北京师范大学经济与工商管理学院

工作论文（working paper）系列

管理类 No.14

张平淡: End-of-pipe or Process-integrated: Evidence from LMDI Decomposition of China's SO2 Emission Density Reduction

2013 年 06 月

End-of-pipe or Process-integrated: Evidence from LMDI Decomposition of China's SO_2 Emission Density Reduction

Pingdan ZHANG[1]

1 School of Economics & Business Administration, Beijing Normal University, Beijing 100875, China

Abstract In this study reduction in sulfur dioxide (SO_2) emission is decomposed into three parts: source prevention, process control and end-of-pipe treatment, using the Logarithmic Mean Divisia Index method (LMDI). Source prevention and process control are defined as process-integrated treatment. It is found that from 2001 to 2010 the reduction of SO_2 emission density of China was mainly contributed by end-of-pipe treatment. From the 10th Five Year Plan (FYP) period (2001-2005) to the 11th FYP period (2006-2010), the Chinese government has attempted to enhance process-integrated treatment. However, given its initial effort, the effect is limited compared with that of the end-of-pipe treatment. The effectiveness of environmental regulation and technology in the reduction of SO_2 density in 30 provinces from 2001 to 2010 is also investigated. This implies that environmental regulation and technology promote process control and end-of-pipe treatment significantly, but does not influence source prevention. Furthermore, environmental technology will only take effect under the circumstances of stringent environmental regulation. Therefore, to fulfill the whole process treatment, environmental regulation should be strengthened and environmental technology, upgraded at the same time.

Keywords End-of-pipe, process-integrated, LMDI, environmental regulation, environmental technology

1 Introduction

Environmental protection has been identified as the basic national policy since the 2nd China Environmental Protection Conference in 1983. Pollution abatement has since played an important role. Since the 21st century, environmental protection has been given a more strategic status, and in particular, since the 11th FYP period (2006-2010), pollution abatement has been considered as the key target for economic and social development. The emission reduction targets of two major pollutants have been achieved in advance, and the emission density of the major pollutants has decreased significantly. Take SO_2 for example. The emission decreased from 25.49 million tons in 2005 to 21.85 million in 2010, and the density, from 143 tons per hundred million Yuan to 54 tons.

Whole Process Treatment (WPT) contains source prevention, process control and end-of-pipe treatment, in western countries the former two are usually combined as process-integrated treatment. End-of-pipe solution refers to treatment of pollutants with equipment so that they meet emission standards for less environmental damage. Its advantages are that it does not require any change in the production process, and has had rather mature technologies to depend on. [1] Process-integrated solution refers to the use of clean energy and green raw materials in the production process and the upgrading of processing technology for less emission of pollutants. Compared with end-of-pipe solution, it is more environment-friendly and cost-effective [2-5]. Zhou [6] argued that environmental protection in most developed countries relied on WPT. However, it has not come true in China by far, before which an environment-friendly and resource-efficient society would not take shape. Thus, environmental protection authorities have been advocating WPT to take the place of end-of-pipe solutions since the 11th FYP period. Has WPT played a dominant role in environmental protection in China? This is the main issue to be discussed in this paper.

Previous research viewed emission density as the outcome of environmental technology, and did not investigate the effect of end-of-pipe treatment or process-integrated treatment separately. [3][7-8] Anderson and Newell [9], Kerr and Newell [10], Frondel et al. [3] checked the effect of a particular environmental policy on the choice of means to pollution abatement. Frondel et al. [3], Lee and Rhee [11], Hammar and Löfgren [12] analyzed the reality of WPT based on evidence from different countries. What factors will influence the trade-off between process-integrated treatment and end-of-pipe solution? Pavitt [13] argued that market pull and technology push were the key factors. In a sense, environmental regulation is equivalent to market pull and environmental technology, technology push.

End-of-pipe treatment depends on the forcefulness of environmental regulation. Although industrialization has not continued as long in China as in developed countries, environmental challenges are complicated and intense. China's pollution treatment is determined by environmental regulation enforced by the powerful central government as evidenced by the requirement that pollution abatement has been identified as an important indicator for the evaluation of local officials. Local governments proposed their own environmental regulation specific to their realities based on a similar evaluation system. Furthermore, public awareness of environmental protection enhances the enforcement of end-of-pipe treatment taken by local governments and producers. However, with rapid economic development, its limitations have become increasingly apparent. [14] Although end-of-pipe treatment may get rid of the pollution which has been produced, it cannot reduce emissions during production processes.

