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A dual strategy for controlling energy consumption and air pollution in China's metropolis of Beijing

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ABSTRACT

It is critical to alleviate problems of energy and air pollutants emissions in the metropolis because these areas serve as economic engines and have large and dense populations. Drivers of fossil fuel use and air pollutants emissions were analyzed in metropolis of Beijing during 1997–2010. The analyses were conducted from both a bottom-up and a top-down perspective based on the sectoral inventories and structural decomposition analysis (SDA). From a bottom-up perspective, the key energy-intensive industrial sectors directly caused the variations in Beijing's air pollution by means of a series of energy and economic policies. From a top-down perspective, variations in production structures caused increases in most materials during 2000–2010, but there were decreases in PM_{10} and $PM_{2.5}$ emissions during 2005–2010. Population growth was found to be the largest driver of energy consumption and air pollutants emissions during 1997–2010. This finding suggests that avoiding rapid population growth in Beijing could simultaneously control energy consumptions and air pollutants emissions. Mitigation policies should consider not only the key industrial sectors but also socioeconomic drivers to co-reduce energy consumption and air pollutions in China's metropolis.

1. Introduction

More than half of the world's population has lived in cities since 2007 [1]. Cities have become the main sink of resources, energy, and the main source of environmental pollution [2–6]. The impact of cities on energy use and associated air pollutions is now increasing, even worse in developing countries because of their rapid urbanization and industrialization [6].

China has already become the second-largest economy and energy consumer in the world after the United States [7]. Along with the booming economy driven by massive industrialization and urbanization, fifty-three percent of China's population lived in cities in 2010 [1], and this rate will grow to 60% (or approximately 900 million urban inhabitants) by 2020 according to China's New Urbanization Plan [8]. Huge urban migrations, expansion of existing cities, and the emergence of new cities during this process of China's urbanization could cause complicated environmental burdens. For example, cities have not only account for the major share (over 80%) of the national total energy consumption and CO_2 emissions [9,10], but also have deleterious health impacts because of increasing air pollution problems [11,12].

In response to these multifaceted environmental challenges, some scholars have proposed the idea of simultaneous beneficial measures ("co-benefits") to mitigate these multiple environmental impacts. The Intergovernmental Panel on Climate Change (IPCC) and the Ministry of the Environment of Japan (MOEJ) have defined co-benefits as a process that could control both greenhouse gasses (GHGs) and other local air pollutants emissions (e.g., CO_2, SO, NO_x, and etc.) simultaneously, and would provide potentially significant savings in abatement costs [13,14]. In particular, because anthropogenic GHGs and air pollutants emissions originate mainly from

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fossil fuel consumptions, there are opportunities to reduce energy consumption and air pollutants emissions simultaneously [15,16].

Most previous studies have explored these co-benefits from a bottom-up perspective. They suggested that advanced technologies should be applied to reduce various air pollutants emissions in the high energy-intensive industrial sectors (e.g., the metals sectors [17]). However, several studies [18] have indicated the possibility of controlling some socioeconomic drivers of energy consumption and the relevant emissions to achieve the co-benefits. This type of analysis is from a top-down perspective, which could be more comprehensive in general.

The techniques that are available for identifying the socioeconomic factors that drive GHGs and air pollutants emissions include index decomposition analysis (IDA) and structural decomposition analysis (SDA). Both techniques have been applied widely for assessing the socioeconomic driving forces for energy consumption and CO_2 emissions at national and regional levels [7,18–23], but they have rarely been to analyze the co-control or co-benefit issues. Comparing to IDA, SDA can capture both direct and indirect environmental impacts depending on input-output (IO) models, and decompose out drivers that uncover more details of an economic structure, such as production structure and final demand structure. We therefore applied the SDA method in this study to analyze the socioeconomic drivers of fossil fuel use and air pollutants emissions and to analyze the co-benefits of mitigating environmental pressures in an urban setting.

Beijing is seen as a special case because it is China's capital and one of the world's largest cities and because of its unique economic status and its serious air pollution. Beijing's per capita GDP (Gross Domestic Product) reached 11,200 U.S. dollars by 2010, and the tertiary industry contribution to the GDP reached 74% by 2010 [24]. These are almost equivalent to comparable values for an entire mid-ranked developed country. Environmental challenges, such as air pollution and climate change, have been recognized as being serious in Beijing over the past two decades, during which time rapid economic development and urbanization have occurred in the city [25]. For example, there was a particularly intense debate among experts, media, and publics in Beijing in December 2011 that focused on $PM_{2.5}$. The debate was triggered by the high frequency of dust storms, and smog, fog, and haze events that occurred in the northern part of China [26].

In the present study, we examined Beijing's fossil fuel use and air pollutants emissions during the period of 1997–2010 to measure the contributions of various drivers from both a sectoral perspective (a bottom-up perspective) and a socioeconomic perspective (a top-down perspective). We focused on the use of coal, fossil oil, and natural gas and the emission of SO_2, NO_x, PM_{10}, $PM_{2.5}$, and CO_2. Section 2 introduces the methods and data, and Section 3 presents the results. A discussion of the results and policy implications is presented in Section 4, and conclusions are presented in Section 5.

2. Methods and data

2.1. Methods

SDA quantifies the drivers of economic structural changes, using a varying set of key parameters in IO tables (IOTs) with a temporal dimension [19,27–31]. SDA has broad applications for examining the socioeconomic drivers of an economic system's environmental impacts, such as its CO_2 emissions and water consumption [10,31–37]. The principal formula of an IO-based SDA can be expressed as:

$$E = F(I - A)^{-1}Y = FLY = p_d PFLy_{ss}y_{ds} \tag{1}$$

Environmental impacts E can be decomposed into six drivers: per capita final demand (p_d [a constant value]), population (P [a constant value]), materials intensities (energy consumption or emissions per unit of output) (F [$1 \times n$ vector]), production structures (L [$n \times n$ matrix]), the sectoral structures of final demand types (y_{ss} [$n \times m$ matrix]), and the composition of final demand (final demand structure) (y_{ds} [$m \times 1$ vector]). The types of final demand are rural and urban household consumption, government consumption, capital formation, and domestic and international exports. Here, n is the number of sectors and m is the number of final demand types. The environmental impacts in the time of (t) and $(t-1)$ can be respectively expressed as:

$$E_{(t)} = p_{d(t)}P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} \tag{2}$$

$$E_{(t-1)} = p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}y_{ds(t-1)} \tag{3}$$

