Energy-Related Carbon Emissions in Shanghai: Driving Forces and Reducing Strategies

Chun-zeng Fan, Hai-ying Gu and Hong Jiang

Abstract This paper calculated the energy-related carbon emissions from production, household and energy transformation sectors in Shanghai and decomposed the effects of their changes in carbon emissions resulting from 11 causal factors of reflecting the changes in socioeconomic activity, intensity of energy and the structure by logarithmic mean divisia index. The results show that the changes of economic activity (EA), population size (PS), total energy consumption in transformation and energy consumption per capita (ECPC) increase CO_2 emissions obviously. The changes of energy intensity (EI), urban and rural population distribution structure, energy mix of household and mix of energy in transformation drive the decrease of CO_2 emissions. The changes of economic structure (ES), energy mix of production, and energy transformation structure (ETS) can't increase or decreased CO_2 emissions continuously in 3 periods respectively. Therefore, adjusting ES, ETS, energy mix of transformation and decreasing the EI of each production sector will be the main routes to reduce CO_2 emissions. Developing clean energy to substitute fossil energy and enforcement of carbon capture will be necessary in the future.

Keywords Energy · Carbon emissions · Factor decomposition · Shanghai

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1 Introduction

Because the energy-related carbon emissions account for the main portion of global anthropogenic carbon emissions. The growth of energy consumption is the prime factor responsible for the increasing CO_2 emissions (Intergovernmental Panel on Climate Change (IPCC) 2007). As the world biggest CO_2 emitter, China emitted 8.9 billion metric tons CO_2, accounting for 27.09 % of global CO_2 emission in 2010 (Olivier et al. 2011). Reducing CO_2 emission to prohibit global warming is an important responsibility for every country including China. Therefore, Chinese government proposed reducing carbon emissions per unit GDP by 40–45 % in 2020 compared with 2005 levels in 2009. China's 12th FYP (2011–2015) proposed that energy consumption should be cut by 16 % per unit of GDP and cut 17 % CO_2 emissions by 2015. Cities are the most important energy consumer and CO_2 emitter, it is also CO_2 reducer supported by its abundance capital and technology.

As China's biggest metropolis, energy consumption and CO_2 emission in Shanghai has increased greatly as a result of rapid economic growth. In 2008, Shanghai was chose to be one of the two (Shanghai and Baoding) pilot cities of constructing low carbon city. In the implemented 12th FYP (2011–2015), one of the important goal of Shanghai was to reduce energy consumption and CO_2 emission. Therefore, studying the energy-related carbon emissions in Shanghai will both help the government make good policies and construct a successful low carbon model city for other regions to formulate.

So far, a lot of researchers have created a substantial amount of literature in this field. For example, Peters and Hertwich (2008) and Chen and Chen (2011a, b), Chen (2011) estimated the global energy-related carbon emissions. Paul et al. (2004), Wang et al. (2005), Tunc et al. (2009) studied national energy-related carbon emissions. Dhakal (2009), Zhao et al. (2009) and Zhou et al. (2010) studied this subject on different cities. However, these studies calculated the energy-related carbon emissions mainly according to 3 production sectors (primary industry, secondary industry, and tertiary industry) and 4 kinds of energy (coal, oil, natural gas and electricity).

Studies about Shanghai, such as Shao et al. (2011), Chen et al. (2013), Zhao and Tan (2010), Li et al. (2011), Liu et al. (2012), Steffen (2013) and so on, also considered a relatively small number (four or fewer) of types of energy. This decreases the accuracy of accounting, and only creates a coarse resolution.

Carefully studying of carbon emissions and the proportion of total emissions accounted for by each sector will do good to policy making and solve more practical problems.

There are a lot of methods of factor decomposition. LMDI is commonly used because of its ability to provide perfect decomposition without residual results and robust theoretical foundations, strong adaptability to a range of situations, e.g., Ang and Zhang (2000), Ang and Liu (2001), Ang (2004, 2005). A lot of Studies of factor decomposition use this method, e.g., Zhang et al. (2009), Oh et al. (2010), Liu (2007).

In this current research, the production sectors have generally been divided into three or four sectors, and the factors that influence carbon emissions have usually been divided into EA, ES, EI, and the energy mix consumed by each sector (Zhang et al. 2009; Oh et al. 2010). The household sector, composed by urban and rural sectors, influences carbon emissions by the changing of PS, of URPDS, of household ECPC, and of household energy mix Zhang et al. (2013). The energy transformation sector can be divided into 8 sub-sectors (Thermal Power, Heating Supply, Coal Washing, Cokeing, Petroleum Refineries, Gas Works, Natural Gas Liquefaction and Briquettes) (NBS DES, National Bureau of Statistics Department of Energy Statistics). Shanghai's energy-related CO_2 emission in the course of energy transformation mainly comes from the first 2 sectors. Therefore the CO_2 emission of energy transformation can be divided into 3 sectors: thermal power, heating supply and the other sector. In recent studies, the production sectors have been divided at a coarse resolution or at a detailed resolution on secondary industry (Zhao and Tan 2010) and haven't consider the energy transformation, while the data is relative older, and haven't given the main reasons of CO_2 emission in the energy transformation. So the reasons why carbon emissions continue to increase is unclear. In general, researchers have not provided data that can be directly used to guide the management of carbon emissions in Shanghai. With the rapid growth of population and economy, Shanghai's energy consumption and CO_2 emissions increase quickly. In order to decrease the CO_2 emissions, it is urgently necessary to conduct a full calculating of Shanghai's energy-related carbon emissions and find its main driving factors.

