Analysis on Abatement Cost and its Influencing Factors on Nitrogen Oxide Emissions from Power Plants in China

Chunyu Yang[1,2,3,4], Mengfan Xia[4], Zhanfeng Dong[3], Junfeng Wang[2,*] and Xiaoqiong Li[3]
[1]Changzhou Research Center on Social and Environmental Management, Changzhou Institute of Technology, Changzhou Jiangsu 213032, China
[2]Research Center for Circular Economy, Nankai University, Tianjin 300350, China
[3]Chinese Academy for Environmental Planning, Beijing 100012, China
[4]Nanjing University, School of Society, Nanjing 210032, China
[*]Corresponding author

***Abstract*—The coal-fired power industry in China is confronted with issues on Nitrogen Oxide (NO_x) abatement and corresponding additional costs. The selection of denitration technologies and measures is a scientific, economic, and political issue. Several domestic studies estimate the denitration costs and their influencing factors in the context of Chinese power industry. The influencing factors on denitration cost during operations and manufacturing can be credited to the average total cost of denitration. Denitration technologies and measures can be evaluated based on the unit cost of pollution reduction (UCPR), which can be calculated from the marginal abatement cost function. The UCPR was used to examine the cost-effectiveness of each emission reduction technologies and measures. Our analysis shows that the factors, electricity capacity, denitration technology, and construction measure, play incredible roles in determining denitration cost, whereas selective catalytic reduction denitration technology and technological transformation construction measure are the most favored options as regards denitration practice from power plants in China. Given that the mean value of the UCPR is 1.19 cent/kWh, compared with the 1 cent/kWh subsidy, the national denitration subsidy on electricity price is reasonable. Although the NO_x abatement strategies provide beneficial effects, some related measures are needed for their implementation.**

Keywords*—Nitrogen Oxide (NO_X) emissions; abatement cost; coal-fired power plants

I. INTRODUCTION

In recent years, environmental awareness of sustainable development grew significantly. This awareness can be attributed to social dissatisfaction with the environment. Air pollution constitutes one of the major problems that impede the process of sustainable development (Chalou-lakou et al., 2008). The main source of air pollution is the combustion processes of fossil fuels used in power plants. Key combustion-generated air contaminants include sulfur oxides, particulate matter, carbon monoxide, unburned hydrocarbons, and nitrogen oxides (NO_x) (Yang et al., 2008). Global warming and local pollutants, such as NO_x, are two main issues during China's sustainable development (Yang et al., 2008). NO_x are considered the primary pollutants of the atmosphere, as they are responsible for environmental problems like photochemical smog, acid rain, troposphere ozone, ozone layer depletion, and even global warming caused by N_2O (Kinga et al.,2010).

Legislation plays an important role in achieving pollutant reduction, meanwhile economic incentives, such as subsidies and green taxation, have always been a key element in achieving the emission abatement purpose (Lex etal., 1998). Many authors have increasingly been focusing on incentive-based instruments for emission reduction on air pollutant, such as CO_2, SO_2, NO_x, and greenhouse gases (Smith, 1998; Oh, Sang and Won-Cheol, 1999; Kamat et al., 1999; Crigui et al., 1999; David et al., 2002; Holdaway et al., 2009; Ali et al., 2010; Mao et al., 2013). A wide variety of marginal abatement cost (MAC) analysis associated with CO_2, SO_2, and greenhouse gases exists (Onno et al., 2009; Ali et al., 2010; Stephane et al., 2011; Yang et al., 2013). However, only a few studies are focused on the MAC of NO_x emission (Oh Sang and Won-Cheol,1999; David et al., 2002; Mao et al., 2013).

A thorough understanding of the abatement cost and its key effect elements is a prerequisite for policymakers to implement efficient environmental policies (Lena et al., 2005). Electricity price on denitration is influenced by a number of factors, and various researches have been focusing on the emission factors and the costs of NO_x, such as the fuel type, facility, and boilers (Oh Sang and Won-Cheol, 1999; Jiming et al., 2002;Jian et al., 2010);however, these studies, which are based on emission factors centered on the availability of raw materials or facilities in denitration, directly affecting the denitration cost given the insufficiency of prominent factors such as power capacity, denitration construction measure, and denitration technology, do not reflect the scientific relationship between the denitration cost and those important factors. Selection of denitration technologies and measures is a scientific, economic, and political issue (Xianqiang et al., 2013). A rational assessment of the electricity policy on denitration and its influencing factors is urgently in demand in China (He et al., 2013). This study analyzes these factors, power capacity, denitration construction measure, and denitration technique based on the average total cost (ATC) and MAC. The ATC of denitration is the average value of the total denitration cost and was used to examine the main impact factors on denitration cost during operations and manufacturing process. The MAC, also considered the unit cost of pollutant reduction (UCPR) (Xianqiang et al., 2013), is the cost of reducing an additional kilowatt per hour of the NO_x emissions (Morteza et al., 2013), and is used to analyze the favored options for denitration reform in power plants, such as the selection of power capacity, technology type, and denitration type.