This paper decomposes SO_2 emission density reduction into three parts: source prevention, process control and end-of-pipe treatment, using the Logarithmic Mean Divisia Index method (LMDI) proposed by Ang and Choi (1997) [15]. The effects of source prevention, process control and end-of-pipe treatment during the 10^{th} FYP period and the 11^{th} FYP period will be evaluated. The effects of environmental regulation and technology on WPT will also be investigated. It is meaningful to decompose the WPT from theoretical and empirical perspectives. This decomposition not only promotes the deep understanding for WPT, but also be helpful for the inspection of environmental economic policy implementation effectiveness. The structure of this paper is as follows: Section 2 describes the decomposition model by LMDI; Section 3 sets out the decomposition results from 2001 to 2010 in 30 Chinese provinces; Section 4 performs the empirical analysis, and Section 5 presents conclusions.

2 Decomposition model

In recent years, factor decomposition method has been widely used to analyze the environmental and energy problems. Factor decomposition method includes Laspeyres Decomposition and Divisia Decomposition. Compared to Divisia Decomposition, the multiplier relation in Laspeyres Decomposition is difficult to split. Therefore, a more advanced decomposition method was proposed in 1924 by Divisia, and this method was named for Divisia Decomposition. Divisia Decomposition is widely used. Later, several researchers improved Divisia Decomposition. Divisia Decomposition was standardized by Howarth et al. (1991)[16] and Park (1992)[17]. Arithmetic Mean Divisia Index Decomposition (AMDI) was proposed by Boyd et al. (1988) [18]and Logarithmic Mean Divisia Index Decomposition (LMDI) was proposed by Ang and Choi (1997)[15]. Compared to original Divisia

Decomposition and AMDI, LMDI does not include any residuals that cannot be explained, which is a more suitable method for factor decomposition for energy and environmental problems. The industrial SO2 whole process management is decomposed by LMDI as follows.

Pollutant emission density represents the result of WPT, i.e. pollutant emission per unit GDP:

$$I_t = \frac{E_t}{Y_t} \tag{1}$$

where I_t refers to the SO_2 emission density in year t. E_t refers to SO_2 emission in year t. Y_t refers to the *GDP* in year t. Eq. (1) can be expressed in the following form:

$$I_t = \frac{G_t}{Y_t} \cdot \frac{E_t}{G_t} \tag{2}$$

where G_t is the total energy consumption in year t; G_t/Y_t is the energy consumption per unit GDP; E_t/G_t is the pollutant emission per unit energy consumption. According to the energy structure, energy consumption can be divided into fossil fuel and clean energy. Eq. (2) can be expressed in the following form:

$$I_t = \frac{G_t}{Y_t} \cdot \frac{DE_t + CE_t}{G_t} = \frac{G_t}{Y_t} \cdot \left(\frac{DE_t}{G_t} + \frac{CE_t}{G_t} \right) = \frac{G_t}{Y_t} \cdot \left(\frac{DG_t}{G_t} \cdot \frac{DE_t}{DG_t} + \frac{CG_t}{G_t} \cdot \frac{CE_t}{CG_t} \right) \tag{3}$$

where DG_t is the fossil fuel consumption in year t; CG_t is the clean energy consumption in year t; DE_t is the emission caused by fossil fuel consumption in year t; CE_t is the emission caused by clean energy consumption in year t; DG_t/G_t is the percentage of fossil fuel consumption and CG_t/G_t is the percentage of clean energy; DE_t/DG_t is the emission caused by per fossil fuel consumption in year t; CE_t/DG_t is the emission caused by per clean energy consumption in year t. Since the clean energy emit more less pollution, compares to the fossil fuel consumption, we define $CE_t=0$ and $DE_t=E_t$. Eq. (3) can be expressed in the following form:

$$I_t = \frac{G_t}{Y_t} \cdot \frac{DG_t}{G_t} \cdot \frac{E_t}{DG_t} \tag{4}$$

where, $a_t = G_t / Y_t$ is the share of fossil fuel consumption in total energy consumption, which represents the choice of energy consumption in source prevention; $b_t = DG_t / G_t$ is the energy consumption per unit GDP, which represents energy efficiency in process control; $c_t = E_t / DG_t$ is the pollutant emission per unit fossil fuel consumption, which represents pollution treatment technology in end-of-pipe solution. Thus, the WPT is decomposed into three parts: a_t, b_t, and c_t. Here, a_t is the structure of energy consumption, which represents source prevention; b_t is the energy consumption density, which represents process control; and c_t is the pollution emission density after the pollution treatment, which represents end-of-pipe solution. Differentiate both sides of Eq. (4), yielding:

$$\frac{d \ln I}{dt} = \frac{d \ln a_t}{dt} + \frac{d \ln b_t}{dt} + \frac{d \ln c_t}{dt} \tag{5}$$

Dividing Eq. (5) by the aggregate density I yields:

$$\ln\frac{I_T}{I_0}=\int_0^T\left(\frac{d\ln a_t}{dt}+\frac{d\ln b_t}{dt}+\frac{d\ln c_t}{dt}\right)dt \tag{6}$$

Eq. (6) can be rewritten as:

$$\frac{I_T}{I_0}=\exp\left(\int_0^T\frac{d\ln a_t}{dt}\right)\cdot\exp\left(\int_0^T\frac{d\ln b_t}{dt}\right)\cdot\exp\left(\int_0^T\frac{d\ln c_t}{dt}\right) \tag{7}$$