In this paper, we collected detailed raw data for a larger number of sectors and energy types than were used in previous research. The goal of this paper is to use LMDI to analyze: (1) Shanghai's total energy-related carbon emissions and its structure. (2) the main forces of driving the recent changes in Shanghai's energy-related carbon emissions. (3) the countermeasures to control Shanghai's energy-related carbon emissions. This will help the government design feasible and effective policies to control and reduce carbon emissions.

2 Data and Methodology

2.1 Data Collection

We contributed Shanghai's energy-related carbon emissions in energy transformation, energy consumption of the production and the household sectors. We defined 6 production sectors: primary industry (farming, forestry, animal husbandry, fisheries and water conservation; secondary industry; construction; TSPS (transportation, storage, and postal systems); WRTHR (wholesale, retail trade, hotel, and restaurant sector) and other production), 2 household sectors (urban households and rural households) and 3 transformation sectors (thermal power, heat supply and other energy transformation). Shanghai's main source of CO_2 emission in energy transformation are electricity, heat, coking, petroleum refineries, briquettes and gas works sectors. This paper divides the energy transformation into 3 sectors: electricity, heat and the other energy transformation sectors. We obtained data on the output values for the production sectors based on constant prices (with 2000 as the base year) and population data of urban and rural households from Shanghai Statistical Yearbooks from 1996 to 2010 (BMBS and NBS). To improve the resolution of the energy analysis, we defined 19 kinds of energy: raw coal, cleaned coal, other washed coal, charcoal briquettes, coke, coke oven gas, other gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), refinery gas, natural gas, other petroleum products, other coking products, heat and electricity. Energy consumption data are obtained from China Energy Statistical Yearbooks that contained data from 1991 to 2010 (NBS DES, National Bureau of Statistics Department of Energy Statistics). We adopted the final energy consumption from the energy-balance tables in these yearbooks as the energy consumption of the first 8 sectors. We adopted the net input (input–output) of energy transformation from the energy-balance tables in these yearbooks as the energy consumption of the other 3 sectors.

Energy consumption data are converted into coal equivalents based on the standard coal-equivalent coefficients obtained from China Energy Statistical Yearbook (NBS DES, National Bureau of Statistics Department of Energy Statistics). In this paper, we assumed complete combustion of energy sources to generate carbon emissions. Energy-related carbon emissions (C) can be calculated based on the following formula:

$$C = \sum_{i} E_i \times Y_i \tag{1}$$

where i denotes the different kinds of energy ($i = 1, 2, 3, \ldots, 19$), E_i denotes the consumption of energy type i, and Y_i denotes the carbon-emission coefficient for energy type i. The carbon-emission coefficients for the 19 kinds of energy were obtained from IPCC (2006). Since the carbon emissions from the processes of electricity and heat generation from fossil energy were already calculated, and consumption of electricity and heat does not cause carbon emissions. This paper assumed the carbon emission coefficients for electricity and heat were 0. The carbon emission coefficients for the output fossil energy by input in the transformation sectors were also 0, because they hadn't been burned and emitted CO_2. Non-energy use of fuels (i.e., as industrial materials) was subtracted from the final energy consumption of secondary industry.

2.2 LMDI Model

The aim of this study is to calculate related-energy carbon emissions of the 11 key sectors and decomposed the changes of CO_2 emissions into several factors. Considering the different characteristics of carbon emissions in the course of production, household consumption and energy transformation, we analyzed them separately.

EI was mainly affected by the technology level of the energy utilization processes the energy consumption structure, the energy consumption quantity and the mixture of energy.

Energy transformation is also an important source of CO_2 emission, including total energy transformation (TET), energy transformation structure (ETS), and energy mix of transformation (EMT).

Using LMDI model, we decomposed energy-related carbon emissions from production, households and energy transformation into the following 11 driving factors: (1) economic activity (EA) (i.e., GDP), (2) economic structure (ES), (3) energy intensity (EI) (i.e., energy consumption per unit of output), (4) the energy mix of the production sectors (EMP) (i.e., the proportion of total energy provided by each of the 19 fuels), (5) population size (PS), (6) the urban and rural population distribution structure (URPDS) (i.e., the proportions of total population accounted for by urban and rural households), (7) energy consumption per capita (ECPC), (8) the energy mix consumed by the two household sectors (EMH), (9) TET, (10) ETS and (11) EMT. According to the model developed by Ang (2005), Shanghai's energy-related carbon emissions (C) can be formulated as follows:

$$\begin{aligned} C = {} & \sum_{ij} \mathrm{GDP} \times \frac{Q_i}{\mathrm{GDP}} \times \frac{E_i}{Q_i} \times \frac{E_{ij}}{E_i} \times \frac{C_{ij}}{E_{ij}} + \sum_{ki} P \times \frac{P_k}{P} \\ & \times \frac{E_k}{P_k} \times \frac{E_{ki}}{E_k} \times \frac{C_{ki}}{E_{ki}} + \sum_{ni} E_{\mathrm{tr}} \times \frac{E_n}{E_{\mathrm{tr}}} \times \frac{E_{ni}}{E_n} \times \frac{C_{ni}}{E_{ni}} \\ = {} & \sum_{ij} \mathrm{GDP} \times S_i \times \mathrm{EI}_i \times \mathrm{ES}_{ij} \times Y_{ij} + \sum_{ij} P \times S_k \\ & \times \mathrm{EI}_k \times \mathrm{ES}_{ki} \times Y_{ii} + \sum_{ni} E_{\mathrm{tr}} \times S_n \times \mathrm{ES}_{ni} \times Y_{ni} \end{aligned} \tag{2}$$

In the formula (2), C_{ij} denotes the CO_2 emissions caused by consumption of energy type i in production sector j; C_{ik} denotes the CO_2 emissions caused by consumption of energy type i by urban or rural households (k); E_j denotes the energy consumption by production sector j; E_{ij} denotes the consumption of energy type i by production sector j; E_k denotes the energy consumption by urban or rural households (k); E_{ik} denotes the consumption of energy type i by urban or rural households (k); EI_j denotes the EI of production sector j; E_k denotes ECPC (k); ES_{ij} denotes the proportion of TEC by production sector j accounted for by consumption of energy type, that is, energy mix of production; ES_{ik} denotes the proportion of total energy consumption by urban or rural domestic households (k) accounted for by consumption of energy type i, that is, energy mix of household consumption; E_{tr} denotes TET, $E_{\mathrm{tr}n}$ denotes the energy transformation of n sector, $E_{\mathrm{tr}ni}$ denotes the transformation of sector n accounted for by consumption of energy type i; GDP denotes the gross domestic product in constant (2000) prices; i denotes the different types of energy ($i = 1, 2, 3, \ldots, 19$); j denotes the production sectors ($j = 1, 2, 3, \ldots, 6$); k denotes the household sectors ($k = 1, 2$); n denotes energy transformation senators ($n = 1, 2, 3$); P denotes the total population; P_k denotes the urban or rural population (k); Q_j denotes the output value of production sector j; Y_{ij} denotes the carbon-emission coefficient for energy type i in production sector j; Y_{ik} denotes the carbon-emission coefficient for energy type i of urban or rural households; Y_{trin} denotes the carbon-emission coefficient for energy type i in transformation sector j; S_j denotes the proportion of GDP accounted for by the output value for production sector j, that is, ES; S_k denotes the proportion of the total population accounted for by urban and rural populations (k); E_{tr} represents the total net fossil input by energy transformation; $ES_{\mathrm{tr}ni}$ denotes the ETS; $ES_{\mathrm{tr}ni}$ denotes EMT. We assumed that the carbon-emission coefficients for each energy source was constant, thus the carbon-emission intensify of a certain energy did not change. The carbon-emission change (ΔC) from year 0 to year T can be expressed as follows:

$$\begin{aligned}\Delta C = C_T - C_0 = \Delta C_{\mathrm{GDP}} + \Delta C_{S_j} + \Delta C_{\mathrm{EI}_j} + \Delta C_{\mathrm{ES}_{ij}} + \Delta C_P \\ + \Delta C_{S_K} + \Delta C_{\mathrm{EI}_k} + \Delta C_{\mathrm{ES}_k} + \Delta C_{E_{\mathrm{tr}}} + \Delta C_{\mathrm{EI}_{\mathrm{trn}}} + \Delta C_{\mathrm{ES}_{\mathrm{trn}}}\end{aligned} \tag{3}$$

where ΔC denotes the change in CO_2 emissions from year 0 to year T; C_T denotes the CO_2 emissions in year T; C_0 denotes the CO_2 emissions in year 0; ΔC_{GDP} denotes the impact of changes in EA, ΔC_{S_j} denotes the impact of changes in ES, ΔC_{EI_j} denotes the impact of changes in EI, $\Delta C_{\mathrm{ES}_{ij}}$ denotes the impact of changes in the EMP, ΔC_P denotes the impact of changes in PS, ΔC_{S_K} denotes the impact of changes in the URPDS, ΔC_{EI_k} denotes the impact of changes in ECPC, ΔC_{ES_k} denotes the impact of EMH, $\Delta C_{E_{\mathrm{tr}}}$ Denotes the impact of changes in the TEC, $\Delta C_{\mathrm{EI}_{\mathrm{trn}}}$ denotes the impact of changes of the ES; $\Delta C_{\mathrm{ES}_{\mathrm{tr}ni}}$ denotes the impact of changes in the EMT. According to the additive decomposition of LMDI, formula (3) can be reformatted as follows:

$$\Delta C_{\mathrm{GDP}} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{\mathrm{GDP}^T}{\mathrm{GDP}^0}\right) \tag{4}$$

$$\Delta C_{S_j} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{S_i^T}{S_i^0}\right) \tag{5}$$

$$\Delta C_{\mathrm{EI}_j} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{\mathrm{EI}_i^T}{\mathrm{EI}_i^0}\right) \tag{6}$$

$$\Delta C_{\mathrm{ES}_{ij}} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{\ln C_{ij}^{T} - \ln C_{ij}^{0}} \ln\left(\frac{\mathrm{ES}_{ij}^{T}}{\mathrm{ES}_{ij}^{0}}\right) \tag{7}$$

$$\Delta C_{P} = \sum_{ki} \frac{C_{ik}^{T} - C_{ik}^{0}}{\ln C_{ik}^{T} - \ln C_{ik}^{0}} \ln\left(\frac{P^{T}}{P^{0}}\right) \tag{8}$$

$$\Delta C_{S_k} = \sum_{ki} \frac{C_{ik}^{T} - C_{ik}^{0}}{\ln C_{ik}^{T} - \ln C_{ik}^{0}} \ln\left(\frac{S_{K}^{T}}{S_{K}^{0}}\right) \tag{9}$$

$$\Delta C_{\mathrm{ES}_{ik}} = \sum_{ki} \frac{C_{ik}^{T} - C_{ik}^{0}}{\ln C_{ik}^{T} - \ln C_{ik}^{0}} \ln\left(\frac{\mathrm{ES}_{Ki}^{T}}{\mathrm{ES}_{Ki}^{0}}\right) \tag{10}$$

$$\Delta C_{\mathrm{EI}_k} = \sum_{ki} \frac{C_{ik}^{T} - C_{ik}^{0}}{\ln C_{ik}^{T} - \ln C_{ik}^{0}} \ln\left(\frac{\mathrm{EI}_{K}^{T}}{\mathrm{EI}_{K}^{0}}\right) \tag{11}$$

$$\Delta C_{E_{\mathrm{tr}}} = \sum_{ni} \frac{C_{ni}^{T} - C_{ni}^{0}}{\ln C_{ni}^{T} - \ln C_{ni}^{0}} \ln\left(\frac{E^{T}}{E^{0}}\right) \tag{12}$$

$$\Delta C_{EI_{\mathrm{tr}}} = \sum_{ni} \frac{C_{ni}^{T} - C_{ni}^{0}}{\ln C_{ni}^{T} - \ln C_{ni}^{0}} \ln\left(\frac{E_{n}^{t}}{E_{n}^{0}}\right) \tag{13}$$

$$\Delta C_{ES_{\mathrm{tr}}} = \sum_{ni} \frac{C_{ni}^{T} - C_{ni}^{0}}{\ln C_{ni}^{T} - \ln C_{ni}^{0}} \ln\left(\frac{E_{ni}^{T}}{E_{ni}^{0}}\right) \tag{14}$$

In these formulas, superscripts 0 and T denote the values for year 0 and year T respectively.

3 Results

3.1 Figures and Tables

Table 1 indicates that energy-related carbon emissions in Shanghai have continued to increase. From 1995 to 2000, carbon emissions increased by 646.02×10^4 t, an average annual growth rate of 3.91 %. From 2000 to 2005, emissions increased by 1054.15×10^4 t, an average annual growth rate of 5.13 %. From 2005 to 2010, emissions increased by 1475.18×10^4 t, an average annual growth rate of 5.857 %. Therefore, Shanghai's energy-related carbon emissions increases quickly. In the different sectors, the secondary industry, the TSPS and thermal power sector emitted over 80 % CO_2 in the year 1995, 2000, 2005 or 2010. The emissions of the

Table 1 Trends of energy-related carbon emissions in Shanghai (×10^4 t)

	1995	2000	2005	2010
Primary industry	21.94	44.89	47	26.05
Secondary industry	1,320.77	1,554.97	1,404.33	1,612.62
Construction	11.24	40.95	83.41	83.95
TSPS	163.33	336.36	799.32	1,169.38
WRTHR	16.82	28.77	91.05	161.64
Other production sectors	35.99	78.48	106.34	232.81
Urban households	57.84	87.45	108.41	196.27
Rural households	72.09	61.91	59.9	69.54
Thermal power	1,010.8	1,312.63	1,782.95	2,250.85
Heat supply	144.15	128.79	185.99	209.95
Other energy transformation sectors	204.86	30.84	91.58	221.9
Total	3,059.85	3,706.02	4,760.28	6,234.96

secondary industry show a decreasing trend, while the emissions of TSPS and thermal power show increasing trends.

During the 3 periods, the average annual growth rates of the TSPS's carbon emissions were 15.54, 18.90, and 7.91 % respectively. The average growth rates of construction's carbon emissions were 29.51, 15.29, and 0.13 %, respectively. And the average growth rates of the WRTHR were 11.33, 25.91, and 12.16 %, respectively.

