Decomposition analysis of air pollution abatement in China: Empirical study for ten industrial sectors from 1998 to 2009

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ABSTRACT

This study analyzes air pollutant substances management in Chinese industrial sectors from 1998 to 2009. Decomposition analysis applying the logarithmic mean divisia index is used to analyze changes in air pollutant substances emissions by the following five factors: coal pollution intensity (CPI), end-of-pipe treatment (EOP), energy mix (EM), productive efficiency change (EFF), and production scale changes (PSC). We focus on the three pollutants which are sulfur dioxide (SO_2), dust substance, and soot substance. We clarify SO_2 emissions from Chinese industrial sectors have increased because of the increase in the production scale. However, the inducing EOP equipment and improvements in energy efficiency have prevented an increase in SO_2 emissions commensurate with the production increasing. Second, soot emissions were successfully reduced and controlled in all industries except the steel industry between 1998 and 2009, even though the production scale expanded for these industries. This reduction is achieved because of improvements in the EOP equipment technology and in energy efficiency. Finally, dust emissions decreased by nearly 65% between 1998 and 2009 in the Chinese industrial sectors. This successful emissions reduction was achieved by implementing EOP and pollution prevention activities during the production processes, especially in the cement industry. We clarify that pollution prevention effect in cement industry is mainly caused by production technological development rather than scale merit.

Keyword: Pollution prevention, End-of-pipe, Air pollution, Scale merit, China.

1. Introduction and background

China, currently facing a serious environmental problem, has identified air pollution as a high-priority issue that it must be address immediately. China became the world's largest sulfur dioxide (SO_2) emitter in 2005 (Su et.al., 2011), and it is now evident that many of the existing air pollution problems are the result of these significant SO_2 emissions. According to You and Xu (2010), economic losses due to acid rain and acid deposition in China amounted to 176.42 billion yuan in 2000, which is 1.97% of China's gross domestic product.

Furthermore, industrial sectors discharge large amounts of soot and dust substances into the air[1]. Because of these serious air pollution problems, twenty Chinese cities were listed among the world's thirty most polluted cities (World Bank, 2007). These air pollution problems affect human health (Kan and Chen, 2004). For example, the mortality rate from respiratory diseases in China is over 17%, making it the third largest killer after circulatory disease and cancer (Ministry of Health, 2008), whereas the world average mortality rate from respiratory diseases is less than 8% (WHO, 2011). Because SO_2, soot, and dust particles are the main air pollution substances that cause respiratory diseases, it is immediately needed to reduce these pollutants emission to improve the overall condition of people's health (Xie et al., 2005).

To solve these air pollution problems, the Chinese government implemented a large number of environmental regulations and projects to promote better air pollution management in the Chinese industrial sectors (see Table 1). First, as early as 1973, environmental regulations for air pollution abatement were enforced. These regulations focused on the discharge standards of industrial wastewater, waste gas, and solid waste. Subsequent to those early regulations, many environmental laws regarding air pollution were revised and enforced (e.g., the law on prevention and control of air pollution in 1987 and the

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[1] Soot is generated by the imperfect combustion of fossil fuels, which is mainly produced in a boiler. Dust is particulate matter that is mainly generated by production processes such as crushing operations and polish finishing. Dust also includes coal combustion fly ash, the share of which in total dust substances is low in the industrial sector. Thus, dust substances are not strongly correlated with fossil fuel combustion processes in comparison with SO_2 and soot substances.

integrated emissions standard of air pollutants in 1997).

<Table 1 about here>

Because of these environmental regulations and policies, soot and dust emissions were reduced in the late 1990s (see Figure 1). During the same period, however, SO_2 emissions did not decrease but instead increased rapidly after 2003. Because SO_2 and soot are generated primarily in the fossil fuel burning process, the amounts of generation of these two air pollutants are correlated. However, we find different trends for the emissions levels between SO_2 and soot substances (see Figure 1). These differences in emission amounts can be explained by the following two conditions.

First, the diffusion rate of fuel gas desulfurization (FGD) equipment was low in China in the late 1990s and early 2000s (see Figure 1). According to You and Xu (2010), the investment cost for FGD equipment shares was approximately 18% of total investment in electric industry sector before 1998. This high proportion of investment costs is likely due to the high level of engineering technology required for FGD equipment, which was unavailable to Chinese domestic companies in the late 1990s and early 2000s. Most of the FGD equipment in China had been imported from developed countries. Meanwhile, in the 1990s, domestic companies in China produced electrostatic precipitators (ESP) and bag houses, which collect soot particles and do not require a high level of technology[2]. Consequently, ESPs and bag houses could be manufactured at a lower cost, and therefore they were more easily developed and distributed in China than FGD equipment.

Second, fuel burning technology is more efficiently developed because soot is the result of the incomplete combustion of heavy oil and coal product as fuels. Thus, the complete combustion of fossil

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[2] Expansion of China's cement industry slowed and the new emissions standard released in 1996 promoted the application of electrostatic precipitators (ESPs) in shaft kilns, resulting in an industry-wide decrease in air pollution emissions (Lei et al., 2011).

fuels can prevent or minimize soot substances generation. Additionally, incomplete combustion causes inefficient energy use, which raises the cost of production for the company. To solve these problems, the Chinese government restricted the use of small and inefficient fuel combustion boilers[3]. Because of these environmental regulations, more efficient boilers were developed.

<Figure 1 about here>

2. Research question and objective

Air pollution substance emissions depend strongly on industrial characteristics because pollutants are the result of various industrial operations. Characteristics differ among industries and include intermediate material input, fuel burning processes, and production processes (see Table 2). Additionally, available air pollution abatement technology and costs also differ among industries.

Table 2 shows that the electric industry discharged huge amounts of SO_2, comprising 57% of the SO_2 emissions in the entire industry in 2009. Soot is discharged mainly by the cement, steel, and electric industries, whereas dust is generated primarily by the cement and steel industries. In fact, the dust emissions from these latter two industries comprised more than 85% of the total dust emissions from whole Chinese industrial sector in 2009. The removal ratios for these three pollutants vary significantly because of the high costs associated with the installation of FGD equipment necessary for reducing SO_2 emissions.

<Table 2 about here>

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[3] For example, Integrated emissions standard of air pollutants, Emissions standard of air pollutants for industrial kiln and furnace, and Emissions standard of air pollutants for coke oven were enforced in 1997 in China. Additionally, emissions standard of air pollutants for coal-burning, oil-burning, gas-fired boiler was implemented in 2001 (see table 1).

Cement, steel, and electric industries tend to discharge large amount of air pollution substances in China. They also have higher air pollution intensity than others. In the meantime, machinery industry discharges a little amount of air pollution substances and has lower air pollution intensity. This is because main energy source of machinery industry is electricity which does not generate air pollution substances in energy use process. Thus, we can understand that industrial air pollution intensity depends on the industrial characteristics. Understanding the differences of these industrial characteristics is important for considering why and how air pollution emission treatment had been implemented in China.

There are many studies focusing on air pollution problems in the Chinese industrial sectors (e.g., Zhang and Wen, 2008; Gao et al., 2009; Fang et al., 2009; He, J., 2010; Kaneko et al., 2010; Lei et al., 2011; Ma et al., 2012). However, no previous studies have analyzed industrial air pollutant emissions management by focusing on treatment (e.g. end-of-pipe, pollution prevention) according to the type of business and the specific pollution substances. This approach is necessary because the technical difficulty associated with reducing the emissions of air pollutants differs by industries and by pollution substances. It is also clear that the required capital equipment and abatement costs for reducing air pollutants vary by industries because the chemical products consumed as intermediate materials are different. Therefore, the characteristics of an industry must be considered when analyzing solutions to the problem of air pollution. The objective of this study is to clarify how the Chinese industrial sectors reduced or increased air pollutant emissions between 1998 and 2009 by industry type.