Therefore, the changes in environmental impacts (ΔE) from time $(t-1)$ to time (t) can be calculated through equation (4), which could be also decomposed into changes in the component driving forces according to the method of SDA (equation (5)).

$$\begin{aligned}\Delta E = E_{(t)} - E_{(t-1)} = & \, p_{d(t)}P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} \\ & - p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}y_{ds(t-1)}\end{aligned} \tag{4}$$

However, there is a non-uniqueness of the decomposing results of the IO-based SDA model [19,36,38]. If the number of decomposed factors is n, the number of possible decomposition forms is $n!$ [29,38]. In our study, there are $6! = 720$ first-order decompositions. One of the 720 possible decompositions is shown as:

$$\begin{aligned}\Delta E = & \, \Delta p_d P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} + p_{d(t-1)}\Delta PF_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}\Delta FL_{(t)}y_{ss(t)}y_{d(st)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}\Delta Ly_{ss(t)}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}\Delta y_{ss}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}\Delta y_{ds}\end{aligned} \tag{5}$$

Each of the six terms in Eq. (2) represents its contribution to the change in environmental impacts that is triggered by one driving force while keeping the rest of variables constant. For example, the first term, $\Delta p_d P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)}$, represents the changes in environmental impacts that are due to changes in per capita final demand, with all other variables (P, F, L, y_{ss}, and y_{ds}) remaining constant. While many equivalent decomposition forms exist, we use the average of all possible first-order decompositions in this research [29]. The equation (Eq. (A.1)) of the average of all possible first-order decomposition for the first term as an example is shown in Appendix A.

To further analyze the effects of various drivers of energy consumption and air pollutants emissions in Beijing, we divided the period of 1997–2010 into three stages according to China's Five-Year Plans: 1997–2000 (9th Five-Year Plan), 2000–2005 (10th Five-Year Plan), and 2005–2010 (11th Five-Year Plan).

2.2. Data sources

This study mainly requires two types of data. One is time-series IOTs, and the other is the corresponding environmental satellite accounts at the sectoral level, including energy consumption (coal, fossil oil, and natural gas) and air pollutants emissions (CO_2, SO_2, NO_x, PM_{10}, and $PM_{2.5}$).

The IOTs for Beijing in 1997, 2000, 2002, 2005, 2007, and 2010 were obtained from the Municipal Bureau of Statistics of Beijing [39]. The final demands columns that are titled “others” in Beijing's IOTs were removed because these columns present errors from different data sources [18,33,36,40,41]. Focusing on Beijing's supply chains, we removed international and domestic imports from IOTs using the method of Weber et al. [42]. The samples of original IOTs and adjusted IOTs are shown in Appendix B (Tables B.1 and B. 2). These IOTs were all converted into constant prices by the method of price indexes of industrial activities compared with 2000 [24].

The consumption of coal, fossil oil, and natural gas for detailed industrial sectors of Beijing were obtained from Beijing Statistical Yearbooks [24], which were expressed as coal-equivalent consumption from physical units using conversion factors [43]. We adopted CO_2 emissions inventories that had been developed in previous studies for the years 1997–2010 [10,44]. CO_2 emissions come from both the combustion of fossil fuels and the production of cement. The electricity and thermal power that consumed by each sector was removed to avoid double-accounting [44].

SO_2, NO_x, PM_{10}, and $PM_{2.5}$ emission inventories were taken from the Multi-resolution Emission Inventory for China (MEIC [http://www.meicmodel.org]). Here, we only accounted the direct $PM_{2.5}$ emissions from emission sources. The MEIC is a technology-based, bottom-up emissions inventory model that was developed by Tsinghua University and includes emissions estimates for more than 700 emitting source categories [45–47]. Because that the MEIC categories differ from the traditional sectoral categories, which are based on economic activities, we reallocated the emissions to economic sectors (Fig. C.1 in Appendix C).

3. Results

3.1. Variations in fossil fuel consumption and air pollutants emissions

Beijing's fossil fuel use increased from 27.9 Mtce in 1997 to 40.3 Mtce in 2010 which represents an annual growth rate of 8%. However, the amount of coal consumption decreased by 12% during this period, from 21.5 Mtce in 1997 to 19.0 Mtce in 2010, although coal consumption fluctuated during 1997–2005. Additionally, the share of coal in total fossil fuel consumption had declined to less than 50% in 2010. Oil consumption increased continually, from 6.2 Mtce in 1997 to 12.7 Mtce in 2010, when it exceeded 30% of total fossil fuel consumption. Natural gas consumption also increased continually during this period. It increased with a dramatic annual growth rate (nearly 20%) after 2005, and represented 20% of total fossil fuel consumption in 2010 (Table 1 and Fig. C.2). Beside this, other clean energies (e.g., hydropower and wind power) consumptions have also increased slowly. For example, despite a lower proportion to the total electricity supply, the hydropower increased from 318 M kWh in 1995 to 490 M kWh in 2007 [48]. Correspondingly, the constant optimization of energy structures has promoted the mitigation of CO_2 and air pollutants emissions [49].

Table 1
Variations of fossil fuel consumption and air pollutants emissions during 1997–2010.