Creating function (7) according to Ang and Choi (1997) [15] yields:

$$f_j\left(t^*\right)=\frac{L\left(\frac{E_{j0}}{Y_0},\frac{E_{jT}}{Y_T}\right)}{L\left(\frac{E_0}{Y_0},\frac{E_T}{Y_T}\right)}=\frac{\left(\frac{E_{j0}}{Y_0}-\frac{E_{jT}}{Y_T}\right)\Big/\ln\left(\frac{E_{j0}}{Y_0}-\frac{E_{jT}}{Y_T}\right)}{\left(\frac{E_0}{Y_0},\frac{E_T}{Y_T}\right)\Big/\ln\left(\frac{E_0}{Y_0},\frac{E_T}{Y_T}\right)} \tag{8}$$

Substituting Eq. (8) into Eq. (7) yields:

$$\frac{I_T}{I_0}=\exp\left[f\left(t^*\right)\ln\frac{a_t}{a_0}\right]\cdot\exp\left[f\left(t^*\right)\ln\frac{b_t}{b_0}\right]\cdot\exp\left[f\left(t^*\right)\ln\frac{c_t}{c_0}\right] \tag{9}$$

Eq. (9) can be rewritten as:

$$D=D_{structure}\times D_{density}\times D_{treatment} \tag{10}$$

where D is the effect of whole process treatment; $D_{structure}$ represents the stage of source prevention, $D_{density}$, that of process control, and $D_{treatment}$, that of end-of-pipe treatment.

3 Result of decomposition

SO_2 is selected as the object of this study, since it is one of the two pollutants under key emission control during the 11th FYP period in China. Furthermore, most SO_2 emission is caused by industrial production. [19] Coal is the predominant source of SO_2 emission, which means that the fossil fuel consumption can be represented by coal consumption. The source of SO_2 emission data is *China Environment Statistical Yearbook (2001–2010)* [20], that of GDP data, *China Statistical Yearbook (2001–2010)*[21], and that of energy consumption, *China Energy Statistical Yearbook (2001–2010)*[22]. The GDP data have been made constant to control the inflation variable (Year 2001=100). The decomposition result of SO_2 emission density by LMDI from 2001 to 2010 in China is shown in Table 1.

Table 1 SO_2 emission density decomposition in China from 2001 to 2010

Period	Whole Treatment (*D*)	Pollution	Source Prevention (*Dstructure*)	Process Control (*Ddensity*)	End-of-pipe Treatment (*Dtreatment*)
2001-2002	-0.00115		0.00652（-568.09%）	-0.00032（27.70%）	-0.00735（640.39%）
2002-2003	-0.00036		0.00015（-40.24%）	-0.00022（61.01%）	-0.00029（79.22%）
2003-2004	-0.00167		-0.00004（2.14%）	-0.00059（35.27%）	-0.00105（62.60%）
2004-2005	0.00013		-0.00077（610.55%）	-0.00026（207.98%）	0.00116（-918.53%）
2005-2006	-0.00100		0.00003（-3.43%）	-0.00036（36.22%）	-0.00067（67.20%）

2006-2007	-0.00208	-0.00012（5.81%）	-0.00100（47.89%）	-0.00096（46.31%）
2007-2008	-0.00179	-0.00003（1.21%）	-0.00108（60.09%）	-0.00069（38.70%）
2008-2009	-0.00039	0.00000（-0.19%）	0.00028（-72.56%）	-0.00067（172.74%）
2009-2010	0.00212	-0.00020（9.31%）	0.00240（-113.52%）	-0.00009（4.22%）
2001-2010	-0.00620	0.00401（-64.69%）	-0.00011（1.70%）	-0.01011（162.99%）
10^{th} FYP period 2001-2005	-0.00306	0.00525（-171.63%）	-0.00144（47.16%）	-0.00686（224.47%）
11^{th} FYP period 2006-2010	-0.00215	-0.00041（19.02%）	0.00124（-57.72%）	-0.00298（138.69%）

Notes: The percentage number in the bracket refers to the contribution of source prevention, process control and end-of-pipe treatment.

The SO_2 emission density went down from 0.014 in 2001 to 0.005 in 2010, which is mainly contributed by end-of-pipe treatment. However, as shown in Table 1, the contribution of end-of-pipe treatment decreased from 224.47% during the 10^{th} FYP period to 138.69% during the 11^{th} FYP period. WPT has begun to come true, but the contributions of source prevention and process control are still small. In particular, the contribution of process control was positive from 2001 to 2008, but then became negative in 2009 and 2010, which may be attributed to the choice of means of emission reduction and the recovery measures taken amidst economic crisis. However, it proves that process control that is based on production technology upgrading has not accounted for the lion share in emission reduction.