The purpose of this study is to provide guidelines for denitration power plants and the government. First, the ATC of the denitration in this study can provide a guideline for future NO_x emission per unit pricing in its marketable permit system. Second, the denitration can provide a guideline for enterprises to select the process with lower cost. Third, the UCPR would provide guidance on whether the current regulation, such as electricity subsidy, on NO_x abatement is reasonable. Consequently, these guidelines are useful in predicting the subsidy level of the electricity price on NO_x abatement in Chinese environmental policy.

The following section surveys the overview of China's NO_x abatement. Section 3 provides an interpretation to the methodology. Section 4 presents the estimation results, and Section 5 concludes the study.

II. OVERVIEW OF CHINA'S NITROGEN OXIDE EMISSION AND ABATEMENT

A. Energy Consumption of China's Power Plants

The importance of energy in economic development has been globally recognized (Kldellis et al., 2005). The power generation sector in China is characterized as an energy intensive industry consuming a large amount of energy. The energy intensity of total energy consumption by GDP increased steadily in China from 1.42 tce/10^4 in 2000 to 1.46 tce/10^4 in 2005, and the GDP is calculated at 2000 constant prices. However, the energy consumption decreased from 1.25 tce/10^4 in 2006 to 0.99 tce/10^4 in 2010, and the GDP is calculated at 2005 constant prices. The trend of electricity consumption is similar to the change of the total energy consumption. Electricity consumption increased from 0.11kwh/10^4 in 2000 to 0.16 wkh/10^4 in 2005(GDP is calculated at 2000 constant prices), and decreased from 0.14kwh/10^4 in 2005 to 0.11 wkh/10^4 in 2010 (GDP is calculated at 2005 constant prices) (Fig.1). However, a considerable growth rate of electricity consumption increase has been observed in China since the economic reform and opening-up in 1978. The average growth rate is about 9.1% (Fig.2). Therefore, the power generation sector in China is characterized as an energy intensive industry consuming a large amount of energy, especially fossil fuels. As a result, this sector takes a large portion of the total airborne pollutant emitted. In 2011, this sector occupied 47.5% of the total industrial sulfur dioxide (SO_2), 66.7% of NO_x, and 21% of industrial dust emissions (China's Environmental Statistics Yearbook, 2011).

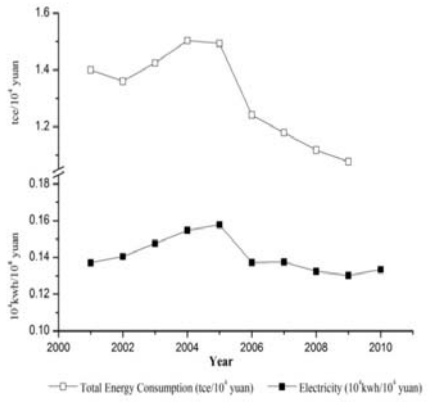

FIGURE I. ENERGY INTENSITY BY GDP IN CHINA FROM 2000 TO 2010.

FIGURE II. FGROWTH RATE OF ELECTRICITY CONSUMPTION IN CHINA FROM 1980 TO 2010(UNIT: %).

Source: China Energy Statistical Yearbook (2011, 2000–2010).

Fig. 3 shows China's major air pollutant emissions since the "Tenth Five-Year" and "Eleventh Five-Year" periods, in which SO_2 emissions and NO_x emissions are two of the highest, followed by fumes and industrial dust. As shown in the figure, NO_x demonstrates an upward trend, increasing from 15,238,000 tons in 2005 to 18,524,000 tons in 2010. The total emission of NO_x increased steadily, where the proportion of industrial NO_x emissions is approximately 77% (Fig.4). In other words, the growth of the total NO_x emissions can be attributed to the growth of the total industrial NO_x emissions. The major sources of NO_x include power plants, vehicle exhaust, and so on. For this status, the Chinese government clearly encouraged power plants for denitration, proposed electricity price subsidy for denitration, and implemented denitration tariff pilot in 2011.

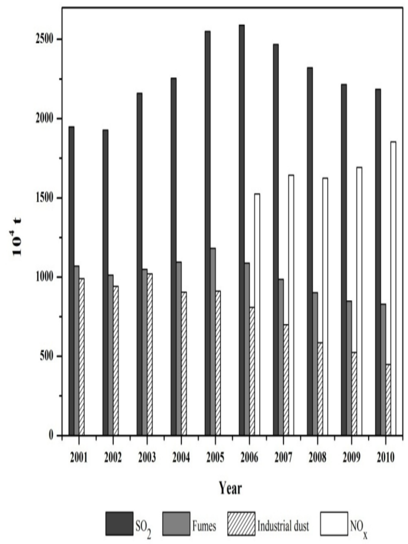

FIGURE III. NATIONAL AIR POLLUTANT EMISSION IN CHINA FROM 2001 TO 2010 (UNIT: 104 T).

