
Washed Coal	100	8.36	97.90	1.00	1.50	0.82
Briquettes	100	26.34	97.90	1.00	1.50	2.59
Coke	100	28.44	107.07	1.00	1.50	3.06
Coke Oven Gas	100	17.35[a]	44.37	1.00	0.10	7.71[b]
Other Gas	100	17.35[a]	44.37	1.00	0.10	7.71[b]
Crude Oil	100	41.82	73.33	3.00	0.60	3.08
Gasoline	100	43.07	69.30	3.00	0.60	3.00
Kerosene	100	43.07	71.87	3.00	0.60	3.11
Diesel	100	42.65	74.07	3.00	0.60	3.17
Fuel Oil	100	41.82	77.73	3.00	0.60	3.26
LPG	100	50.18	63.07	1.00	0.10	3.17
Refinery Gas	100	46.06	66.73	1.00	0.10	3.08
Natural Gas	100	38.93[a]	56.10	1.00	0.10	21.86[b]

[a] The unit is 10^3 J/m^3.
[b] The unit is ton- CO_2e/10^4 m^3.
Data Source: IPCC [28], NBSC [30].

industrial processes, and product use; and agriculture, forestry and other land use (AFOLU), which are determined as per IPCC guidelines. Scope 2 emissions include out-of-boundary emissions due to electricity used in cities [8]; Scope 3 emissions include all the embodied emissions associated with producing the food and materials consumed in cities, and emissions that are upstream of electric power plants. Due to data limitations, we only consider energy-related GHG emissions from scope 1 and scope 2.

The direct energy-related GHG emissions (scope 1) can be estimated based upon IPCC national GHG inventory guidelines [28]. The global warming potential of GHGs attributable to cities, including carbon dioxide, methane, nitrous oxide and several other gases, is expressed in terms of carbon dioxide equivalents, CO_2e. In this study, in order to keep in line with China national GHG inventory,[1] we only consider three kinds of GHG emissions, namely CO_2, CH_4 and N_2O [28]. The global warming potential (GWP) parameters of CO_2, CH4 and N_2O are 1, 21 and 310, respectively. The total energy-related CO_2 emissions within a city's boundary are estimated based upon energy consumption, carbon emission factors (EF) and the fraction of oxidized carbon by fuels as follows:

$$E_{CO_2} = \sum_i \sum_j C_{ij} EF_i O_j M \tag{1}$$

where E_{CO_2} represents the direct CO_2 emission (in tons, t), subscript i represents energy consumption sectors, subscript j represents the type of energy fuels, C_{ij} is the energy consumption (TJ) of fuel type j from i sector, EF_j is the carbon EF of the type j fuel (t C/TJ), O_j is the oxidation rate of fuel type j, and M is the molecular weight ratio of carbon dioxide to carbon (44/12). The CH_4 and N_2O emissions can be estimated based upon similar equations by adopting their own emission factors. Emission factors of CO_2, CH_4 and N_2O are presented in (Table 2).

Data source for this study comes from *Chinese Energy Statistics Year Book* [30], where 15 fuel types are considered for computation, including Raw Coal, Cleaned Coal, Washed Coal, Briquettes, Coke, Coke Oven Gas, Other Gas, Gasoline, Kerosene, Diesel, Crude Oil, Fuel Oil, Liquefied Petroleum Gas (LPG), Refinery Gas and Natural Gas. Our computation does not consider the consumption of other petroleum products and other coking products because there is no energy consumption related with the consumption of these two kinds of fuels.

There are 11 kinds of energy consumption sectors for four megacities, comprising "Thermal Power", "Heating Supply", "Agriculture", "Industry", "Construction", "Transportation", "Commercial Industry", "Urban Residential Consumption", "Rural Residential Consumption", "Other Consumption" and the emissions from cross-boundary electricity. The "Agriculture" sector includes energy consumption from farming, forestry, animal husbandry, fishery and water conservancy; Energy consumption from "Industry" sector excludes the emission from combustion for industrial energy supply; Energy consumption from "Transportation" sector includes the energy use for transport, storage, postal and telecommunication. Transport energy use include the energy consumed by domestic airplanes/ships refueling out-of-boundary, but exclude the oversea airplanes/ships refueling in boundary; Energy consumption from "Commercial Industry" includes energy use of wholesale, retail trade and catering service; All these definitions are based upon *Chinese Energy Statistics Year Book* [30]. GHG emissions from each sector are calculated and presented in CO_2 equivalent (in tons).

