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Ma, Teng

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Teng Ma
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Technology Choice for Reducing NO_x Emissions: An Empirical Study of Chinese Power Plants

Teng Ma and Kenji Takeuchi*

Graduate School of Economics, Kobe University

Rokko, Kobe, 657-8501 Japan

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Abstract

This study investigates the choices of denitration technology in the Chinese thermal power sector. Using a multinominal logit model of the choices among 1,135 boilers in thermal power plants operating in China in 2013, we analyze how the choices were influenced by government policies, the stringency of national standards, and subsidies for using specific technology. The results are as follows. First, China's 12th Five-year Plan might make it more attractive for plants to choose the cheapest denitration technology among the three options examined in this study. Second, technology choices differed significantly by region before the 12th Five-year Plan period. These differences have disappeared, perhaps due to the economic development across all regions of China. Third, electricity price subsidies offered to plants that use denitration equipment might affect their technology choice. These results suggests that plants might choose the cheapest technology available, in order to lower investment costs.

Keywords: technology choice; NO_x emissions; China; thermal power sector

JEL Classification Numbers: O33, Q53, Q55

*E-mail: `mt_yx@hotmail.com` (Ma), `takeuchi@econ.kobe-u.ac.jp` (Takeuchi).

1 Introduction

A large proportion of air pollution in China stems from coal combustion: coal was the source of 90% of all sulfur dioxide (SO_2) emissions and 67% of nitrogen oxides (NO_x) emissions in 2005 (Liang et al., 2011). Although total SO_2 emissions from the industrial sector decreased from 22.37 million tons in 2006 to 18.35 million tons in 2013, total NO_x emissions increased from 11.36 million tons to 15.45 million tons during the same period (China State Statistical Bureau, 2007, 2014). NO_x emissions contribute to the formation of fine particles (PM10/PM2.5) that inflict significant damage to the health of Chinese citizens (Chen et al., 2015).

The regulation of NO_x emissions in China has lagged behind that of SO_2 emissions. Between 2005 and 2010, the share of thermal power plants that installed desulfurization equipment increased from 14% to 86%. As a result, total SO_2 emissions decreased 14.29% during the same period. In contrast, the Chinese government shifted its focus to the regulation of NO_x, starting with the 12th Five-year Plan initiated in 2011. This plan announced, for the first time, a concrete target for reducing nitrogen oxide emissions: a 10% reduction in NO_x emissions from the 2010 levels by 2015 (State Council of the People's Republic of China, 2011a).

Several policies were implemented to control NO_x emissions during the 12th Five-year Plan (2011–2015). The *12th Five-year Plan on Environmental Protection* insists that all newly built power generation units and existing units whose capacities exceed 300 MW be coupled with denitration equipment (State Council of the People's Republic of China, 2011a). The new NO_x emission standards were released in July 2011 and took effect in January 2012. Furthermore, the government issued the *12th Five-year Plan for the Prevention and Control of Air Pollution in Key Regions* (Key Regions Plan) in October 2012 (Chinese Ministry of Environmental Protection, 2012). It sets higher emissions reduction targets in specific regions designated according to the type and level of air pollutants experienced there. The government also offered subsidies to thermal power plants that used denitration equipment.

As a result, the use of technology for controlling NO_x began to proliferate. As of 2013, 1,238 pieces of denitration equipment had been installed on 7,515 boilers in 3,102 power plants in China.[1] By 2013, NO_x emissions from the thermal power sector had decreased 1.2 million tons (or by 11%) from the 2012 volume (Chinese Ministry of Environmental Protection, 2014a).

Several engineering studies have investigated the role of technological options for controlling NO_x emissions in the thermal power sector in China. Xiong et al. (2016) investigated the emission inventory of coal-fired power plants in Shandong and projected future emissions under three scenarios. Under the assumption that the penetration of selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technology would increase from 10% and 2% in 2012 to 95% and 5% in 2030, respectively, they predict that NO_x emissions will decrease by 80.63% relative to the 2012 baseline. Zhao et al. (2008) evaluate the cost-effectiveness of various coal-power technologies and estimate the differences in capital costs and overall cost of electricity. The net plant efficiency for the integrated gasification combined cycle (IGCC) technology is 45%, and NO_x emissions are minimized by using IGCC among all the technological options. However, the cost per unit of electricity generated while using IGCC is 30% to 40% higher than the option using SNCR technology, even when charges related to pollutant emissions are included. While these studies suggest that the technology adoption will play a key role in reducing NO_x emissions in China, details on the actual adoption process and its driving force have not been analyzed.

On the other hand, economic studies of the technology choices for controlling NO_x have focused on cases in developed countries. For example, Popp (2010) investigates links between knowledge stock and the adoption of NO_x control technology in US coal-fired power plants. His results suggest that an increased level of knowledge stock—measured by patent count—increases the adoption rates of combustion modification techniques and

[1] The number is the total of utility power plants and non-utility power plants. The latter consists of power plants managed by industrial sectors for their own energy consumption. There were 1,853 utility power plants and 1,249 non-utility power plants in China in 2013. They have 4,825 and 2,690 boilers, respectively. Among them, 1,076 utility boilers and 162 non-utility boilers had installed denitration equipment in 2013.

post-combustion treatments. Examining the impact of Swedish emission regulations, Sterner and Turnheim (2009) considered the process of technological change in relation to NO_x abatement from large stationary sources. They regressed the plant emission intensities of NO_x on various explanatory variables, including specific technological options. Their results suggest that the most significant and sizeable reduction was attained by using SCR, followed by that attained using SNCR. Bonilla et al. (2015) studied how the use of various NO_x abatement technologies has diffused under the Swedish system of refunded emission payments by analyzing the determinants of the time to adoption. Their results revealed an economy of scale: the greater the capacity of the boiler, the more likely it is that post-combustion technologies will be adopted. Their results also suggest that stringent standards increase the regulatory costs of NO_x emissions and motivate firms to invest in more than one NO_x-reducing technology. They attribute no explanatory power to the predicted decrease in net charge liabilities or to most of the other covariates across the subsamples in Sweden.

This study focuses on the choices of NO_x control technology in the thermal power sector in China, where air pollution is a major issue under conditions of rapid economic growth. We analyze how technological choices have been influenced by government policies, the stringency of national standards, and subsidies for using specific technologies. We focus on the available post-combustion technologies, as the removal efficiency of NO_x through post-combustion technology is higher than that through the pre-combustion or combustion process. We find that SNCR adoption increased after 2010 and identify a clear distinction in regional distribution between the pre- and post- 2010 periods concerning the adoption of SCR technology. We also investigate how subsidies for operating denitration equipment affected SCR adoption and find that subsidies somewhat discouraged it, perhaps because SCR is more expensive than the other technological options.

In Section 2, we provide background information and develop our hypothesis. We also introduce the denitration technology, national standards, and various policies relevant to the NO_x emitted by thermal power sector in China. Section 3 explains the study's empirical strategy and data. Section 4 presents the study's empirical results, and Section 5 concludes the paper.

2 Background, and Hypothesis Development

2.1 Technological Options for Post-combustion Control

The abatement of NO_x emissions occurs by way of three different processes: pre-combustion control, combustion modification, and post-combustion capture (Skalska et al., 2010; Cheng and Bi, 2014). Pre-combustion control involves fuel purification, used to reduce the nitrogen content of the fuel. Combustion modification refers to technology improvements in the boiler design, which can reduce NO_x formation during the combustion processes. Post-combustion technologies are end-of-pipe solutions that reduce NO_x in the flue gases following the combustion stage. Post-combustion technologies can remove up to 90% of NO_x (Guo et al., 2012), while that of pre-combustion control and combustion modification control can reduce NO_x by only less than 50% (Radojevic, 1998). Therefore, the adoption of post-combustion technology is important for making any significant reductions in NO_x emissions.

The SCR and SNCR technology are representative post-combustion processes. SCR technology is usually applied to thermal power plants with capacities greater than 200 MW and that work at a temperature in the range of 300 to 400 °C (Cofala and Syri, 1998). While the denitration efficiency of SCR is high (i.e., up to 80−90%), one problem is that catalyst pollutes the environment (Zhou et al., 2012). The ammonia used in the catalytic process can corrode the equipment, produce ash pollution, and damage the environment. SNCR is another technology used to control NO_x emissions from coal-fired power plants. Since it does not require any catalyst, the denitration process produces no pollution. It incurs a lower investment cost and can be applied to any size of unit. On the other hand, it requires a high working temperature (i.e., 870−1100 °C), and its rate of denitration efficiency is usually lower than 40% (Liang et al., 2011).

Table 1 summarizes the characteristics of these two technologies. SCR requires catalyst, while SNCR does not, and there is a pressure loss with SCR but not with SNCR. The removal efficiency of SCR is as high as 80%, while that of SNCR is 40% at most. The construction cost of SCR is higher than that of SNCR. SCR produces ammonium hydrogen sulfate, while SNCR does not (Zhou et al., 2012). In addition to the SCR and SNCR technologies, a hybrid of these two technologies, SNCR−SCR, is used in Chinese thermal power plants (Liang et al., 2011). It is more environmentally friendly and cost-effective than SCR and is more denitration-efficient than SNCR. SCR and SNCR technologies were initially installed in the early 2000s, while the first SNCR−SCR technology was installed in 2006 (Chinese Ministry of Environmental Protection, 2014b). As we will see in a later section, a large proportion of these technologies were installed after 2010.

[Table 1]

2.2 National Emission Standards

Table 2 summarizes the national standards for NO_x control in China. National emissions standards for NO_x from thermal power plants were introduced and updated in 1997, 2003, and 2012. These are included in direct regulations of various air pollutants from the power generation sector, named GB13223-1996, GB13223-2003, and GB13223-2011. These GBs are implemented on the basis of the Air Pollution Prevention and Control Law.