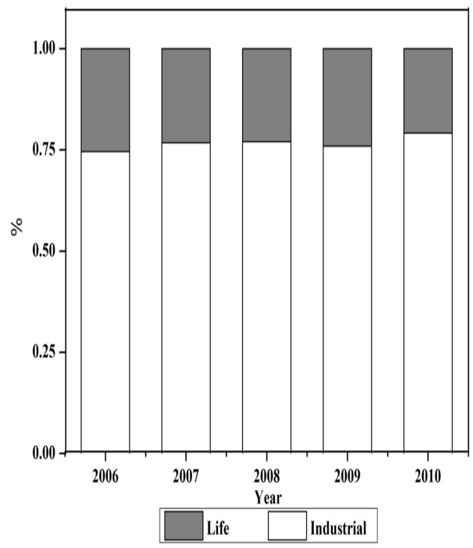

FIGURE IV. NATIONAL NOX YEARLY EMISSION CHANGE IN CHINA FROM 2006 TO 2010.

Source: Environmental Statistical AnnualReport from Ministry of environmental protection of China (2011, 2001–2010).

As of the end of 2011, the amount of denitration unit capacity on operation was approximately 140 million kilowatts, accounting for 18% of the thermal power capacity. The amount of planning and constructing a denitration unit was more than 100 million kilowatts, including 85 million kilowatts for simultaneous construction of denitration facilities and 15 million kilowatts for technological denitration facilities. In China, seven central enterprises in Power Group exist. These enterprises include the State Grid Corporation of China, China Southern Power Grid, China Huadian Group, China Datang Corporation, China Huadian Corporation, China Guodian Corporation, and China Power Investment Corporation, which accounted for the largest proportion of the country's total power generation capacity. By the end of August 2011, the amount of denitration unit capacity on operation in these seven corporations was 73.06 million kilowatts, accounting for approximately 17% of its coal-fired unit capacity (Chinese Academic for Environmental Planning, 2013).This low capacityis caused by the additional denitration cost being higher than its compensation.

B. Policy of Electricity Power Price Subsidy on Nitrogen Oxide Abatement in China

Parallel to the support of technology development, the market introduction of clean, low NO_x technology can be supported by subsidies. In China, these subsidies have been granted for low NO_x gas engines and for high-efficiency low NO_x small boilers. Another economic incentive is the denitration subsidy for electricity price.

To encourage the power plants to accomplish the denitration reform and payment for their additional cost, a 0.8 cent/kWh subsidy policy was proposed by the National Development and Reform Commission to the power plants that had attained the denitration requirement on 30Nov. 2011.

China's policy on denitration tariff subsidies began to launch pilot in 14 cities and provinces, including Beijing, Tian-jin, Hei-bei, Shan-xi, Shan-dong, Gan-su, Ning-xia, Shang-hai, Zhe-jiang, Jiang-su, Fu-jian, Si-chuan, Guang-dong, and Hai-nan since 2011. To strengthen the NO_x control and encourage the fired power plants implementing the denitration transformation, the Chinese Ministry of Environmental Protection and the National Development and Reform Commission jointly issued an announcement called "Some Notice on Strengthening the Coal-fired Power Plant Denitration Acceptance and Implementing the Denitration Facilities Tariff Policy," in 2013.

The methods of denitration tariff policies specifically indicated that coal-fired generating units in operation, which obtained acceptance from the national or provincial environmental protection department but have not implemented the denitration tariff, should apply the denitration price since 1Jan. 2013.This policy means that most of the electricity power plants in the pilots should have achieved denitration transformation until 1Jan. 2013.

Recently, the National Development and Reform Commission issued a notice called "Support for Renewable Energy Development," which encouraged coal-fired power generation companies to perform denitration measures. This notice determines some appropriated adjustment on denitration compensation standards on renewable energy tariff and coal-fired power plants. The subsidy on the price of coal-fired power plants increased from 0.8 cents/kwh to 1 cent/kwh. The above notice on denitration electricity price subsidy would be implemented on 25 Sept. 2013.

III. METHODOLOGY

A. Data Acquisition

The empirical analysis is based on information collected through field investigations in 2012–2013 from12 electricity plants being subjected to the NO_x abatement cost in Guang-zhou and An-hui provinces in China. The analyzed material includes 23 electricity generation units.The investigated data contain unit capacity, denitration type, technology type, annual operating hours, power generation, denitration efficiency, NO_x reduction cost, NO_x emission, entrance concentration, exit concentration, and so on. For analysis, these power generation units are divided into two groups as 300 and 600MW, as the survey of generators showed that their unit capacity is always around the two numbers listed following 265, 300, 320, 350MW, 600, 630, and 640MW.

The NO_x emission reduction measures for the power industry include technical measures, structure-adjustment measures, and scale-restriction measures. This paper presents three denitration construction measures, which are new construction, synchronized construction, and technological transformation. Half of the 300-MW power plants's denitration type is synchronized constrution, and the other half is new construction.All of the 600-MW power plants's denitration type is technological transformation.