	Fossil fuel				Air pollutants				
	Coal	Oil	Natural gas	Total	CO_2	SO_2	NO_x	PM_{10}	$PM_{2.5}$
Units	Mtce				Mt	kt			
1997	21.5	6.2	0.1	27.9	58.0	186.3	249.8	205.1	130.9
2000	23.5	5.7	1.0	30.2	79.3	184.9	274.0	202.4	132.3
2002	21.8	6.6	2.1	30.4	69.8	209.7	285.4	170.8	112.7
2005	24.1	7.9	3.5	35.5	82.6	263.1	358.5	170.3	114.5
2007	22.9	10.5	4.7	38.1	84.5	226.9	377.5	136.9	91.6
2010	19.0	12.7	8.6	40.3	78.33	123.0	327.0	105.1	68.9

The amount of CO_2 emissions fluctuated during 1997–2010, but grew by 20.2 Mt during this period. CO_2 emissions decreased during 2000–2002, rebounded during 2002–2007, and declined again during 2007–2010. NO_x emissions increased from 250.0 kt in 1997 to 377.5 kt in 2007, and then declined rapidly at a rate of −5% per year to 327.0 kt in 2010. SO_2 emissions decreased by 63.4 kt between 1997 and 2010, although there was an emission peak of 263.1 kt in 2005. PM_{10} and $PM_{2.5}$ emissions showed similar trends and decreased by 100.0 kt and 62.1 kt, respectively, during 1997–2010 (Table 1 and Fig. C.2).

3.2. Variations in key sectors

The electricity, heating, gas, and water (EHGW) sector has accounted for most of the fossil fuel consumption in Beijing, accounting for 20% (7.4 Mtce) in 1997 and 31% (12.6 Mtce) in 2010. The proportion of total CO_2 emissions that was contributed by EHGW showed a trend that was similar to that for fossil fuel consumption. EHGW contributed 25% (14.5 Mt) of CO_2 emissions in 1997 and 31% (24.1 Mt) in 2010. EHGW was also the largest source of SO_2 emissions because it consumed large amounts of coal (e.g., 47% in 2010 in Beijing (Table B.3)). However, EHGW's share of total SO_2 emissions decreased continually from 52% in 1997 to 35% in 2010 (from 97.2 kt to 43.6 kt, respectively) with the implementation of a series of end-of-pipe control measures (e.g., installation of FGD (flue gas desulfurization) systems at all newly built thermal power units [50]) (Fig. 1). EHGW was the second-largest source of NO_x emissions, with a relatively stable share of approximately 30%. However, the absolute value of NO_x emissions increased from 73.6 kt in 1997 to 110.0 kt in 2010. Similarly, EHGW's average shares of PM_{10} and $PM_{2.5}$ emissions have been approximately 17% during 1997–2010, but their absolute emissions values decreased from 39.1 kt and 24.9 kt in 1997 to 23.9 kt and 16.2 kt in 2010, respectively.

The contribution of the metals sector to total fossil fuel consumption has been decreased steadily from 34% to 0.6% during 1997–2010 because of the removal or transfer of major metal producers from Beijing over the last decade [51]. At the same time, the metal sector's share of Beijing's GDP declined from 5% in 1997 to less than 1% in 2010 (Fig. C.3). All emissions from the metals sector consequently decreased during this period (e.g., from 20.8 Mt to 0.3 Mt of CO_2, and from 21.0 kt to 8.8 kt of $PM_{2.5}$).

Despite their lower share of fossil fuel consumption (an average of 6%), nonmetal minerals, followed by the EHGW and the metals sector, was the main source of PM_{10} and $PM_{2.5}$ emissions. But the contributions of this source to total PM_{10} and $PM_{2.5}$ emissions have been reduced to from 51% (105 kt) and 46% (61 kt), respectively, in 1997 to 30% (32 kt) and 19% (13 kt) in 2010. These reductions were due to a series of PM (Particulate Matter) emission control measures (e.g., fugitive dust control at construction sites and material piles, shutdown of quarry and sand plants, and PM emission control in the building material industry [52]). The contributions to the emissions of other pollutants from the nonmetal minerals sectors were relatively stable and were lower than those of EHGW in Beijing during 1997–2010. For example, the share of total SO_2 emissions of nonmetal minerals sector was approximately 13%, and absolute SO_2 emissions decreased by 7.7 kt.

The contributions of other manufacturing sectors, such as the chemicals sector and the petroleum & coking sector, to total fossil fuel consumption also decreased during 1997–2010, although their

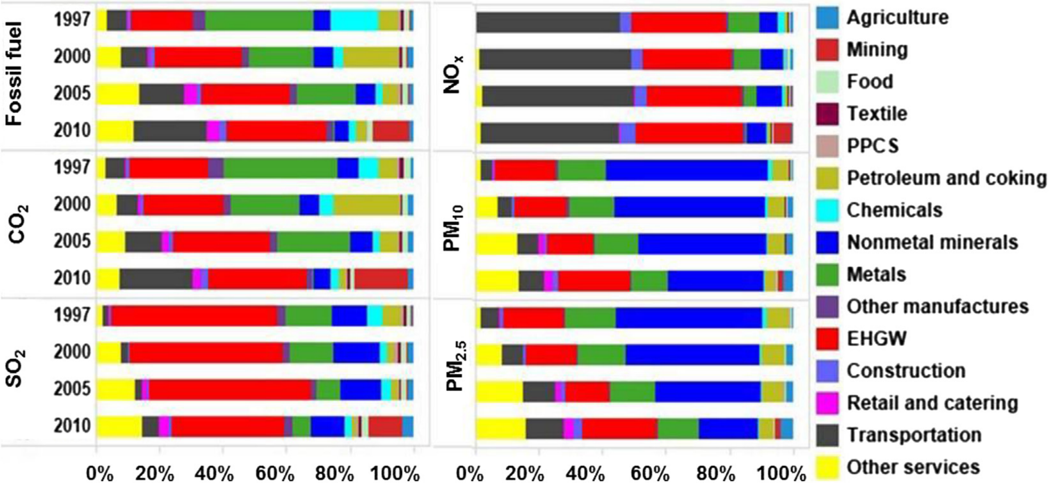

Fig. 1. Sectoral contributions of fossil fuel use and air pollutants emissions from 1997 to 2010. Paper, print, culture, and sports (PPCS), and electricity, heating, gas, and water (EHGW).

proportions were much lower than those of the EHGW and metal sectors. For example, the contribution of the chemicals sector to total fuel consumption fell from 15% to 2%, and that of the petroleum and coking sector fell from 6% to 3% (Fig. 1). Correspondingly, the air pollutants emissions from these sectors also decreased during this period.