[Table 2]

GB13223-1996 included the first national standard for controlling NO_x emissions from the thermal power sector. It requires that effluent concentrations be less than 650 mg/m^3. The regulation applies only to boilers with a maximum continuous rating greater than 1,000 t/h and that began operating after January 1997. GB13223-1996 was updated to GB13223-2003 in 2003; the emissions standard in this GB varied according to the year in which the plant was built. The first category contains plants that started operations before the end of

1996; the second category includes plants that started operations between January 1997 and December 2003; and the third category includes plants that started operations after January 2004. For plants in the first category, the most stringent standard was 1,100 mg/m^3. For the second and third categories, the values were 650 mg/m^3 and 450 mg/m^3, respectively. More stringent standards were applied to newer plants. Subsequently, GB13223-2011 was introduced in 2012. The most stringent standard is 450 mg/m^3 and applies to plants that were in operation until 2012; it is 100 mg/m^3 for those that started operations after 2012.

It is reasonable to expect that more stringent standards would encourage firms to employ denitration technology that features higher removal efficiency. On the other hand, firms might not control their emissions, even under tighter standards, due to insufficient monitoring and enforcement. In such a case, regulation via stringent standards might not be effective in inducing firms to invest in better emissions control equipment.

2.3 Policy Instruments under Five-year Plans

The Chinese government mentioned NO_x control as a policy agenda for the first time in the 11th Five-year Plan (2006–2010). The government announced that it would control the growth trend of NO_x emissions and reduce the power sector's NO_x emissions intensity by 2010. The government also announced that it would control the total NO_x discharge by 2020. However, the plan did not specify any concrete target during that period (Chinese Ministry of Environmental Protection, 2012).

The subsequent 12th Five-year Plan (2011–2015) introduced a concrete target for NO_x emissions for the first time in the history of Chinese environmental policy. Based on the *12th Five-year Plan on Environmental Protection* in December 2011, it announced a 10% reduction in NO_x emissions by 2015 from 2010 levels (State Council of the People's Republic of China, 2011a). The emissions target for each province in China was also announced (State Council of the People's Republic of China, 2011b). The targets exceed 15% in the eastern regions such as the Yangtze River Delta area, the Beijing–Tianjing–Tangshan area, and the Pearl River Delta area (see Table 3), and are approximately 10% in the inland areas. Areas such as Hainan and Qinghai were allowed to increase their emissions, suggesting that differences in economic development levels were considered when these targets were set (Xing, 2012).

In October 2012, the *12th Five-year Plan for the Prevention and Control of Air Pollution in Key Regions* (Key Regions Plan) was issued to promote the enforcement of air pollution control in specific regions. The 2015 reduction target for NO_x emissions in key regions was 13%, and that for the NO_x concentration was 7%, both from 2010 levels. Furthermore, the Key Regions Plan defines Key Control Areas with regards to different types of air pollution, where even stricter pollution control measures were implemented. Concerning NO_x control, 44 cities in the central region of Liaoning, around of Wuhan, Changsha–Zhuzhou–Xiangtan, Chengdu–Chongqing, and the urban area of Western Taiwan Straits were designated as Key Control Areas (Chinese Ministry of Environmental Protection, 2012). We can expect that the reduction target of each province and the designation of the Key Control Areas impacted firms' choices of NO_x control technology during this period.

[Table 3]

Regarding the means of controlling NO_x emissions, the 12th Five-year Plan insists that all newly built power generation units and large existing units ($\geq$ 300 MW) be equipped with flue gas denitrification equipment (Zhao et al., 2013). The Key Regions Plan announced that thermal power generating units larger than 200 MW that had been operating for fewer than 20 years should have denitration equipment installed, and it required that the removal efficiency of that equipment be greater than 85%. Moreover, the government would strengthen its monitoring of installed equipment to ensure its stable operation. To offer an incentive for operating control equipment, in November 2011, the Chinese National Development and Reform Commission introduced a subsidy via higher on-grid electricity prices for coal-fired power plants that were using NO_x emissions control equipment. The policy was first implemented in 14 pilot provinces selected from China's 31. The subsidy level was

0.008 RMB/kWh in addition to the baseline electricity price. In the first half of 2012, NO_x emissions declined by 0.24% from the previous year. Denitration efficiency was 40.3%, a 16.1% increase over the previous year. In January 2013, the application for a subsidy was extended nationwide, although the subsidy level remained unchanged from the 2011 level (Chinese National Development and Reform Commission, 2013). These policy instruments might influence the adoption of particular technologies, as plants might choose cheaper and less-effective technologies if monitoring and enforcement instruments are not strong.

3 Empirical Strategy and Data

3.1 Empirical Model

We focus on the choices of technologies used to control NO_x within China's thermal power sector. We assume that these choices are affected by the policies, subsidies, and economic characteristics of each region. We also assume that there are three options ($j = 1, 2, 3$) for control technology (i.e., SCR = 1, SNCR = 2, SNCR−SCR = 3). The expected profit that the ith boiler (i =1,...,n) derives from the jth option can be expressed as V_{ij}. The expected profit function is written as:

$$V_{ij} = \beta_{j1}P_i + \beta_{j2}S_i + \beta_{j3}O_i + \beta_{j4}E_i + \epsilon_{ij} = Z_{ij} + \epsilon_{ij}, \tag{1}$$

where P represents the policies applied when the boiler is transformed, S represents the standards applied to the emissions from the thermal power plant, O denotes boiler-specific characteristics, and E represents regional economic characteristics. We use a multinomial logit model to analyze plants' choices among the three technologies.

A plant will choose the technological option m if and only if it brings the highest economic return among all the available choices. In other words, the probability that plant i will choose alternative m is

$$
\begin{aligned}
Pr(Y_i = m) = Pr(V_{im} > V_{ij}) \quad & for\ all\ j = 1, 2, 3,\ j \neq m \\
& \Longrightarrow Pr(Z_{im} + \epsilon_{im}) > Pr(Z_{ij} + \epsilon_{ij}) \\
& \Longrightarrow Pr(Z_{im} - Z_{ij}) > Pr(\epsilon_{ij} - \epsilon_{im}) \quad for\ all\ j = 1, 2, 3,\ j \neq m.
\end{aligned} \tag{2}
$$

Based on McFadden (1973), the error terms ϵ_{ij} are assumed to be independently and identically distributed with Weibull distribution $F(\epsilon_{ij}) = exp[exp(-\epsilon_{ij})]$; then,

$$
Pr(Y_i = m) = \frac{exp(Z_{im})}{exp(Z_{i1}) + exp(Z_{i2}) + exp(Z_{i3})}, \tag{3}
$$

$$
Pr(Y_i = k) = \frac{exp(Z_{ik})}{exp(Z_{i1}) + exp(Z_{i2}) + exp(Z_{i3})}. \tag{4}
$$

From equations (3) and (4), the logarithm of the ratio of the probability of outcome $j = m$ to that of outcome $j = k$ is

$$
log\left(\frac{Pr(Y_i = m)}{Pr(Y_i = k)}\right) = (\beta_{m1} - \beta_{k1})P_i + (\beta_{m2} - \beta_{k2})S_i + (\beta_{m3} - \beta_{k3})O_i + (\beta_{m4} - \beta_{k4})E_i \tag{5}
$$

P_i includes policies for controlling NO_x emissions. In our analysis, there are five explanatory variables for policies. *12th FYP* is a dummy variable denoting whether a boiler was transformed during the 12th Five-year Plan. *NO_x Control Area* is a dummy variable denoting whether a boiler was built in the NO_x control area designated under the Key Regions Plan.[2] This dummy variable takes the value of one if a boiler was operating in a NO_x control area and transformed after 2012. *Subsidy 2011* and *Subsidy 2013* are dummy variables for subsidy policies for boilers operating denitration equipment implemented in November 2011 in 14 specific provinces and January 2013 nationwide, respectively. *Subsidy 2011* takes

[2]These are 44 cities and areas that belong to the central region of Liaoning, around Wuhan, and in each of Changsha–Zhuzhou–Xiangtan, Chengdu–Chongqing, and the urban area of Western Taiwan Straits.

the value of one if the boiler operates in 14 pilot provinces and was transformed in 2011 or 2012. *Subsidy 2013* takes value of one if the boiler was transformed in 2013. *Provincial Target* represents the reduction target for NO_x until 2015 in each province; it is denoted by a percentage reduction from 2010 emissions in each province. Since the provincial target is announced in 2011, the variable takes zero for all boilers that installed the control equipment before that year.

S_i is the stringency of emissions standards for NO_x emitted by the thermal power sector. This is represented by the *Emission Standard* variable, which uses the values applied to each boiler under GB13223-1996, GB13223-2003, and GB13223-2011. For example, we set the value of *Emission Standard* equal to 1,100 if a boiler started operations before 1996 and transformed before 2010 because the GB applied to this boiler when it installed control equipment was GB13223-2003, and, under this GB, the emissions standard applied to this boiler was 1,100 mg/m^3. Likewise, we set the emissions standard level equal to 650 if operations started between 1997 and 2003 and the transformation took place earlier than 2010. Similarly, the value equals 450 if the boiler started operations earlier than 2003 and transformed after 2011 or if its first operation year was between 2004 and 2011. We set the value equal to 100 if the first year of operation was after 2012.

O_i summarizes the individual characteristics of boilers. *Capacity* is a variable reflecting boiler capacity. *Installation Age* measures the years that passed between when the boiler started operations and when NO_x control equipment was installed. *Selfbuilt* is a dummy variable that takes the value of one if the plant installed control equipment that it had manufactured; if the plant installed control equipment manufactured by other companies, the value is zero.

