An analysis of the driving forces behind pollutant emission reduction in Chinese industry

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ABSTRACT

The rapid economic development of China has been accompanied by the emission of a great number of pollutants, which in turn have caused severe environmental problems. To strengthen environmental management and to establish a pollution source information database covering all key pollution sources and activities, China carried out its first National Census of Pollution Sources (NCPS) in 2007. The survey contents include the basic environmental situation in 2007, the generation levels of the main pollutants at that time, and the amount of pollution actually discharged into the environment after end-of-pipe treatment at all kinds of pollution sources. Based on the first NCPS report for China released in 2011, and taking two typical industry pollutants, sulfur dioxide (SO₂), and chemical oxygen demand (COD) as examples, we first revised the historical data concerning environmental statistics based on the NCPS documents. Subsequently, we analyzed the overall industrial scale in the change of SO₂ and COD emissions using index decomposition analysis, and then studied the contributions and comparative significance of the “three pollution emission reduction measures” put forward by the Chinese government. The latter are: Engineering Emission Reduction (EER), Structure Emission Reduction (SrER) and Supervision Emission Reduction (SuER). From these analyses, we were able to identify the main driving forces for SO₂ and COD emission reduction in China's industrial system. The results indicate that, with continually increasing pollution pressure caused by rapid economic development, EER and SuER have made the greatest contributions to reducing SO₂ and COD emissions; but SrER has not had an obvious effect. In the future, EER and SuER will gradually have less and less potential and become more challenging, while SrER should be achievable through adjusting the economic structure.

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1. Introduction

As the most populous country and now the second largest economy in the world, China has achieved an unprecedented economic rate of growth in the past 30 years. But it has also been confronted with extraordinary environmental problems and challenges (Kan, 2009; Liu et al., 2003) as result of this growth. At present, China has approximately 1.43 million sources of industrial pollution (National Pollution Census Compilation Committee, 2011). Meanwhile, industries with high resource consumption, high energy consumption, and high pollution emissions make up a large proportion of the total industrial sector domestically, while also being significant at the global level. For example, the steel, coal, cement and chemical fiber industries of China, respectively,

accounted for 38.4%, 38%, 45% and 57% of total global capacity in 2010 (Chinese Academy of Engineering, 2010; Stern, 2002). Furthermore, many industries do not possess up-to-date production technologies, lack pollution control facilities, or only have facilities that cannot be operated reliably or stably (Ministry of Environmental Protection of China, 2010). It is also challenging for the government to have to supervise the millions of small- and middle-sized companies that also produce pollution. How China can solve these environmental problems has been a focus of the world's attention (Liu and Diamond, 2005; WWF, 2010).

According to Chinese environment statistics, only key enterprises are included in the annual environmental report; a large number of middle- and small-sized enterprises are not included within the scope of the statistics (Ministry of Environmental Protection of China, 2002–2007). In order to strengthen environmental supervision and management, and establish a pollution source information database covering all kinds of pollution sources activities, the Chinese government launched the National Census of

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Pollution Sources (NCPS) from 2007 to 2009. The survey contents include the basic situation of enterprises, main pollutants generated, and discharged after end-of-pipe treatment at all kinds of pollution sources. Overall, 5,925,600 targets were investigated and 1.1 billion data points relating to various pollution sources were obtained. Data on the emission levels and whereabouts of the main pollutants, and on the operating conditions of pollution control facilities, were comprehensively investigated. The NCPS report is the most complete information about pollution sources and pollution emissions available in China. Previous environmental statistics can be updated and made more accurate based on this NCPS data.

On the other hand, in order to reduce pollution emissions and prevent continual environmental deterioration, three key measures for pollution reduction—Engineering Emission Reduction (EER, or emission reduction by engineering measures), Structure Emission Reduction (SrER, emission reduction through economic structure change) and Supervision Emission Reduction (SuER, emission reduction through the strengthening of management measures)—were implemented in 1996 (Cao et al., 2009; Pasche, 2002; Qi et al., 2011). Through solid efforts, China successfully reduced the total amount of sulfur dioxide (SO₂) and chemical oxygen demand (COD) emitted from 2005 to 2010. Meanwhile, China maintained rapid economic growth; growth in gross domestic product (GDP) achieved an average increase of 11.4% from 2005 to 2010, a cumulative increase of 71.6%. This is a further indication that the amount of SO₂ and COD emitted per unit of GDP has decreased significantly (Cao et al., 2009).