2.3. *Emission from cross-boundary electricity*

The per unit GHG emission from electricity generation is determined by the energy mix for electricity generation. Due to different technology level and energy mix in different years, emission factors (EFs) of electricity generation will vary significantly over time. Besides, four cities' electricity supply comes from different state grids. The electricity supply of Beijing and Tianjin is from North China Grid. The electricity supply of Shanghai is from East China Grid. The electricity supply of Chongqing is from South China Grid. In this study, we calculate the total GHG emissions from each state grid. The EFs of electricity for each grid are calculated by using the following equation:

$$EF_e = \sum_k E_k / G_k \tag{2}$$

where EF_e represents the EF of electricity for state gird, k is the province which the state grid served. E_k is the total GHG emission from k province calculated by Equation (1). G_k is the total electricity supply from k province, which contains the electricity from power plant, renewable energy and unclear power sources. The emission

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[1] The People's Republic of China Initial National Communication on Climate Change, see also "http://unfccc.int/resource/docs/natc/chnnc1e.pdf".

factors of state grid electricity are calculated by adopting data from *Chinese Electricity Statistics Year book* [31], and presented in Table 3.

2.4. Index decomposition analysis

To quantify the effects of different factors shaping the trajectories of energy consumption and CO_2 emission, decomposition analysis (e.g. structural decomposition analysis "SDA" and index decomposition analysis "IDA") have been widely applied due to its adaptability and simplicity [32,33]. SDA model has advantages in analyzing detailed industrial sectoral emissions but requires the complete input–output table, which is a big challenge at a city scale and mainly used for national implementation [34,35]. IDA uses index number concept in decomposition analysis and has advantages for temporal analysis. There are several types of IDA, mainly grouped by Laspeyres index decomposition analysis and Divisia index decomposition analysis. Ang et al., reviewed various index decomposition analysis methods, compared their advantages and disadvantages and recommended the logarithmic mean Divisa index (LMDI) method, due to its sound theoretical foundation, adaptability, ease of use and ease of result interpretation [36,37], especially when the zero-value problem was solved [38]. Recently, abundant studies addressed such kinds of decomposing methods for analyzing driving factors of energy use and GHG emission increment at national level [23,39–42].

In this study, the driving factors of GHG emissions at city level are explored by using LMDI method. LMDI method can be applied in a period-wise (also called no-chaining method) or time-series (chaining method) manner. Most of previous studies use period-wise manner, comparing indices between the first and the last year of a given period. However, the results of a period-wise decomposition are sensitive to the choice of baseline year and final year and are often unable to show how the effects of the decomposed factors have evolved over the studied period. Hence, a time-series LMDI is employed to express a comprehensive analysis in this study.

Driving factors for the evolution of GHG emissions through time line can be grouped as three explanatory factors: overall industrial activity (Activity Effect), activity mix (Structure Effect) and sectoral GHG intensity (Intensity Effect). The index decomposition of GHG emissions is presented by:

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i I_i \tag{3}$$

E is the total GHG emissions from industrial sectors, Q is the total GDP from all sectors, and S_i and I_i are the GDP share and GHG intensity of sector i, respectively. Contributors of driving factors from baseline year to final year can be expressed as:

Additive form

$$\Delta E_t = E^t - E^0 = \Delta E_{\text{act}} + \Delta E_{\text{str}} + \Delta E_{\text{int}} \tag{4}$$