There was a dramatic increase in the number of motor vehicles in Beijing during the last decade, which is from 82 vehicles per 1000 residents in 1997 to 245 per thousand in 2010 [24]. Correspondingly, the contribution of transportation to total fossil fuel consumption increased from 6% (1.7 Mt) in 1997 to 23% (9.3 Mt) in 2010. At the same time, the contribution of transportation to total CO$_2$ emissions has increased from 6% (3.7 Mt) in 1997 to 23% (17.8 Mt) in 2010 (Fig. 1). This rate is much higher than the average levels for other Chinese cities [5]. Transportation-related NO$_x$ emissions have increased from 113 kt in 1997 to 141 kt in 2010, and transportation has been the largest contributor to NO$_x$ emissions since 1997 (Fig. 1). However, the share of NO$_x$ from transportation has decreased slightly since 2007 because of a series of traffic control policies that were implemented to ease traffic pressure during the 2008 Beijing Olympic Games. For example, the more rigorous Euro III and IV emissions standards have been fully implemented for the newly registered passenger cars in Beijing since 2005 and 2008, respectively [50]. Travel restrictions (e.g., even-odd car banning system during the Olympic period in Beijing) also reduced air pollution by decreasing average traffic flow and improving driving conditions [53]. The amounts of transportation-related PM$_{10}$ and PM$_{2.5}$ emissions have also decreased, for the same reasons.

Beijing has been shifting from an industry-oriented to a service-oriented economy [10]. Correspondingly, the contributions of other services sectors have increased, and their contributions to SO$_2$, PM$_{10}$, and PM$_{2.5}$ emissions increased as well (Fig. 1).

3.3. *Effects of socioeconomic drivers*

The variation in per capita final demand was positively correlated with the changes in energy consumption and air pollutants emissions caused by this driver (Fig. C.4). According to the per capita final demand effect on all materials during 1997–2000, we normalized the results of absolute effects of socioeconomic drivers on the materials in different periods. The slight decline of per capita final demand offset the increase in fossil fuel use and air pollutants emissions that occurred during 1997–2000. We set the change of per capita final demand as −1 in this period. Since all changes of energy consumption and air pollutants emissions caused by this driver were decreased during this period, we set all these changes as −1 too. Here, the negative sign means decreasing effect on the materials. Correspondingly, the positive sign means increasing effect on all materials. All effects of drivers in different periods get the relative effects value by dividing the effect of per capita final demand during 1997–2000. For example, the rapid growth of per capita final demand caused positive effects during 2000–2005, and the effect range was approximately from 6.2 to 8.2 for fossil fuel use and air pollutants emissions. Similarly, the effect of per capita final demand caused a slight decline for all materials during 2005–2010 (Fig. 2 and Fig. C.5).

Beijing's permanent population increased to 19.6 million in 2010, with the annual growth rate of 3.6% since 1997, and the proportion of floating population increased from 11% to 36% in the same period [24]. These population growths caused increases in energy consumption and air pollutants emissions during 1997–2010. However, the population growth rates were different for different periods between 1997 and 2010. The highest annual growth rate (5%) occurred during 2005–2010. The annual rate was 3% during 1997–2000 and 2% during 2000–2005 (Fig. C.5). Correspondingly, the population effects on all materials were the largest during 2005–2010 (the range is from 6.0 for PM$_{10}$ to 8.4 for NO$_x$), followed by the periods of 2000–2005 (from 3.0 for PM$_{10}$ to 4.1 for NO$_x$) and 1997–2000 (approximately 2.5) (Fig. 2).

The change in production structure, as measured by the Leontief inverse matrix in the IO model, caused decrease in fossil fuel use and air pollutants emissions during 1997–2000. PM$_{10}$ showed the largest effect (−5.4), and SO$_2$ showed the smallest effect (−2.7). However, the effects of the change in production structures became positive (from 4.5 for PM$_{10}$ and PM$_{2.5}$ to 18.3 for SO$_2$) for all materials during 2000–2005. The effects also caused additional increases in fossil fuel consumption, and in CO$_2$, NO$_x$, and SO$_2$ emissions during 2005–2010. But these effects were weaker for all materials compared with the period 2000–2005. As shown in Fig. 2, the effects decreased for most materials (the range from 3.7 for coal to 9.1 for NO$_x$) during 2005–2010 compared with that (from 4.5 for PM$_{10}$ to 18.3 for SO$_2$) during 2000–2005. The effects changed to negative values for PM$_{10}$ and PM$_{2.5}$ between 2005 and 2010 (Fig. 2).