Although China has achieved real progress in the reduction of pollutant emissions, the country has also been confronted with many severe challenges (Chinese Academy of Engineering, 2010; Richerzhagen and Scholz, 2008). Industry is the main source of the generation and emission of pollutants in China (Ma et al., 2014); industrial emissions of three key pollutants SO₂, COD and NO_x account for 91%, 42% and 66% of the total emissions, respectively (Wei et al., 2014). Industry is also the main emission source of dust and soot, heavy metals and toxic organic compounds (Ministry of Environmental Protection, 2010). Therefore, it is necessary to analyze the driving forces behind the generation and emission of industrial pollutants in China, discover the key factors for pollution control, and explore more effective emission reduction measures.

This paper analyzes the industrial system in China (mainland) and its key pollutants (SO₂ and COD), revises historical environmental statistical data with the more accurate data from the first NCPS, and analyzes the contributions and comparative significance of pollution reduction using the three measures (EER, SrER, and SuER) from 2001 to 2010, through using an index decomposition analysis method. This analysis thus recognizes the key driving forces behind pollution reduction in Chinese industry, and suggests more efficient and sustainable pollution reduction strategies.

2. Method and data

2.1. Index decomposition analysis

Index decomposition analysis is frequently used to analyze the impact of factors such as economic growth, economic structure transformation, and technical progress, on the transformation of economic or environmental indicators (Ang, 2004, 2005; Sun, 2001). This method can, for example, directly decompose the variation in pollutant emissions and make a quantitative analysis of the influencing factors (Chen et al., 2004; Fujii et al., 2013). Furthermore, the decomposition method separates the contributions and relative importance of the various mechanisms available for changes in pollution emission, and this provides an empirical basis for

establishing and examining the pollution reduction measures used (Selden et al., 1999; Shao et al., 2014). Here a specific index decomposition analysis model is developed. First, the amount of pollution emissions can be expressed as the product of four different factors:

$$Q = E \cdot I \cdot S \cdot T \quad (1)$$

where Q refers to the total emission of pollutants; $E = (e_1, e_2, \dots, e_k, \dots, e_{39})^T$ is a 1×39 vector and indicates the impact of the EER measure, specifically the pollutant emission rate in 39 industries in the national economy of China, with element e_k referring to the emission rate of pollutants in the k th industry after the end-of-pipe treatment; I is a 39×39 diagonal matrix and refers to the factor of SuER measure, with its diagonal vector $(i_1, i_2, \dots, i_k, \dots, i_{39})^T$ indicating the pollutants produced per unit output of each industry; S is also a 39×39 diagonal matrix and refers to the factor of SrER measure, with its diagonal vector $(s_1, s_2, \dots, s_k, \dots, s_{39})^T$ indicating the proportion of the industrial output of each industry to the total industrial output value; and T refers to the total amount of the industrial economy, indicating the scale effect of economic growth.

Equation (1) indicates that the three measures of pollution reduction (EER, SuER, and SrER) and economic growth all lead to variations in the amount of pollutants emitted. Following these assumptions, during a certain period t_0 to t_1 , the total emission amount of pollutants changes from Q_0 to Q_1 , and the variation can be described as follows:

$$\Delta Q = Q_1 - Q_0 = \Delta Q_E + \Delta Q_I + \Delta Q_S + \Delta Q_T \quad (2)$$

where ΔQ refers to the variation in the total amount; and $\Delta Q_E, \Delta Q_I, \Delta Q_S, \Delta Q_T$ respectively refer to the driving effects of the four factors EER, SuER, SrER, and economic growth, namely the contribution to ΔQ . Briefly, the change in pollutant emission amount is the sum of the driving effects of the four factors during a certain period.