E_i summarizes the economic characteristics of each province. We use four variables: gross regional products (GRP), value-added in the manufacturing sector, utilization of the thermal power sector, and share of thermal power to total capacity. *GRP* represents the real GRP in each province, and *Industrial Value-added* is the real value added of the manufacturing sector in each province. *Utilization* represents the utilization of thermal power capacity in each province; we calculate this variable by dividing the generated electricity by the capacity of thermal power plants in each province. *Share of Thermal Power* measures the capacity share of the thermal power sector; it is calculated by dividing the capacity of thermal power generation by the total capacity of the electricity sector in each province.

3.2 Data

We use boiler-level data from the *Denitration Equipment List of National Coal-Fired Boilers*, which is accessible from the website of the data center of the Chinese Ministry of Environmental Protection (http://datacenter.mep.gov.cn). The list contains information on 1,135 utility and non-utility boilers that have installed denitration equipment and are operating in China as of 2013. Since the Chinese Ministry of Environmental Protection (2014a) reports that there are 1,238 pieces of denitration equipment in thermal power plants in China as of 2013, it captures 92% of equipment operating at that moment. We collect information on the name of the plant, the generation capacity, the year in which it started operations, the year in which it adopted denitration equipment, the construction company that installed the equipment, the type of denitration technology chosen, and the province in which each boiler is operating. Unfortunately, the database does not contain information on the boilers without denitration equipment, restricting our analysis to the technology choices of those that installed them. Figure 1 presents the cumulative number of boilers with denitration equipment in our dataset and compares it with the total number of boilers with capacity larger than 6MW from 2001 to 2013. It is clear that our dataset captures only a fraction of boilers operating in China.[3]

Descriptive statistics are shown in Table 4. On average, the boilers in our sample had a capacity of 381 MW and were 6.78 years old when denitration equipment was installed. Figure 2 shows the number of boilers that started operation in each year. In the sample,

[3]In 4.4, we analyze the decision to install denitration equipment by looking at the installation situation of 1,083 boilers operating in 2012.

81.59% of the boilers were built after 2000. There was a significant increase in the number of boilers after 2003, as the Chinese economy started to grow rapidly after China joined the World Trade Organization in 2000. Many boilers in our dataset had denitration equipment installed after 2007 (see Figure 3). Although the earliest installation took place in 2001, only nine boilers featured denitration equipment until 2006. The number of boilers with the NO_x control equipment exceeded 100 after 2011; among these, 84% of the boilers installed control equipment during the 12th Five-year Plan period.

[Table 4]

[Figure 1]

[Figure 2]

[Figure 3]

Among the 1,135 boilers in our dataset, 894 (79%) installed SCR technology, 209 (18%) installed SNCR technology, and 32 (3%) installed SNCR−SCR technology. Various factors potentially affect these choices. Figure 4 is a box chart indicating the distribution of the boiler size for the three technology choices. It suggests that SCR technologies are chosen by larger boilers while SNCR are installed on smaller units. The age of the boiler also matters for technology choice. Figure 5 shows that SNCR−SCR is installed on old boilers, while SCR is installed on new units.

Of the total, 275 boilers (24%) installed denitration equipment in the year they began operations.[4] It is very likely that these boilers are equipped with NO_x control technology when they are constructed. Interestingly, many boilers that installed equipment in the first year of their operation choose SCR and SNCR technology, but none installed SNCR−SCR. This can be also confirmed by Figure 6, which shows the relationship between the year the

[4] In Appendix A, we investigate the characteristics of these boilers that installed the denitration equipment in the first year of their operation.

boilers began operating and the year they installed their NO_x control equipment. The upper parts of these figures include frontier lines indicating boilers that installed equipment in the year they began operating. While there are dots on the frontier lines in the SCR and SNCR panel, there are no dots on the line in the SNCR−SCR panel. The dots in the SNCR panel are concentrated on the right, indicating that most of the boilers installed SNCR technology after 2010.

[Figure 4]

[Figure 5]

[Figure 6]

4 Empirical Results

4.1 Baseline analysis

We use a multinomial logit model to investigate the factors affecting plants' choices among the three denitration technologies. The results are shown in Table 5. Since we take SNCR technology as the base technology, the coefficients in the models show the effect of various factors on the choice of SCR or SNCR–SCR technology over SNCR technology. As noted earlier, SNCR has the lowest investment cost but also the lowest denitration efficiency. To avoid correlation with the dummy variable for the 12th Five-year Plan period (*12th FYP*), we exclude variables concerning the subsidy policy (i.e., *Subsidy 2011* and *Subsidy 2013*) in these estimations.

[Table 5]

Column (1) in Table 5 shows how various policies influence each plant's choices of technology. We also estimate models with control variables (*GRP* and *Industrial Value-added*); the results are in columns (2) and (3). The coefficient of *12th FYP* has a negative sign and is statistically significant for the choice of SCR over SNCR. On the other hand, the coefficient of *NO_x Control Area* variable has a positive sign and is statistically significant for SCR technology (columns (1)–(3)). While SNCR technology (the cheapest technology) was preferred during the 12th Five-year Plan period over SCR technology (the most expensive technology), this is not the case for the plants located in the NO_x control areas. In columns (4) to (6) of Table 5, we use *Targeted Plant in 12th FYP*, rather than *12th FYP*. The variable is a dummy denoting plants targeted in the 12th Five-year Plan; taking the value of one when a boilers is larger than 300 MW and transformed during the 12th Five-year Plan, and zero otherwise. The coefficient of this variable is statistically insignificant for the choice of SCR over SNCR, suggesting that there is no difference among these technologies in terms of firm preference.

Regarding boiler characteristics, *Capacity* is both positive and statistically significant, in line with our expectation that plants with larger boilers tend to choose SCR or SNCR–SCR over SNCR technology. *Installation Age* is positive and statistically significant for SCR technology, suggesting that the plants with older boilers tend to choose SCR technology. The dummy variable for the self-built denitration equipment (*Selfbuilt*) is negative and statistically significant for the choice of SNCR–SCR. *Emission Standard* is negative and statistically significant for the choice of SCR over SNCR technology; since a lower-value for this variable means stricter regulation, it is reasonable to derive a negative coefficient for the choice of a more efficient technology option.

Therefore, we find a negative and statistically significant results for the dummy variable of the 12th Five-year Plan concerning the more expensive technological choices. On the other hand, the effect is statistically insignificant when we use the *Targeted Plant in 12th FYP*; this difference suggests that plants with boilers larger than 300 MW are indifferent about which technologies to choose to control NO_x. Furthermore, two policies might have promoted the choice of SCR technologies during the 12th Five-year Plan period. The positive coefficient of the *NO_x Control Area* dummy can be interpreted to mean that plants in NO_x control areas tend to choose more expensive technology to control NO_x and thus fulfill the stringent requirements under the policy. The statistically significant coefficient of *Emission Standard* also suggests that SCR technology was chosen under more stringent emission regulations.

As an additional analysis, we create the dummy variable *Targeted Plant in Key Regions* to denote the installation of denitration equipment in thermal power generating units that are larger than 200 MW, had operated for fewer than 20 years by 2013, and operated in key regions. The results are shown in Table 6. The coefficient of the variable is negative but statistically insignificant for both SCR and SNCR–SCR technologies, suggesting that the boilers targeted in the Key Regions Plan did not strictly comply with the requirement immediately.

[Table 6]

Regarding boiler capacity, plants with larger-sized boilers might obey the policy by choosing a higher-efficiency technology because doing so is economically reasonable for them. This is also suggested by the positive and significant coefficient of the *Capacity* variable for choosing SCR and SNCR–SCR than SNCR technology. To investigate whether the effect of the targeted policy might differ according to boiler size, we use different boiler sizes (i.e., 300–800 MW instead of 200 MW) to create the *Targeted Plant in Key Regions* variable. The results are presented in Table 7. *Targeted Plant in Key Regions* is positive and statistically significant when the boiler is larger than 600 MW, suggesting that, under this policy, boilers operating for fewer than 20 years will choose SCR technology when the boiler is larger than 600 MW. Thus, the requirement stipulated in the Key Regions Plan might affect the choice of plants with larger boilers but not that of plants with smaller ones.

[Table 7]

4.2 Comparisons before and after 2010

This subsection examines changes in plants' choices of technology before and after the 12th Five-year Plan. We conduct separate estimations for subsamples based on the timing of their installation of control equipment in boilers (i.e., before or after 2010). We also investigate differences among the eastern, central, and western regions of China by including dummy variables (*East* and *West*) and using the central region as a base category. Income is the highest in the eastern region, and the western region lags behind in terms of economic development. Some studies have pointed out that the regional differences among Chinese provinces affect their energy consumption and environmental policies (Song et al., 2013; Xu and Lin, 2016).

[Table 8]

The estimation results are presented in Table 8. *East* and *West* are positive and statistically significant until 2010; during the 12th Five-year Plan period, however, they were not significant for the choice of SCR technology. These results suggest that regional differences do not play a significant role in the plants' choice of SCR technology after 2010.

Capacity is also positive and statistically significant after 2010 but is statistically insignificant for choices of SNCR–SCR until 2010. *Installation Age* is positive and statistically significant after 2010 for SCR but negative and statistically significant for the period until 2010 for the choice of SNCR−SCR. Plants with newer boilers prefer SNCR−SCR technology before 2010, and those with older boilers prefer SCR technology after 2010.