Multiplicative form

$$D_t = E^t / E^0 = D_{\text{act}} D_{\text{str}} D_{\text{int}} \tag{5}$$

The subscripts act, str and int denote the factors of activity effect, structure effect and intensity effect, respectively. E^0 is the GHG emission from baseline year and E^t is the GHG emission from final year. Detail of the calculation process is based on the guideline proposed by Ang [43]. In this study, by developing the time-series manner, E^0 from 1995 to 2008 and E^t from 1996 to 2009 are considered with one year step. Where activity effect is indicated by associated GDP for each sector, structure effect is indicated by sectoral share and intensity effect is indicated by sectoral GHG intensity. The city's aggregate GDP is divided into 4 sectors: Agriculture, Industry, Construction and Commercial Industry. Thus, GHG emissions from 10 kinds of energy consumption sectors mentioned above need to map into these four sectors, in accordance with the principle of national economic statistics [29]. Here we combine "Heating Supply", "Thermal Power", and "Industry" as the new "Industry" sector, and combine "Transportation", "Commercial Industry", and "Other Consumption" as the new "Commercial Industry" sector, while keeping "Agriculture" sector and "Construction" sector unchanged. "Urban Residential Consumption" sector and "Rural Residential Consumption" sector have no corresponding GDP, therefore, not being considered in LMDI decomposition, as well as the cross-boundary electricity. GHG emissions from these three sectors are listed separately. In order to consider the inflation effect, the values of annual GDP are changed into comparable values of year 1995.

Table 3
GHG emission factors on power generation from 1995 to 2009.

Year	Emission factor of North China grid (ton $CO_2e/10^4$ KMh)	Emission factor of East China grid (ton $CO_2e/10^4$ KMh)	Emission factor of central China grid (ton $CO_2e/10^4$ KMh)
1995	10.80	9.05	8.22
1996	11.08	9.44	8.21
1997	10.31	8.86	7.86
1998	10.04	8.55	7.49
1999	9.78	8.54	6.93
2000	8.87	8.35	6.82
2001	9.20	8.30	7.01
2002	9.41	8.08	7.06
2003	9.97	8.20	7.57
2004	10.44	8.31	7.92
2005	10.58	8.23	7.31
2006	10.14	8.09	7.33
2007	9.89	7.86	7.25
2008	10.20	7.68	6.49
2009	9.73	7.55	6.16

Data Source: authors' calculation based on Equation (2).

3. Results

3.1. GHG emission features and trajectories

All the four cities have rapid growth of GHG emissions from 1995 to 2009 (for Chongqing from 1997 to 2009 due to data available), in which Beijing increased from 81 million tons of CO_2e in 1995 to 155 million tons of CO_2e in 2009, Tianjin increased from 65 million tons of CO_2e in 1995 to 176 million tons of CO_2e in 2009, Shanghai increased from 100 million tons of CO_2e in 1995 to 218 million tons of CO_2e in 2009, Chongqing increased from 58 million tons of CO_2e in 1997 to 144 million tons of CO_2e in 2009, respectively. In total, four big cities emitted approximate 700 million tons of CO_2e in 2009 and contribute to about 2% of global anthropogenic GHG emissions.

Fig. 1 shows the proportion of GHG emissions from different sectors in four cities between 1995 and 2009. Clearly industrial energy consumption and energy use for thermal power plant (including territorial consumption and upstream consumption) are two main sources for GHG emissions, followed by transportation sector, heating supply energy use sector and other sectors.

In particular, emission from cross-boundary electricity contributes significantly to the total amount of GHG emissions and shows a considerable increase both in Beijing and Shanghai. The proportion of this cross-boundary emission in Beijing increased from 17% in 1995 to 32% in 2009, accounting for 50 million tons of CO_2e in 2009. Shanghai had no input cross-boundary emissions in 1995 and then had 13% of cross-boundary emission proportion in 2009, accounting for 28 million tons of CO_2e in 2009. The fractions of