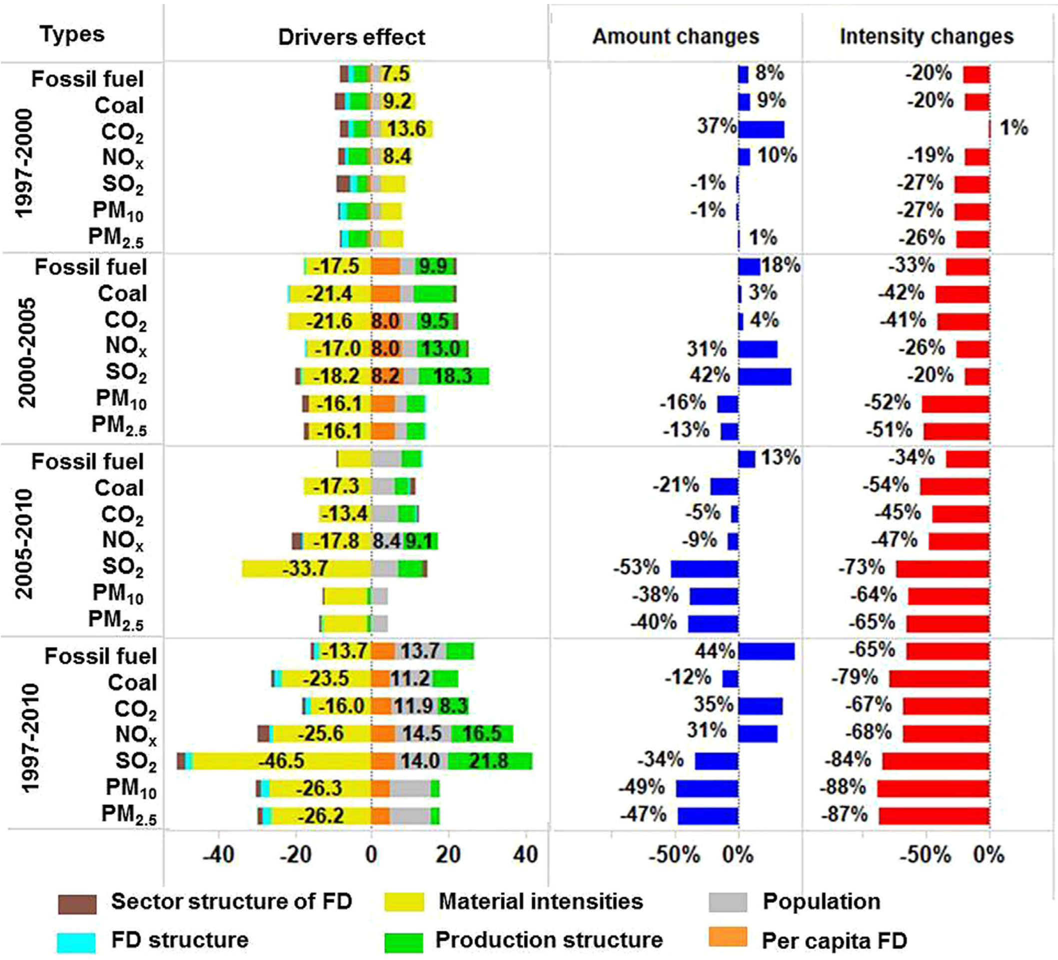

Fig. 2. Relative values of all drivers effects, amount changes of all materials, and intensity changes (energy consumption and air pollutants emissions per GDP (2000 constant price)) of all materials at different periods, FD (final demand). The negative value means negative effect of increasing energy consumption and air pollutants emissions, and positive value mean positive effect of that.

Variation in material intensities increased fossil fuel consumption and air pollutants emissions in Beijing during 1997–2000, even though the energy consumption and air pollutants emissions per unit of GDP have decreased. The effects of material intensities were the largest on CO_2 (13.6) and the smallest on PM_{10} (5.6) during this period. In contrast, given the larger decline of intensity changes during 2000–2005 compared with the period from 1997 to 2000, material intensities became negative effects on almost all materials, with the highest effect on CO_2 (−21.6), and the lowest on $PM_{2.5}$ and PM_{10} (−16.1) (Fig. 2). Further changes in material intensities between 2005 and 2010 caused a continual reduction in all materials due to more efficient control measures and policies (e.g., super-critical and ultra-super-critical units and end-of-pipe treatment [50]). The changes in material intensities caused the greatest decrease (−33.7) for SO_2 emission reduction, which was almost twice that for coal (−17.3) and NO_x (−17.8), because of mandatory policies that required installation of flue gas desulfurization (FGD) treatment during the 11th Five-Year Plan [50,54].

Variation in final demand structures had some small effects for fossil fuel consumption and air pollutants emissions over the last decade. For example, there were slightly negative effects for all materials (from −0.7 for NO_x to −2.3 for PM_{10}) (Fig. 2), despite obvious changes in final demand structures between 1997 and 2010. Specifically, the shares of household consumption and capital formation to total final demand decreased from 23% and 30%, respectively, in 1997 to 14% and 21% in 2010, and the proportion of domestic export increased from 24% to 40% during the same period (Fig. C.6).

Changes in the sectoral structures of final demand types had more complex impacts than other drivers on fossil fuel consumption and air pollutants emissions, even though they had only slight comprehensive effects on all materials during 1997–2010 (from −0.8 for coal to −3.4 for NO_x). Specifically, household structures gradually shifted from satisfying peoples' basic living needs (e.g., food decreased by 11% and textiles decreased by 5%) to the service sectors (e.g., education and medical treatment), which increased by 18% during this period. This phenomenon led to a reduction of all materials (e.g., −3.0 Mt for CO_2 and −15.9 kt for SO_2). Capital formation structures gradually shifted from manufacturing (e.g., equipment industries decreased by 17%) to services (e.g., other services increased by 35%), leading to a reduction in all materials (e.g., −18.8 kt for PM_{10}). However, for domestic export structures, the contributions of manufacturing sectors increased substantially (e.g., equipment manufacturing sectors increased by 16%), which led to an increase in all materials except NO_x (−18.1 kt). Exports and government consumption structures had no obvious effects on all materials because of their relatively stable structures (Tables B.4 and B.5).

4. Discussions and policy implications

4.1. Limitations on control of the key sectors

From a bottom-up perspective, a series of energy relevant policies that were applied to the key energy-intensive industrial sectors (e.g., EHGW and metals) caused a dramatic decrease in air pollutants emissions in Beijing during 1997–2010. These policies and measures fall generally into three categories. First, Beijing's policy required its key high-energy sectors to move out of the city to surrounding regions (e.g., removing the Shougang Steel Group to Heibei province [55]), which reduced local energy consumption and emissions directly. Second, the high energy-intensive sectors adopted end-of-pipe treatment technologies to cut the air pollutants emissions (e.g., largely installing desulfurization equipment in industrial boilers to reduce SO_2 emissions during 11th Five-Year Plan [52]). Third, power plants applied advanced technologies to improve energy efficiency and reduce coal consumption (e.g., developing super-critical and ultra-super-critical technologies in the EHGW sectors [50]).

However, with the further improvement of energy technology and end-of-pipe treatment, the marginal cost would greatly increase to reduce energy consumption and air pollutants emissions [56], especially when these technologies (e.g., ultra-super-critical technology) have already been widely implemented in Beijing. It is crucial to find other effective ways to reduce fossil fuel consumption and relevant air pollutants emissions simultaneously.