The SO_2 emission density in 30 different provinces from 2001 to 2010 is decomposed. The results during the 10^{th} FYP period and the 11^{th} FYP period in different provinces are shown in Table 2. Due to lack of data in several provinces, 26 provinces are compared between the two periods in Table 2. In terms of end-of-pipe solution, its contribution during the 11^{th} FYP period is smaller than that during the 10^{th} FYP period in 16 provinces. Thus process-integrated treatment has started to become more dominant. By contrast, in the other 10 provinces, the contribution of end-of-pipe treatment during the latter period exceeds that during the previous period. End-of-pipe solution is still heavily relied upon. In terms of process control, its contribution during the 11^{th} FYP period is larger than that during the 10^{th} FYP period in 17 provinces. Thus, technology upgrading is the main factor influencing pollution treatment, and the treatment is effective at the source of emission. But process control in the other 9 provinces is not satisfactory.

The 26 provinces are categorized into four types (Table 3). Some provinces rely more on end-of-pipe treatment, and some on process-integrated solution; and some improve process control, some not.

Table 2 SO_2 emission density decomposition in 30 provinces from 2001 to 2010

Province	10th FYP Period			11th FYP Period		
	Source Prevention	Process Control	End-of-pipe Treatment	Source Prevention	Process Control	End-of-pipe Treatment
Beijing	-0.0003（13.66%）	-0.0009（46.23%）	-0.0008（40.11%）	-0.0002（27.56%）↑	-0.0003（37.02%）↓	-0.0002（35.42%）↑
Tianjin	0.0002（-4.89%）	-0.0026（67.53%）	-0.0014（37.36%）	-0.0007（21.76%）↑	-0.0010（33.92%）↓	-0.0013（44.32%）↑
Hebei	-0.0025（34.89%）	0.0006（-8.39%）	-0.0053（73.49%）	0.0005（-9.23%）↓	-0.0020（36.78%）↑	-0.0039（72.45%）↓
Shanxi	0.0040（-25.68%）	-0.0103（65.74%）	-0.0094（59.94%）	-0.0031（27.82%）↑	-0.0055（49.76%）↓	-0.0025（22.42%）↓
Inner Mongolia	0.0019（-39.19%）	0.0013（25.19%）	0.0057（114.00%）	0.0016（-9.44%）↑	-0.0077（46.40%）↑	-0.0104（63.04%）↓
Liaoning	0.0005（-719.06%）	-0.0017（2399.26%）	0.0011（-1580.21%）	-0.0006（11.11%）↑	-0.0026（49.82%）↓	-0.0020（39.07%）↑
Jilin	-0.0001（29.94%）	-0.0009（184.38%）	0.0006（-114.32%）	-0.0001（3.32%）↓	-0.0022（59.19%）↓	-0.0014（37.49%）↑
Heilongjiang	-0.0011（78.85%）	-0.0014（-105.16%）	0.0017（126.31%）	0.0001（-5.50 %）↓	-0.0009（38.70%）↑	-0.0015（66.80%）↓
Shanghai	-0.0010（62.40%）	-0.0010（60.72%）	0.0004（-23.12%）	-0.0003（13.93%）↓	-0.0006（27.78%）↓	-0.0012（58.29%）↑
Jiangsu	-0.0001（3.41%）	-0.0002（3.67%）	-0.0040（92.93%）	-0.0004（15.58%）↑	-0.0010（34.35%）↑	-0.0014（50.06%）↓
Zhejiang	-0.0004（19.14%）	-0.0004（21.05%）	-0.0011（59.81%）	0.0000（-0.89%）↓	-0.0009（37.06%）↑	-0.0014（62.05%）↑
Anhui	0.0003（-24.75%）	-0.0027（229.50%）	0.0012（-104.75%）	0.0009（-24.21%）↑	-0.0017（47.90%）↓	-0.0027（76.31%）↑
Fujian	0.0007（32.52%）	0.0010（49.48%）	0.0004（18.00%）	0.0000（-1.85%）↓	-0.0009（35.76%）↓	-0.0017（66.09%）↑
Jiangxi	-0.0015（-81.95%）	-0.0002（-9.44%）	0.0034（191.39%）	-0.0006（10.39%）↑	-0.0025（42.36%）↑	-0.0027（47.24%）↓
Shandong	-0.0005（8.27%）	0.0020（-32.50%）	-0.0075（124.23%）	-0.0002（5.04%）↓	-0.0012（33.51 %）↑	-0.0022（61.45%）↓
Henan	0.0015（-955.50%）	-0.0010（656.96%）	-0.0003（198.53%）	-0.0004（6.67%）↓	-0.0021（37.40%）↑	-0.0032（55.93%）↑
Hubei	-0.0015（52.15%）	-0.0003（12.11%）	-0.0010（35.73%）	-0.0006（13.17 %）↓	-0.0018（39.60%）↑	-0.0022（47.23%）↑
Hunan	0.0010（-28.12%）	0.0020（-53.33%）	-0.0067（181.45%）	-0.0012（23.84%）↑	-0.0018（34.59%）↑	-0.0021（41.56%）↓
Guangdong	-0.0004（21.55%）	-0.0004（20.11%）	-0.0012（58.34%）	-0.0001（2.71 %）↓	-0.0007（30.56%）↑	-0.0015（66.73%）↑
Guangxi	-0.0460（894.18%）	0.0443（-860.94%）	-0.0034（66.76%）	-0.0004（4.90 %）↓	-0.0033（37.74%）↑	-0.0050（57.36%）↓
Hainan	——	——	——	0.0003（-34.00%）	-0.0003（28.61%）	-0.0009（105.39%）
Chongqing	——	——	——	0.0005（-4.79%）	-0.0032（27.82%）	-0.0088（76.97%）
Sichuan	-0.0077（119.76%）	0.0073（-112.28%）	-0.0060（92.52%）	0.0008（-13.50%）↓	-0.0022（34.69%）↑	-0.0050（78.81%）↓
Guizhou	-0.0021（12.48%）	0.0022（-12.86%）	-0.0172（100.38%）	0.0006（-2.10 %）↓	-0.0132（44.54%）↑	-0.0171（57.57%）↓
Yunnan	0.0020（-140.74%）	0.0017（-119.75%）	-0.0051（360.49%）	-0.0002（3.53%）↑	-0.0021（46.51%）↑	-0.0023（49.96%）↓