These 3 sectors had the fastest-growing carbon emissions among the production sectors. The composition of Shanghai's energy-related carbon emissions (Fig. 1) shows that the proportion of total carbon emissions accounted for by the emissions from secondary industry fell sharply. The proportion of total carbon emissions from the power sector accounted for over 30 %. The proportion of emissions by rural households sector and heat supply sector decreased.

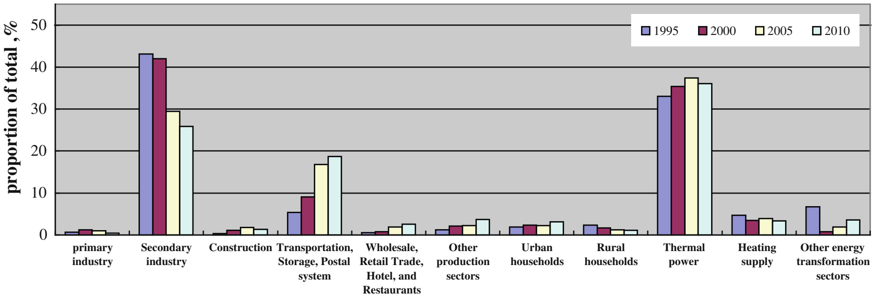


Fig. 1 Trends of Shanghai's total energy-related carbon emissions

The proportion of emissions by the TSPS and WRTHR increased. While, the proportion of emissions by the other production sectors, urban household sector and coking sector increased.

The proportions of emissions by primary industry and construction initially increased and then decreased.

The proportion of emissions by thermal power sector fluctuates repeatedly. TSPS gradually became one of the major sources of carbon emissions, increasing from 5.34 % in 1995 to 18.76 % of the total in 2010. The Secondary industry emitted 43.18 % of total CO_2 emissions in 1995, decreased to 25.86 % in 2010. The thermal power sector emitted 33.04 % of total CO_2 emissions in 1995, decreased to 36.10 % in 2010.

In addition, the proportion of emissions from the other production increased from 1.187 % in 1995 to 3.73 % in 2010. Although the proportions of emissions by urban and rural households did not exceed 5 % in any year, the proportions of emissions by urban households increased from 1.89 % in 1995 to 3.15 % in 2010. The growth of emissions by urban households should be closely monitored.

The heat supply sector and the other energy transformation sectors emitted 4.17 and 6.70 % of the total CO_2 emissions in 1995, and decreased to 3.37 and 3.56 % in 2010 respectively.

3.2 Driving Forces of Increasing Energy-Related Carbon Emission

In the 3 study periods, EA, PS, ECPC and the total energy consumption in transformation were stimulatory factors that increased emissions (Fig. 2). Industry structure, EI, the population of urban and rural distribution, and the mix of energy consumption in transformation obviously decreased CO_2 emission. The energy mix of household sector was an inhibitory factor during the first and second periods and a stimulatory factor during the third period. The energy consumption structure in transformation was inhibitory factor during the first and third periods and a stimulatory factor during the second period (Fig. 2).

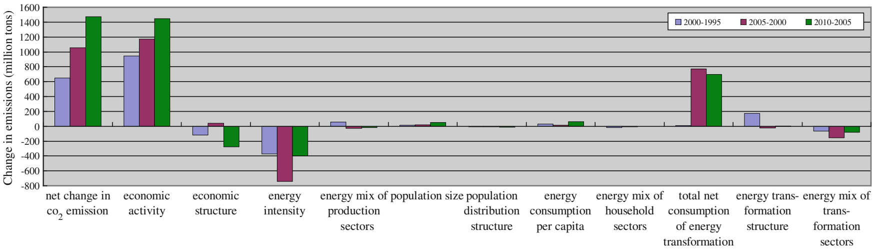


Fig. 2 Emissions changes of different sectors

3.2.1 The Main Driving Forces of Increasing CO_2 Emission

During each of the 3 periods, Shanghai's carbon emissions increased as a result of economic growth, energy transformation enlargement, population increase, and ECPC growth. However, the stimulatory effects of these factors on carbon emissions were different. EA was the dominant stimulatory factor, but the effects of PS and ECPC is smaller. The EA factor contributed to 946.06 × 10^4, 1172.39 × 10^4, and 1448.41 × 10^4 t carbon emissions, respectively, during the three study periods (Fig. 2). Shanghai's GDP increased from 265.83 × 10^9 RMB in 1995 to 1315.35 × 10^9 RMB in 2010 (an increase of 394.80 %), with annual growth rates during the three periods of 11.25 %. Over 10 % annual economic growth rate inevitably let the EA become the dominant factor in stimulating carbon emissions.

The growth of energy transformation increased 7.58 × 10^4, 767.65 × 10^4, and 697.23 × 10^4 t carbon emissions respectively in the 3 periods. The contributions of PS to changes in carbon emissions during the three periods were 15.16 × 10^4, 17.41 × 10^4, and 49.69 × 10^4 t respectively (Fig. 2).