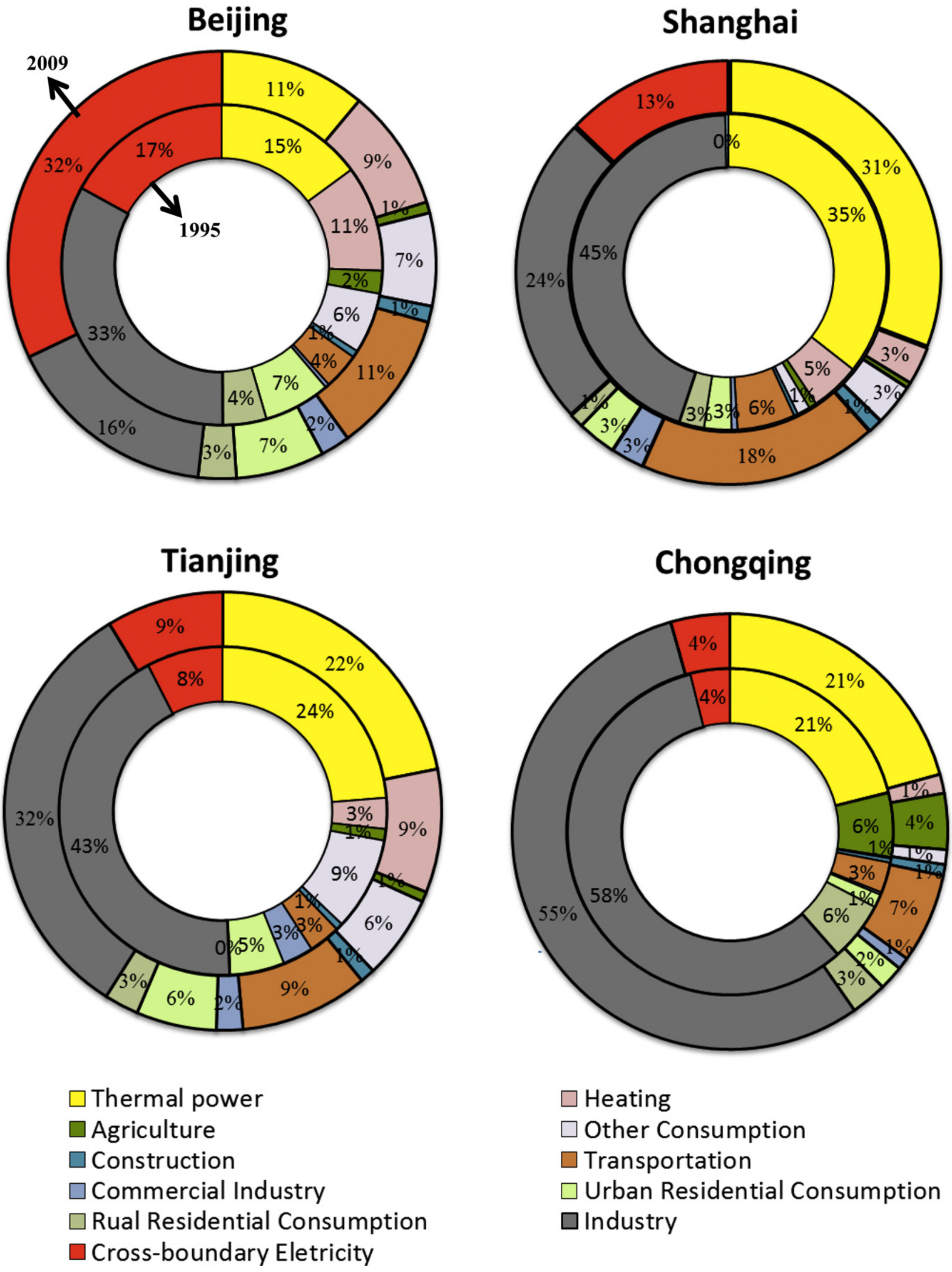

Fig. 1. GHG emission from different sectors, inner: year 1995 (Chongqing 1997); external: year 2009.

cross-boundary emissions both in Tianjin and Chongqing in 2009 are relatively small, namely, 9% (15 million tons of CO_2e) in Tianjin and 4% (6 million tons of CO_2e) in Chongqing. The proportion of emissions from heating supply sectors is influenced by the city's geographical positions. Due to China's vast territory and differentiated climatic zones, cities in north China usually have more energy consumption for winter's heating. According to Chinese energy management policies, cities north to Yangtze river (such as Beijing and Tianjin) are allowed to provide public heating services in winter, while cities south to Yangtze (such as Shanghai and Chongqing) are not allowed [44]. Consequently, the proportions of emissions from heat supply both in Beijing (9%) and Tianjin (9%) are higher than those in Shanghai (3%) and Chongqing (1%). The proposition of residential consumption sector in all four cities is also small because the IPCC accounting methods focus on primary energy use, and the direct use of primary energy from residents is much less. Another feature is that GHG emission from transportation sector in four cities had a sharp increase. Such figures increased from 4% in 1995 to 32% in 2009 in Beijing, increased from 1% in 1995 to 9% in 2009 in Tianjin, increased from 6% in 1995 to 18% in 2009 in Shanghai, and increased from 3% in 1997 to 7% in 2009 in Chongqing.