4.2. Co-reduction by control of socioeconomic drivers

From a top-down perspective, there are socioeconomic drivers that affect energy use and air pollutants emissions. Excessive population growth caused large increases of energy and air pollution pressures in Beijing. For example, the population effect (8.1) on fossil fuel consumption nearly offset the fossil fuel intensity effect (−8.9) during 2005–2010 because of the high rate of population growth (Fig. 2).

Beijing's permanent population has actually increased by an average of nearly 600,000 annually since 2000 and reached 20.7 million by the end of 2012. The floating population comprised 30% of this total [57]. These increases far exceeded the total 2020 population target of 18 million, of which 10% would be floating population, and that was set in the Beijing City Plan from 2004 to 2020. Beijing's population is approximately 2.6 times that of London and 2.5 times that of New York as of 2013 [58]. Moreover, Beijing's average population density has increased almost twice from 1997 (644 capita/km^2) to 2010 (1261 capita/km^2) [24]. However, it is unlikely to make policies of controlling the population amount at a lower level in the next decade at the background of urbanization in China [59]. But some policies of achieving a reasonable population density are feasible to avoid the excessive rapid population growth for abating the environmental pressures in Beijing. In fact, Beijing's government is considering new measures to curb the local excessive population growth. For example, Beijing will amend its industrial and employment policies to raise the threshold for attaining the status of local residency. The city will also implement a residence certificate system that would strengthen the floating population registration and an overall service management system for its actual population [60]. All these population policies will be effective measures for co-reducing the energy consumption and air pollutants emissions.

The input of resources and technologies uncovered by production structures, have become much more complex in the processing of producing activities, with the increase of additional value in products in Beijing in the last decade. However, this increased complexity does not necessarily mean that production structures have become more efficient. Our results showed that the variations in production structures increased fossil fuel use and air pollutants emissions during 2000–2005 and 2005–2010. And this increase effect was smaller for the period 2005–2010 than that was for the period 2000–2005. These differences could indicate that production structures became more efficient during 2005–2010 than they had been in the previous period. Improving overall supply chains efficiency (e.g., choosing production materials that are more energy-efficient) is therefore as significant as adopting advanced energy technologies in production activities.

Variation in final demand structures and in the sectoral structures of final demand types could also have a small impact on fossil fuel consumption and air pollutants emissions. Although it is hard to change final demand structures and sectoral structures of final demand types intentionally, policies that increase the sustainability of household consumption would be required. Policies that promote a shift from exporting more energy-intensive products (e.g., chemicals) to exporting higher value-added products (e.g., education and technologies) are also desirable.

5. Conclusions

The drivers of fossil fuel use and air pollutants emissions were analyzed for Beijing during 1997–2010 from both bottom-up and top-down perspectives. From a bottom-up perspective, changes of the high energy-intensive industrial sectors caused the large decreases of fossil fuel use and air pollutants emissions with the implement of advanced technologies in Beijing. However, the marginal cost would increase greatly if mitigation policies focused only on key energy-intensive industrial sectors. From a top-down perspective, the increase in Beijing's population and the change of production structure resulted in the largest increases in energy consumption and air pollutants emissions during 1997–2010. Better urban planning to achieve a more reasonable population density would be a positive way to co-reduce energy consumption and air pollution in Beijing. The Adjustment of other socioeconomic drivers (e.g., encouraging sustainable household consumption and focusing the export structure on higher value-added products) could also affect energy consumption and air pollutants emissions. Both key sectors and socioeconomic drivers should be considered to co-reduce fossil fuel use and emissions in metropolis.

Additionally, the energy consumption and air pollutants emissions inventories that were used in this study were based on the city's geographic boundary. Cities actually have strong interactions with surrounding regions [61]. Because of the limitations of SDA, we could not quantitatively analyze the environmental influences of Beijing on its surrounding regions. This type of question could be studied in greater detail using multi-regional input–output models (MRIO), which we plan to utilize in our future research.

Acknowledgments

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Appendix A

$$\begin{aligned}\Delta p_d = 1/720{*}\Big(&120{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t)} + 24{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t-1)} + 24{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t)}\\
&+ 24{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t)} + 24{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t)} + 24{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t)}\\
&+ 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t-1)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t-1)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t-1)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t)}{*}y_{ds(t-1)} + 12{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t)}\\
&+ 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t)} + 12{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t)}\\
&+ 24{*}\Delta p_d{*}P_{(t)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t-1)} + 24{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t-1)}\\
&+ 24{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t)}{*}y_{ss(t-1)}{*}y_{ds(t-1)} + 24{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t)}{*}y_{ds(t-1)}\\
&+ 24{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t)} + 120{*}\Delta p_d{*}P_{(t-1)}{*}F_{(t-1)}{*}L_{(t-1)}{*}y_{ss(t-1)}{*}y_{ds(t-1)}\Big)\end{aligned} \tag{A.1}$$

Appendix B

Table B.1
The sample of original input–output tables (IOTs) of Beijing (unit: Million yuan in current price).

Intermediate outputs		Final demand				International import	Domestic import	Others	Total outputs
		Final consumption expenditure	Gross capital formation	International export	Domestic export				
S_1	Z	y_1	y_2	y_3	y_4	y_5	y_6	y_7	$X = (Z + y_1 + y_2 + y_3 + y_4) - y_5 - y_6 + y_7$ $= x - y_5 - y_6 + y_7$
S_2									
$\vdots$									
S_n									
Value added									
Total inputs									

Table B.2
The sample of final IOTs of Beijing that we adjusted (unit: Million yuan in 2000 price).

Intermediate outputs		Final demand				International import	Domestic import	Other	Total outputs
		Final consumption expenditure	Gross capital formation	International export	Domestic export				
S_1	$Z' = Z\left(1 - \frac{y_5+y_6}{x}\right)$	$y'_1 = y_1\left(1 - \frac{y_5+y_6}{x}\right)$	$y'_2 = y_2\left(1 - \frac{y_5+y_6}{x}\right)$	$y'_3 = y_3\left(1 - \frac{y_5+y_6}{x}\right)$	$y'_4 = y_4\left(1 - \frac{y_5+y_6}{x}\right)$	0	0	Removed	$X' = Z' + y'_1 + y'_2 + y'_3 + y'_4$
S_2									
$\vdots$									
S_n									
Value added									
Total inputs									

Table B.3
Coal consumption proportions at sectoral level during 1997–2010.