The population of Shanghai increased from 14.14 × 10^6 persons in 1995 to 23.03 × 10^6 persons in 2010, with average annual growth rates during the three periods of 2.61, 2.38, and 4.94 %, respectively. Because the population growth rate increased throughout the whole study period, PS played an increasingly important role in stimulating carbon emissions. The contributions of ECPC to changes in carbon emissions during the three periods were 29.17 × 10^4, 15.60 × 10^4, and 60.74 × 10^4 t, respectively (Fig. 2). Urban and rural household ECPC increased throughout the study period (Fig. 3). Urban ECPC increased from 0.0784 tce/person in 1995 to 0.1824 tce/person in 2010, an increase of 1.4 times, while rural ECPC increased from 0.2463 tce/person in 1995 to 0.4178 tce/person in 2010, an increase of 69.63 % times. Obviously urban and rural ECPC increased, and stimulated the carbon emissions obviously during the studying periods.

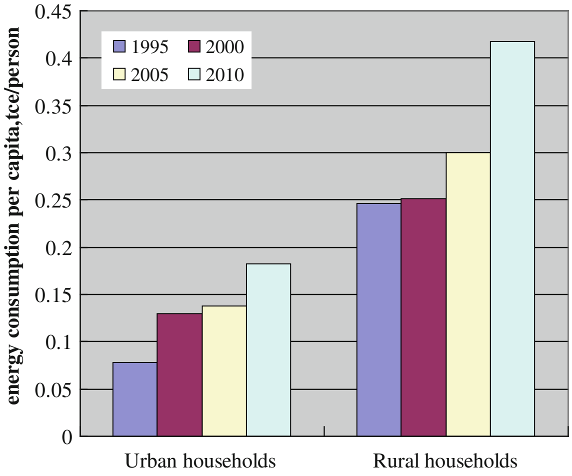


Fig. 3 Trends in energy consumption per capita of Shanghai's households

In the energy transformation, the main material is still raw coal, and its consumption increased continuously. This increased CO_2 emission greatly.

3.2.2 The Main Driving Forces of Reducing CO_2 Emission

Figure 2 shows that EI, URPDS, EMT and EMH are the main driving forces of reducing CO_2 emission. EI is the dominant inhibitory factor. In the 3 study periods, changes of EI bring to carbon emissions reduction of 373.49×10^4, 742.49×10^4 and 398.32×10^4 t respectively (Fig. 2).

Figure 4 demonstrates the trends for the EI of production sectors in Shanghai. The EI of secondary industry decreased significantly, from 1.56 tce/10^4 RMB in 1995 to 0.38 tce/10^4 RMB in 2010 (a decrease of 76.92 %).

Figure 4 also shows that the energy intensities of primary industry and construction increased first and then decreased slightly, whereas the energy intensities of TSPS and WRTHR increased quickly. The energy intensities of the other sectors show an increase-decrease-increase trend.Although the proportion of total energy consumption accounted for by secondary industry fell from 1995 to 2010. It still consumed about a quarter of the total energy. Thermal power sector consumes over 30 % total energy, and it showed an increasing trend (Fig. 5). Such that, these decreased EI of secondary industry played a key role in decreasing carbon emissions. Among these production sectors, the secondary industry, TSPS, and primary industry have higher energy intensities. While the other 3 production sectors have lower energy intensities.

Therefore, we should pay special attention to the sectors with higher energy intensities: secondary industry, TSPS, and primary industry. Thermal power sector emitted over 30 % of the total CO_2 emissions. It also needs to be paid more attention.