NO_x emissions could be controlled either during or after the conbustion (McCahey et al., 1999).Three main types of denitration technologies were observed, which include selective catalytic reduction (SCR),selective noncatalytic reduction（SNCR）, and low-nitrogen conbustion in China. In this study, 90% of the power plants used the SCR technologyandthe other 10% is either low-nitrogen conbustion or SNCR. Moreover, the denitration efficiency of those electricity generation units is more than 70%.

B. Analysis Methods

1) The ATCD

The ATCD is the ATC of the denitration. Some authors estimate the denitration cost based on the externality internalization theory and cost-efficiency theory, using dynamic breakeven analysis model and cost-efficiency method (Jian et al., 2010). Obtaining first–hand data on the denitration cost in enterprises is difficult, thus no research analysis using the actual data from this study was provided.

In this study, the total denitration cost comprises operations and manufacturing costs. The manufacturing cost specifically includes engineering and construction cost, installation cost, engineering and technical services cost, and others. Meanwhile, the operation cost includes reducing agents cost, catalysts cost, depreciation charges cost, annual maintenance fees, annual labor costs, and others.

In this study, the manufacture cost is discounted, and the discount rate is 15%, which is calculated using Eq. (1):

$$C_m=C_e+C_i+C_s+C_{ot} \quad (1)$$

Where C_m is the manufacturingcost, C_e is the engineering and construction cost, C_s is the engineering and technical services cost, and C_{ot} is other cost.

The operation cost is calculated using Eq. (2):

$$C_o=C_r+C_c+C_d+C_{mai}+C_{lab}+C_{ot} \quad (2)$$

Where C_o is the operation cost, C_r is the reducing agents cost, C_c is the catalysts cost, C_d is the depreciation charges cost, C_{mai} is the annual maintenance fees, C_{lab} is the annual labor costs, and C_{ot} is other cost.

$$C_{TC}=C_m + C_o$$

$$C_{AM}=C_m/Q \quad (3)$$

$$C_{AO}=C_o/Q \quad (4)$$

$$C_{ATC}=C_{AM}+C_{AO}=\frac{C_m+C_o}{Q} \quad (5)$$

Where Q is the annual generation, C_{TC} is the total cost, C_{AM} is the average manufacturing cost (AMC), C_{AO} is the average operation cost (AOC), and C_{ATC} is the ATC.

2) The MAC Function

The methodology adopted here is the joint abatement cost functions which relate total costs to treatment volume and the simultaneous effect of reductions in several pollutants developed by Susmita et al.(1996) and applied to the China industrial enterprise pollution behaviors by Dong et al.(2009). In contrast to Dong et al., we simultaneously estimate the marginal abatement costs of single pollutant, the NO_x, and analyze the rationality on the electricity price subsidy based on the econometric result on the marginal abatement costs.

MAC functions are a commonly used policy instrument indicating emission abatement potential and associated abatement cost (Fabian et al., 2011). They have been extensively used for a range of environmental issues in different sectors and are increasingly applied to denitration electricity price subsidy policy.The method of MAC is gradually used in calculating the marginal abatement costs of the airborne pollutants in power plants (Oh Sang and Won-Cheol, 1999; David et al., 2002).

MAC functions focus on the direct costs associated with emission reductions, such as investment cost, operation and maintenance cost, and fuel cost for abatement measures (Brown et.al, 2001). Many non-financial costs are excluded from the cost definition in MAC functions, such as supervising and waiting for the installer, costs for re-decorating parts of the house after installations have been performed, and disruption costs (Holdaway et al., 2009).

For k pollutants, the environmental engineering literature suggests that an appropriate joint cost function for plant I should include the following variables:

$$C_i=f\left(W_i,\frac{E_{in}}{I_{in}},M_j,X_i\right) \quad (6)$$

Where C_i is the total annual cost of abatement for the plant, W_i is the total annual pollutant emission, E_{in}/I_{in} is the vector of effluent/influent ratio for n pollutants, which can be interpreted either as concentration ratios or volume ration(as waste water volume is constant across influent and effluent for each plant, it cancels the concentration ratio), M_j is the vector of input prices at location, and X_i is the vector of relevant plant characteristics (sector, age, ownership, productive efficiency, etc.).

For the *k*th pollutant, the marginal abatement cost function is expressed as (Hua et al., 1996):

$$\frac{\partial Ci}{\partial Ei}=\frac{\partial f(Wi,\frac{E_{in}}{I_{in}},M_j,X_i)}{\partial Ei} \tag{7}$$

We specify a second-order quadratic approximation to the general cost function (or translog function) as follows:

$$InC=\alpha_0+\alpha_1 InW+\alpha_{11}Inw^2+\sum_{i=1}^{n}\beta i\, In\left(\frac{E_{in}}{k_{in}}\right)+\sum_{i=1}^{n}\sum_{j=1}^{n}\beta ij\, In\left(\frac{E_{in}}{I_{in}}\right)InW_j+$$
$$\sum_{i=1}^{n}\sum_{j=1}^{n}\gamma ij\, In\left(\frac{E_i}{I_i}\right)In\left(\frac{E_j}{I_j}\right)+\beta jj\left\{In\left(\frac{E_{in}}{I_{in}}\right)\right\}2+\varepsilon \tag{8}$$

Abatement in Eq.8 is measured by *E*/*I*, which reflects the percent reduction in the pollutant as it passes from pre-abatement influent concentration *I* to post-abatement effluent concentration *E*.