3. Data and Model

3-1. Data

We use three air pollutant emissions variables: SO_2 emissions, soot emissions, and dust emissions because these pollutants are considered high-priority substances in China that must be treated[4]. Furthermore, these three pollutants are object substances of China's levy system.

We apply two data variables for air pollution, emissions amount data and removal amount data, taken from the China Statistical Yearbook (CSY)[5]. We also have the sale data and producer price indices as a deflator by type of industry from the CSY. We access coal consumption data and total energy use data from the China Energy Statistical Yearbook (CESY). The data for decomposition analysis by type of industrial sector cover twelve years from 1998 to 2009. There are three reasons why we focus on this time periods.

First is coverage of pollution data in CSY is different before and after 1998. Fujikura et al. (2006) estimated SO_2 emissions using energy consumption data and combustion efficiency in China and compared the results with the data in CSY. They concluded that pollution emissions data in 1996 and 1997 did not include the emissions from township and village industrial enterprises (TVIEs) even though sale and energy use data of TVIEs were included. To avoid the differences of data coverage among energy, economy data, and pollution data, we select our research time period after 1998.

Second is that Chinese government implemented several new environmental policies in this period (see Table 1). Thus, we can consider the effect of new environmental policy to reduce air pollution emissions by comparing before and after environmental policy implemented. Third is, Chinese domestic manufacturer of environmental protection equipment had technological progress to produce more cost-effective product to remove emissions in this period (Kaneko et.al., 2010). Thus, we can clarify how each polluted industrial sector react the air pollution problems with new environmental standards and

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[4] Nitrogen oxide (NOx) is also important substances to improve air quality problem in China. However, NOx is mainly emitted by automobile. According to Yi et al. (2007), NOx emission from motor vehicles accounted for 41% ~ 70% of total urban NOx pollution in 2002. Additionally, CSY does not cover the industrial NOx emission data. Thus, we do not focus NOx in this study.

[5] The data coverage of CSY is not included some of small scale firm and pointed out the emission data is underestimated. While, we consider the effect of underestimation is limited, which does not affect significantly to our results. Additionally, there are many journal papers using the data of CSY because CSY is only dataset which has comprehensive environmental data published by Chinese government during long time. Based on these points, we use data of CSY for our estimation.

technology, which is important empirical evidence for environmental policy making considering industrial characteristics.

This study focuses on ten industrial sectors which are mining, food and beverage, textile, paper and pulp, chemical, cement, steel, non-ferrous metal, machine, and electric industries. These ten industries account for a substantial share of the air pollutant emissions of SO_2 (93%), soot (91%), and dust (91%) in the entire industry in China in 2009 (CSY 2010). We also use data for the entire industrial sector to understand the overall trend.

This study uses two variables of air pollutant data, the total release of air pollution (E) and the total removed amount of air pollution (R). We create one additional variable, namely, total generation amount of air pollution (G), defined as "$G = E + R$". Additionally, we use two energy variables, total energy consumption (ENE), and coal and coke consumption (C) from CESY[6]. We apply the sales data deflated 2005 prices as production of each industry (Y).

3-2. Model

3-2-1. Decomposition model for SO_2 and Soot emissions

We establish two decomposition models. The first model analyzes SO_2 and soot emissions, which are strongly correlated with coal combustion. To decompose emissions changes of these two air pollutants, we use the following five indicators: the end-of-pipe treatment (EOP), the coal pollution intensity (CPI), the energy mix (EM), the productive efficiency change (EFF), and the production scale change (PSC). We define the EOP indicator as calculated by E/G, which means the share of emissions in the total generation. This indicator can be decreased if the share of the removed amount in the total air pollutant generation is increased. Because pollution removal can be achieved by an EOP treatment, the E/G indicator reflects the

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[6] To avoid the double counting of energy consumption from coal and coke, we canceled out the amount of coal consumption which is input as coking process by using energy balance matrix data provided by CESY.

end-of-pipe treatment activity.

Next, the CPI indicator is defined as G/C, which yields air pollutant generation per amount of coal and coke consumption. Air pollution substances are generated by fossil fuel combustion processes, especially coal and coal products combustion (Fujikura et al., 2006). Based on a study by Chen and Xu (2010), coal is responsible for 90% of the SO_2 emissions and 70% of the soot emissions in China. Therefore, we focus on the relationship between coal products consumption and air pollution generation in China. The CPI indicator can be decreased by reducing the generation of air pollutants while keeping the amount of coal products combustion constant. This reduction can be achieved by a quality change from high pollution intensity coal to low pollution intensity coal (i.e., a shift to low sulfur content coal) and by improving the inefficient and imperfect combustion of coal.

The EM indicator represents the share of coal consumption for total energy use. This indicator can be decreased if coal consumption decreases (increases) more rapidly (slowly) than total energy use. The EM indicator reflects the dependency on coal with respect to total energy use. Next, the EFF indicator is calculated by total energy use per revenue. This indicator reflects the energy efficiency of production process. EFF can be decreased by reducing the total energy consumption while keeping the total revenue constant, or increasing the total revenue without total energy consumption growth.

Finally, the PSC indicator shows the change in the amounts of production. It is difficult to collect data on product amount by type of products. Therefore, total revenue data deflated by 2005 prices are used as a proxy for production amount data. Generally, the volume of air pollutants depends on the fossil fuel consumption amounts that generate air pollution substances during the combustion processes. Furthermore, fossil fuel consumption also strongly correlates with production amount because the industrial sector requires the energy use for its production processes. As a result, the production scale becomes one factor for determining air pollutant emissions. The air pollution emissions amount (E) is decomposed as in equation (1).

$$\mathrm{E} = \mathrm{E/G} \times \mathrm{G/C} \times \mathrm{C/ENE} \times \mathrm{ENE/Y} \times \mathrm{Y} = \mathrm{EOP} \times \mathrm{CPI} \times \mathrm{EM} \times \mathrm{EFF} \times \mathrm{PSC} \qquad (1)$$

We consider the emissions change from t-1 year (E^{t-1}) to t year (E^{t}). By using equation (1), the growth ratio of emissions can be represented as follows.

$$\frac{\mathrm{E}_i^t}{\mathrm{E}_i^{t-1}} = \frac{\mathrm{EOP}^t}{\mathrm{EOP}^{t-1}} \times \frac{\mathrm{CPI}^t}{\mathrm{CPI}^{t-1}} \times \frac{\mathrm{EM}^t}{\mathrm{EM}^{t-1}} \times \frac{\mathrm{EFF}^\mathrm{t}}{\mathrm{EFF}^\mathrm{t-1}} \times \frac{\mathrm{PSC}^t}{\mathrm{PSC}^{t-1}} \qquad (2)$$

We transform equation (2) to a natural logarithmic function and thus obtain equation (3)[7].

$$\ln\mathrm{E}_i^t - \ln\mathrm{E}_i^{t-1} = \ln\left(\frac{\mathrm{EOP}^t}{\mathrm{EOP}^{t-1}}\right) + \ln\left(\frac{\mathrm{CPI}^t}{\mathrm{CPI}^{t-1}}\right) + \ln\left(\frac{\mathrm{EM}^t}{\mathrm{EM}^{t-1}}\right) + \ln\left(\frac{\mathrm{EFF}^\mathrm{t}}{\mathrm{EFF}^\mathrm{t-1}}\right) + \ln\left(\frac{\mathrm{PSC}^t}{\mathrm{PSC}^{t-1}}\right) \qquad (3)$$

Multiplying both sides of equation (3) by $\omega_i^t = (\mathrm{E}_i^t - \mathrm{E}_i^{t-1})/(\ln\mathrm{E}_i^t - \ln\mathrm{E}_i^{t-1})$ yields equation (4), as follows.[8]

$$\mathrm{E}_i^t - \mathrm{E}_i^{t-1} = \triangle\mathrm{E}_i^{t,t-1} = \omega_i^t\ln\left(\frac{\mathrm{EOP}^t}{\mathrm{EOP}^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{CPI}^t}{\mathrm{CPI}^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{EM}^t}{\mathrm{EM}^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{EFF}^\mathrm{t}}{\mathrm{EFF}^\mathrm{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{PSC}^t}{\mathrm{PSC}^{t-1}}\right) \qquad (4)$$

Therefore, changes in the emissions of air pollution substance *i* ($\triangle\mathrm{E}_i$) is decomposed by the changes in EOP (first term), CPI (second term), EM (third term), EFF (fourth term,), and PSC (fifth term).