Fig. 2 shows the trajectories of GHG emissions from four cities. All the four cities present relatively constant GHG emissions during the period of 1997–2003, and then sharply increased since 2004. Among all the emission sectors, industrial sector, thermal power and cross-boundary electricity are main contributors to fast growth of GHG emissions in four cities, but with different mix. Rapid growth of GHG emissions in Tianjin and Chongqing is mainly caused by increases in industrial sector and thermal power sector, as the GHG emissions (CO_2e) from industrial sector increased from 28 million tons in 1995 to 57 million tons in 2009 in Tianjin and increased from 34 million tons in 1997 to 80 million tons in 2009 in Chongqing. Such an industrial GHG emission growth in Shanghai is not dramatic, namely, from 45 million tons in 1995 to 52 million tons in 2009 due to their industrial change (from manufacturing-oriented to service-oriented). With respect to Beijing, GHG emissions (CO_2e) from industrial sector in 1995–2009 decreased from 27 million tons in 1995 to 25 million tons in 2009 mainly due to their industrial relocation actions (relocating polluting and energy-intensive industries outside Beijing). All the four cities expressed increasing trends in "Heating" and "Thermal Power" sectors during 1997–2007. Importantly, the cross-boundary electricity use has a dynamic effect on the emission trajectories. Without accounting for the emission from cross-boundary electricity use, Beijing and Shanghai present a constant or even decrease trend of total GHG emission in 2007–2009.

3.2. *Driving forces of the GHG emission changes in four mega-cities*

Driving forces of GHG emission changes in four mega-cities are uncovered by adopting a time serial LMDI decomposition method. Results are presented by additive form and expressed in Fig. 3. It should be noticed that the decomposing analysis only involved those sectors which have associated GDP, so here we do not consider those emissions from cross-boundary electricity uses and emissions from residential energy consumption.

Results show that activity effect (ΔE_{act}) is the main driver for GHG emission changes in these four cities, followed by intensity effect (ΔE_{int}) and structure effect (ΔE_{str}). Particularly, economic activity effect keeps positive and pushes up the growth of emissions in all cities during 1995–2009. Besides, intensity effect plays an important role for offsetting total emission increments in all four cities. There is a decreasing trend of GHG emissions in Beijing and Shanghai since 2004, which is caused by both intensity effect and structure effect, implying not only the efficiency improvements but also an economic transition into less energy-intensity pattern during 2004–2009. The structure changes had limited impact on the total emission trends, especially in Chongqing. There was a proportional increase in economic activity effect and decrease in intensity effect in Chongqing during 1997–2009, implying that the decrease of intensity might mainly be caused by "marginal utility" of economic growth.

4. Discussions

All four cities together discharge about 700 million tons of CO_2e per year, more than the total emission amount of United Kingdom [45]. In addition, all the four cities still present growth trends, despite the scope 1 emissions decreased in Beijing and Shanghai since 2004. From per capita point of view, the per capita GHG emissions in Tianjin, Shanghai and Beijing are amongst at the average international level [7,25], while such a figure in Chongqing (5.1 tons of CO_2e per capita) is still low, indicating a potential increasing emission due to their further urbanization initiatives and improvements of citizens' living standards.

Urbanization is considered as one of the main drivers for accelerating economic growth and related GHG emissions in China. The process of industrialization and urbanization will continue for decades, implying a great challenge for Chinese cities respond climate change. From our observation, four cities present different emission perspectives. Both Beijing and Shanghai have relatively higher level of urbanization (78% and 88% in 2009, respectively) and higher fractions of GHG emissions from cross-boundary electricity and transportation sectors, but less fractions of GHG emissions from industrial sectors, indicating that these two cities are moving toward more service-oriented industrial structure and phasing out their polluting and energy-intensive industries; while both Tianjin and Chongqing have relatively lower urbanization level (60.9% and 30% in 2009 respectively) and their economic development heavily rely on manufacturing industries. Especially, more than half of the GHG emission in Chongqing is from industrial energy use. This reflects a trend that more developed cities are more dependent on trades and imported products and therefore have more embodied CO_2 emissions, while developing cities are more dependent on providing various products to other regions and therefore have less embodied CO_2 emissions. Hence, policies for energy conservation and emission in different cities should be based upon their own industrial structures and development stages.