From the log–log form of Eq.8, with potential quadratic scale effects, we have derived the following plant-lever total and marginal cost equations (Susmita et al., 1997):

$$C=e^{\alpha_0}\cdot W^{\alpha_1+\alpha_2 logW}\cdot\prod_{i=1}^{n}\left[\frac{E_i}{I_i}\right]^{\beta_i} \tag{9}$$

To consider that the NO_x is the only pollutant in our study, the total cost of the NO_x can be expressed as:

$$C=e^{\alpha_0}\cdot W^{\alpha_1}\cdot\left[\frac{E_i}{I_i}\right]^{\beta_i} \tag{10}$$

In the paper, we draw Eq. 8 to estimate marginal costs of pollution abatement (in annual Yuan/kilometer) by pollutant,

$$\frac{\partial C}{\partial Ei}=\frac{\beta i}{Ei}\cdot e^{\alpha_0}\cdot W^{\alpha_1}\cdot\left[\frac{E_i}{I_i}\right]^{\beta_i} \tag{11}$$

Where α_0, α_1, and βi are the regression coefficients.

According to Eq.10, combined with survey data, we use EVIEWS 7.2 software with sample data regression, and then use the calculated results into Eq.11. We can obtainthe result of EVIEWS data regression.

We add the investigated data, including NO_x emission (*W*), entrance concentration (I_{in}), and exit concentration (E_{in}) into Eq.11, with the regression coefficients,and thenobtainthe marginal abatement cost of NO_x emission, but now the unit is RMB/kg, the electricity subsidy is compensation by kWh.

$$\text{Marginal abatement cost (cent/kWh)=Marginal abatement cost(RMB/kg)}\times\frac{\text{Nitrogen Oxide Emission Reductions (kg)}}{\text{Annual Generation Capacity of Power Plants (kWh)}} \tag{12}$$

To compare the UCPR with the denitration subsidy, based on Eq.12, we can change the unit from RMB/kg to cent/kWh.

IV. Estimation Results

A. *Analysis of the Influencing Factors of Denitration Cost*

The total denitration cost comprises engineering and construction cost, installation cost, engineering and technical services cost, reducing agents cost, catalysts cost, depreciation charges cost, annual maintenance fees, annual labor costs, and others (including fees on water and electricity).

The ATC, which can be calculated by dividing the total cost with the electricity generation, is used to measure the average cost required to reduce one mass unit (such as kWh) of a specific pollutant. In this study, the ATC of denitration was divided into two parts, the average manufacture cost and the average operation cost, indicating the difference between the processes of manufacturing and operating in different denitration technologies and measures.

A number of differences can be observed in compounding denitration cost between the 300- and 600-MW electricity generation units (see Fig.5). First, as shown in Fig.5, the cost of engineering and construction and the installation, both accounted for 19% of the total denitration cost, are two of the highest denitration cost in the 300-MW electricity generation units, whereas depreciation charges occupied 39% of the total denitration cost in the 600-MW electricity generation units. Second, catalysts and reducing agents have been consuming a large amount of the total cost of the 300-MW electricity generation units, accounting for 11% and 13%, respectively. However, both accounted only 9% of the total cost for the 600-MW electricity generation units. As shown in Table1, compared with the 300-MW electricity capacity, the ATC of denitration cost for the 600-MW electricity capacity is 1.01 cent/kWh, approximately 0.07 cent/kWh higher in the operating process. Therefore, the electricity capacity impacting on deniration cost in the operating process is higher than the manufacturing process.

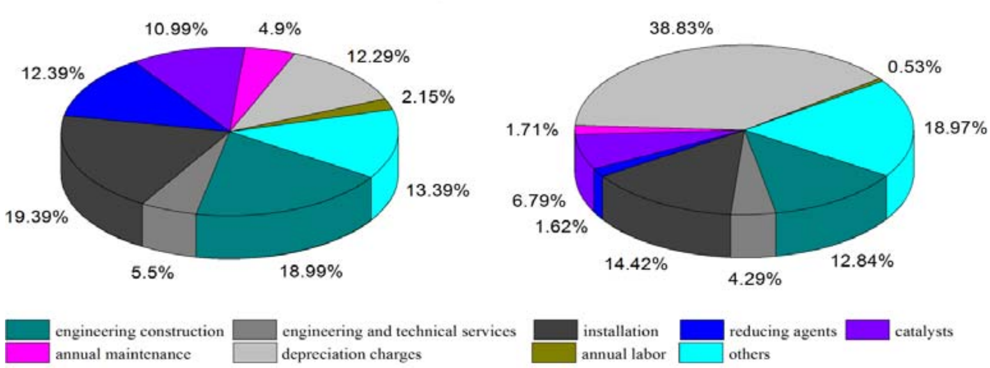

FIGURE V. COST COMPOUND OF DENITRATION ABATEMENT FOR 300AND 600MW

TABLE I. THE ATC OF DENITRATION FOR DIFFERENT ELECTRICITY CAPACITY, TECHNOLOGIES, AND MEASURES (UNIT: CENT/KWH)