Tibet	——	——	——	——	——	——
Shaanxi	0.0008（-15.65%）	0.0005（-9.82%）	-0.0065（125.47%）	-0.0004（4.46%）↑	-0.0041（42.83%）↑	-0.0051（52.71%）↓
Gansu	-0.0318（2462.94%）	0.0275（-2132.23%）	0.0030（-230.72%）	-0.0003（3.96%）↓	-0.0040（46.67%）↑	-0.0042（49.36%）↑
Qinghai	——	——	——	0.0023（-32.09%）	-0.0047（66.16%）	-0.0047（65.93%）
Ningxia	——	——	——	0.0041（-14.30%）	-0.0149（52.00%）	-0.0179（62.30%）
Xinjiang	-0.0014（-204.52%）	-0.0013（-192.47%）	0.0035（496.99%）	0.0039（-189.11%）↑	-0.0016（77.45%）↑	-0.0043（211.65%）↓

Notes: ↑ refers to the ascent of decomposition from the 10th FYP period to the 11th FYP period, and ↓refers to the decent of decomposition from the 10th FYP period to the 11th FYP period.

Table 3 Choice of Approaches to SO_2 Whole Process Treatment from 2001 to 2010

	Contribution of process-integrated treatment similar to that of end-of-pipe treatment (16 provinces)	Contribution of process-integrated treatment smaller than that of end-of-pipe treatment (10 provinces)
Better effect of process control (17 provinces)	13 provinces (Hebei, Inner Mongolia, Heilongjiang, Jiangsu, Jiangxi, Shandong, Hunan, Guangxi, Sichuan, Guizhou, Yunnan, Shaanxi, Xinjiang)	4 provinces (Zhejiang, Hubei, Guangdong, Gansu)
Effect of process control as usual (9 provinces)	3 provinces (Beijing, Shanxi, Henan)	6 provinces (Tianjin, Liaoning, Jilin, Shanghai, Anhui, Fujian)

As shown in Table 3, 13 provinces have started WPT, and the contribution of process-integrated treatment is similar to that of end-of-pipe treatment. Take Jiangxi province for example. During the 10^{th} FYP period, the reduction of SO_2 emission was mostly contributed by end-of-pipe treatment as evidenced by the ratio of 191.39%, while the contribution of process-integrated treatment was negative. During the 11^{th} FYP period, however, the contributions of source prevention, process control and end-of-pipe-treatment are all positive. The contribution rate of process control increased significantly to 42.36%, while that of end-of-pipe treatment decreased dramatically to 47.24%, roughly at the same level of the former. What merits particular attention are the 6 provinces, where WPT has not come true and the effect of process control has been unimproved.

4 Empirical analysis

4.1 Research design

As shown in Table 3, different provinces have chosen different ways to reduce SO_2 emission density, and every province has chosen different ways in different periods. Some provinces have started the process-integrated treatment, but some provinces still rely on end-of-pipe treatment. What are the factors that can influence the approaches chosen by different provinces? It is believed that it depends on the environmental regulation and technology in those provinces. In order to reduce SO_2 emission density, three options are available, i.e. source prevention, optimizing energy consumption structure; process control, bringing down energy consumption density; and end-of-pipe solution, reducing SO_2 emission per energy consumption unit. The decision to choose a particular option is a trade-off of the benefits and costs among the three on the basis of the local reality of regulation and technology. The following model tests the factors that influence the choice of approaches to whole process treatment.

