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ANALYSIS

Environmental policy, fuel prices and the switching to natural gas in Santiago, Chile ☆

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ABSTRACT

In this study I analyzed the role of environmental policies and energy cost savings on the pattern of switching to natural gas by stationary sources in Chile. According to the data most of the switching was induced by the lower cost of natural gas, although environmental policies played a small role and showed that sources were more sensitive to the cost of energy than to the environmental regulation.

1. Introduction

Santiago, Chile is one of the most polluted cities in Latin America. During the early 1990s, it was officially declared a non-attainment zone for several atmospheric pollutants. However, during the late 1990s, there was major improvement due to a switch to natural gas by stationary sources. The switch allowed stationary sources to reduce particulate matter emissions, the pollutant which produces the worst health effects, by about 67%. The process of switching coincided with major new policy initiatives designed to improve air quality, including both command and control and market-based policies. But, it also coincided with the increased availability and reduced price of natural gas.

What was responsible for the switch to natural gas in Santiago—environmental regulations, market forces, or both? In this study, I used a panel data set of stationary sources to identify the impact of environmental policies and fuel prices on the inducement to switch to cleaner gas as fuel.

The extent to which the environmental policy successfully improved the air quality in Santiago allows us to understand whether regulations can trigger technological innovations that benefit the environment, to learn how regulators can engineer this feat, and be sensitive to the constraints they face in the process in a less developed country. In fact, there is an ongoing debate about whether less developed countries should rely on market-based policies given financial and institutional constraints that make environmental regulation far more problematic than in developed countries (e.g., Eskeland and Jimenez, 1992; Krupnick, 1997; Blackman and Harrington, 2000; Bell and Russell, 2002; Krueger et al., 2003; Bell, 2004). However, experience with environmental policies in less developed countries is not very large or deep. Although previous studies have analyzed the performance of environmental policies in Chile (e.g., Montero et al., 2002; O'Ryan, 2002; Palacios and Chávez, 2005; Coria and Sterner, 2008),[1] this paper contributes to such discussion by disentangling the role of environmental regulations behind a major air quality improvement in Santiago.

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[1] These studies have focused on the analysis of the Chilean tradable permit program. Montero et al. (2002) pointed out that the grandfathered allocation of permits encouraged incumbent sources to more readily declare their emissions. O'Ryan (2002) emphasized the role of natural gas in decreasing the abatement costs and reducing the efficiency gains from tradable permits. Palacios and Chávez (2005) reviewed monitoring and enforcement, concluding that noncompliance by some sources coexists with an aggregated level of overcompliance. Finally, Coria and Sterner (2008) looked closely at the program's performance over the past 10 years, stressing its discrepancies with successful trading programs implemented in developed countries.

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Table 1
Tradable permit program.

Variable	1997	1998	1999	2000	2001	2002	2003	2004	2005
Number of sources	593	583	516	534	495	513	521	526	519
Existing sources	430	402	332	324	286	277	273	264	251
New sources	163	181	184	210	209	236	248	262	268
Permits in force (kg/day)	4045.40	4044.40	4054.56	3710.37	3680.43	3087.34	2944.86	2856.05	2315.87
Initial daily emissions (IDE)	4045.40	3963.36	3672.76	3195.08	2981.53	2162.52	1897.75	1746.98	1123.49
Daily permitted emissions (DPE)	0	81.04	381.80	515.29	698.90	924.82	1047.11	1109.07	1192.38
Aggregate emissions (kg/day)	2544.79	1804.60	865.75	824.55	650.21	603.59	649.76	624.33	688.51
Existing sources	1684.27	1214.04	622.29	599.92	465.75	439.43	404.40	445.87	498.61
New sources	860.52	590.56	243.46	224.63	184.46	164.16	245.36	178.46	189.90
Excess of Permits [a]	1500.61	2239.80	3188.81	2885.81	3030.22	2483.75	2295.10	2231.72	1627.36
Existing sources	2361.13	2749.32	3050.47	2595.15	2515.78	1723.09	1493.35	1301.11	624.88
New sources	−860.52	−509.52	138.34	290.66	514.44	760.66	801.75	930.61	1002.48

Source: elaborated from PROCEFF databases.
[a] Excess of permits corresponds to the difference between the permits in force and the aggregate emissions.