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[7] If there is a case of zero value in the dataset, it causes problems in the formulation of the decomposition because of the properties of logarithmic function. To solve this problem, the literature on LMDI suggests replacing the zero value with a small positive number (Ang and Liu, 2007).

[8] $\omega_i^t = 0$ if $\mathrm{E}_i^t = \mathrm{E}_i^{t-1}$.

The term ω_i^t operates as an additive weight of emissions estimated within the LMDI framework. This decomposition technique of emission change factor is called logarithmic mean Divisia index (LMDI) developed by Ang et al. (1998). LMDI has been applied mainly to energy studies (Charlita de Freitas and Kaneko, 2011). Recently, decomposition framework was applied to chemical pollution issues (e.g. He, 2010; Fujii and Managi, forthcoming). Ang (2004) noted that LMDI is the preferred method for decomposition analysis because of its theoretical foundation, adaptability, ease of use and results interpretation, and lack of a residual term, which is generated by Laspeyres-type methodologies.

3-2-2. Decomposition model for Dust emissions

We introduce another decomposition model to analyze dust emissions. Because dust emissions are not strongly correlated with fossil fuel combustion, we use the pollution prevention (PP) indicator as substitute for CPI, EM, and EFF indicators. We use the following framework for the decomposition analysis of dust emissions.

$$\mathrm{E} = \mathrm{E}/\mathrm{G} \times \mathrm{G}/\mathrm{Y} \times \mathrm{Y} = \mathrm{EOP} \times \mathrm{PP} \times \mathrm{PSC} \qquad (5)$$

Here, the PP indicator defined by dust generation per production reflects the performance of dust generation prevention during the production process. The PP indicator goes down if dust generation decreases while maintaining the same amount of production or if production amounts increase without growth amount of dust generation. The amount of dust generation is correlated with resource inefficiency of production. The PP indicator can be decreased by an improved production process and product design, thereby reducing the intermediate input amount. We also apply the LMDI approach in this framework and obtain equation (6). Thus, we can decompose the change in dust emissions into EOP treatment effect (first term), pollution prevention effect (second term), and production scale change effect (third term).

$$\mathrm{E}_i^t - \mathrm{E}_i^{t-1} = \triangle \mathrm{E}_i^{t,t-1} = \omega_i^t \ln\left(\frac{\mathrm{EOP}^t}{\mathrm{EOP}^{t-1}}\right) + \omega_i^t \ln\left(\frac{\mathrm{PP}^t}{\mathrm{PP}^{t-1}}\right) + \omega_i^t \ln\left(\frac{\mathrm{PSC}^t}{\mathrm{PSC}^{t-1}}\right) \tag{6}$$

3-2-3. Decomposition model for scale merit effect

Li and Wang (2012) pointed out pollution reduction is achieved by rigorous policy of elimination of inefficient excess production capacities, in particular the small coal mines, obsolete power plants as well as manufacturing sectors. Government also promoted transferring the production allowances from small to large scale firms under China's Eleventh Five-Year plan (for 2006 through 2010)[9]. Cai et al. (2009) summarized the impact of policy of closing down small and inefficient firms focusing three Chinese industries which are coal-fired power plant, cement, and aluminum industries. They showed the energy use efficiency are improved by reconstruction and scale up in three industries. Thus, policy of elimination of small and inefficient firms have important role to improve technological development of Chinese manufacturing sectors. However, there is no previous study focusing on the elimination policy impact to air pollution management in China by type of industry. One reason of that is limitation of data access about emissions from old and new production equipment, and investment data for new building and update equipment for industries. Considering this data limitation, we try to clarify the scale merit impact for pollution abatement technology in Chinese industrial sectors by using the number of firms and sales data which are available to access by CSY. We set decomposition framework focusing on the environmental efficiency (EE)[10] as follows.

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[9] According to Price et al. (2011), in 2007, China's State Council announced a Comprehensive Working Plan of Energy Conservation and Emission Reduction to accelerate the closing of small plants and outdated capacity in 14 high energy-consumption industries: electric power, iron-making, steel-making, electrolytic aluminum, ferroalloy, calcium carbide, coking, cement, coal, plate glass, pulp and paper, alcohol, monosodium glutamate, and citric acid. The policy estimates that the closures will save 118 Mtce (3.46 EJ) and reduce 2.4 Mt of sulfur dioxide (SO_2) by 2010.

[10] In general, environmental efficiency is defined as desirable output (e.g. sales, production) per pollution emissions. In other words, EE is the inverted score of environmental pollution per unit of production, which represents the production scale-adjusted environmental pollution which is strongly related production technology.

$$EE = \frac{Y}{E} = \frac{Y_S + Y_L}{E} = \frac{Y_S}{E} + \frac{Y_L}{E} = \frac{N_S}{E} \times \frac{Y_S}{N_S} + \frac{N_L}{E} \times \frac{Y_L}{N_L} \tag{7}$$

Where, Y_S is the total revenue of small scale firms, N_S is the number of small scale firms, Y_L is the total revenue of large and medium scale firms, and N_L is the number of large and medium scale firms. The left side of equation (7) represents environmental efficiency which is defined by total revenue per air pollution emissions. the Number of firms per emissions show that inverted score of pollution per firms, which reflect pollution abatement technology of firm (TECH). Then, decrease of TECH indicator represents increase emission amount per firm. While, the sales per number of firms shows that the productions scale of individual firm (SCALE). Increase of SCALE indicator reflects the scale up of individual firm production. Because the number of firms and the sales data by firm scale is available from CSY from 1999 to 2009, we calculate two indicators by firm scale group (small scale firm or medium and large scale firm[11]). Applying LMDI into equation (7), we have equation (8) as follows.

$$EE^{t} - EE^{t-1} = \Delta EE^{t,t-1} = \varphi_i^t \ln\left(\frac{TECH_S^t}{TECH_S^{t-1}}\right) + \varphi_i^t \ln\left(\frac{SCALE_S^t}{SCALE_S^{t-1}}\right) + \varphi_i^t \ln\left(\frac{TECH_L^t}{TECH_L^{t-1}}\right) + \varphi_i^t \ln\left(\frac{SCALE_L^t}{SCALE_L^{t-1}}\right) \tag{8}$$

The term $\varphi_i^t = (\mathrm{EE}_i^t - \mathrm{EE}_i^{t-1})/[\ln(\mathrm{EE}_i^t) - \ln(\mathrm{EE}_i^{t-1})]$ operates as an additive weight of EE estimated within the LMDI framework. Changes in the EE is decomposed by the changes in $\mathrm{TECH_S}$ (first term, effect of number of small scale firm per emissions), $\mathrm{SCALE_S}$ (second term, effect of production scale change within small firm group), $\mathrm{TECH_L}$ (third term, effect of number of large and medium scale firm per emissions), and $\mathrm{SCALE_L}$ (fourth term, effect of production scale change within large and medium firm

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[11] Firms which have both more than 1000 employees and annual sales of 400 million Yuan are defined as large scale. Firms which have both between 300 and 1000 employees and annual sales of 20 to 400 million Yuan are defined as medium scale (CSY 2010).

group). Comparing the each indicator's contribution effect into the EE change, we discuss the scale merit effect for pollution abatement technology change by type of industry.