$$D_{it} = \alpha_0 Regulation_{it} + \alpha_1 ETech_{it} + \alpha_2 EI_{it} + \alpha_3 EIndustry_{it} + \alpha_4 Industry_{it} + \sum YEAR + \varepsilon_{it} \quad (11)$$

in which dependent variable is the decomposition of SO_2 emission density, represented by whole process treatment (*D*), source prevention (*Dstructure*), process control (*Ddensity*) and end-of-pipe treatment (*Dtreatment*). Here *i* represents for different provinces in China, *t* represents for different period, such as

2001 to 2002, 2002 to 2003,……, and ε represents for other invisible factors which are not included in model (10). According to the previous researches, the SO_2 emission density is influenced by environmental regulation and environmental technology, and so on. All these factors should be put in the regression model as independent variables. Independent variables are environmental regulation (*Regulation*) and environmental technology (*Etech*). The producers which located in areas with more stringent environmental regulation have more pressure to reduce pollution emission. But it is not quite sure that, whether the producers reduce pollution emission by process-integrated treatment or end-of-pipe treatment. Environmental regulation is represented by four variables, namely the number of environmental proposals by CPPCC (Chinese People's Political Consultative Conference) per unit GDP, the number of regional environmental laws and regulations, the number of enforcement officers for environmental protection per unit GDP, and the number of institutions for environmental protection per unit GDP. Following the upgrade of environmental technology, less energy will be used and less pollution emission will be caused, under a certain production. Respectively *ETech* is expressed by the number of environmental research projects per unit GDP, and the fund of environmental research projects per unit GDP. Controlled variables include environmental investment (*EI*) represented by the percentage of investment into treating industrial pollution sources in GDP; environmental industry (*EIndustry*) is represented indicated by the percentage of environmental industry output in GDP; industrial structure (*Industry*) is represented by the percentage of secondary industry output in GDP, and the year (*YEAR*) is a dummy varaible.

Data of 30 provinces are collected from *China Environment Statistical Yearbook (2001–2010)* and *China Statistical Yearbook (2001–2010)* (Special Administrative Regions like Hong Kong and Macao, as well as Tibet and Taiwan Province are not included in the current study due to missing data).

4.2 Descriptive statistics

The descriptive statistics for dependent and independent variables are shown in Table 4.

Table 4 Descriptive statistics

Variable	Sample	Mean	Std. Dev.	Minimum	Maximum
D	259	-0.0013	0.003	-0.014	0.019
Dstructure	259	-0.0004	0.004	-0.050	0.021
Ddensity	265	-0.0003	0.004	-0.023	0.046
Dtreatment	259	-0.0006	0.003	-0.013	0.021
Regulation	270	0.043	0.032	0	0.176
ETech	267	0.017	0.024	0	0.145
EI	270	0.002	0.001	0	0.010
EIndustry	270	1.078	0.011	0	8.189
Industry	270	0.450	0.084	0.200	0.600

Notes: The sample size for each variable is not consistent due to lack of data in some provinces.

4.3 Regression analysis

Table 5 shows the regression result of model (10) by random effects model, using the provincial data from

2001 to 2010. Regulation is represented by the number of environmental proposals by CPPCC (Chinese People's Political Consultative Conference) per unit GDP, and *ETech* by the number of environmental research projects per unit GDP. The dependent variables are whole treatment (D)in model (1), source prevention (*Dstructure*) in model (2), process control (*Ddensity*) in model (3), and end-of-pipe treatment (*Dtreatment*) in model (4).

Table 5 Regression result

Variable	Model (1)	Model (2)	Model (3)	Model (4)
	D	*Dstructure*	*Ddensity*	*Dtreatment*
Regulation	-0.011**	0.002	-0.007**	-0.008**
	(-2.67)	(0.23)	(-2.67)	(-2.33)
ETech	-0.013**	0.003	-0.009**	-0.006**
	(-2.68)	(0.22)	(-2.08)	(-2.97)
EI	-0.221	0.260	-0.398**	-0.067
	(-1.61)	(1.25)	(2.02)	(-0.55)
EIndustry	0.027	-0.018	0.023	0.024
	(1.52)	(-0.63)	(0.85)	(1.47)
Industry	-0.006*	0.002	-0.002	-0.005*
	(-1.81)	(0.48)	(-0.55)	(-1.81)
Adj- R^2	0.051	0.003	0.005	0.039
Hausman	0.426	0.193	0.121	0.748
Method	random effect	random effect	random effect	random effect
Sample	200	200	200	200

Notes: *** significant at the 1% level, two-tailed; ** significant at the 5% level, two-tailed; * significant at the 10% level, two-tailed.