Generally, the above analysis provides a solid foundation for preparing appropriate mitigation policies in different cities. Cities like Chongqing and Tianjin whose economy is of heavy reliance on manufacturing industries show a fast growth of GHG emissions from industrial sectors and local thermal power plants. Thus, GHG emission mitigation actions and policies need to be addressed from industrial production perspective, such as application of cleaner production technologies, industrial symbiosis (namely byproducts exchange and energy/water cascading among different companies) and energy efficiency programs in local thermal power plants; while cities like Beijing and Shanghai are moving toward more service-oriented industrial structure, with a decreasing proportion of GHG emissions from industrial sectors and an increasing dependence on electricity from upstream power plants, thus, policies that address sustainable consumption, energy conservation and efficiency improvement need to be released by considering local realities. Moreover, a common feature in all the four cities is that the GHG emissions in transportation sector present a fast growth picture due to the fact that more Chinese urban families purchased their home vehicles in the last decade. Therefore,

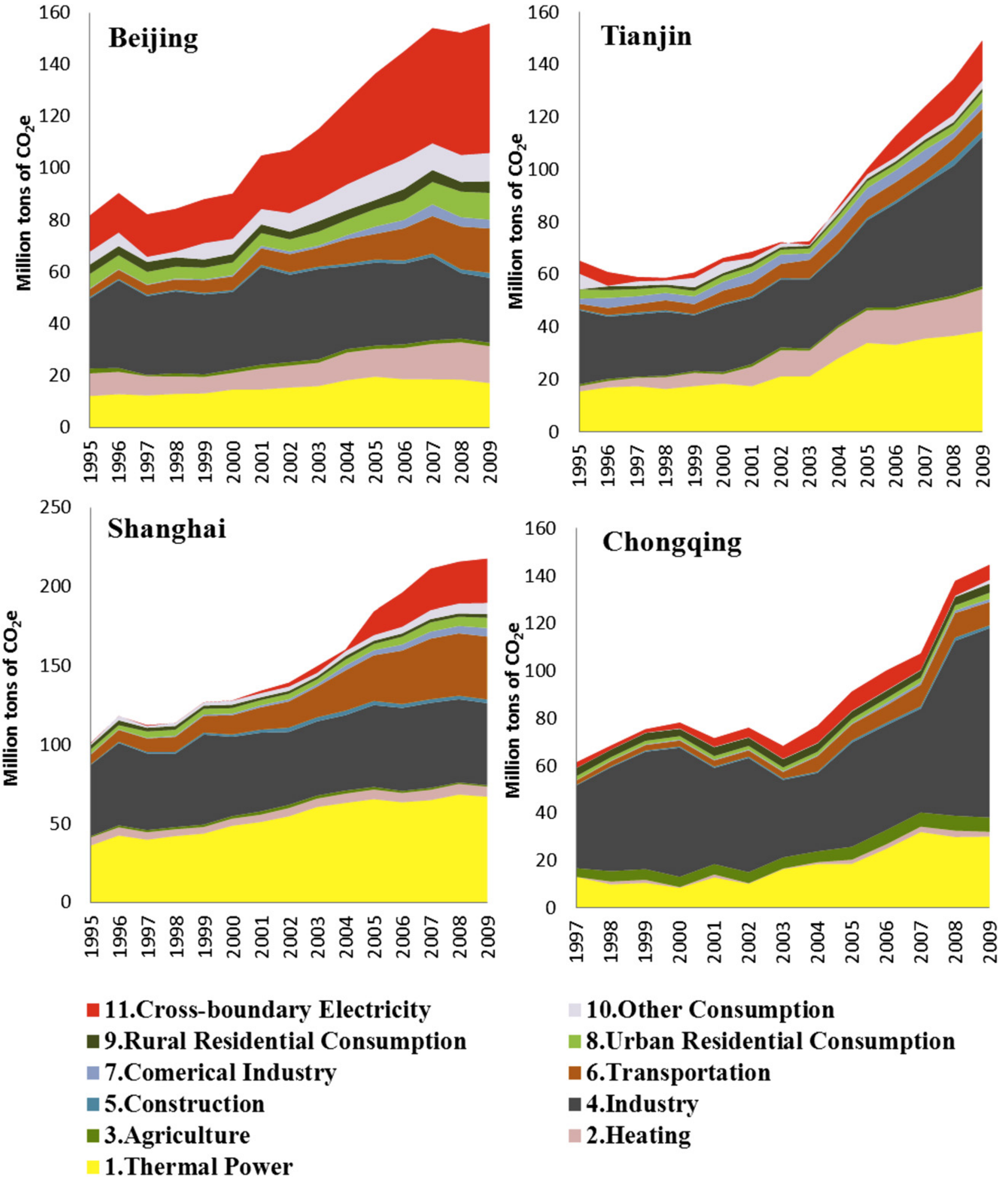

Fig. 2. Trajectory of GHG emission from Beijing, Tianjin, Shanghai and Chongqing (1995–2009).