4. Results and discussion

Table 3 through Table 5 and Figure 2 through Figure 4 show the accumulative changes in three air pollutants emissions calculated by the LMDI model. A positive score indicates an emissions increase, whereas a negative score indicates an emissions decrease. Each table reflects the accumulative change of absolute emissions and the ratios from 1998 to 2009 by industry and by pollution substance. In Figure 2 through Figure 4, the line chart indicates the accumulative emission change ratio compared in 1998, and the bar chart shows the cumulative effect of each indicator with respect to the emission change. The sum of the accumulated bars is equivalent to the charted line. To compare the results in each table and figure, we can distinguish the characteristics of air pollutant treatments by type of industry. Table 6 represents the result of decomposition analysis of environmental efficiency score by firm scale.

4-1. Results of SO_2 emissions

According to figure 2 and table 3, SO_2 emissions from entire industrial sector in China increase by 7% from 1998 to 2009. Although SO_2 emissions do not change much from 1998 to 2003, the cumulative emissions change of each factor is mixed during this period. In 2003, the cumulative effects of PSC affect SO_2 emissions to increase 68%. However, this emissions increase is countered by the effects of EOP, CPI, and EFF. After 2003, SO_2 emissions expand rapidly because of the significant effect of PSC. EOP and EFF contribute to emissions reduction, especially EOP affect to reduce emissions after 2005. One interpretation of this result is that China's Eleven Five-Year plan set the target to reduce SO_2 emissions by 10% and improve energy use per GDP by 20% between 2005 and 2010. Also included in the target goals was the incorporation of FGD equipment in a new coal-fired power plant. Additionally, the Chinese government promotes the development of environmental control equipment, such as FGD equipment and bag filters, for the domestic market. These governmental policies provide strong incentives for domestic equipment manufacturer to produce air pollution prevention equipment.

According to Kaneko et al. (2010), the number of coal-fired power plant facilities with installed FGD equipment increased from 886 in 2001 to 2,297 in 2006. Furthermore, the removal amount of SO_2 emissions increased from 0.7 million per ton to 4.1 million per ton during this period. Kaneko et al. (2010) pointed that this sharp increase of the installation of FGD equipment has been achieved by cost reduction for inducing FGD equipment due to technological development in domestic manufacturer.

Next, we consider the results by type of industries. According to the results in Table 3, five industries successfully reduced SO_2 emissions between 1998 and 2009. However, five industries increased SO_2 emissions, especially the steel and electric industries increase huge amount of SO_2 emission. Table 3 also shows that EOP and EFF contribute to reduce SO_2 emissions in all industries except EOP in machinery industry. There are two significant explanations for the effective reduction of SO_2 emissions by EOP, especially in the electric industry. First, the costs for installing the FGD have declined because of technological advancements in the domestic desulphurization company. Furthermore, with more than 100 desulphurization companies operating in China, the domestic FGD market has extensive competition. In addition, the localization rate of FGD equipment is constantly increasing, and as a result, the capital costs of desulphurization have fallen from 1,000 yuan/kW in the 1990s to approximately 200 yuan/kW in 2009 (Chen and Xu, 2010).

Second, the government promotes FGD equipment for thermal power plants by implementing projects. The Chinese government announced short-term goals for controlling SO_2 emissions from the electric industry in the Existing Thermal Power Plant SO_2 Control Plan in the Eleventh Five-Year Period (for 2006 through 2010). This plan calls for a total of 221 projects between 2006 and 2010. At the end of this period, several FGD units with a total capacity of 137 GW are to be installed in thermal power plants, thus reducing SO_2 emissions by 4.9 million tons per year (Li et al., 2011).

Meanwhile, the EFF effect contributes to all industries by reducing SO_2 emissions by more than 50%. Note that the main explanations for this reduction are the increase in energy prices and enforcement of the Chinese energy policy. Energy cost savings are strong motivation for improving energy efficiency for the firms. Since 2002, energy prices, including those for coal, oil and natural gas, have increased rapidly (Shafiee and Topal, 2010), motivating firms to reduce energy use. Furthermore, the Chinese government has attached great importance to energy conservation as a fundamental national policy. To meet the national target while continuing the robust development of China's industrial sector, the government is promoting to induce more modern and efficient production equipment to improve energy efficiency.

However, energy price increases provide incentives for firms to shift their energy input from oil and natural gas to coal because of the energy cost reduction. This energy substitution, hence, increases coal dependency in the Chinese industrial sectors. Because of this increase in coal dependency, the EM effect is positive, especially in the electric industries. Additionally, because China has a substantial coal resource, the Chinese government is attempting to satisfy the growing demand for electricity by building coal-fired power plants. This rapid thermal power plant building is another reason that the EM effect is positive in the electric industry.

Another effect of energy price increase is consumption growth of high sulfur content coal which is cheaper than low sulfur content coal. Zhao et al. (2010) pointed the concentrations of combustion-generated SO_2 were very closely related to sulfur content of coal. Rapid oil price increase during late 2000's make industrial sector switch their energy source from oil to coal. As a result of this fuel substitution for energy cost saving in many industrial firms, coal demand is growing and coal price increase, especially low sulfur content coal in China. From table 2, the CPI has positive effect to SO_2 emission increase in six industries including steel and electric. From these results, rapid oil price growth affect to increase SO_2 emissions in China though the coal dependency increase and consumption growth of high sulfur content coal.

Finally, PSC strongly affects the increase in SO_2 emissions in all industries. While, all industries have reduced SO_2 emissions by more than half of the PSC effect. Thus, the environmental activities for SO_2 emissions reduction in these industries are effective. However, SO_2 emissions amount increase due to PSC in the electric industry, suggesting that the electric industry has huge impact to increase amount of SO_2 emissions with the growth in production scale. As a consequence, most SO_2 substances are emitted by the electric industry in China. Furthermore, the demand for electricity in China is anticipated to increase rapidly in the near future, and the Chinese government has identified an increase electricity supply as a target of China's Twelve Five-Year plan (for 2011 through 2015)[12]. Therefore, promoting the use FGD equipment and decrease coal dependency, especially high sulfur content, are major priority for reducing SO_2 emissions with the increasing scale of the electricity supply.

<Figure 2 about here>

<Table 3 about here>

4-2. Results of soot emissions

Next, we consider the results of soot emissions in China. According to Figure 3, soot emissions

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[12] According to China Electricity Council (2011), Chinese government set the target to increase electricity supply capacity from 962 million kW in 2010 to 1,437 million kW in 2015, which include power generation capacity increase from 650 million kW to 933 million kW in Coal-fired power plant.

decreased because of both EOP and EFF treatments from 1998 to 2003. After 2003, soot emissions increased because of PSC increases but decreased again after 2005 by enhancing EOP and EFF. A negative EOP effect was achieved by installing soot collection equipment in China. Based on Chen and Xu (2010), soot emissions from the power sector in China were effectively controlled between 1980 and 2005 because of the popularization of high-efficiency electric soot removal systems, which have recorded removal efficiencies as high as 99.6%. Additionally, soot emissions were reduced by improvements in energy efficiency.

From the positive PSC effects, production scale expansion affect to increase soot emissions in Chinese industrial sectors. However, the technological progresses of EOP and production equipment have increased removal rates and energy efficiency, thus offsetting possible negative effects on soot emissions.

Next, we discuss the results by industry. In China, most soot emissions are emitted by the cement, steel, and electric industries (see Table 1). Table 4 shows that the cement and electric industry decreased soot emissions by 65% and 35% between 1998 and 2009, which was achieved mainly through EOP and EFF. However, soot emissions in the steel industry increase 46% between 1998 and 2009. In the steel industry, PSC and CPI are main factors behind this increase. Additionally, negative effect of the EM is small comparing with other industries. One interpretation of this result is that the steel industry uses coal both as a fuel and for oxidation-reduction reactions in shaft furnaces. In this case, without the technological innovation of the intermediate material technology, it is difficult to reduce coal and coke consumption while maintaining the same level of production[13]. Thus, Steel industry has difficulty to decrease coal dependency to reduce soot amount generations. Considering the industrial characteristics, more efficient coal use technology (i.e., clean coal technologies (CCTs)[14]) is important for the steel industry to reduce soot

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[13] Alternatively, electric arc furnaces, which use scrap steel as an intermediate material, can be used to make steel without huge inputs of coal. Shifting the steel production process to electric arc furnaces allows the steel industry to reduce the consumption of coal as an intermediate fuel. However, electric arc furnaces require a large stock of steel scrap (e.g., scrap cars), and the generation of this scrap metal increases with economic growth. To satisfy the huge steel product demand, Chinese steel firms need to produce steel using shaft furnaces.