Capacity	300MW			600MW		
Type	AMC	AOC	ATC	AMC	AOC	ATC
	0.94	0.97	1.91	1.01	1.46	2.47

Denitration Technologies	SCR			Low-nitrogen combustion and SCR			Low-nitrogen combustion and SNCR		
Type	AMC	AOC	ATC	AMC	AOC	ATC	AMC	AOC	ATC
	1.00	1.46	2.46	0.56	0.86	1.42	1.65	0.7	2.35

Construction Measures	New construction			Synchronized construction			Technological transformation		
	1.01	1.45	2.46	0.56	0.86	1.42	1.14	1.31	2.45

Approximately 75% of coal-based power plants use low-nitrogen combustion technology to modify combustion, including low-NO_x burners. This technology can remove 37% to 68% of NO_x emissions (Balat, 2007). SCR is a popular technology, which uses NH_3 or other nitrogen sources in the presence of a catalyst to transform NO_x into nitrogen and water, used mainly to reduce NO_x emission from combustion processes (Bruggemann and Keil, 2008). This technology can be used at moderate temperature (150 °C to 450 °C) and is characterized as a relatively expensive abatement strategy. In contrast to SCR in the case of SNCR, higher temperature (876 °C to 1,149°C) is required to enable NO_x reduction (Gomez-Garcia et al., 2005).SNCR is easy to install in existing plants and can be applied in all types of stationary-fired equipments (Javed et al., 2007). However, the main drawback of SNCR is its low efficiency from 30% to 75%, which must be premised with the combustion modification techniques, combined with other post-combustion modification techniques, or combined with another post-combustion method.

As regards denitration technology in this study, in the process of operating, the ATC of the low-nitrogen combustion and SCR technology is the lowest at 0.56 cent/kWh and is the SCR technology that is approximately 0.44 cent/kWh higher than the Low-nitrogen combustion and SCR technology. The ATC of low-nitrogen combustion and SNCR technology is the highest at 1.65 cent/kWh, which is three times than that of the low-nitrogen combustion and SCR technology. However, this trend appears much different in the operating process. The ATC of the SCR technology is the highest at 1.46 cent/kWh, which is about two times more than the ACT of the low-nitrogen combustion and SNCR technology, which is the lowest. The relationship among the technologies appears difficult to be interpreted scientifically here, but different denitration technologies are also important factors influencing the denitration cost.

According to the construction measures, in the process of manufacturing, the ATC of the new construction is approximately 1.01 cent/kWh, and the technological transformation measure is 1.14 cent/kWh, which is two times higher than the synchronized construction measure. Meanwhile, not so much gap among the ATC of those construction measures in the operating process can be observed.The gaps among different construction measures still exit.

Therefore, the electricity capacity, denitarion technologies, and construction measures are three of the striking factors that impact the denitration cost.

B. *Evaluation on the Denitration Technologies and Measures*

The UCPR, which can be calculated from the MAC function, was used to examine the cost-effectiveness of each emission reduction technologies and measures (Xianqiang et al., 2013). As in a cost-effective reduction scheme, technologies or measures with lower UCPR should be adopted prior to those with higher UCPR (Xianqiang et al., 2013), so that the UCPR can be used as a basis or a guidance to select the best denitration method, such as the electricity capacity, technology type, and construction type in this study.

TABLE II. THE UCPR OF DENITRATION FOR DIFFERENT CAPACITY, DENITRATION TECHNOLOGIES, AND MEASURES (UNIT: CENT/KWH)

Unit capacity	300MW		600MW
UCPR	1.35		1.03
Denitration Technology	Low-nitrogen combustion +SCR		SCR
UCPR	1.59		1.06
Construction measure	New construction	Synchronized construction	Technological transformation
UCPR	1.12	1.59	1.03

Our study provides the estimation results and their corresponding unit capacity in Table 2. First, the UCPR is strongly influenced by different unit capacities, the 300-MW electricity generation unit is approximately 1.35 cent/kWh, which is appropriate and is 0.32 cent/kWh higher than the 600MW. Thus, the higher the unit capacity of the flight crews, the lower is the UCPR of NO_x.

Second, results also display the impact of denitration technology on UCPR. Two main denitration technologies in the targeted power plants exist, which include SCR and low-nitrogen combustion. The UCPR of the SCR is 1.06 cent/kWh, which is 0.53cent/kWh lower than that of the mixture technology. From this analysis, we observed that the denitration technology takes a profound influence on marginal abatement cost of NO_X, and the SCR technology is better than the mixture technology. Thus, we can conclude that SCR is the most favored denitration technology.