Sectors	1997	2000	2002	2005	2007	2010
Agriculture	0.1%	1.4%	1.5%	1.3%	1.6%	1.8%
Mining	0.7%	0.4%	0.6%	0.4%	0.4%	22.6%
Food	2.0%	1.8%	1.9%	2.0%	2.2%	2.4%
Textile	1.3%	0.9%	0.8%	0.8%	0.8%	0.7%
PPCS	0.7%	0.6%	0.5%	0.5%	0.5%	0.6%
Petroleum and coking	0.0%	20.9%	10.1%	6.4%	0.6%	0.1%
Chemicals	18.6%	3.4%	3.4%	2.7%	3.9%	4.1%
Nonmetal minerals	6.4%	7.5%	7.2%	7.8%	7.9%	6.9%
Metals	41.7%	24.5%	36.4%	26.2%	27.2%	0.4%
Other manufactures	4.6%	2.4%	2.5%	2.5%	2.7%	2.3%

Table B.3 (*continued*)

Sectors	1997	2000	2002	2005	2007	2010
EHGW	21.3%	29.2%	28.3%	37.6%	40.4%	47.1%
Construction	0.5%	0.3%	0.3%	0.6%	0.5%	0.7%
Transportation	0.4%	0.7%	0.7%	0.7%	0.9%	0.8%
Retail and catering	0.1%	0.0%	0.0%	1.2%	1.9%	1.6%
Other services	1.7%	6.3%	5.8%	9.3%	8.4%	8.1%
Total	100%	100%	100%	100%	100%	100%

Table B.4
Variations of sectors structures of final demand from 1997 to 2010.

Sectors	Household consumption (%)		Government consumption (%)		Capital formation (%)		Domestic export (%)		International export (%)	
	1997	2010	1997	2010	1997	2010	1997	2010	1997	2010
Agriculture	7.1	10.9	0.0	2.2	0.7	1.3	0.7	0.0	0.6	1.9
Mining	0.2	0.3	0.0	0.0	0.3	0.0	0.1	4.5	0.0	1.6
Food	18.8	7.4	0.0	0.0	1.1	0.9	3.3	2.6	1.7	0.4
Textile	7.1	2.6	0.0	0.0	1.1	0.3	1.1	0.4	10.0	1.1
PPCS	1.6	0.3	0.0	0.0	1.1	0.1	0.1	0.2	1.0	0.0
Petroleum and coking	0.2	1.3	0.0	0.0	0.3	−0.2	0.1	1.7	0.3	4.5
Chemicals	4.0	2.1	0.0	0.0	1.3	0.4	0.9	3.6	2.9	1.5
Nonmetal minerals	1.1	0.1	0.0	0.0	1.7	0.4	0.3	0.7	0.5	0.1
Metals	0.7	0.6	0.0	0.0	4.6	0.7	0.2	0.6	3.3	1.2
Other manufactures	9.3	8.4	0.0	0.0	30.5	13.9	3.7	20.2	13.0	16.3
EHGW	5.3	3.9	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
Construction	0.0	1.8	0.0	0.0	49.8	42.1	2.3	7.0	1.6	10.2
Transportation	2.3	1.7	0.0	0.0	1.0	0.4	6.3	1.1	3.6	7.2
Retail and catering	12.3	11.0	0.0	0.0	4.0	2.5	1.4	10.1	9.7	4.9
Other services	30.0	47.7	100.0	97.8	2.5	37.2	79.3	47.3	51.8	49.1

Table B.5
Effects of variations of sectoral structures of household consumption, capital consumption, domestic export, and international export on all materials.

Types	Unit	Household consumption	Capital consumption	Domestic export	International export
Fossil fuel	Mtce	−1.4	−1.6	1.5	0.3
CO_2	Mt	−3.4	−3.7	4.0	0.5
SO_2	kt	−15.9	−7.2	7.4	−0.1
NO_x	kt	−15.7	−8.9	−18.1	7.3
PM_{10}	kt	−9.6	−18.8	10.8	3.0
$PM_{2.5}$	kt	−5.4	−10.9	5.8	2.4

Appendix C

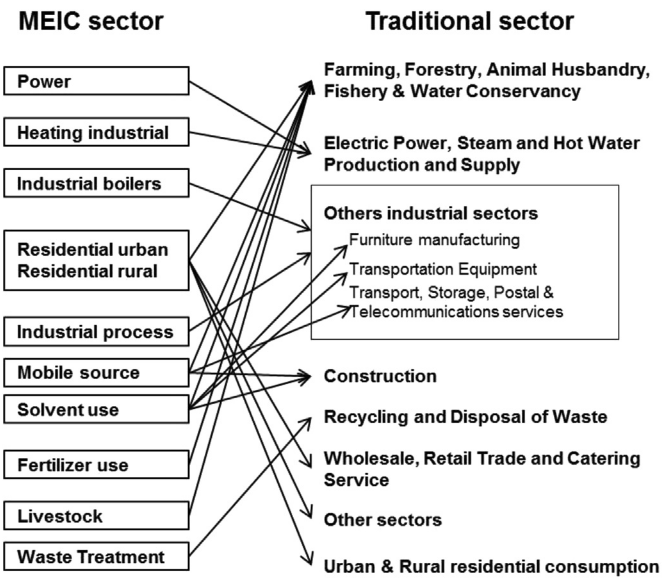


Fig. C.1. Reallocation principles of MEIC sector to economic sectors. MEIC (Multi-resolution Emission Inventory).