The residual produced by the coupling effect of the variation of factors will be modified in order to completely include the variation of pollution emissions into different effects. The residual decomposition is as follows:

$$\begin{aligned} Q_1 - Q_0 &= E_1 \cdot I_1 \cdot S_1 \cdot T_1 - E_0 \cdot I_0 \cdot S_0 \cdot T_0 \\ &= (E_0 + \Delta E)(I_0 + \Delta I)(S_0 + \Delta S)(T_0 + \Delta T) - E_0 \cdot I_0 \cdot S_0 \cdot T_0 \\ &= \dots + \Delta E \cdot \Delta I \cdot S_0 \cdot \Delta T + \dots + \Delta E \cdot \Delta I \cdot \Delta S \cdot \Delta T \end{aligned} \quad (3)$$

Here, Q_0 and Q_1 respectively refer to the total emissions in the time of t_0 and t_1 ; E_0, I_0, S_0, T_0 and E_1, I_1, S_1, T_1 respectively refer to the four driving factors of t_0 and t_1 ; and $\Delta E, \Delta I, \Delta S, \Delta T$ refer to the variation value of the four driving factors during t_0 – t_1 .

At present, the residual decomposition methods that are extensively applied include fixed weight, applicable weight, and equal distribution of residuals methods (Ang and Zhang, 2000; Sun, 1998). This study adopts the equal distribution of residuals suggested by Sun (1998), to achieve the complete decomposition of the factors. This method distributes the residual item between relevant factors under the principles of equal distribution based on the Laspeyres decomposition. For instance, the residual item $\Delta E \cdot \Delta I \cdot S_0 \cdot \Delta T$ can be deemed to be driven by changes in the three factors E, I , and T . Therefore this residual item decomposes into three equal portions ($\frac{1}{3} \Delta E \cdot \Delta I \cdot S_0 \cdot \Delta T$), which are then added respectively to $\Delta Q_E, \Delta Q_I, \Delta Q_T$. For instance:

$$\begin{aligned} \Delta Q_E &= \Delta E \cdot I_0 \cdot S_0 \cdot T_0 + \frac{1}{2} \Delta E \cdot \Delta I \cdot S_0 \cdot T_0 + \frac{1}{2} \Delta E \cdot I_0 \cdot S_0 \cdot \Delta T \\ &\quad + \frac{1}{3} \Delta E \cdot \Delta I \cdot S_0 \cdot \Delta T + \frac{1}{4} \Delta E \cdot \Delta I \cdot \Delta S \cdot \Delta T \end{aligned} \quad (4)$$

The other three driving factors are treated in a similar manner. The values of ΔQ_E , ΔQ_I , ΔQ_S , ΔQ_T denote the contributions of EER, SuER, SrER and economic growth to the variation of pollution emissions respectively. In short, the index decomposition analysis method can be used to quantify the effects of China's pollution reduction efforts.

2.2. Data sources and revisions

As mentioned before, the Chinese government launched the first NCPS in 2007, and obtained more comprehensive, accurate, and reliable data on pollutant emissions. The pollutant emission amount obtained from the NCPS is obviously different from other forms of environmental statistical data, for the following reasons: (1) the two statistics have different scopes of investigation. The traditional environmental statistics only cover about 300,000 pollution sources, while the NCPS includes all the industrial sources, approximately 1,576,000 enterprises (Ministry of Environmental Protection of China, 2010); and (2) The two statistics adopt different pollution emission coefficients in the calculation, and the NCPS updates the coefficients for each industry according to the evidence of technological progress (National Pollution Census Compilation Committee, 2011). In other words, the narrow survey coverage and inaccurate emission coefficient are two main reasons why previous environmental statistics cannot be an accurate measure of the actual emissions of pollutants.