Third, estimation results were provided, including their corresponding construction type. Three kinds of denitration construction types exist, which include new construction, synchronized construction, and technological transformation. The UCPR of the generation units whose denitration type is the new construction is 1.12 cent/kWh; the synchronized construction is 1.59 cent/kWh, and the technological transformation is 1.03 cent/kWh. Thus, we can conclude that the UCPR oftechnological transformation in electricity generation units is the lowest, which is 0.09cent/kWh lower than that of the new construction and 0.47cent/kWh lower than that of the synchronized construction.

In summary, technological transformation, the new construction is the most favored type for denitration, with the least being the synchronized construction.

C. Rationality Analysis

TABLE III. THE UCPR OF DENITRATION

Unit	**cent/kWh**
Mean	1.19
Maximum	1.61
Minimum	0.87

As shown in Table 3, in our analysis, the UCPR of denitration ranges from 0.87 cent/kWh to 1.61 cent/kWh, and its average value is 1.19 cent/kwh, which is approximately 0.19 cent/kwh higher than the 1 cent/kWh denitration subsidy. The UCPR will be implemented by the government on 25 Sep. 2013. The present subsidy on denitration appears reasonable, but a necessity arises for the government to adjust the existing tariff subsidy among denitration given the fluctuation of the denitration cost.

V. CONCLUSIONS

The electricity generation units' unit capacity, both denitration technology, and denitration construction measures particularly have an incredible influence on UCPR of the denitration, where as the SCR technology and technological transformation are the most favored options for enterprises in selecting the denitration technologies and measures. This study estimates the mean value and UCPR of denitration for the coal-fired power plants in the province of An-hui and Guang-zhou in China. In addition to the subsidy policy, the government should promulgate related measures to promote the denitration transformation in power plants, such as strengthening the market regulation on reducing agent, arranging reasonable downtime to guarantee the normal supply of electricity production, conducting NO_x emission trading pilot, and developing some relevant incentives on power index, bank lending rates, and taxes.

ACKNOWLEDGMENTS

This research was supported by the Research Centre for Circular Economy and Low Carbon Development and the Chinese Academy for Environmental Planning. The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (nos. 71003056 and 71373134), the Environmental Protection Gongyi Project (Re:201209001-4) , financial support from Changzhou Institute of Technology(YN1523), and Research fund for philosophy and social science of universities in Jiangsu province (2017SJB1800).

REFERENCE

[1] Ali Hasangeig, ChristophMenke, Lynn Price, 2010. The CO2 abatement cost curve for the Thailand cement industry. Journal of Cleaner Production 18,1509-1518.

[2] Baumol, W.J., Oates, W., 1988. The theory of environmental policy,2. Cambridge Universit Press, Cambridge.

[3] Brown, M.A, 2001, Market failures and barriers as a basis for clean energy policies, Energy Policy 29,1197-1207.

[4] Bruggermann TC, Keil FJ, 2008. Theoretical investigation of the mechanism of the selective catalytic reduction of nitric oxide with ammonia on H-form zeolites.JPhysChem C,112: 17378-87.

[5] Chaloulakou A, MavroidsI. Gavriil I, 2008.Compliance with the annual NO2 air quality standard in Athens.Atoms Environment 43,454-65.

[6] Chinese Academic for Environmental Planning, Economic policy for nitrogen oxides emissions research paper, 2013.

[7] Crigui P., Mima, S., Viguier, L., 1999.Marginal abatement cosy of CO2emission reductions geographical flexibility and concrete ceilings an assessment using the POLES model. Energy Policy 27, 585-601.

[8] David Soloveritchik, Nissim Ben-Aderet, Mira Grinman, and Alexander Lotov,2002.Multiobjective optimization and marginal pollution abatement cost in the electricity sector-An Israeli case study. European Journal of Operational Research 140,571-583.

[9] DES, NSB, 2011. China Energy Statistical Yearbook 2011.China Statistical Press, Beijing, China.

[10] Dong Cao, Cun-yi Song, Jin-nan Wang, Hong-qiang Jian, Wan-xin Li, and Guo-zhi Cao, 2009.Establishment and empirical analysis of cost function for pollution combination abatement, Research of Environmental Science 3(22),971-976.

[11] Fabian Kesicki, and Neil Strachan, 2011. Marginal abatement cost(MAC) curves: confronting theory and practice, Environmental Science and Policy, 14,1195-1204.

[12] Gomez-Garrcia MA, Pitchon V, Kienemann A, 2005. Pollution by nitrogen oxides: an approach to NOxabatement by using sorbing catalytic materias, Environ Int, 31, 445-67.

[13] Holdaway, E. , Samuel, B., Greenleaf, J., Briden, A., Gardiner, A., The hidden costs and benefits of domestic energy efficiency and carbon saving measures, Ecofys UK,London,2009.