The stringency of emission standards (*Emission Standard*) is statistically insignificant for SCR and is positive and statistically significant for SNCR–SCR technology until 2010; after 2010, however, it is negative and statistically significant for both SCR and SNCR–SCR technologies. Since the lower value of *Emission Standard* points to a stricter emission regulation, the negative sign means that the technology is chosen when the regulation is tighter. The result suggests that plants under a stricter regulation prefer SCR and SNCR–

SCR technologies over SNCR technology after 2010. Until 2010, however, the effects of emissions standards had no impact on the choice of technology.

The results discussed above can be summarized as follows. First, until 2010, SCR technology was chosen more readily by plants in the eastern and western regions than by plants in the central region. This can be explained by the regional differences in capital investment in the early 2000s. Since the western region was less developed than the other two regions, huge investments were made in this region under the Western Development Program. Because of this, plants in the western region were more able to purchase expensive pollution control equipment than those in the central region were. After 2010, as the economy in the central region caught up, these regional differences might have become insignificant. Second, the results suggest that plants under stricter emission standards will choose SCR and SNCR–SCR technologies during the 12th Five-year Plan period. A more stringent standard might play a role in plants' preference for efficient technology during this period.

4.3 Subsidy policy

This subsection discusses the effect of subsidy policies during the period of the 12th Five-year Plan. The subsidy is offered to plants whose boilers are fitted with denitration equipment and takes the form of a premium on the electricity prices. We use the dummy variables *Subsidy 2011* and *Subsidy 2013* to express two kinds of subsidies. *Subsidy 2011* refers to the 14 provinces taking part in this subsidy's pilot program, initiated in November 2011. *Subsidy 2013* takes the value of one if the installation of control equipment took place after January 2013, when the subsidy was extended nationwide.

[Table 9]

The results in Table 9 show that *Subsidy 2011* is negative and statistically significant for choosing SCR and SNCR–SCR technology over SNCR technology. This suggests that the subsidy policy offered in the 14 pilot provinces might have promoted investment in cheaper technology. On the other hand, the coefficient for *Subsidy 2013* is statistically insignificant in most of the estimations. When the subsidy was extended nationwide, it did not affect the plants' choice of technology. After January 2012, stringent emission standards were implemented, which might have promoted the choice of technologies that were highly efficient at removing emissions; this effect might have been strong enough to offset the impact of the subsidy (i.e., to choose a cheaper technology).

4.4 Analysis of the installation status in 2012

All boilers in our dataset had installed denitration equipment by 2013. In this subsection, we investigate the decision to install pollution control equipment by looking at the installation status as of 2012. In our dataset, the 538 boilers (50% of 1,083 boilers operating in 2012) installed denitration equipment in 2013 did not have denitration equipment in 2012. Therefore, we can use a logit model to investigate the factors affecting the installtion decision as of 2012 by regarding these 538 boilers as being without denitration equipment.[5] We define *Installation2012* as a dummy variable reflecting the installation status of denitration equipment as of 2012. It takes the value of one if the boiler had denitration equipment installed by 2012 and zero otherwise. We estimate the following model:[6]

$$logit(Pr(Installation2012_i)) = \beta_1 P_i + \beta_2 O_i + \beta_3 E_i \tag{6}$$

[Table 10]

The estimation results are shown in Table 10. The number of observation is reduced

[5]There remains the issue of sample selection, since all the 1,083 boilers in this analysis had installed control equipment by the end of 2013. As of 2013, there were 7,515 boilers in China, including non-utility power plants (Chinese Ministry of Environmental Protection, 2014a).

[6]Some variables used in the technology choice model are not included or are modified in the logit model because of difference in assumptions. We cannot include *Targeted Plant in 12th FYP* or *12th FYP*, since these variables perfectly predicts the installation status. We include *Provincial Target 2012* to represents the reduction target for NO_x until 2015 in each province as of 2012. Moreover, as we assumed that the 538 boilers are without equipment, the variable *Selfbuilt* and *Emission Standard* are not used. We used the variable *First Operation Year* instead of *Installation age*. *First Operation Year* represents the year that the boiler started their operation.

to 1,083, since 52 boilers that started their operation in 2013 are excluded in this analysis. *Provincial Target 2012* is positive and statistically significant in all models, while *NO_x Control Area* is mostly not statistically significant. These results suggest that provincial (rather than national) policy is more effective in promoting control equipment. *Capacity* and *First Operation Year* is positive and statistically significant, suggesting that larger sized boilers and newer boilers tend to introduce denitration technologies. *Utilization* and *Share of Thermal Power* are not statistically significant. In other words, the results can be interpreted to mean that boilers that are smaller, older, and are in provinces with lower emissions reduction targets tend not to have the NO_x control equipment installed.

5 Conclusion

This study investigated the choices of denitration technology in the Chinese thermal power sector. Considering the choices made by 1,135 boilers operating in China in 2013, we derived the following results. First, the 12th Five-year Plan might encourage plants to choose SNCR technology, the cheapest of the three denitration technological options. We consider that, under the 12th Five-year Plan, strict policy enforcement was implemented, and plants chose the technology that would satisfy the emission target at the cheapest cost. The results suggest that the plants have some flexibility in choosing a preferred technology even though command-and-control policies constitute major instruments of Chinese environmental policy. As Liu et al. (2013) point out, the affordability of energy costs is an important driver of their energy management strategies for Chinese companies.

Second, prior to the 12*th* Five-year Plan period, regional differences had significant effects on technology choices; these later disappeared, perhaps due to the economic development that occurred across all regions of China. On the other hand, the effect of emission standards was statistically significant only during the 12th Five-year Plan period. The implementation of emission standards after 2011 is thought to be ever more stringent.

Finally, the subsidy of electricity prices for plants with denitration equipment might have affected their technology choice. Unfortunately, since the subsidy does not depend on the technology option chosen, plants might choose the cheapest technology to lower their investment costs. As many studies have pointed out, an incautious subsidy policy may lead to overcapacity, overinvestment, and fierce competition in the power sector (Shen and Luo, 2015; Zhang et al., 2016).

Chinese policy for controlling SO_2 has advanced in the 11th Five-year Plan period (Schreifels et al., 2012; Ma and Takeuchi, 2016). Control of NO_x began in earnest during the 12th Five-year Plan period. Our results suggest that incentives to save investment costs and receive subsidies might influence the choice of technology: therefore, the sophistication of the design of economic instruments could play a role in China's development of effective and efficient environmental policy.

While this study focused on the technology choice of boilers that installed NO_x control equipment, it is important to note that it does not capture the decision making for the large portion of boilers that have not installed the equipment. We attempted to consider this decision in subsection 4.4, but it is not free from the sample selection bias, and the result should be interpreted with caution. Further study is necessary to understand the full picture of NO_x control strategy in the Chinese thermal power sector.

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Appendix A

To examine the difference between boilers with equipment installed from the beginning and boilers with it installed after years of operation, we use the following logit model:

$$logit(Pr(AgeZero_i)) = \beta_1 P_i + \beta_2 S_i + \beta_3 O_i + \beta_4 E_i \tag{7}$$

where *AgeZero* is a dummy variable that takes value of one when the boiler has NO_x control equipment installed at the start of operations and zero otherwise. The model also includes dummy variables *SCR* and *SNCR−SCR* to indicate the use of these technologies. By looking at the coefficient of these variables, we can investigate the characteristics of boilers with control equipment installed in the first year.

[Table 11]

The estimation results are summarized in Table 11. *Capacity* and *First Operation Year* are positive and statistically significant in all models, suggesting that larger and recent boilers tend to have denitration equipment installed in the first year. *SCR* is positive and statistically significant in all models, meaning that SCR technology tends to be installed in the first year, relative to SNCR technology. On the other hand, *SNCR−SCR* is not statistically significant. *12th FYP*, *NO_x Control Area* and *Provincial Target* are all negative and statistically significant. These results might be interpreted to mean that these policies for NO_x control promote the installation of control equipment on boilers that did not have equipment in their first year of operation.

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Table 1: Comparison of SCR and SNCR technology

	SCR	SNCR
Catalyst	Yes (30% of investment)	No
Pressure loss	Yes	No
Size	Large	Small
Reduction process	Outside of the boiler	Inside of the boiler
Efficiency	80%	$25-40\%$
Cost of construction	High	Low
Side effect	Produce NH_4HSO_4	–

Table 2: Emission standards for NO_x in China

	Classification based on first year of operation		
	I	II	III
GB13223-1996	N.S.	N.S.	$650 mg/m^3$
	(Before $Aug.1, 1992$)	($Aug.1, 1992$–$Dec.31, 1996$)	(After $Jan.1, 1997$)
GB13223-2003	$1100 mg/m^3$	$650 mg/m^3$	$450 mg/m^3$
	(Before $Dec.31, 1996$)	($Jan.1, 1997$–$Dec.31, 2003$)	(After $Jan.1, 2004$)
GB13223-2011	$450 mg/m^3$	$100 mg/m^3$	
	(Before $Dec.31, 2011$)	(After $Jan.1, 2012$)	

Note: The values indicate the most stringent standards applied for boilers that started operations in each period (as shown in the bracket). N.S.: not specified. GB 13223-1996 standards are applied only to cases of 1000t/h or more.