This study revises the traditional environmental statistics with data from the NCPS; to obtain more comprehensive and reliable historical data on pollution emissions in China. The main strategy is that the statistical coverage and emission coefficients are amended at the same time. The economic output of the enterprises included in environmental statistics is considered as a measure of the statistical coverage, while the national industrial output is used as a measure of NCPS coverage. The difference between these two industrial output values identifies where historical environmental statistics are missing. China's environmental statistics used the same set of emission coefficients to account for major pollutants between 2001 and 2010 (Ministry of Environmental Protection of China, 2008), and NCPS adopted a new set of emission coefficients in 2007, so the core of the data revision work is to find out the industry-level conversion relationships between these two sets of emission coefficients. In the following section, the first task is to calculate the conversion coefficients between these two sets of emission coefficients, using a comparison of the 2007 environmental statistics and NCPS results. Then, based on the conversion between the two emission coefficients and the adjustment of statistical coverage differences, the data points of the historical environmental statistics will be revised.

As mentioned earlier, the scope of the statistical coverage is represented by the total economic output value of the surveyed industries. The ratio of the total economic output of a certain industry to the total output value of the enterprise that is determined by annual environmental studies, is equal to the ratio of the data revealed by the pollution census to that of the resulting environmental statistics. This equality relationship can be used to link the annual environmental statistics and the pollution census. In addition, a nondimensional conversion coefficient is used to quantify the conversion between the old emission coefficients (historical environmental statistics) and the new ones (2007 NCPS). For a specific industry at year 2007, this conversion can be expressed as:

$$\frac{x_i^{07}}{\bar{x}_i^{07}} = k_i \cdot \frac{y_i^{07}}{\bar{y}_i^{07}}, k_i = \frac{x_i^{07} \cdot \bar{y}_i^{07}}{\bar{x}_i^{07} \cdot y_i^{07}} \quad (5)$$

where x_i^{07} refers to the quantity of pollutants produced by the i th industry in 2007 according to the census statistical data; $\bar{x}_i^{07}$ refers to the quantity of pollutants produced by the i th industry in 2007 according to environmental statistics; y_i^{07} refers to the total output value of the enterprise under investigation for the i th industry in 2007 according to the census data; $\bar{y}_i^{07}$ refers to the total output value of the enterprise under investigation for the i th industry in 2007 according to the environmental statistics; and k_i is a nondimensional quantity, indicating the industry-level conversion coefficient between the old emission coefficients (historical environmental statistics) and the new ones (2007 NCPS) (Ministry of Environmental Protection of China, 2010).

Because the historical environmental statistics (2001–2010) adopted a fixed set of emission coefficients for the accounting of major pollutants, the conversion relationship between the old emission coefficients (used in historical environmental statistics) and the new ones (used in 2007 NCPS) can be considered to be static, that is, not being sensitive to the time change involved. Furthermore, the revision process uses a production coefficients of pollutants calculation, rather than end-of-pipe discharge coefficients, while the dynamic discharge ratio (1-removal ration) is introduced to reflect the increases in end-of-pipe reduction capacity, thus further ensuring that the conversion coefficient k_i is robust. After obtaining the conversion coefficient k_i , the calculation of the quantity of pollutant production and emission in year can be expressed as:

$$x_i^T = k_i \cdot \frac{\bar{x}_i^T \cdot y_i^T}{\bar{y}_i^T}, q_i^T = x_i^T \cdot e_i^T \quad (6)$$

where x_i^T refers to the quantity of pollutants of the i th industry in year T after revision; $\bar{x}_i^T$ refers to the quantity of pollutants of the i th industry in year T according to the environmental statistics; y_i^T refers to the total economic output value of the i th industry in year T ; $\bar{y}_i^T$ refers to the total output value of the enterprise of the i th industry according to the environmental statistics; q_i^T refers to the quantity of pollutants emitted by the i th industry in year T after revision; and e_i^T refers to the emission rate of pollutants by the i th industry in year T .

The environmental statistical data adopted in this study were obtained from the China Environment Yearbook 2002–2007 and the Annual Statistic Report on Environment in China 2007–2010, and the industrial economic data come from the China Statistical Yearbook 2002–2011 (Ministry of Environmental Protection of China, 2002–2007; Ministry of Environmental Protection of China, 2007–2010; National Bureau of Statistics of China, 2002–2011). In addition, the industrial classification system is divided into 39 industries in this study, according to the principles in the statistics. The total industrial output values of the various years were revised using the industrial price index of 2001 as the base year, to eliminate the influence of price fluctuations.