[14] Hua Wang, David Wheeler, 1996, Pricing Industrial pollution in China, Policy Research Working Paper, the World Bank.

[15] JimingHao, HezhongTian, and Yongqi Lu, 2002. Emission inventories of NOx from commercial energy consumption in China, 1995-1998. Environmental Science and Technology 32, 552-560.

[16] J.K. Kldellis, G.th. Vlachos, A.G. Paliatsos, and E.M. Kondili, 2005.Detailed examination of the Greek electricity sector nitrogen oxides emissions for the period 1995-2002, Environmental Science and Policy 8, 502-514.

[17] Jian-guo Zhou, Bing Cui, and Yi Zhao, 2010.Research on denitration electricity price based on internalization of externality and state intend to pay, Technology Economics5, 48-57.

[18] Jian-guo Zhou, Yuan-yuan An, San-liangDuan, and Yi Zhao, 2010. Research of denitration price in coal-fired plant based on externality and dynamic breakeven analysis, Power System Protection and Control 8, 85-91.

[19] Jian -guo Zhou, Huai-tao Liang, and Yi Zhao, 2010. Research on denitration electricity price in coal-fired power plant:baesd on operation period price and simulated annealing, Technology Economics 8, 68-71.

[20] Kamat R., Rose, A., Alber, D., 1999. The impact of carbon tax on the Susquehanna River Basin economy, Energy Economics 21, 363-384.

[21] KingaSkalska, Jacek S. Miller, StainislawLedakoecz, 2010. Trends in NOx abatement: A review. Science of the Total Environment 408,3916-3989.

[22] Lena HoglundIsaksson, 2005. Abatement costs in response to the Swedish charge on nitrogen oxide emissions. J. Environ. Econ. Manage 50, 102-120.

[23] Lex de Jonge, 1998. Policies and instruments for reducing nitrogen oxide emissions from stationary sources in the Netherlands, Environmental Pollution 102(S1), 671-675.

[24] M.Balat, 2007. Coal-fired power generation: proven technologies and pollution control systems. Energy Sources 30:2, 132-140.

[25] McCahey, S., McMullan, J.t., Williams, B.C., 1999.Techno-economic analysis of NOx reduction technology in p.f. boilers. Fuel 78, 1771-1778.

[26] MEP, 2011.Environmental Statistical Report 2011.Ministry of environmental protection, Beijing, China.

[27] NSB,2011. China Environmental Statistics Yearbook 2011.China Statistical Press, Beijing, China.

[28] Oh Sang Kwon, and Won-Cheol Yun,1999. Estimation of marginal abatement costs of airborne pollutants in Korea's power generation sector, Energy Economics 21, 547-560.

[29] OnnoKuik, Luke Brander, Richard S.J. Tol, 2009. Marginal abatement costs of greenhouse gas emissions: A meta-analysis, Energy Policy 37, 1395-1403.

[30] Smith, S., 1998.Environmental and public finance aspect of the taxation of energy. Oxford Review of Economic Policy14(4): 64-83.

[31] S.MortezaMesbah, Amir Hakami, and Stephan Schott, 2013.Optimal ozone reduction policy design using adjoint-based NOx marginal damage information. Environmental Science and Technology 47, 13528-13535.

[32] SusmitaDasgupta, MainulHuq, et.al,1996, Water Pollution Abatement by Chinese Industry: Cost Estimates and Policy Implications, Policy Research Working Paper, the World Bank.

[33] SusmitaDasgupta, Hua Wang,and David Wheeler, 1997, Surviving Success: Policy Reform and the Future of Industrial pollution in China, Policy Research Working Paper, the World Bank.

[34] Stephane De Cara, Pierre-Alain Jayet, 2011. Marginal abatement costs of greenhouse gas emission from European agriculture, cost effectiveness, and the EU non-EST burden sharing agreement, Ecological Economics 70, 1680-1690.

[35] Tietenberg, T.H., 1985. Emissions Trading: An exercise in reforming pollution policy. Resources for the Future, Washington DC.

[36] Xianqiang Mao. An Zeng, Tao Hu, Ji Zhou. Youkai Xing, and Shengqiang Liu, 2013. Co-control of local air pollutants and CO2 in the Chinese iron and steel industry. Environmental Science and Technology 47, 12002-12010.

[37] X.Q.Mao, A. Zeng, T. Hu, Y.K. Xing, J.Zhou, Z.Y. Liu, 2013. Co-control of local air pollutants and CO2 from the Chinese coal-fired power industry. Journal of Cleaner Production xxx, 1-8.

[38] Yang Xi, TengFei, Wang Gehua, 2013. Quantifying co-benefit potentials in the Chinese cement sector during 12th Five Year Plan: an analysis based on marginal abatement sector with monetized environmental effect. Journal of Cleaner Production 58, 102-111.

[39] Yongxiu He, Tian Xia, Wei Xiong, Bing Wang, Yangyang Liu, 2013. Risk transmission on assessment of electricity price chain in China based on ISM. Electrical Power and Energy System 46, 274-282.