Table 3: NO_x target in 12th Five-year Plan for each province

Province	Emissions in 2010	Target	
		Target in 2015	Change from 2010 (%)
Beijing	19.8	17.4	-12.3
Tianjin	34	28.8	-15.2
Hebei	171.3	147.5	-13.9
Shanxi	124.1	106.9	-13.9
Inner Mongolia	131.4	123.8	-5.8
Liaoning	102	88	-13.7
Jilin	58.2	54.2	-6.9
Heilongjiang	75.3	73	-3.1
Shanghai	44.3	36.5	-17.5
Jiangsu	147.2	121.4	-17.5
Zhejiang	85.3	69.9	-18
Anhui	90.9	82	-9.8
Fujian	44.8	40.9	-8.6
Jiangxi	58.2	54.2	-6.9
Shandong	174	146	-16.1
Henan	159	135.6	-14.7
Hubei	63.1	58.6	-7.2
Hunan	60.4	55	-9
Guangdong	132.3	109.9	-16.9
Guangxi	45.1	41.1	-8.8
Hainan	8	9.8	22.3
Chongqing	38.2	35.6	-6.9
Sichuan	62	57.7	-6.9
Guizhou	49.3	44.5	-9.8
Yunnan	52	49	-5.8
Xizang	3.8	3.8	0
Shannxi	76.6	69	-9.9
Gansu	42	40.7	-3.1
Qinghai	11.6	13.4	15.3
Ningxia	41.8	39.8	-4.9
Xinjiang	67.6	67.6	0
Total	2,273.6	2,021.6	-11.1

Source: Xing (2012).
Note: The unit is in $10,000t$; the total emissions target is $20,462kt$. The difference in the total emissions target in this table is used by the Chinese government for reduction of NO_x emissions trading.

Table 4: Descriptive statistics

	N	Mean	Std.Dev.	Min	Max
12th FYP (*dummy*)	1,135	0.843	0.364	0	1
Targeted Plant in 12th FYP (*dummy*)	1,135	0.082	0.275	0	1
NO_x Control Area (*dummy*)	1,135	0.033	0.178	0	1
Subsidy 2011[a](*dummy*)	1,135	0.186	0.389	0	1
Subsidy 2013 (*dummy*)	1,135	0.520	0.500	0	1
Selfbuilt (*dummy*)	1,135	0.025	0.155	0	1
Provincial Target (%)	1,135	0.108	0.067	-0.223	0.180
Capacity (GW)	1,135	0.381	0.256	0.003	1.03
Installation Age[b](*year*)	1,135	6.782	7.247	0	52
Emission Standard ($1,000\ mg/m^3$)	1,135	0.434	0.158	0.1	1.1
Utilization ($1,000\ h$)	1,135	4.956	1.821	3.295	46.44
Share of Thermal Power (%)	1,135	0.787	0.159	0.137	0.999
GRP (*trillion RMB*)	1,135	22.22	13.64	1.299	47.98
Industrial Value-added (*trillion RMB*)	1,135	11.41	7.807	0.463	27.46

Note: Data regarding the Key Control Area and provincial targets were obtained from the Chinese Ministry of Environmental Protection (2012) and Xing (2012). GRP and the value-added of the manufacturing sector were obtained from the China Statistical Yearbook (China State Statistical Bureau, 2002-2014). Province-level capacity and generation data were obtained from the CEIC database (CEIC, 2015).

[a] The 14 pilot provinces that implemented trial subsidies on electricity price starting in November 2011 were: Beijing, Tianjin, Hebei, Shanxi, Shandong, Shanghai, Zhejiang, Jiangsu, Fujian, Guangdong, Hainan, Sichuan, Gansu, and Ningxia. The dummy variable *Subsidy 2011* takes the value of one if the control equipment was installed after November 2011 and it is located in one of these 14 provinces.

[b] Installation Age refers to the number of years that passed between the first operation of the boiler and the installation of denitration equipment.

Table 5: Baseline results

	(1)	(2)	(3)	(4)	(5)	(6)
SCR						
12th FYP	-1.822**	-1.698**	-1.738**			
	(0.776)	(0.813)	(0.825)			
Targeted Plant in 12th FYP				-0.258	-0.392	-0.379
				(0.735)	(0.732)	(0.731)
Provincial Target	0.019	0.012	0.014	-0.057**	-0.067***	-0.066***
	(0.040)	(0.042)	(0.043)	(0.025)	(0.024)	(0.025)
NO_x Control Area	1.835*	1.846*	1.831*	1.645	1.674	1.632
	(1.060)	(1.079)	(1.072)	(1.060)	(1.091)	(1.089)
Capacity	17.21***	17.45***	17.35***	16.16***	16.87***	16.79***
	(1.358)	(1.479)	(1.457)	(1.178)	(1.370)	(1.353)
Installation Age	0.080***	0.079***	0.079***	0.072***	0.072***	0.072***
	(0.021)	(0.021)	(0.021)	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.013	-0.039	-0.024	-0.402	-0.405	-0.383
	(0.468)	(0.471)	(0.471)	(0.396)	(0.394)	(0.398)
Emission Standard	-2.713**	-2.714**	-2.712**	-1.671	-1.955*	-1.947*
	(1.123)	(1.131)	(1.138)	(1.177)	(1.081)	(1.083)
Utilization	0.903***	0.899***	0.899***	0.918**	0.897**	0.896**
	(0.348)	(0.342)	(0.345)	(0.365)	(0.349)	(0.351)
Share of Thermal Power	-0.799	-0.904	-0.828	0.133	-0.154	-0.026
	(1.015)	(1.035)	(1.023)	(0.988)	(1.002)	(0.994)
GRP		0.007			0.017	
		(0.013)			(0.012)	
Industrial Value-added			0.007			0.026
			(0.022)			(0.020)
Constant	-4.242**	-4.364**	-4.324**	-5.917***	-5.876***	-5.886***
	(1.766)	(1.782)	(1.805)	(1.446)	(1.415)	(1.419)
SNCR	(Baseline)					
SNCR-SCR						
12th FYP	-5.244*	-4.612*	-4.886*			
	(2.705)	(2.683)	(2.732)			
Targeted Plant in 12th FYP				-12.28***	-14.18***	-12.49***
				(0.918)	(0.908)	(0.911)
Provincial Target	0.239	0.194	0.214	-0.031	-0.062	-0.056
	(0.167)	(0.166)	(0.169)	(0.047)	(0.042)	(0.042)
NO_x Control Area	-7.239***	-7.583***	-8.559***	-9.418***	-10.99***	-9.405***
	(1.578)	(1.566)	(1.578)	(1.233)	(1.250)	(1.261)
Capacity	9.166***	9.540***	9.366***	7.486***	8.833***	8.605***
	(2.167)	(2.203)	(2.210)	(2.027)	(2.105)	(2.111)
Installation Age	0.030	0.029	0.030	0.023	0.024	0.024
	(0.033)	(0.033)	(0.033)	(0.032)	(0.032)	(0.032)
Selfbuilt	-11.90***	-12.64***	-13.46***	-13.65***	-15.33***	-13.64***
	(0.597)	(0.602)	(0.603)	(0.457)	(0.460)	(0.458)
Emission Standard	0.404	0.350	0.386	1.666	1.018	1.125
	(2.034)	(1.996)	(2.013)	(2.209)	(2.128)	(2.144)
Utilization	1.046***	1.037***	1.040***	1.065***	1.033***	1.037***
	(0.351)	(0.345)	(0.348)	(0.368)	(0.352)	(0.354)
Share of Thermal Power	5.808**	5.577**	5.759**	6.645***	6.112***	6.470***
	(2.279)	(2.256)	(2.272)	(2.034)	(2.081)	(2.070)
GRP		0.017			0.038**	
		(0.018)			(0.018)	
Industrial Value-added			0.016			0.055*
			(0.031)			(0.031)
Constant	-12.30***	-12.51***	-12.46***	-14.15***	-14.15***	-14.27***
	(2.952)	(2.961)	(3.001)	(2.719)	(2.774)	(2.788)
N	1135	1135	1135	1135	1135	1135
$Pseudo\ R_2$	0.543	0.544	0.544	0.536	0.539	0.538

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Targeted plant in key regions

	(1)	(2)	(3)
SCR			
Targeted Plant in Key Regions	-0.297	-0.353	-0.343
	(0.516)	(0.524)	(0.523)
NO_x Control Area	1.746*	1.797*	1.754
	(1.054)	(1.082)	(1.080)
Provincial Target	-0.054**	-0.062***	-0.062***
	(0.025)	(0.023)	(0.024)
Capacity	16.37***	17.08***	17.00***
	(1.354)	(1.559)	(1.546)
Installation Age	0.072***	0.071***	0.072***
	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.429	-0.438	-0.415
	(0.409)	(0.410)	(0.413)
Emission Standard	-1.543	-1.768*	-1.767*
	(1.047)	(0.977)	(0.979)
Utilization	0.949***	0.933***	0.930***
	(0.361)	(0.345)	(0.347)
Share of Thermal Power	0.098	-0.210	-0.082
	(0.997)	(1.005)	(0.997)
GRP		0.016	
		(0.012)	
Industrial Value-added			0.025
			(0.020)
Constant	-6.152***	-6.152***	-6.152***
	(1.545)	(1.522)	(1.525)
SNCR	(Baseline)		
SNCR-SCR			
Targeted Plant in Key Regions	-1.304	-1.473	-1.442
	(0.981)	(1.028)	(1.032)
NO_x Control Area	-7.828***	-7.778***	-8.083***
	(1.425)	(1.464)	(1.475)
Provincial Target	-0.013	-0.044	-0.038
	(0.051)	(0.043)	(0.043)
Capacity	8.302***	9.780***	9.533***
	(2.245)	(2.376)	(2.388)
Installation Age	0.027	0.028	0.027
	(0.031)	(0.031)	(0.031)
Selfbuilt	-12.81***	-13.06***	-13.24***
	(0.453)	(0.453)	(0.452)
Emission Standard	2.114	1.502	1.601
	(2.022)	(1.924)	(1.942)
Utilization	1.103***	1.074***	1.077***
	(0.365)	(0.348)	(0.350)
Share of Thermal Power	6.751***	6.211***	6.604***
	(2.040)	(2.064)	(2.070)
GRP		0.040**	
		(0.019)	
Industrial Value-added			0.059*
			(0.034)
Constant	-14.97***	-15.08***	-15.21***
	(2.772)	(2.832)	(2.872)
N	1135	1135	1135
$Pseudo\ R_2$	0.537	0.540	0.539