[14] CCTs are technologies to use coal in a more environmentally friendly way. CCTs include liquefaction and gasification of coal, recycling of

emissions.

Table 4 shows that all industries except the steel industry successfully reduced soot emissions, even though production scales increased rapidly between 1998 and 2009. Additionally, soot emissions were reduced mainly because of the EOP and EFF effects in nine industries. Therefore, the reduction of soot emissions is mainly achieved as a result of the technological improvements of the EOP and production equipment in China.

<Figure 3 about here>

<Table 4 about here>

4-3. Results of dust emissions

Here, we discuss the results of dust emissions in China. According to figure 4 and table 5, the entire industrial sector in China reduced dust emissions by 64% between 1998 and 2009, especially decreasing rapidly from 1998 to 2001. During this period, dust emissions were reduced mainly by EOP. Chinese industrial sectors successfully reduced dust emissions even though the PSC affect to increase dust emissions strongly. One interpretation of this result is that dust emissions are strictly controlled through several environmental regulations established in 1997 (see Table 1). These environmental policy enforcements may be a main driver behind the installation of EOP equipment for dust emissions reduction in the Chinese industrial sectors.

PP contributes to reduce dust emissions in China, while EOP effect becomes smaller after 2005. This is because available amount of EOP treatment is strongly correlated with generation amount of dust

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coal ash, and removal of air pollution generated by coal combustion (Lu et al., 2008).

substances which can be reduced by PP treatment. In this case, the PP treatment absolutely affects the possible extent of the EOP treatment. The Chinese industrial sectors have decreased dust generation amounts in their production processes improvement, and this decrease is mainly achieved by the enforcement of two environmental policies: the law on the promotion of cleaner production in 2003 and the emissions standard for air pollutants for the cement industry in 2004. These new environmental policies provide strong incentives for firms to manage dust substances, especially in the cement industry, which contributed 71% of the dust emissions in the Chinese industrial sectors in 2004.

Next, we discuss the result by type of industries. From Table 5, we find the both EOP and PP contribute to reduce dust emissions in eight industries. The results in table 5 have several different points with table 3 and table 4. First, the electric industry reduces dust emissions, even though SO_2 and soot emissions increase. Second, the steel industry successfully controls dust emissions by EOP and PP, whereas SO_2 and soot emissions significantly increase. One interpretation of this result is that the generation process of dust emissions is different from that of SO_2 and soot emissions. On the one hand, SO_2 and soot substances are primarily the result of the process of fossil fuel burning. On the other hand, dust substances are primarily the result of production processes, including the polishing of products and the crushing of intermediate materials, neither of which is directly related to fossil fuel combustion. Because the creation of dust substances represents resource inefficiency during the production process, efficient production processes contribute both improving resource efficiency and decreasing dust generation.

We introduce a case study, "The Environment-oriented Cost Management (EoCM) Project in Zhejiang Province," as a success story in the prevention of dust emissions by the introduction of cleaner production.[15] The objective of the EoCM project is to improve the implementation of cleaner production in Zhejiang province. Intermediate cost-saving effects compensate the initial investment and the operating

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[15] The cleaner production approach is defined as "the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment" (UNEP, 2006).

costs associated with cleaner production in most of the firms. Additionally, cleaner production treatment contributes to reduced dust emissions. In fact, two of the pilot firms in the EoCM project successfully decreased dust emissions by more than 80% because of the cleaner production approach of the EoCM project (Hicks and Dietmar, 2007).

Table 5 shows that the change ratio of dust emissions between 1998 and 2009, indicating they were lower than the PSC effects in all industries. This result suggests that the Chinese industrial sectors successfully reduced dust emissions by implementing pollution prevention practices during the production process and by implementing removal treatment practices.

<Figure 4 about here>

<Table 5 about here>

4-4. Scale merit effect to environmental efficiency

Table 6 shows the results of contribution ratio to environmental efficiency change by firm scale from 1999 to 2009. EE_{SO2}, EE_{SOOT}, and EE_{DUST} represent environmental efficiency defined by sales per SO_2 emissions, soot emissions, and dust emissions, respectively. From table 6, EE_{SO2} is increased by 148% due to increase of $SCALE_L$ indicator which reflects production scale up within large and medium firms. Second biggest contributor is $TECH_L$ which increase 85% of EE_{SO2} from 1999 to 2009. Thus, improvement of EE_{SO2} is strongly affected by scale merit of production in Chinese industrial sectors. From table 6, this strong scale merit effect is observed in Steel and electric industries.

One interpretation of this result is these two industries have characteristics of having scale merit. According to Cai et al. (2009), China actively carries out command and control including the promotion of large power plants, closure of small ones, and the transfer of more generation allowances to bigger and cleaner generators. China closed down 14.38 GW installed capacity of small coal-fired power plant in 2007, which make average coal consumption per kWh decrease from 357gram in 2001 to 332 gram in 2007. Guo and Fu (2010) pointed out elimination of small and inefficiency firm significantly affect to reduce the overall energy consumption, the total emission of SO_2, the total soot emission, and the total mill dust emission per tonne of steel. Thus, we understand the elimination of small scale firms and scale up policy is strongly effective to the reduction of industrial SO_2 emissions, especially steel and electric industries which are first and second largest SO_2 emitter in Chinese industrial sectors in 2009.

Meanwhile, improvement of EE_{SOOT} and EE_{DUST} are mainly achieved by increasing of number of firms per emissions, especially cement industry. This result implies the reduction of soot and dust emissions from cement industry are mainly affected the increase of firms with modern technology rather than scale merit. According to Lei et al. (2011), nationwide replacement of shaft kilns with precalciner kilns from 2007 to 2008 led to a 20% of reduction in cement production from shaft kilns, which emit several times more SO_2 per mass unit of cement. They also pointed out dust and soot emissions gradually decreased due to the replacement of shaft kilns by precalciner kilns and the application of high-performance emission removal technology after 2004, although the average annual increase in cement production was greater than 12%. We understand our result is evidence what prove the major reasons for emissions reduction is massive closures of small and inefficient cement manufacturers with shaft kilns, which were replaced by new plants with horizontal rotary kilns.

5. Conclusion and policy implications

This article has analyzed how the Chinese industrial sectors have addressed the problem of air pollution and the effects of the changes made in the industrial sector on air pollution between 1998 and

2009. We focused on the three main air pollutants, SO_2, soot substances, and dust substances, and found the following three key results. First, SO_2 emissions from Chinese industrial sectors have increased because of the production scale expansion. However, improvements of energy efficiency have prevented an increase SO_2 generation commensurate with the scale change. Additionally, EOP treatment has contributed to reducing SO_2 emissions. The electric industry, which accounts for 55% of the SO_2 emissions in the industrial sector in 2009, tends to increase SO_2 emissions as the production scale growth. Therefore, the installation of FGD equipment at thermal power plants is a major priority for reducing SO_2 emissions from the Chinese industrial sectors. Furthermore, we clarify that electric and steel industries successfully improve their SO_2 emission abatement technology due to the scale merit of production.

Second, soot emissions were successfully reduced in all industries except the steel industry between 1998 and 2009, even though the production scale expanded for these industries. This reduction is achieved because of improvements in the EOP equipment technology and in energy efficiency. Many industrial sectors have reduced soot generation by decreasing their dependency on coal. However, the steel industry remains highly coal dependent, and thus it emits substantial amounts of soot. Consequently, implementing clean coal technology and production structure change from shaft furnaces to electric arc furnaces are important measures for controlling soot emissions from the steel industry.