corresponding policies for transportation energy conservation, such as tax and regulation preferences for low-emission vehicles and public transportation, should be integrated with China's city development plan.

Given the critical role of cross-boundary emissions from imported electricity use, it is important to have a clear boundary definition for city's GHG inventory. Previous studies explained that the decease of direct GHG emissions in Beijing is due to the outcomes of energy conservation policy implementation [46]. But our analysis indicates that such a decrease is mainly due to the shift of direct emissions to cross-boundary emissions and a phase-out of polluting and energy-intensive industries. Therefore, a life cycle perspective can provide a comprehensive picture on each city's GHG emission so as to clarify the key reduction responsibilities for different stakeholders. Otherwise, an incomplete analysis may result in misunderstandings on allocating such responsibilities.

Driving factors for annual ups and downs of GHG emissions are uncovered through LMDI analysis. Different from generally

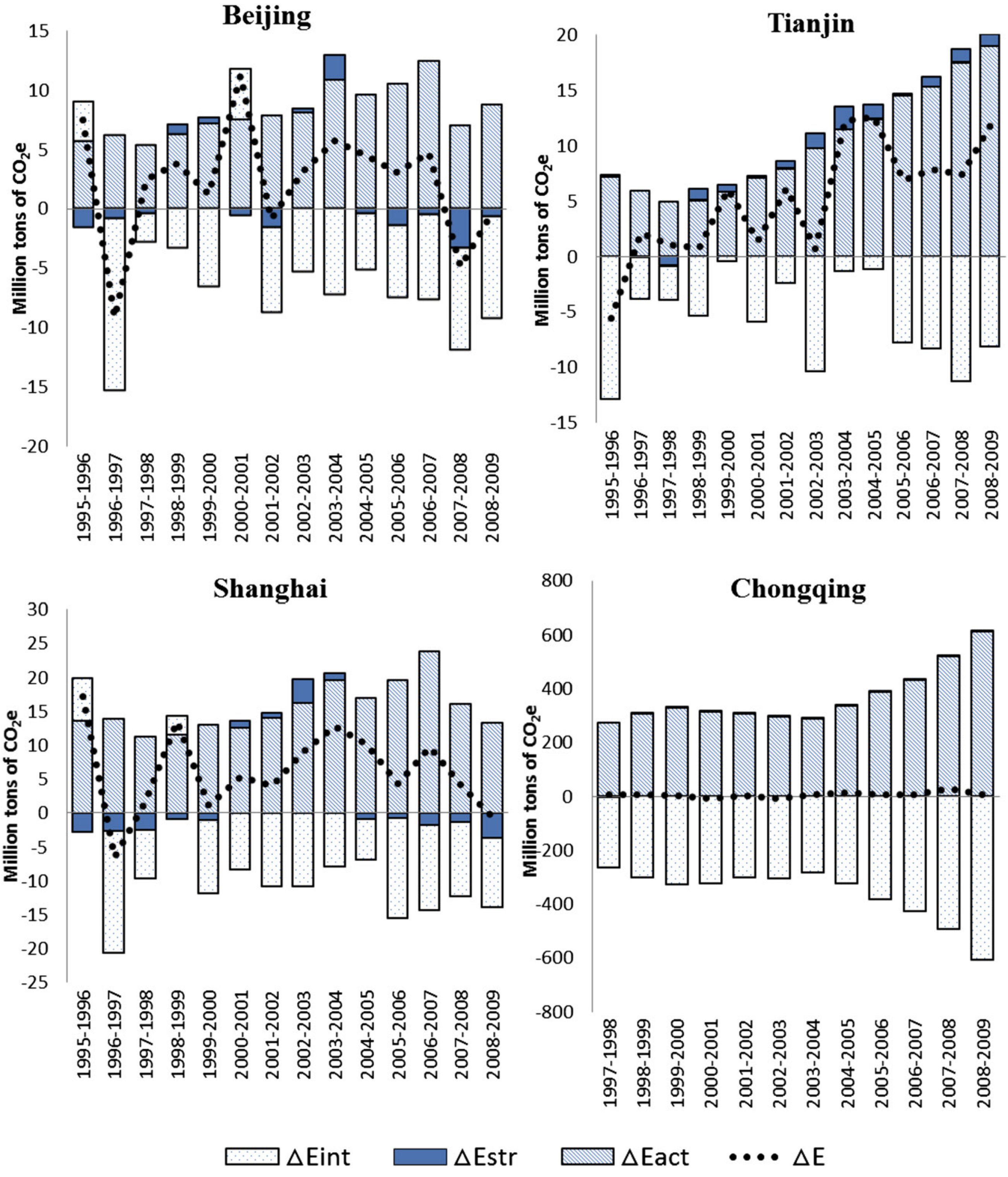

Fig. 3. Driving forces for GHG emissions increment in Beijing, Tianjin, Shanghai and Chongqing (1995–2009).

period-wise approach of LMDI decomposing analysis, the use of time serial approach reveals the historical change of various drivers. Time serial LMDI approach indicates that decrease of energy efficiency can actually increase the total GHG emission, such as GHG emissions in the year 1995–1996 and the year 2000–2001 in Beijing, GHG emissions in the year 1995–1996 and the year 1997–1998 in Shanghai. With the continuous economic growth and the dominance of economic activity effect, the special role of energy efficiency partially explains why national strategy should focus on energy-intensity improvements. Time serial LMDI also illustrates that the proportional relationship of economic activity effect and intensity effect might cause by "marginal utility" of economic growth. Given the advantage for analyzing the details of GHG emission changes based on time serial LMDI approach, this method is strongly recommended in the future studies.

5. Conclusions

With China's rapid urbanization and industrialization, GHG emissions in Chinese cities deserve a special attention, especially in those big cities where various industries locate and a great amount of energy and materials is being consumed. In this paper we present GHG emission features, trajectories and driving forces for growth trends in Beijing, Tianjin, Shanghai and Chongqing for the period of 1995–2009. A top-down GHG inventory including both direct emissions (scope 1) and the imported electricity emission (scope 2) is presented. Our main focus is to explore the contributors of GHG emissions from economic activity effect, industrial structure effect and intensity effect by using time serial LMDI decomposition analysis. Our research outcomes indicate that:

(1) China's four mega-cities experienced a rapid growth of GHG emission during 1995–2009. The total amount of each city had been approximately doubled during this period. With different urbanization level, industrial structure as well as different development stages, however, these four cities presented different GHG emission scenarios. Among all the sectors, energy use of industrial sectors and thermal power are the main sources for GHG emissions growth in all four cities, which is in line with national industrialization and urbanization process.

(2) The indirect GHG emissions from imported electricity use (scope 2 emissions) play a significant role in the evolution of the GHG emissions during 1995–2009. Beijing and Shanghai reversed their growth trends of GHG emissions when considering the indirect GHG emissions from imported electricity use since 2004. Besides, the proportion of GHG emissions from cross-boundary electricity keeps growing with city's development. It implies that with city's further development and industrial structure changes (such as more dependence on service-oriented industries), cross-boundary activities will further strengthen, and such cities will further rely on products, energy supply, and material supply from other regions.

(3) The growth of GHG emissions in four mega-cities during 1995–2009 is mainly due to economic activity effect, partially offset by improvement in carbon intensity. Structure effect shows uncertainties in shaping city's GHG emissions. For instance, with relatively higher urbanization and development levels, Beijing and Shanghai are transiting their economic structure into less energy-intensive pattern, namely, service-oriented industrial structure, while Tianjin and Chongqing still heavily rely on energy-intensive manufacturing industry and coal-burning thermal power plants, hence, different GHG emission patterns presented. Our case study outcomes indicate that different Chinese cities need different mitigation policies. A comprehensive analysis by considering life cycle perspectives of urban metabolism can help provide a more comprehensive picture to those decision-makers so that appropriate mitigation policies can be prepared by considering the local realities.

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