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Comparisons by capacity

	(1) 200MW	(2) 300MW	(3) 400MW	(4) 500MW	(5) 600MW	(6) 700MW	(7) 800MW
SCR							
Targeted Plant in Key Regions	-0.297	-0.267	-0.267	-0.267	-0.267	6.609***	3.494***
	(0.516)	(0.592)	(0.592)	(0.592)	(0.592)	(0.952)	(1.160)
Provincial Target	-0.054**	-0.054**	-0.054**	-0.054**	-0.054**	-0.055**	-0.055**
	(0.025)	(0.026)	(0.026)	(0.026)	(0.026)	(0.024)	(0.024)
NO_x Control Area	1.746*	1.747	1.747	1.747	1.747	1.680	1.680
	(1.054)	(1.069)	(1.069)	(1.069)	(1.069)	(1.051)	(1.051)
Capacity	16.37***	16.28***	16.28***	16.28***	16.28***	16.10***	16.10***
	(1.354)	(1.344)	(1.344)	(1.344)	(1.344)	(1.149)	(1.149)
Installation Age	0.072***	0.072***	0.072***	0.072***	0.072***	0.072***	0.072***
	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.429	-0.424	-0.424	-0.424	-0.424	-0.410	-0.410
	(0.409)	(0.405)	(0.405)	(0.405)	(0.405)	(0.400)	(0.400)
Emission Standard	-1.543	-1.509	-1.509	-1.509	-1.509	-1.554	-1.554
	(1.047)	(1.050)	(1.050)	(1.050)	(1.050)	(1.045)	(1.045)
Utilization	0.949***	0.929**	0.929**	0.929**	0.929**	0.919**	0.919**
	(0.361)	(0.363)	(0.363)	(0.363)	(0.363)	(0.366)	(0.366)
Share of Thermal Power	0.098	0.099	0.099	0.099	0.099	0.095	0.095
	(0.997)	(0.994)	(0.994)	(0.994)	(0.994)	(0.981)	(0.981)
Constant	-6.152***	-6.054***	-6.054***	-6.054***	-6.054***	-5.967***	-5.967***
	(1.545)	(1.524)	(1.524)	(1.524)	(1.524)	(1.504)	(1.504)
SNCR	(Baseline)						
SNCR-SCR							
Targeted Plant in Key Regions	-1.304	-15.392***	-15.392***	-15.392***	-15.392***	-4.249***	-6.056***
	(0.981)	(0.664)	(0.664)	(0.664)	(0.664)	(1.440)	(1.642)
Provincial Target	-0.013	-0.005	-0.005	-0.005	-0.005	-0.023	-0.023
	(0.051)	(0.050)	(0.050)	(0.050)	(0.050)	(0.046)	(0.046)
NO_x Control Area	-7.828***	-9.063***	-9.063***	-9.063***	-9.063***	-11.143***	-10.398***
	(1.425)	(1.560)	(1.560)	(1.560)	(1.560)	(1.214)	(1.214)
Capacity	8.302***	8.678***	8.678***	8.678***	8.678***	7.379***	7.378***
	(2.245)	(2.155)	(2.155)	(2.155)	(2.155)	(2.065)	(2.064)
Installation Age	0.027	0.027	0.027	0.027	0.027	0.020	0.020
	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)	(0.032)	(0.032)
Selfbuilt	-12.81***	-15.54***	-15.54***	-15.54***	-15.54***	-15.32***	-14.58***
	(0.453)	(0.451)	(0.451)	(0.451)	(0.451)	(0.456)	(0.456)
Emission Standard	2.114	2.278	2.278	2.278	2.278	2.152	2.152
	(2.022)	(2.027)	(2.027)	(2.027)	(2.027)	(2.042)	(2.042)
Utilization	1.103***	1.084***	1.084***	1.084***	1.084***	1.072***	1.072***
	(0.365)	(0.367)	(0.367)	(0.367)	(0.367)	(0.369)	(0.369)
Share of Thermal Power	6.751***	6.746***	6.746***	6.746***	6.746***	6.749***	6.751***
	(2.040)	(2.032)	(2.032)	(2.032)	(2.032)	(2.085)	(2.085)
Constant	-14.97***	-15.10***	-15.10***	-15.10***	-15.10***	-14.61***	-14.61***
	(2.772)	(2.735)	(2.735)	(2.735)	(2.735)	(2.705)	(2.705)
N	1135	1135	1135	1135	1135	1135	1135
$Pseudo\ R_2$	0.537	0.541	0.541	0.541	0.541	0.535	0.535

Note: The dummy variables of *Targeted Plant in Key Regions* in columns (2)–(7) denotes the capacities of 300–800MW, as shown, have operated for fewer than 20 years as of year 2013, and operated in key regions. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Comparisons before and after 2010

	(1) Until 2010	(2) After 2010	(3) Until 2010	(4) After 2010	(5) Until 2010	(6) After 2010
SCR						
East	2.517*	0.417	4.346***	0.200	4.409***	0.214
	(1.438)	(0.394)	(1.277)	(0.411)	(1.301)	(0.418)
West	16.413***	1.043	15.04***	1.085	15.89***	1.099
	(1.114)	(0.874)	(1.149)	(0.875)	(1.153)	(0.876)
Capacity	21.19**	17.23***	16.91*	17.49***	16.54*	17.508***
	(9.132)	(1.281)	(9.354)	(1.345)	(9.058)	(1.358)
Installation Age	0.016	0.103***	-0.004	0.101***	-0.009	0.101***
	(0.038)	(0.021)	(0.046)	(0.022)	(0.047)	(0.022)
Selfbuilt	9.937***	-0.195	10.469***	-0.227	11.444***	-0.214
	(3.676)	(0.449)	(3.718)	(0.451)	(3.647)	(0.453)
Emission Standard	-0.979	-3.149**	0.285	-3.158**	0.478	-3.133**
	(2.661)	(1.490)	(2.548)	(1.494)	(2.527)	(1.492)
Utilization	1.254**	0.538	-0.011	0.505	-0.035	0.480
	(0.553)	(0.429)	(0.072)	(0.420)	(0.057)	(0.427)
Share of Thermal Power	-4.109*	0.260	-2.990	0.011	-3.305	0.139
	(2.466)	(1.218)	(2.824)	(1.299)	(2.927)	(1.273)
GRP			-0.078	0.015		
			(0.051)	(0.017)		
Industrial Value-added					-0.135	0.025
					(0.085)	(0.029)
Constant	-6.424*	-5.195***	-0.769	-5.081***	-0.586	-5.038**
	(3.419)	(1.986)	(4.281)	(1.950)	(4.171)	(1.965)
SNCR	(Baseline)					
SNCR-SCR						
East	17.06***	16.04***	17.83***	14.61***	18.66***	14.63***
	(1.587)	(0.508)	(1.417)	(0.777)	(1.423)	(0.819)
West	15.23***	16.52***	13.53***	16.28***	14.43***	16.37***
	(0.936)	(1.505)	(0.981)	(1.568)	(0.971)	(1.578)
Capacity	15.25	8.341***	10.054	9.279***	9.822	9.288***
	(9.298)	(2.518)	(9.706)	(2.498)	(9.468)	(2.478)
Installation Age	-0.130**	0.075*	-0.167**	0.069	-0.180**	0.067
	(0.052)	(0.041)	(0.067)	(0.043)	(0.071)	(0.043)
Selfbuilt	10.230***	-15.116***	10.729***	-15.010***	11.720***	-14.874***
	(3.542)	(0.662)	(3.558)	(0.694)	(3.499)	(0.699)
Emission Standard	7.275**	-5.179**	9.621**	-5.041**	10.006**	-5.058**
	(3.383)	(2.197)	(3.883)	(2.295)	(3.910)	(2.287)
Utilization	1.416**	1.119*	0.152	1.075	0.115	0.952
	(0.564)	(0.648)	(0.126)	(0.704)	(0.116)	(0.690)
Share of Thermal Power	4.432	10.045***	5.507	7.751**	4.869	8.490***
	(4.698)	(3.067)	(5.168)	(3.266)	(5.202)	(3.133)
GRP			-0.138**	0.054*		
			(0.062)	(0.029)		
Industrial Value-added					-0.246**	0.096*
					(0.104)	(0.056)
Constant	-34.03***	-31.47***	-26.58***	-29.87***	-27.08***	-29.756***
	(5.775)	(3.776)	(6.642)	(3.560)	(6.622)	(3.507)
N	178	957	178	957	178	957
$Pseudo\ R_2$	0.489	0.577	0.526	0.580	0.535	0.580

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: The effects of subsidy on technological choice