Finally, dust emissions decreased by nearly one third between 1998 and 2009 in the Chinese industrial sectors. This successful emissions reduction was achieved by implementing EOP treatment and PP during the production processes, especially in the cement industry. We clarify the effect of PP is mainly caused by technological development rather than scale merit.

Further research is needed on emissions of NOx and particulate matter, including coal combustion fry ash from households and vehicle exhaust dust, which causes serious health problems in urban areas (Bi et al., 2007). Controlling these air emissions from the household and transportation sectors is another high-priority target for reducing health problem caused by air pollutants.

References

1. Ang BW. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 2004;32:1131-1139.
2. Ang B.W., F.Q. Zhang, and K.H. Choi. 1998. Factorizing changes in energy and environmental indicators through decomposition. Energy 23: 489-495.
3. Ang B.W. and N. Liu. 2007. Handling zero values in the logarithmic mean Divisia index decomposition approach. Energy Policy 35(1): 238-246.
4. Bi X, Feng Y, Wu J, Wang Y, Zhu T. Source apportionment of PM_{10} in six cities of northern China. Atmospheric Environment 2007;41:903–912.
5. Cai W., Wang C., Liu W., Mao Z., Yu H., Chen J. Sectoral analysis for international technology development and transfer: Cases of coal-fired power generation, cement and aluminium in China. Energy Policy 2009; 37(6): 2283-2291.
6. Charlita de Freitas L, Kaneko S. Decomposition of CO_2 emissions change from energy consumption in Brazil: Challenges and policy implications. Energy Policy 2011;39(3):1495-1504.
7. Chen W, Xu R. Clean coal technology development in China. Energy Policy 2010;38:2123–2130.
8. China electricity council. China electric industry development plan and research report. "中国电力行业发展规划研究报告". 2011. China Water & Power Press, Beijing, China.
9. Fang M., Chan, C.K., Yao, X. Managing air quality in a rapidly developing nation: China. Atmospheric Environment 2009; 43(1): 79–86.
10. Fujii H, Managi S. Decomposition of toxic chemical substance management in three U.S. manufacturing sectors from 1991 to 2008. Journal of Industrial Ecology, (forthcoming).
11. Fujikura R, Kaneko S, Nakayama H, Sawazu N. Coverage and reliability of Chinese statistics regarding sulfur dioxide emissions during the late 1990s. Environmental Economics and Policy Studies 2006;7(4):415-434.
12. Gao C, Yin H, Ai N, Huang Z. Historical analysis of SO_2 pollution control policies in China. Environmental Management 2009;43:447–457.
13. Guo ZC, Fu ZX. Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China. Energy 2010; 35(11): 4356-4360.
14. He J. What is the role of openness for China's aggregate industrial SO2 emission?: A structural analysis based on the Divisia decomposition method. Ecological Economics 2010;69(4):868-886.
15. Hicks C, Dietmar R. Improving cleaner production through the application of environmental management tools in China. Journal of Cleaner Production 2007;15(5):395-408.
16. Kan H, Chen B. Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. Science of The Total Environment 2004;322(1-3):71-79.

17. Kaneko S, Fujii H, Sawazu N, Fujikura R. Financial allocation strategy for the regional pollution abatement cost of reducing sulfur dioxide emissions in the thermal power sector in China. Energy Policy 2010; 38: 2131–2141.
18. Lei, Y., Zhang, Q., Nielsen, C., He, K.B. An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. Atmospheric Environment 2011; 45(1): 147–154.
19. Li L, Tan Z, Wang J, Xu J, Cai C, Hou Y. Energy conservation and emission reduction policies for the electric power industry in China. Energy Policy 2011;39(6):3669-3679.
20. Li J., Wang X. Energy and climate policy in China's twelfth five-year plan: A paradigm shift. Energy Policy 2012; 41: 519-528.
21. Lu X., Yu Z., Wu L., Yu J., Chen G., Fan M. Policy study on development and utilization of clean coal technology in China. Fuel Processing Technology 2008; 89(4): 475–484.
22. Ma S., Wen Z., Chen J. Scenario Analysis of Sulfur Dioxide Emissions Reduction Potential in China's Iron and Steel Industry. Journal of Industrial Ecology 2012; 16(4): 506-517.
23. Ministry of Health. China Health Statistical Yearbook 2008, Ministry of Health, Beijing;2008.
24. Price L., Levine MD., Zhou N., Fridley D., Aden N., Lu H., McNeil M., Zheng N., Qin Y., Yowargana P. Assessment of China's energy-saving and emission-reduction accomplishments and opportunities during the 11th Five Year Plan. Energy Policy 2011; 39(4): 2165-2178.
25. Shafiee S, Topal E. A long-term view of worldwide fossil fuel prices. Applied Energy 2010;87(3):988-1000.
26. Su S, Li B, Cui S, Tao S. Sulfur Dioxide Emissions from Combustion in China: From 1990 to 2007. Environmental Science and Technology 2011; 45: 8403-8410.
27. United Nations Environment Program (UNEP), Environmental Agreements and Cleaner Production, UNEP, 2006.
28. World Bank. East Asia and Pacific Regional Update, World Bank, Paris;2007.
29. World Health Organization (WHO). Causes of death 2008 summary tables, WHO, Geneva;2011.
30. Xie RK, Seip HM, Leinum JR, Winje T, Xiao JS. Chemical characterization of individual particles (PM10) from ambient air in Guiyang City, China. Science of The Total Environment 2005;343(1-3):261-272.
31. Yi, H., Hao, J., and Tang, X. Atmospheric environmental protection in China: current status, developmental trend and research emphasis. Energy Policy 2007; 35: 907–915.
32. You CF, Xu XC. Coal combustion and its pollution control in China. Energy 2010;35:4467–4472.
33. Zhang KM, Wen ZG. Review and challenges of policies of environmental protection and sustainable development in China. Journal of Environmental Management, 2008;88(4):1249-1261.
34. Zhao Y, Wang S, Nielsen C.P., Li X., Hao J. Establishment of a database of emission factors for

atmospheric pollutants from Chinese coal-fired power plants. Atmospheric Environment 2010; 44(12) : 1515–1523.

Table 1. History of laws and regulations for industrial air pollution in China

Year	Environmental regulations
Before 1986	The standard on discharge of industrial wastewater, waste gas, and solid waste (1973) Law on environmental protection (trial) promulgated (1979) Regulation on pollution levy (1982)
1986–1990	Law on prevention and control of air pollution (1987, revised 1995, 2000) National environmental protection agency was upgraded to an organization directly under the state council (1988) Law on environmental protection amended (1989)
1991–1995	Implementation of the law on air pollution prevention and control (1991) Second national conference on the prevention and control of industrial pollution proposes the notion of "three shifts" (1993) China's agenda 21 (1994)
1996–2000	Integrated emissions standard of air pollutants (1997) Emissions standard of air pollutants for industrial kiln and furnace (1997) Emissions standard of air pollutants for coke oven (1997) State council approves plotting programs for acid rain control region and SO_2 control region (enacted in 1998, implemented in 2002)
2001–2005	Emissions standard of air pollutants for coal-burning, oil-burning, gas-fired boiler (2001) Technology policies on SO_2 emissions control from coal combustion (2002) Law on the promotion of cleaner production (2003) State council issues the regulations on pollution levy (2003) Emissions standard of air pollutants for cement industry (2004)
2006–2010	Renewable energy law (2006) Comprehensive working plan of energy conservation and emission reduction (2007) State environmental protection administration was upgraded to ministry of environmental protection in China (2008) Measures on open environmental information (2008) Circular economy promotion law (2008)