As shown in Table 5, the regression results in model (1), model (3) and model (4) are similar. The coefficient of *Regulation* is significantly negative, which means that *Regulation* and *Etech* are strongly correlated with process control, end-of-pipe treatment and whole process treatment. The finding is consistent with the current environmental practice in China and with the conclusions of most research projects. The coefficient of *EI* is obviously negative in model (3), which means *EI* promotes the upgrading of environmental technology. This result was proved by Lin et al., which proved that the environmental investment promoted production technology significantly. [23]

In model (2), however, the coefficients of *Regulation* and *ETech* are positive, which means that the effects of environmental regulation and technology on source prevention have not appeared, while the two are not significantly positive. In fact, energy consumption at the stage of source prevention is mainly influenced by energy price, and weakly relates to environmental regulation and technology.

Table 6 shows the regression results during the 10th FYP period and the 11th FYP period.

Table 6 Regression result (during the 10th FYP period and the 11th FYP period)

Variable	10th FYP period (2001-2005)	11th FYP period (2006-2010)

Regulation	-0.012**	-0.012**
	(-2.18)	(-2.39)
ETech	-0.009	-0.015**
	(-0.71)	(-2.60)
EI	-0.045*	-0.093
	(-1.75)	(-0.60)
EIndustry	0.040	0.004
	(1.50)	(0.15)
Industry	-0.004	-0.007*
	(-0.74)	(-1.92)
Adj- R^2	0.036	0.094
Method	random effect	random effect
Sample	87	113

Notes: *** significant at the 1% level, two-tailed; ** significant at the 5% level, two-tailed; * significant at the 10% level, two-tailed.

As shown in Table 6, the coefficients of *Regulation* are significantly negative in both periods. The environmental regulation has a positive impact on the reduction of SO_2 emissions, thus on the whole process treatment. The coefficient of *ETech* is much more significant during the 11th FYP period than the previous period, which proves that environmental technology takes effect since the 11th FYP period.

Environmental regulation and environmental technology play an important role in the whole process treatment. So the samples of environmental regulation are divided into two groups according to the mean of *Regulation* (0.043), namely high *Regulation* and low *Regulation*. Those of environmental technology are also categorized into two groups according to the mean of *ETech* (0.017), i.e. high *Etech* and low *Etech*. The regression results are shown in Table 7.

Table 7 Regression result (under different circumstances of environmental regulation and technology)

Variable	Environmental regulation		Environmental technology	
	High	Low	High	Low
Regulation	-0.014**	-0.001	-0.003	-0.016*
	（-1.96）	（-0.03）	(-0.34)	(-1.82)
ETech	-0.010*	-0.012	-0.009	0.019
	（-2.59）	（-0.75）	(-0.96)	(0.32)
EI	-0.033*	-0.013	-0.033	-0.074
	(-1.18)	（-1.22）	(-1.58)	(-0.44)
EIndustry	0.021*	0.034	0.021	0.028
	(1.66)	（0.81）	(0.96)	(1.02)
Industry	0.001	-0.008	-0.001	-0.008*
	(0.46)	（-1.50）	(-0.23)	(-1.68)
Adj- R^2	0.128	0.061	0.034	0.063
Method	random effect	random effect	random effect	random effect
Sample	106	94	66	134

Notes: *** significant at the 1% level, two-tailed; ** significant at the 5% level, two-tailed; * significant at the 10% level, two-tailed.

As shown in Table 7, in the regression of high *Regulation* group, the coefficients of *Regulation* and *ETech* are significantly negative. However, the coefficients of *Regulation* and *ETech* are not significant in the regression of low *Regulation* group. The regression results in high and low *Etech* are similar, and environmental technology does not have a strong impact on whole process treatment irrespective of its level of advancement. Overall, the effect of environmental regulation is the premise of environmental technology's visible impact.

The number of enforcement officials for environmental protection per unit GDP and the number of institutions for environmental protection per unit GDP are also used to represent *Regulation,* and the fund of environmental research projects per unit GDP, to represent *Etech* for robust test. The conclusions are similar and robust.

5 Conclusions

Following the improvement of environmental management in China, it is inevitable to resort to whole process treatment instead of end-of-pipe treatment for better environmental protection. This paper decomposed SO_2 emission density reduction into three parts: source prevention, process control and end-of-pipe treatment, using the LMDI method. The finding is that from 2001 to 2010 the reduction of SO_2 emission density of China was mainly contributed by end-of-pipe treatment. Despite that, China has started to enhance whole process treatment as evidenced by the fact that 13 provinces have introduced the effort with an increasing contribution rate of process control.

The effect of environmental regulation and environmental technology on whole process treatment is investigated on the basis of the decomposition result of data of 30 Chinese provinces from 2001 to 2010. We found that the high environmental regulation and technology promoted process control and end-of-pipe treatment significantly. While the effect of environmental regulation and technology on source prevention has not taken. Furthermore, environmental regulation is positively correlated with whole process treatment, and environmental technology will only take effect when the environmental regulation is strict.