	(1)	(2)	(3)
SCR			
Subsidy 2011	-0.990**	-0.971*	-0.971*
	(0.501)	(0.505)	(0.504)
Subsidy 2013	-0.571	-0.582	-0.573
	(0.468)	(0.472)	(0.473)
Provincial Target	0.017	0.0072	0.008
	(0.039)	(0.043)	(0.044)
Capacity	16.76***	16.99***	16.97***
	(1.290)	(1.375)	(1.374)
Installation Age	0.101***	0.0992***	0.0992***
	(0.024)	(0.025)	(0.025)
Selfbuilt	0.035	-0.007	0.005
	(0.484)	(0.490)	(0.490)
Emission Standard	-3.223**	-3.190**	-3.183**
	(1.575)	(1.622)	(1.623)
Utilization	0.795*	0.765*	0.753*
	(0.412)	(0.410)	(0.416)
Share of Thermal Power	-0.851	-1.021	-0.934
	(1.039)	(1.074)	(1.064)
GRP		0.009	
		(0.016)	
Industrial Value-added			0.0146
			(0.029)
Constant	-4.675**	-4.522**	-4.505**
	(2.005)	(2.000)	(2.011)
SNCR	(Baseline)		
SNCR-SCR			
Subsidy 2011	-1.710*	-1.720**	-1.722**
	(0.885)	(0.870)	(0.867)
Subsidy 2013	-1.106	-1.242	-1.232
	(0.815)	(0.811)	(0.812)
Provincial Target	0.305*	0.119	0.116
	(0.177)	(0.179)	(0.182)
Capacity	8.180***	8.578***	8.514***
	(2.625)	(2.531)	(2.521)
Installation Age	0.073	0.069	0.067
	(0.045)	(0.045)	(0.046)
Selfbuilt	-10.81***	-13.12***	-13.08***
	(0.800)	(0.770)	(0.767)
Emission Standard	-6.084***	-5.697***	-5.695***
	(2.139)	(2.182)	(2.198)
Utilization	2.372***	2.129***	2.049***
	(0.627)	(0.583)	(0.568)
Share of Thermal Power	5.168*	3.951	4.660
	(3.122)	(2.915)	(3.038)
GRP		0.051*	
		(0.026)	
Industrial Value-added			0.086*
			(0.050)
Constant	-21.21***	-17.64***	-17.59***
	(5.988)	(4.726)	(4.555)
N	957	957	957
$Pseudo\ R_2$	0.574	0.577	0.576

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 10: Installation status on 2012: logit models

Dependent variable: Installation2012	(1)	(2)	(3)	(4)	(5)	(6)
Provincial Target 2012	0.038***	0.081***	0.074***	0.038***	0.080***	0.072***
	(0.014)	(0.024)	(0.023)	(0.014)	(0.024)	(0.023)
NO_x Control Area				-0.560*	-0.516	-0.505
				(0.328)	(0.327)	(0.328)
Capacity	0.648***	0.574**	0.603**	0.692***	0.615**	0.643**
	(0.249)	(0.250)	(0.250)	(0.251)	(0.252)	(0.251)
Operation Year	0.041***	0.039***	0.039***	0.040***	0.039***	0.039***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Utilization	0.007	0.010	0.009	0.002	0.005	0.004
	(0.028)	(0.027)	(0.027)	(0.028)	(0.027)	(0.027)
Share of Thermal Power	0.224	0.178	0.115	-0.028	-0.051	-0.107
	(0.418)	(0.446)	(0.447)	(0.440)	(0.466)	(0.466)
GDP		-0.025***			-0.024***	
		(0.007)			(0.007)	
Industrial Value-added			-0.036***			-0.035***
			(0.012)			(0.012)
Constant	-82.79***	-79.42***	-79.30***	-81.49***	-78.25***	-78.19***
	(26.44)	(25.63)	(25.57)	(26.25)	(25.45)	(25.41)
N	1083	1083	1083	1083	1083	1083
$Pseudo\ R_2$	0.027	0.036	0.033	0.029	0.038	0.035

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 11: Installation in the first year of operation

Dependent variable: AgeZero	(1)	(2)	(3)	(4)
Capacity	1.845***	2.298***	1.857***	1.943***
	(0.461)	(0.572)	(0.450)	(0.488)
Operation Year	0.730***	1.453***	0.715***	0.943***
	(0.073)	(0.254)	(0.073)	(0.129)
Selfbuilt	-0.406	-0.561	-0.449	-0.679
	(0.589)	(0.520)	(0.600)	(0.567)
Emission Standard	-2.056*	-0.883	-2.530**	-3.002**
	(1.098)	(1.469)	(1.152)	(1.298)
Utilization	0.037	0.005	0.024	0.043
	(0.051)	(0.038)	(0.050)	(0.034)
Share of Thermal Power	0.049	-1.192*	-0.547	1.771***
	(0.576)	(0.719)	(0.642)	(0.620)
SCR	1.420***	1.022*	1.499***	1.007**
	(0.385)	(0.528)	(0.394)	(0.408)
SNCR-SCR	-0.766	-0.864	-0.778	-1.084
	(0.705)	(0.776)	(0.720)	(0.824)
GDP	-0.004	0.005	-0.003	0.055***
	(0.008)	(0.011)	(0.008)	(0.012)
12th FYP		-5.846***		
		(0.715)		
NO_x Control Area			-1.851***	
			(0.483)	
Provincial Target				-0.253***
				(0.026)
Constant	-1.5e+03***	-2.9e+03***	-1.4e+03***	-1.9e+03***
	(148.1)	(510.9)	(147.7)	(259.6)
N	1135	1135	1135	1135
$Pseudo\ R_2$	0.502	0.715	0.510	0.615

Note: Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

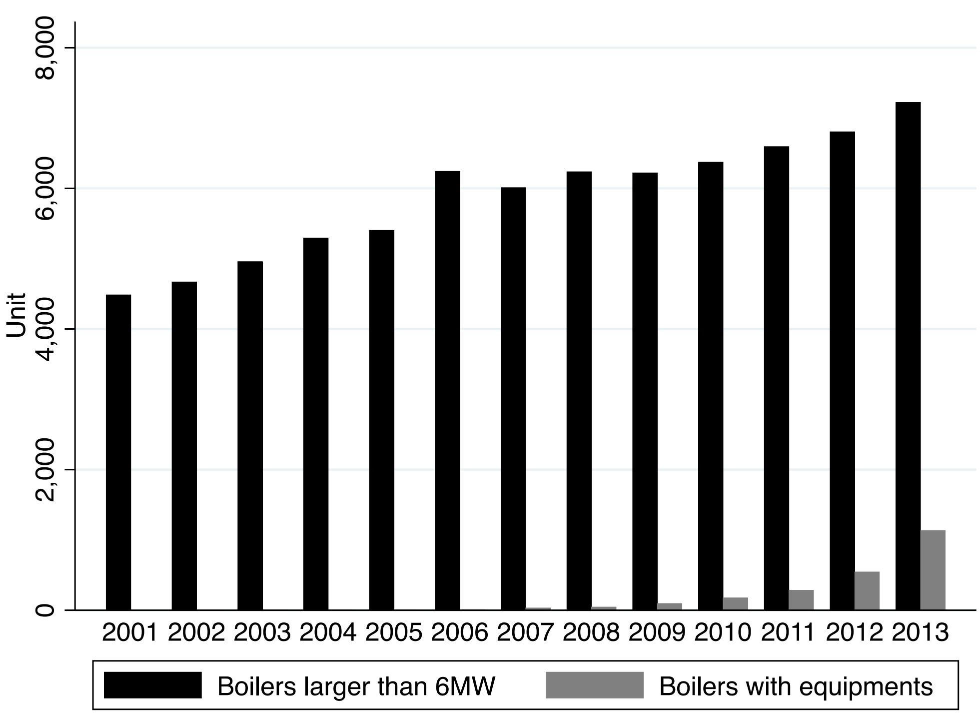

Figure 1: Total number of boilers and boilers with NO_x control equipment: 2001–2013

Note: Total number of boilers is taken from respective years' edition of China Electric Power Yearbook. Since the historical data is available only for boilers with capacity larger than 6MW, it does not coincide with numbers mentioned in Section 1.