On the other hand, the link between environmental policy and technological change has been mainly the subject of theoretical work with exceptionally little empirical analysis (Jaffe et al., 2002 and Requate, 2005). Some studies have analyzed the effects of the choice of policy instruments on the adoption of energy-efficiency and abatement technologies in developed countries (e.g., Greene, 1990; Newell et al., 1999; Kerr and Newell, 2003; Keohane, 2001 and Snyder et al., 2003). Nevertheless, to my knowledge, this is one of the first papers analyzing the extent to which environmental policies encourage the adoption of an environmentally friendly technique in a less developed country.

The paper has five sections. Section 2 provides some background about environmental regulations, fuel prices and the switching to natural gas in Santiago. Section 3 presents the methodology used to identify the impact of environmental policies and fuel prices on the inducement to switch to natural gas. Section 4 presents the results, and Section 5 concludes.

2. Background

2.1. Chilean environmental regulation

During the early 1990s, 20% of total emissions of particulate matter (PM_{10}) in Santiago came from stationary sources. Industrial boilers and industrial processes were the largest emitters (47% and 46%, respectively), with a small contribution coming from residential boilers and bakery ovens (6% and 1%, respectively). Three major environmental policies were implemented to control their emissions: a cap and trade program, a concentration standard, and a contingency program.

The cap and trade program was implemented in 1992 by Supreme Decree 4 (SD 4), although it started in practice in 1997. It affected emissions coming from large boilers (both industrial and residential), which discharged emissions through a duct or stack with a maximum flow rate higher than 1000 m^3/h.

SD 4 established an individual cap on the emissions of large boilers and a tradable permit program that allowed them to exceed this cap through offsetting their emissions with other, less polluting large boilers. For the purpose of granting permits, it differentiated between existing and new large boilers. Existing boilers were those installed or approved before 1992 and were granted emission permits. New large boilers were required to offset their emissions fully through the emissions abatement of existing large boilers.

Initially, the daily cap on emissions (kg/day) of existing large boilers was calculated according to a formula that allowed them to emit a maximum derived from a target on emissions concentration equal to $56*10^{-6}(kg/m^3)$ times the maximum flow rate (m^3/h) of the gas in the stack times 24 h of operation.

However, the environmental authority realized that the initial allocation was too generous and decreased the quantity of allowable emissions for existing large boilers by decreasing the target on emission concentration to $50*10^{-6}(kg/m^3)$ in 2000 and to $32*10^{-6}(kg/m^3)$ in 2005. The offsetting rate, that is, the number of permits sources need to buy in order to emit 1 kg of particulate matter, was also modified. Initially, it was set at 1. In 1998 it was increased to 1.2, and in 2000 it was increased to 1.5.

For the rest of the stationary sources, SD 4 established a standard for allowable emissions concentration equal to $56*10^{-6}(kg/m^3)$, which was reduced to $32*10^{-6}(kg/m^3)$ in 2005.

Table 1 summarizes some statistics about the number of sources in the tradable permit program, aggregate permits in force and aggregate emissions from 1997 to 2005.

At the beginning of 1997, 4045.40 kg of emitted particulate matter were allocated among 430 existing sources. In 2005, only 57.3% of the initial mass of permits remained in force and more than 50% was in the hands of new large boilers. Notice that although the aggregate cap on emissions was accomplished from the beginning, new sources did not offset their emissions during the first years of the program. Montero et al. (2002) argued that one of the reasons behind this outcome was the lack of institutional capability to regulate stationary sources. Before permits could be allocated, it was necessary to develop a comprehensive inventory of sources and their historical emissions. Because of limited resources, the regulator concentrated its regulatory activity on the completion of the inventory and the allocation of permits and did not track trading activity until the process was completed. As a consequence, there was no reconciliation of permits and emissions until 1998.

The daily cap on emissions weight far overestimated real emissions from existing large boilers, producing an excess of permits in force since the beginning of the program that has been intensified because of the switch to cleaner fuels. According to Coria and Sterner (2008), this excess number of permits in force has prevented the market from fully developing, in the sense that many sources rely on autarkic compliance instead of participating in the permits market.