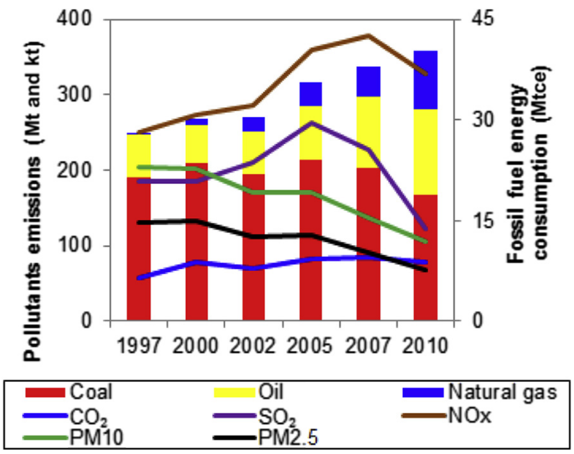
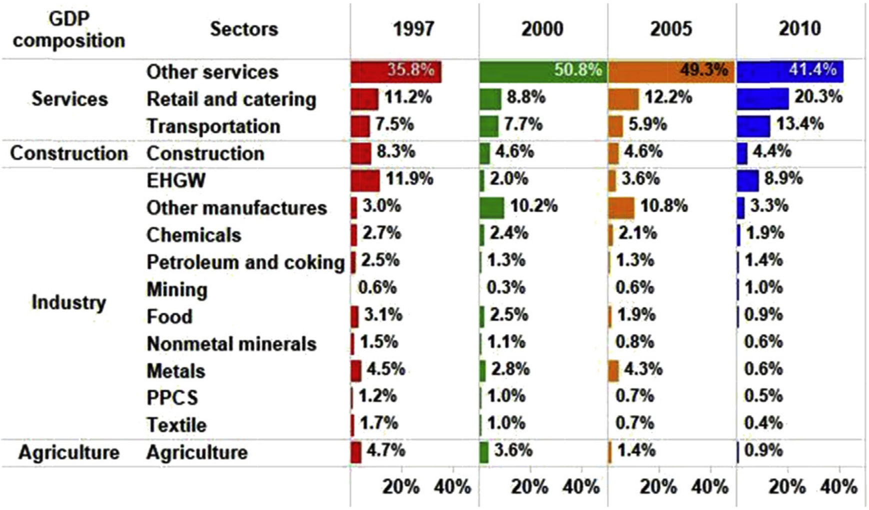


Fig. C.2. Total amounts for materials from 1997 to 2010.



GDP composition	Sectors	1997	2000	2005	2010
Services	Other services	35.8%	50.8%	49.3%	41.4%
	Retail and catering	11.2%	8.8%	12.2%	20.3%
	Transportation	7.5%	7.7%	5.9%	13.4%
Construction	Construction	8.3%	4.6%	4.6%	4.4%
Industry	EHGW	11.9%	2.0%	3.6%	8.9%
	Other manufactures	3.0%	10.2%	10.8%	3.3%
	Chemicals	2.7%	2.4%	2.1%	1.9%
	Petroleum and coking	2.5%	1.3%	1.3%	1.4%
	Mining	0.6%	0.3%	0.6%	1.0%
	Food	3.1%	2.5%	1.9%	0.9%
	Nonmetal minerals	1.5%	1.1%	0.8%	0.6%
	Metals	4.5%	2.8%	4.3%	0.6%
	PPCS	1.2%	1.0%	0.7%	0.5%
	Textile	1.7%	1.0%	0.7%	0.4%
Agriculture	Agriculture	4.7%	3.6%	1.4%	0.9%

Fig. C.3. GDP contributions of economic sectors from 1997 to 2010. The proportion is current price.

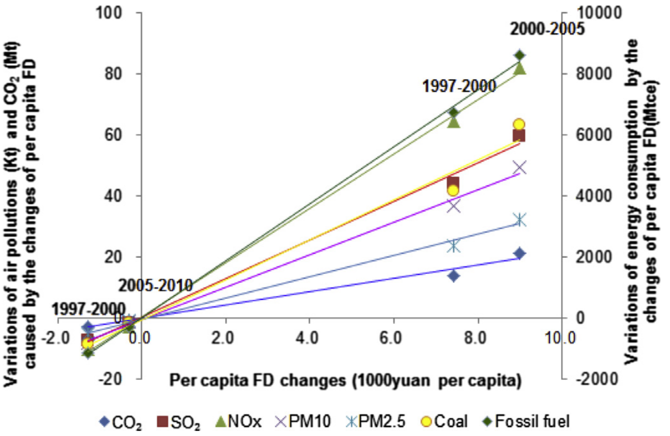


Fig. C.4. Linear regressions of the variation of per capita final demand and the changes of energy consumption and air pollutants emissions because of this driver at different periods, respectively. FD (final demand).

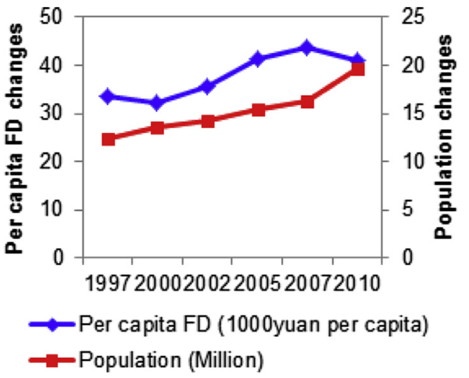


Fig. C.5. Changes of population and per capita FD (final demand) during 1997–2010. The value of per capita GDP is 2000 constant price.

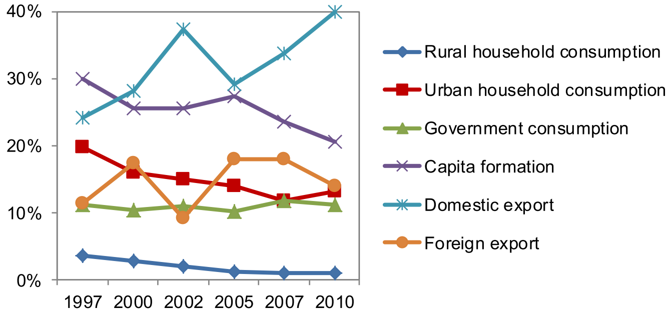


Fig. C.6. Variations of final demand structures from 1997 to 2010.

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