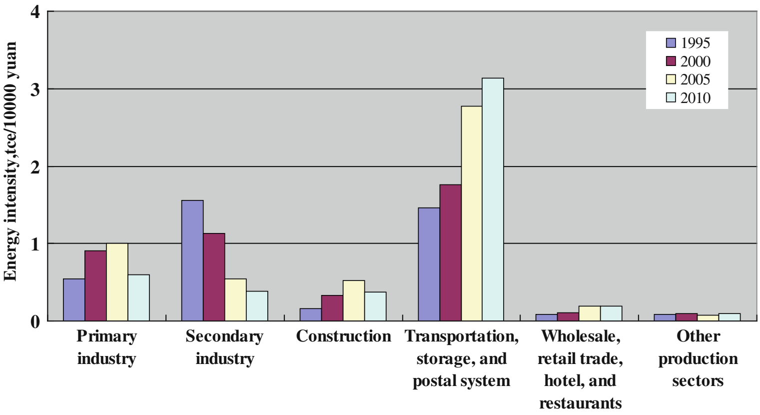


Fig. 4 Trends of energy intensify for Shanghai's production sectors

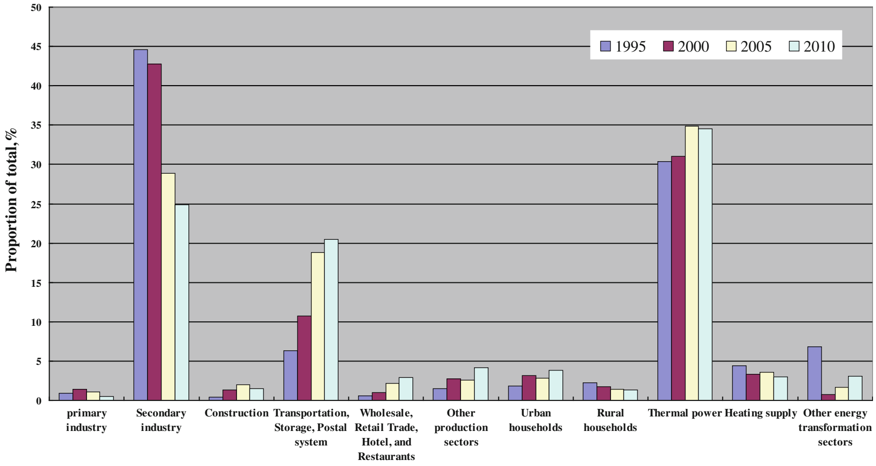


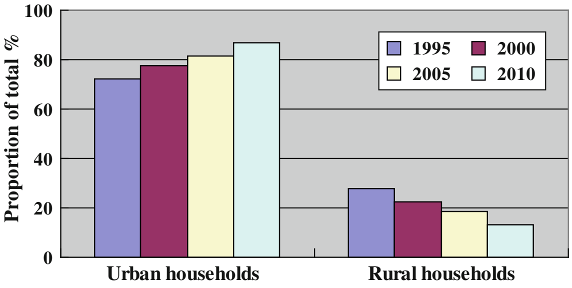
Fig. 5 Trends of total energy consumption by Shanghai's 11 sectors

During the 3 study periods, the changes of URPDS reduced 9.30 × 10^4, 6.10 × 10^4, and 11.74 × 10^4 t carbon emissions respectively (Fig. 2).

Total population in Shanghai increased continuously, the ECPC of rural households was higher than that of urban households. The proportion of rural households decreased (Fig. 6). Due to the need to provide part of agriculture products and retain some rural land as an ecological buffer for the city, it isn't practical to reduce carbon emissions by further decreasing the rural proportion of Shanghai's total population. Emission reduction should rely on reducing the ECPC and the clean energy alternatives both for urban and rural households.

In the household sectors, the proportion of urban household energy consumption accounted for by raw coal decreased and the proportions accounted for by gasoline and natural gas increased. This change is the result of government efforts to provide incentives for residents to switch from fuels that produce high carbon emissions (e.g., coal) to more efficient fuels such as natural gas and electricity.

Fig. 6 Trends of Shanghai's URPDS



The energy consumption of households changed from raw coal, natural gas and electricity into natural gas, gasoline diesel oil and electricity. The net result is that the energy mix consumed by the 2 household sectors became less carbon-intensive. During the 3 study periods, the changes of household energy mix reduces 15.04×10^4, -8.08×10^4, and -1.12×10^4 t CO_2 emission respectively (Fig. 2). The inhibitory effect of the energy mix consumed by the household sectors was becoming small in the 3 study periods.

Due to the energy mix improving, the changes of EMT brings 66.00, 155.57 and 80.74 carbon reduction, while the changes of EMH brings 15.04, 8.08 and 1.12 t carbon reduction respectively during the 3 study periods. EMT and EMH improvement act as 2 of the important factors to reduce CO_2 emission in Shanghai.

3.2.3 The Fluctuating Driving Forces of CO_2 Emission

During the 3 study periods, the contribution of changes in ES to the changes in carbon emissions fluctuated, from reduction of 117.12×10^4 t during the first period to increase of 42.13×10^4 t during the second period and finally to a decrease of 275.93×10^4 t during the last period (Fig. 2). The proportion of GDP accounted for by the output value of primary industry increased and then decreased, whereas the proportion of GDP accounted for by secondary industry, construction, transportation, storage and postal system sector, WRTHR and other production sectors increased continuously (Fig. 7).

The results also show that the energy intensities of secondary industry, of TSPS, and of the primary industry were greater than those of the construction, WRTHR, and the other production sectors (Fig. 4).