3. Results

3.1. Revised emissions

As shown in Fig. 1, the value of industrial output continued to increase at a steady rate from 2001 to 2010, whereas the rate of change of SO₂ emissions varied greatly. SO₂ emissions increased rapidly from 2001 to 2004, went slowly down from 2004 to 2006, recorded an inflection point in 2007, and then maintained a steady rate thereafter. The inter-annual change of COD emission by Chinese industry was not obvious, however, and showed an inflection

Fig. 1. Revised SO₂ and COD emissions and the output value of Chinese industry, 2001–2010.

point before a slow decrease in 2007. It can initially be concluded then that SO₂ and COD emissions from Chinese industry have produced inflection points in the Environmental Kuznets Curve, and have also shown a tendency toward decoupling from industrial economic growth. More detailed data are given in Table 1.

3.2. Driving factors behind the changes in SO₂ emissions

Table 2 and Fig. 2 respectively indicate the absolute and relative contribution rates of the four driving factors (EER, SuER, SrER, and economic growth) to the reduction of SO₂ in Chinese industry. Among these factors, growth in the economic scale of industry has always increased SO₂ emissions, and has made the largest contribution among the four factors. The contribution of industrial scale reached a maximum of 34.75% in 2005–2006. Subsequently, although the scale of Chinese industry rapidly increased (Fig. 1), its SO₂ emissions gradually decreased, which is in accordance with the decoupling tendency between industrial scale and amount of SO₂ emissions. Conversely, the factor of EER has always reduced SO₂ emissions; with the contribution rate gradually increasing from –1.94% in 2002–2003 to –17.43% in 2008–2009. This is in agreement with the improvement in industrial desulfurization capability recently in China.

The functions of the SuER and SrER measures are relatively complicated. From 2005 to 2008, the SuER measure reduced SO₂ emissions at a greater rate, as a result of intensified environmental supervision and improvement in cleaner production in China during the “Eleventh Five-Year Plan” period. The SrER measure made the lowest—but the most complicated—contribution to the reduction of SO₂ emissions; its maximum contribution rate was

Table 2

Contribution of the four driving factors to the reduction of SO₂ emissions in Chinese industry (10⁶ tons).

Year	EER	SuER	SrER	Economic growth	Total reduction
2001–2002	–0.41	–0.89	–0.26	1.74	0.19
2002–2003	–0.20	–0.03	–0.65	2.84	1.96
2003–2004	–0.35	0.37	1.36	3.78	5.17
2004–2005	–0.90	1.24	–1.16	2.97	2.16
2005–2006	–1.62	–3.85	0.12	7.57	2.22
2006–2007	–3.04	–4.34	–0.42	5.01	–2.79
2007–2008	–2.49	–0.87	–0.64	3.44	–0.57
2008–2009	–3.60	1.33	–0.26	2.74	0.22
2009–2010	–1.41	–1.71	–0.51	4.29	0.66

Fig. 2. Relative contributions of the four driving factors to the reduction of SO₂ emissions in Chinese industry (%).

only –6.22% in 2002–2003. In addition, the changes in industrial structure in 2003–2004 and 2005–2006 increased SO₂ emissions.

3.3. Driving factors behind the changes in COD emissions

The same method was used to study the contribution of the driving forces behind the changes in COD emissions from Chinese industry from 2001 to 2010. As shown in Table 3 and Fig. 3, growth in the scale of industrial economy has always increased COD emissions, but at a relatively stable rate of 16.36%–33.62%, and has been the main factor behind the increase of COD emissions. The EER measure has always reduced COD emissions, with a contribution rate gradually increasing from –2.29% in 2001–2002 to –17.71% in 2007–2008, as a result of the continuously expanding construction of end-of-pipe pollution control facilities, and a gradually

Table 1

The revised statistical data from the National Census on Pollution Sources.