Given the grave environment reality and mounting environment stress in most parts of China, the 12th FYP plan for environmental protection has set out more targets and higher requirements than the previous plan. Thus, in order to reduce the SO_2 emission density before and after emission at the same time, the powerful role of environment regulation on whole process treatment and environment technology should be given full recognition. Environment regulation should be made more stringent, which helps to enhance technology advancement. Whole process treatment should be better delivered, so more provinces will be encouraged to shift from end-of-pipe treatment towards whole process treatment which will lead to a nation-wide move.

Acknowledgements This paper is sponsored by the R&D Special Fund for Public Welfare (Environment) by the Ministry of Finance and Ministry of Science and Technology of China (No. 201009066).

References

[1] Zotter Karl A., 2004. “End-of-pipe” versus “process-integrated” water conservation solutions – a comparison of planning, implementation and operating phases, Journal of Cleaner Production 12: 685–695.

[2] Hitchens, D., Trainor, M. J. Clausen, Thankappan, S.B., De Marchi, 2003. Small and medium sized companies in Europe – environmental performance. Competitiveness and Management. Springer Verlag, Heidelberg.

[3] Frondel, Horbach and Renings, 2004. End-of-pipe or cleaner production? An empirical comparison of environmental innovation decisions across OECD countries, ZEW Discussion Papers, No. 04-82.

[4] Rennings, K., Ziegler, A., Zwick T., 2004. Employment changes in environmentally innovative firms. Business Strategy and the Environment, ZEW Discussion Papers, No. 01-46.

[5] Rennings, K., Kemp, R., Bartolomeo, M., Hemmelskamp J., Hitchens D., 2004. Blueprints for an integration of science, technology and environmental policy. Centre for European Economic Research (ZEW), Mannheim.

[6] Zhou S. X., 2011. Exploring a new road for environmental protection in China, and building a strong technology support system, Environmental Economics 3:515. (in Chinese)

[7] Jaffe, A.B., Newell, R.G., Stavins, R.N., 2002. Environmental policy and technological change. Environmental and Resource Economics 22: 41-69.

[8] Brunnermeier S.B., Cohen M.A. 2003. Determinants of environmental innovation in US manufacturing industries. Journal of Environmental Economics and Management 45: 278-293.

[9] Anderson, S.T., Newell, R.G., 2002. Information programs for technology adoption: the case of energy-efficiency audits. Resources for the Future, Washington, DC.

[10] Kerr, S., Newell, R., 2003. Policy-induced technology adoption: evidence from the U.S. lead phase down. Journal of Industrial Economics LI (3): 317-343.

[11] Lee Su-Yol and Rhee Seung-Kyu, 2005. From end-of-pipe technology towards pollution preventive approach: the evolution of corporate environmentalism in Korea. Journal of Cleaner Production 13: 387-395.

[12] Henrik Hammar and Asa Löfgren, 2010. Explaining adoption of end of pipe solutions and clean technologies – Determinants of firms' investments for reducing emissions to air in four sectors in Sweden. Energy Policy 38: 3644–3651.

[13] Pavitt, K. 1984. Sectoral patterns of technical change: towards a taxonomy and a theory. Research Policy 13: 343-373.

[14] Sun, X., Lei, H. Y., 2012. Empirical research on the effect of whole process pollution reduction in China – take the provincial SO_2 reduction as an example. East China Economic Management 26(7): 58-61. (in Chinese)

[15] Ang, B.W. and K.H. Choi, 1997. Decomposition of Aggregate Energy and Gas Emission Intensities for Industry: A Refined Divisia Index Method, Energy, 18(3):59-73.

[16] Howarth, R.B. and Schipper, L., 1991. Manufacturing Energy Use in Eight OECD Countries. Energy Economics 13(2): 135-42.

[17] Park, S.H., 1992. Decomposition of Industrial Energy Consumption: An Alternative Method. Energy Economics 14(4): 265-270.

[18] Boyd, G.A., Hanson, D.A., Sterner, T., 1988. Decomposition of Changes in Energy Intensity-a Comparison of the Divisia Index and Other Methods. Energy Economics 10 (4):309-312.

[19] Yu, F., Qi, J. G., 2007. Decomposing and analyzing the environmental pollution under the opening economic circumstances. Statistical Research 24(1): 47-53. (in Chinese)

[20] Ministry of Environmental Protection of China. China Environment Statistical Yearbook (2001-2010). Beijing: China Environmental Press, 2002-2011. (in Chinese)

[21] National Bureau of Statistics of China. China Statistical Yearbook (2001-2010). Beijing: China Statistics Press, 2002-2011. (in Chinese)

[22] National Bureau of Statistics of China. China Energy Statistical Yearbook (2001-2010). Beijing: China Statistics Press, 2002-2011. (in Chinese)

[23] Lin, Q.H., Chen, G.Y., Du, W.C., Niu, H.P., 2012. Spillover effect of environmental investment: evidence from panel data at provincial level in China. Frontiers of Environmental Science & Engineering 6(3):412-420.