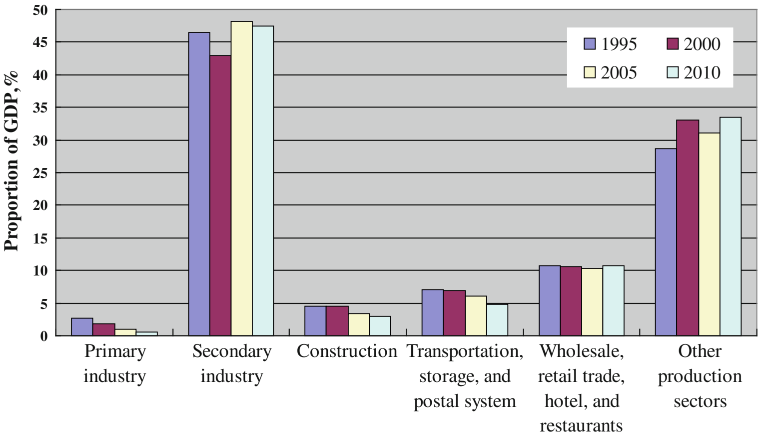


Fig. 7 Trends of Shanghai's economic structure

The ES of Shanghai has been adjusted since 1995, the proportions of GDP accounted for by the primary sector, by the transportation, storage and postal sector, and by construction decreased. While the proportions accounted for by secondary industry, by WRTHR, and by the other production sectors showed fluctuation. Because the adjustments of the ES sometimes increased and sometimes decreased carbon emissions, the proportion accounted for by secondary industry fluctuated, which causes the synchronous fluctuations in sector's effect on carbon emissions.

During the 3 study periods, the contributions of changes in EMP to the changes in carbon emissions were 58.51×10^4, -25.60×10^4, and -19.12×10^4 t, respectively (Fig. 2).

The main changes in EMP are that the proportion of secondary industry's energy consumption accounted for by raw coal firstly increased quickly and then slowly. The proportion of energy consumption by the other production sectors accounted for by raw coal decreased quickly, while the proportions accounted for by natural gas and electricity surged. And the proportion of energy consumption by WRTHR accounted for by LPG and heat increased.

The carbon-emission coefficients are highest for coal, followed by oil and various forms of gas. The coefficients for electricity and heat were assumed to be 0 in this study. In the energy transformation sectors, if the coal or oil has not combusted and hasn't given off CO_2, then transformation is just from one coal and oil product into another coal or oil products, the coefficients for the transformed coal products and oil products are 0. Because the proportions accounted for by energies with higher carbon-emission coefficients decreased and the proportions accounted for by energies with lower coefficients increased, this led to the less carbon-intensive EMP.

The adjustment of the energy mix consumed by the production sectors strengthened throughout the study period, so the inhibitory effect of the energy mix continued to increase (Fig. 7).

Due to the unstable energy demands, the changes of ETS bring to 170.50 and 6.08 t carbon emission increase in the first and third periods, but bring to 23.39 t carbon emission reduction in the second period. Therefore, ETS is one of the fluctuating driving forces of CO_2 emission.

4 Conclusions

This paper estimated and analyzed the energy-related carbon emissions by using the data of 19 type of energy, 6 production sectors, 2 household sectors, 3 transformation sectors and 11 driving factors in Shanghai. That is a finer resolution than that of the previous studies. It will provide a scientific basis of designing emission-reduction measures for policy-makers.

From 1995 to 2010, Shanghai's energy-related carbon emissions increased continuously, which is mainly caused by production, household and energy transformation sectors. Secondary industry, thermal power and TSPS accounted for a large proportion of total carbon emissions. Changes in EA, PS, ECPC and TET stimulated emissions throughout the study period. Whereas changes in EI, the URPDS, EMT and EMH decreased emissions. In addition, changes in the ES, EMP and ETS had fluctuating effects on emissions. Changes in EA belong to the dominant stimulatory factor. However changes in EI belong to the dominant inhibitory factor. The EI of secondary industries decreased continuously, which strongly reduced the CO_2 emissions. Changes in the ES played a strong role in reducing carbon emissions from 2005 to 2010. Changes in EMH decreased emissions slightly. Changes in the energy mix consumed in the energy transformation obviously decreased the CO_2 emission. The effect of changes in the EMP show a weak increasing trend.

The results show that the decrease of CO_2 emission caused by the changes of EI, URPDS, and EMT can not offset the CO_2 emission increase caused by EA, PS, ECPC and TET. The total CO_2 emission increased quickly in the studying periods.

Therefore, the main approaches to reduce Shanghai's carbon emissions in the future will be continuing to reducing the EI of the production sectors, to adjust the ES to favor less energy-intensive sectors, to improve energy transformation efficiency and to improve the energy mix to favor energy sources with lower carbon emissions per unit of energy consumed and enforcement of carbon capture. Certainly, enhancing clean energy alternative to fossil energy and carbon capture will be the fundamental way of reducing carbon dioxide emissions.

This study can provide a more scientific basis for policy-makers to develop policies to reduce carbon emissions due to the analysis with finer resolution. Certainly, there is still room for improvement in the study. For example, the production and energy transformation sectors were divided more coarsely than is desirable because of no enough available data for higher resolution. This study assumed that all combustion processes are 100 % efficient, this was unrealistic. Among the carbon emissions from energy transformation processes, we only considered emissions from electricity, heat generation and the other that was divided more coarsely too.

In the future research, we plan to divide the production and energy transformation sectors more finely as data with higher resolution becomes available, incorporate a coefficient to account for incomplete combustion, and add carbon emissions from other energy transformation processes (e.g., petroleum refineries, gas work). Moreover, carbon emissions result from many processes (e.g., iron and steel smelting, non-ferrous metal smelting, cement production, et al.), and other indirect emission from electricity and heat should be included in the analysis.

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