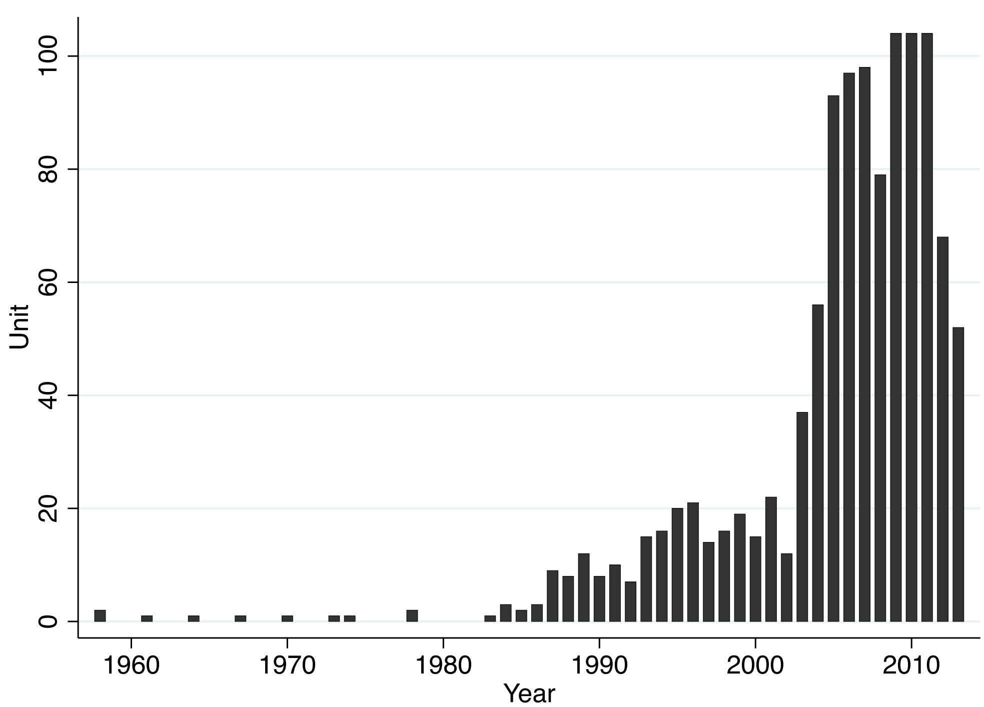

Figure 2: Number of boilers starting operations: 1950s–2010s

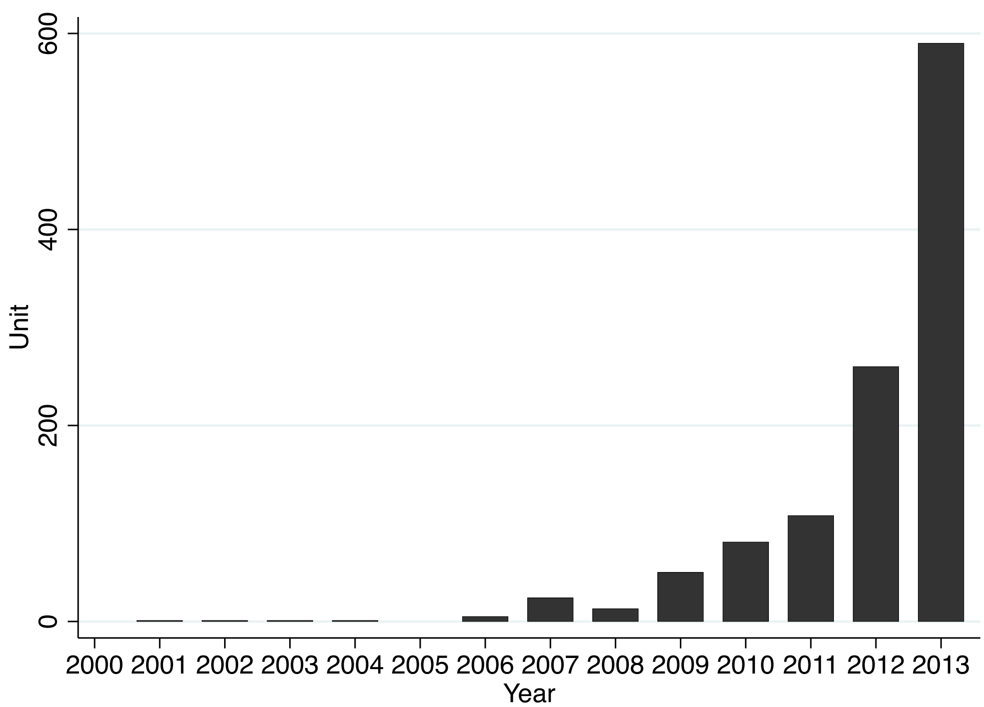

Figure 3: Number of boilers installed NO_x control equipment: 2000–2013

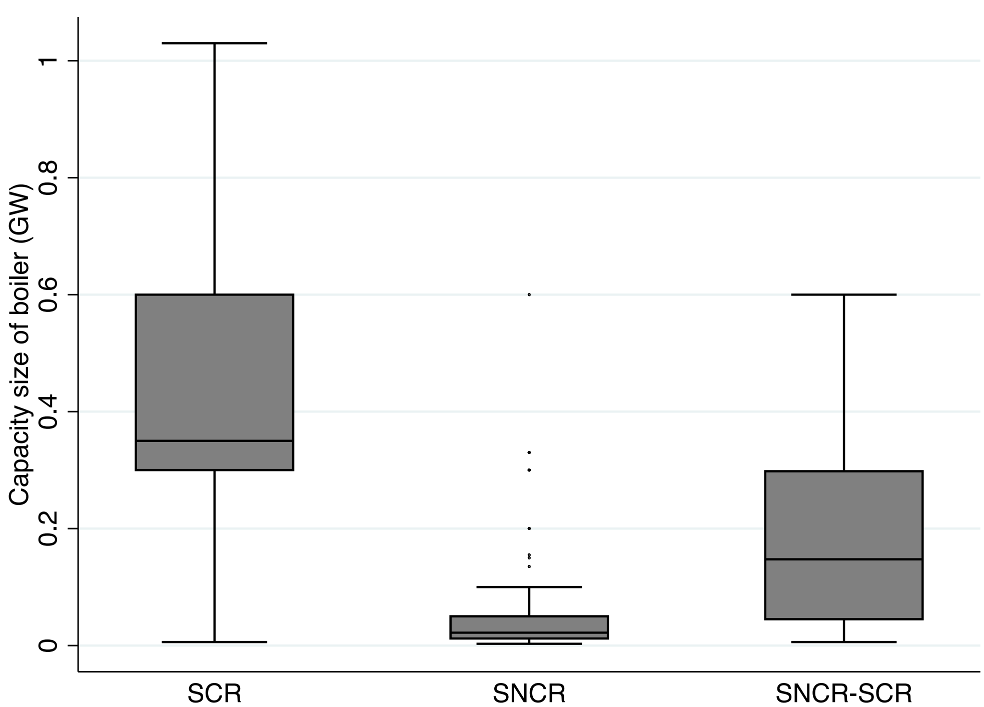

Figure 4: Distribution of boiler capacity for each technology

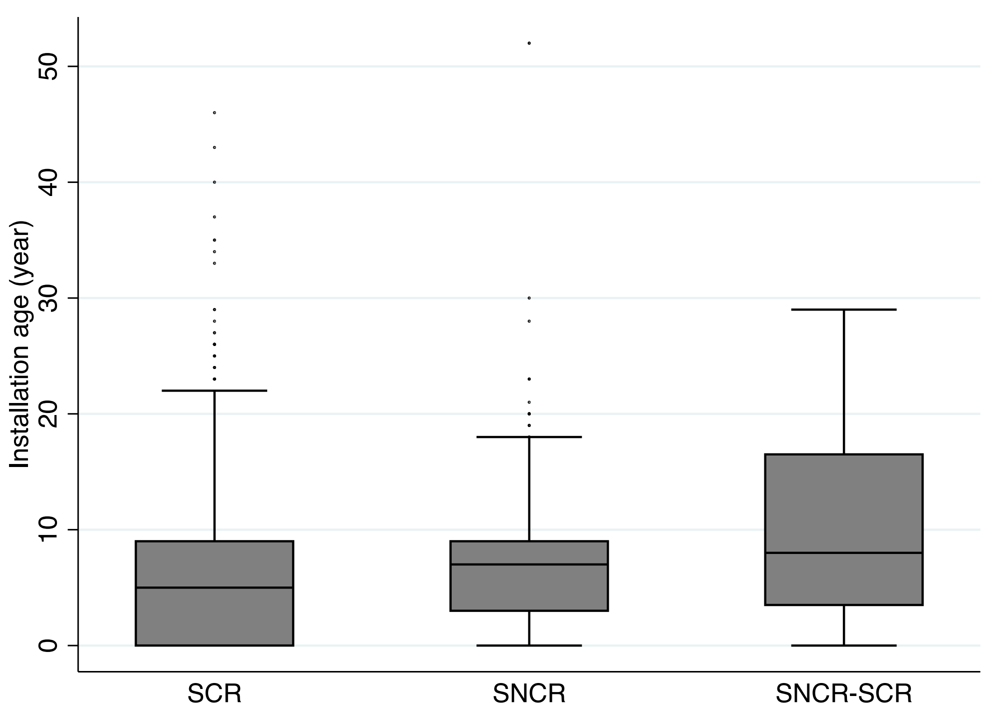

Figure 5: Distribution of installation age for each technology

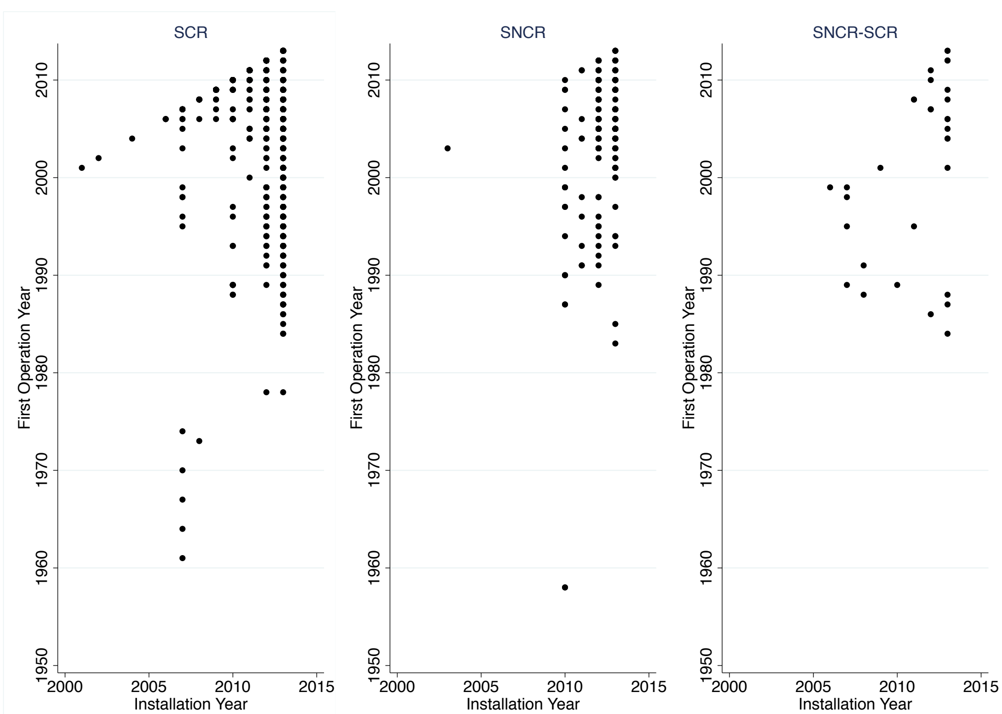

Figure 6: First operation year and installation year