Table 2. Characteristics of industrial air pollution by type of business in 2009

	SO_2 emissions amount	Soot emissions amount	Dust emissions amount	SO_2 Removal ratio	Soot Removal ratio	Dust Removal ratio	SO_2 emissions per sale	Soot emissions per sale	Dust emissions per sale
	(1,000 ton)	(1,000 ton)	(1,000 ton)	%	%	%	[ton/ million yuan]	[ton/ million yuan]	[ton/ million yuan]
Industrial sector	16,941	5,446	4,762	63%	98%	95%	33.18	10.67	9.33
Mining	409	164	264	66%	93%	61%	13.37	5.36	8.62
Food	386	242	7	31%	93%	95%	9.06	5.68	0.17
Textile	256	127	2	29%	92%	84%	7.81	3.86	0.05
Paper	457	192	8	34%	95%	66%	56.21	23.57	0.92
Chemical	975	417	112	54%	95%	90%	27.16	11.62	3.11
Cement	1,605	925	3,090	21%	92%	94%	69.39	39.99	133.59
Steel	1,702	518	841	43%	96%	97%	42.89	13.07	21.21
Non-ferrous metal	661	123	88	92%	97%	98%	34.51	6.41	4.61
Machine	46	30	30	21%	78%	94%	0.28	0.18	0.18
Electric	9,330	2,221	7	61%	99%	72%	305.19	72.67	0.22

Source: China environmental yearbook 2010.

Table 3. Results of SO_2 emissions by type of business from 1998 to 2009

	Emissions change (ton)	Emissions change (%)	EOP	CPI	EM	EFF	PSC
Industrial sector	1,077,379	7%	-84%	8%	-7%	-113%	203%
Mining	-432	0%	-86%	24%	3%	-117%	176%
Food	-78,501	-17%	-23%	0%	-19%	-119%	144%
Textile	-30,302	-11%	-21%	-8%	-41%	-94%	152%
Paper	97,907	27%	-35%	1%	-14%	-136%	212%
Chemical	34,398	4%	-36%	-13%	-17%	-130%	199%
Cement	-676,310	-30%	-11%	-68%	-6%	-88%	143%
Steel	911,520	115%	-74%	26%	-8%	-116%	288%
Non-ferrous metal	-39,572	-6%	-95%	26%	-45%	-119%	226%
Machine	-216,455	-82%	5%	-81%	-21%	-56%	70%
Electric	2,361,978	34%	-131%	33%	4%	-141%	269%

Table 4. Results of soot emissions by type of business from 1998 to 2009

	Emissions change (ton)	Emissions change (%)	EOP	CPI	EM	EFF	PSC
Industrial sector	-6,202,721	-53%	-127%	20%	-5%	-71%	130%
Mining	-828,458	-83%	-74%	-23%	-2%	-29%	44%
Food	-62,318	-20%	-67%	34%	-21%	-146%	180%
Textile	-21,941	-15%	-72%	45%	-35%	-81%	129%
Paper	-67,725	-26%	-96%	20%	-13%	-109%	172%
Chemical	-100,310	-19%	-70%	3%	-17%	-115%	178%
Cement	-1,744,504	-65%	-109%	12%	-5%	-56%	92%
Steel	164,039	46%	-168%	47%	-8%	-115%	291%
Non-ferrous metal	-22,926	-16%	-127%	30%	-58%	-153%	292%
Machine	-147,514	-83%	4%	-83%	-19%	-54%	69%
Electric	-1,198,294	-35%	-147%	16%	3%	-100%	194%

Table 5. Results of dust emissions by type of business from 1998 to 2009

	Emissions change (ton)	Emissions change (%)	EOP	PP	PSC
Industrial sector	-8,460,317	-64%	-98%	-76%	110%
Mining	97,215	58%	125%	-330%	264%
Food	-5,141	-41%	-58%	-230%	246%
Textile	612	56%	191%	-508%	372%
Paper	-96,954	-93%	-31%	-100%	38%
Chemical	-34,592	-24%	-92%	-117%	185%
Cement	-8,175,611	-73%	-98%	-62%	87%
Steel	-184,167	-18%	-106%	-113%	201%
Non-ferrous metal	-37,354	-30%	-103%	-212%	286%
Machine	-19,899	-40%	-94%	-70%	124%
Electric	-55,757	-89%	-3%	-209%	123%

Table 6. Results of contribution ratio to environmental efficiency change by firm scale from 1999 to 2009

	Change of EE_{SO2}				Change of EE_{SOOT}				Change of EE_{DUST}			
	$SCALE_S$	$TECH_S$	$SCALE_L$	$TECH_L$	$SCALE_S$	$TECH_S$	$SCALE_L$	$TECH_L$	$SCALE_S$	$TECH_S$	$SCALE_L$	$TECH_L$
Industrial sector	59%	82%	148%	85%	96%	224%	211%	301%	150%	414%	322%	576%
Mining	84%	74%	85%	178%	131%	186%	93%	471%	77%	46%	102%	93%
Food	97%	111%	136%	77%	87%	147%	114%	127%	176%	604%	208%	610%
Textile	40%	94%	70%	42%	43%	90%	78%	32%	44%	155%	73%	93%
Paper	101%	56%	154%	8%	160%	212%	227%	140%	409%	879%	460%	778%
Chemical	119%	117%	184%	32%	132%	165%	192%	84%	98%	128%	140%	65%
Cement	200%	250%	170%	89%	358%	613%	287%	273%	380%	800%	297%	384%
Steel	30%	1%	150%	25%	32%	23%	156%	129%	54%	67%	261%	328%
Non-ferrous metal	153%	210%	257%	240%	167%	362%	262%	467%	126%	350%	191%	465%
Machine	402%	928%	1483%	1445%	405%	919%	1367%	1548%	150%	250%	637%	258%
Electric	33%	8%	265%	55%	31%	76%	426%	299%	-63%	548%	1045%	1948%

* Score represent how much each indicator contributes to the accumulative change of environmental efficiency from 1999 to 2009. Summation of each score is equal to change of EE from 1999 to 2009 [$(EE^{2009}-EE^{1999}) / EE^{1999} = SCALE_S + TECH_S + SCALE_L + TECH_L$].

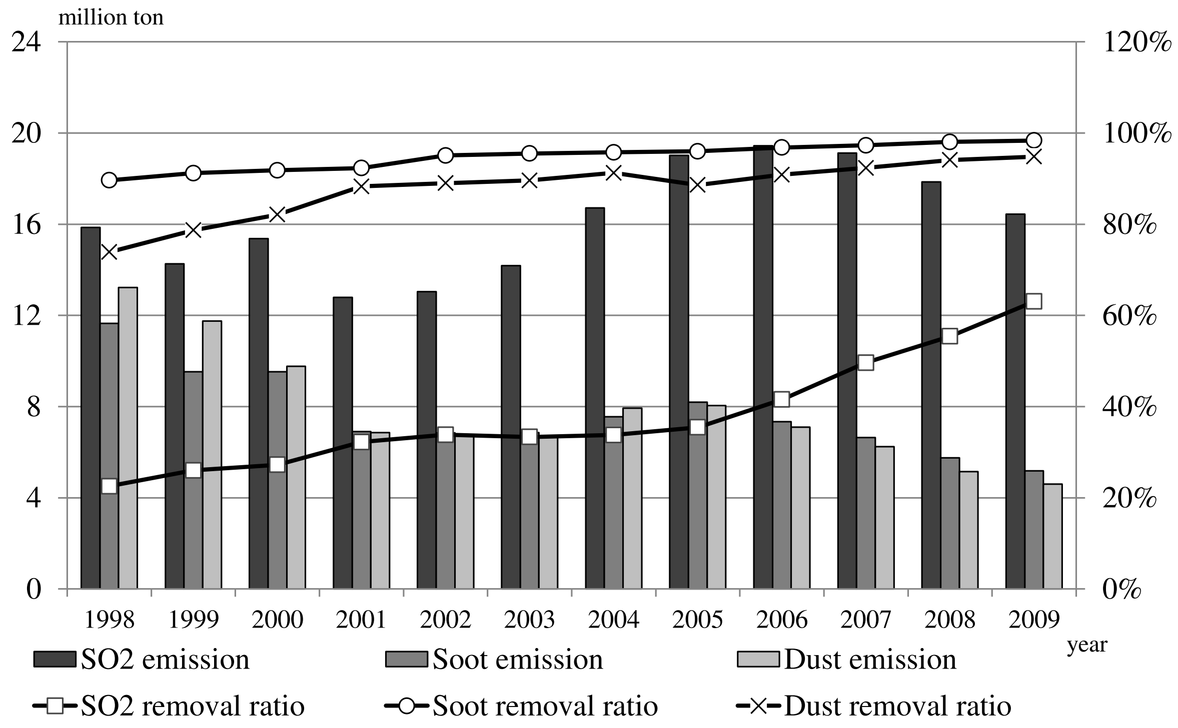

Figure 1. Emissions amount change in industrial air pollution

* Bar chart shows amount of emissions of each pollutant t (left axis, million ton).