Year	Industrial output value (10 ¹² RMB)	Pollutant produced per unit output (t/10 ⁶ RMB)		Produced pollutant (10 ⁶ t)		Emitted pollutant (10 ⁶ t)		Pollution emission rate (%)	
		SO ₂	COD	SO ₂	COD	SO ₂	COD	SO ₂	COD
2001	9.43	1.67	2.63	15.78	24.81	10.19	7.89	0.65	0.32
2002	11.17	1.78	2.22	19.95	24.84	11.57	7.70	0.58	0.31
2003	14.35	1.72	1.77	24.71	25.38	14.33	7.71	0.58	0.30
2004	17.95	1.75	1.51	31.43	27.07	19.61	8.11	0.62	0.30
2005	20.72	1.66	1.36	34.43	28.28	21.77	8.81	0.63	0.31
2006	28.75	1.49	1.07	42.88	30.77	23.99	9.01	0.56	0.29
2007	35.82	1.21	0.88	43.45	31.45	21.20	8.47	0.49	0.27
2008	42.18	1.19	0.85	50.27	35.99	20.63	8.33	0.41	0.23
2009	48.11	1.25	0.81	60.15	38.79	20.85	8.53	0.35	0.22
2010	58.82	1.09	0.73	64.39	42.84	21.51	8.62	0.33	0.20

Table 3
Contribution of the four driving factors to the reduction of COD emissions in Chinese industry (10^6 tons).

Year	EER	SuER	SrER	Economic growth	Total reduction
2001–2002	−0.18	−1.16	−0.12	1.33	−0.13
2002–2003	−0.24	−1.43	−0.37	1.95	−0.09
2003–2004	−0.16	−0.74	−0.45	1.78	0.43
2004–2005	−0.08	−0.97	0.18	1.19	0.33
2005–2006	−0.60	−1.95	−0.21	2.96	0.20
2006–2007	−0.40	−2.03	−0.05	1.94	−0.54
2007–2008	−1.50	0.07	−0.09	1.39	−0.14
2008–2009	−0.40	−0.70	0.18	1.11	0.20
2009–2010	−0.95	−0.51	−0.19	1.74	0.09

increasing removal rate of pollution (Table 1). The SuER and SrER measures have had relatively complicated impacts on COD emissions. In most years, the SuER measure reduced emissions, by −9.65% to −22.50%, as the main driving force for COD emission reduction. This is because the COD produced per unit monetary value of industrial output has decreased noticeably from 2.63 t/106 RMB in 2001, to 0.73 t/106 RMB in 2010, owing to intensified environmental supervision and cleaner production (Table 1). In a similar way to its impact on SO_2 , the SrER measure also had the least—but most complicated—impact on COD emissions, with a contribution rate of −5.78% to +2.21%. Its contribution is relatively slight overall, however, and has slightly decreased in recent years compared with 2001–2004.

Overall, the EER and SuER measures have been the main driving forces for COD emission reduction in the industrial system in China since 2001, and the increase in the contribution due to EER measure in 2005–2008 was the key reason for the occurrence of the inflection point in COD emissions. However, the adjustment of the industrial structure (SrER measure) did not have an obvious effect on SO_2 emission reduction.

4. Discussion

From the contributions of the three measures of emission reduction we can see that, since China began to implement its policy of pollutant emission reduction in 2005, the EER measure has always been the main factor in SO_2 emission reduction, and the main reason for the inflection point of SO_2 emissions. The SuER measure has also played an important role, but it has limited potential for emission reduction in the future, because SO_2 produced

per unit of industrial output has obviously decreased (Table 1). The SrER measure did not have an obvious effect on the reduction of SO_2 emissions.

Compared with SO_2 , COD is an indirect and macroscopic surrogate indicator. This situation leads to more influencing factors, and a more complicated influence in the production, reduction, and emission of COD. In the past 10 years, China has obviously improved pollution reduction through upgraded management and better facilities, such as strengthening end-of-pipe treatments, greater environmental supervision, and cleaner production. All of these activities have played a major role in the reduction of COD emissions (Huang et al., 2013). Nevertheless, the pollution reduction contributed by EER and SuER measures will gradually become smaller and more difficult in the future.