** Removal ratio represents removal amount divided by emission amount plus removal amount (line chart, right axis).

*** Data source: China Statistical yearbook, each year.

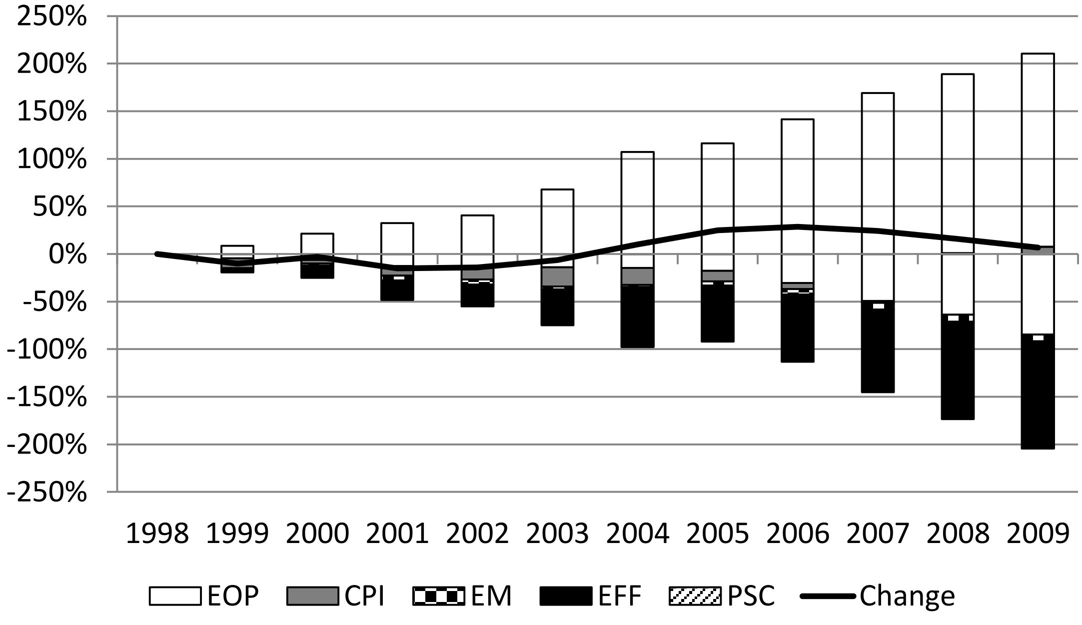

Figure 2. Results of SO_2 emissions in the entire industrial sector

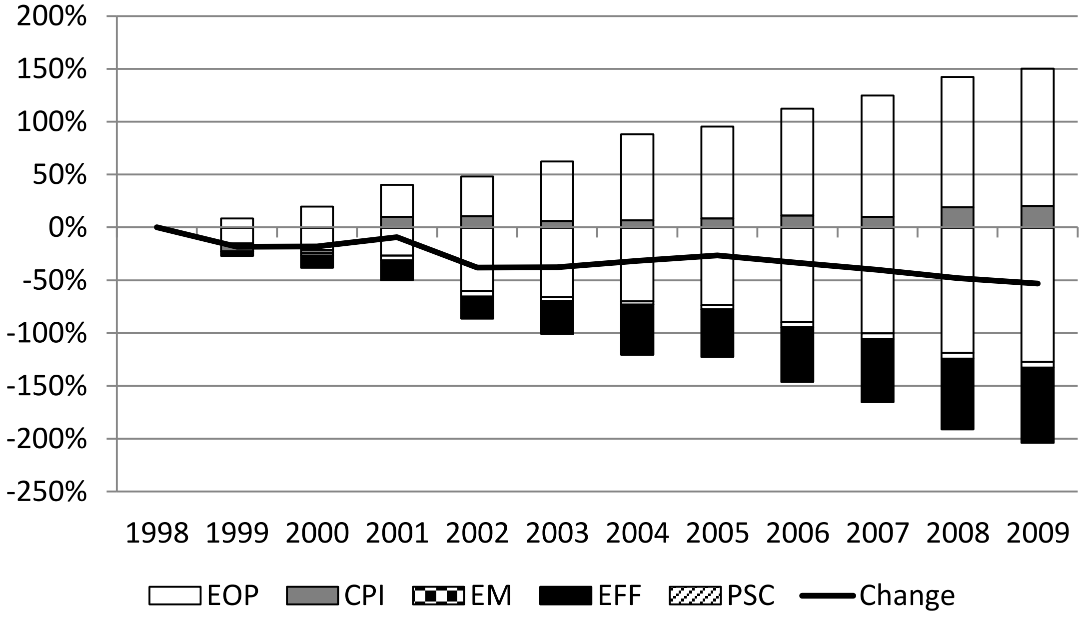

Figure 3. Results of soot emissions in the entire industrial sector

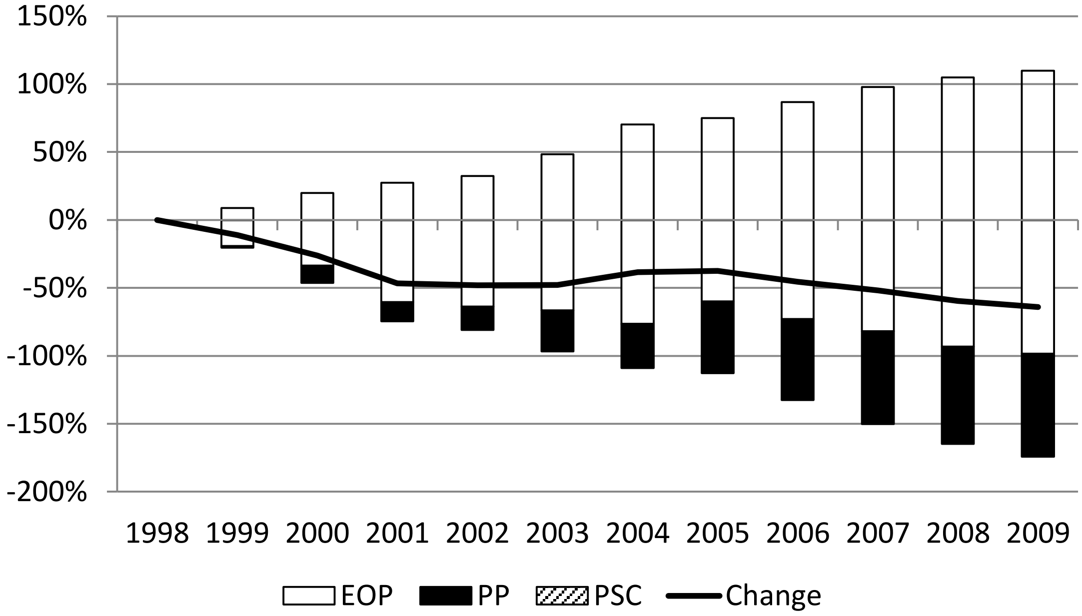

Figure 4. Results of dust emissions in the entire industrial sector.