It can be seen from the results that the emissions of the main pollutants SO_2 and COD and the economic growth of Chinese industry have shown a tendency to decouple since 2007, as a result of the powerful pollution emission reduction measures undertaken by the Chinese government in recent years. Since the “Eleventh Five-Year Plan” from 2006 to 2009, the Chinese government and enterprises have invested 1375 billion RMB to reduce pollution by industry (Cao et al., 2009). For example, coal-burning power stations with desulfurization facilities have recently increased their capacity by 411 million kilowatts, and the proportion of coal-burning power stations with desulfurization facilities increased from 12% in 2005 to 71% in 2009. In addition, municipal sewage treatment capacity has increased by 4.46 million tons/day, and the municipal sewage treatment rate has increased from 52% in 2005, to 72.3% in 2009. During this period, pollution reduction by facilities was the main factor behind the reduction of SO_2 and COD emissions. In addition, the SO_2 and COD produced per unit of output by Chinese industry has obviously decreased in recent years, and management has played an important role in these reductions. However, it should be pointed out that, when compared with the past, the end-of-pipe treatment rate of SO_2 and COD by Chinese industry has reached a relatively high level, and the pollutants produced per unit output value have decreased noticeably. Thus EER and SuER measures will have less potential in the future, while their cost will increase continuously.

As for the SrER measure, the Chinese government adopted powerful controls: in 2006–2009 hundreds of thousands of middle- and small-sized enterprises creating heavy pollution were shut down, including small thermal power stations. These actions reduced electricity generation by 60.06 million kilowatts, iron production by 81.72 million tons, steel production by 60.38 million tons, coke production by 18.09 million tons, cement production by 214 million tons, and paper production by 1.5 million tons. Conversely, China has recently established many large-scale heavy industrial enterprises. For example, in 2006–2009, 300 million kilowatts of thermal power capacity, an annual output of 590 million tons of cement, and 25 million tons of paper were added. The economic structure of China therefore has not changed, and the proportion of the heavy industry is still increasing. Therefore, the SrER measure did not have an obvious effect. However, it can be predicted that, with the adjustment and updating of the economic structure of China, further changes in the industrial sector will have an obvious effect on pollution reduction in the future.

5. Conclusion

According to the analysis presented in this paper, rapid economic growth in China has resulted in great scale effects, and has become the main driving force for the increase in SO_2 and COD emissions. It is predicted that China will maintain its rapid economic growth, vigorous investment, high levels of export and consumption,

Fig. 3. Relative contributions of the four driving factors to the reduction of COD emissions in Chinese industry (%).

continuous industrialization and urbanization, higher consumption levels per capita, and greater pollution emission pressure, and ecological risks for the next 10 years (Stern et al., 1996). Meanwhile, the base numbers for the emission of the main pollutants in China are still very large, and pollution emission in some regions is exceeding social and ecological carrying capacity (Chinese Academy of Engineering, 2010). Pollution emission reductions will remain the theme in the future until there is an obvious improvement of environmental quality in China (Jiang et al., 2013). According to this analysis, China should increase pollution reduction using the SrER measure, upgrade its economic structure, transform its economic development model, reduce the emission of pollutants from industry, and improve environmental quality. Otherwise, pollution emission reduction will have less and less effect, cost more, and meet with greater difficulty in implementation.

It should be pointed out that as the statistical data, data processing, and analysis methods used in this study may have errors or limitations; therefore the conclusions of the study cannot completely reflect the pollution situation attributable to Chinese industry. For instance, the contribution of the SrER measure can only reflect the changes in the pollution levels contributed by the 39 studied industries, not that from the entire industrial system. Some industries have replaced middle- and small-sized enterprises with larger-sized enterprises, and these new enterprises have adopted new technology, better management, and effectively used scale effects. As a result, the pollution produced and emitted per unit of industrial output has decreased, but such changes cannot be reflected in the contribution of the SrER measure. Another example, the impact of the SuER measure in this study, indicates the change in pollution produced per unit of industrial output from industrial inner structure change, cleaner production, and environmental supervision, which cannot otherwise be distinguished. But, on the whole, the analyses in this study basically accord with the actual situation in Chinese industry, and reveal the relationship between pollution emissions and the driving forces of Chinese industry, while recognizing how the key factors of pollution reduction may be used to explore more effective and sustainable approaches to pollution reduction in the future.

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