Supreme Decree 32 (1990) implemented a contingency program to control emissions from all stationary sources, during declared states of "environmental contingencies" of bad air quality. These episodes occur when an environmental quality index reaches high values.[2] If the index reaches a value over 300, a "pre-emergency" episode is declared. If it reaches a value over 500, an "emergency" episode is declared. Every year, the environmental authority prepares the contingency lists. Sources on the pre-emergency list must shut down during a "pre-emergency" episode, while sources on in the emergency list must shut down during an "emergency" episode.

[2] The environmental authority measures the levels of PM_{10} per hour in a set of monitoring stations. The measuring is used to construct the environmental quality index ICAP that varies between 0 and 500.

Table 2
Contingency program.

Sources in the contingencies lists									
Year	1997	1998	1999	2000	2001	2002	2003	2004	2005
Sources in the pre-emergency list									
Days in pre-emergency	13	12	14	11	4	11	5	2	2
Number of sources in the list	141	230	1007	1176	521	336	359	178	155
Pre-emergency concentration									
Threshold (10^{-6} kg/m^3)	92.9	77	35.4	30.1	32	32	32	32	32
Industrial boilers	63.83%	47.39%	18.77%	19.64%	17.85%	21.43%	14.76%	8.99%	11.61%
Residential boilers	16.31%	26.09%	54.42%	62.50%	58.73%	53.87%	42.34%	5.06%	3.23%
Bakery ovens	0.00%	4.78%	12.91%	4.85%	4.22%	8.04%	7.24%	0.00%	0.00%
Industrial processes	19.86%	21.74%	13.90%	13.01%	19.19%	16.67%	35.65%	85.96%	85.16%
Sources in the emergency list									
Days in emergency	0	1	1	0	0	0	0	0	0
Number of sources in the list	421	887	2619	2483	1657	1472	1574	1584	1635
Emergency concentration									
Threshold (10^{-6} kg/m^3)	63	50	28.9	22	28	28	28	28	28
Industrial boilers	57.24%	33.26%	15.43%	15.67%	12.55%	12.23%	10.80%	9.53%	12.42%
Residential boilers	12.83%	39.57%	54.98%	45.63%	44.00%	38.25%	33.48%	29.29%	28.56%
Bakery ovens	0.48%	4.96%	20.47%	27.18%	34.52%	42.05%	43.07%	46.91%	46.61%
Industrial processes	29.45%	22.21%	9.13%	11.52%	8.93%	7.47%	12.64%	14.27%	12.42%

Source: elaborated from data provided by PROCEFF.

To construct the lists, sources are ordered according to their PM_{10}-emission concentration. The source with the highest PM_{10} concentration is at the top of the list, and the source with the lowest PM_{10} concentration is at the bottom. From 1998 to 2000, those sources exhibiting the higher PM_{10} concentration—and held responsible for 30% of the total mass emissions—were included in the pre-emergency list while those held responsible for 50% of the total mass of emissions were included in the emergency list. In 2001 the regulation was redefined in terms of absolute pollution. The authorities established a new threshold of $32*10^{-6}(\mathrm{kg/m^3})$ and $28*10^{-6}(\mathrm{kg/m^3})$ of PM_{10}-emission concentration to shut down the sources during pre-emergencies and emergencies, respectively.

Table 2 shows some information about critical episodes and the number of sources included in the lists. As critical episodes have not been rare, sources have tried to avoid being included in the contingency lists. However, the criterion used until 2000 implied that, because some sources took steps to reduce pollution, it became increasingly difficult for the rest to avoid being included. Therefore, the number of sources in the lists increased as the concentration threshold decreased abruptly. The number of sources in the pre-emergency list decreased after the criterion was modified in 2001, while the number of sources in the emergency list stayed the same for the most part.

The relative importance of stationary sources within the lists changed from 1998 to 2005. During 1997 and 1998, industrial boilers became the most affected group. Residential boilers became the most affected group after that, until 2003. On the other hand, bakery ovens have not been very affected by pre-emergencies, although their share on the emergency list has increased since 1999. Finally, the relative importance of industrial processes increased from 2004 onwards.

Given the fiscal and technical resources constraints, monitoring and enforcement activities were mostly focused on industrial boilers because of their relative importance in total emissions. From 2000 to 2003, the average rate of industrial boilers inspected was 85%. In the same period, just 35% of residential boilers and 30% of bakery ovens were inspected.[3]

[3] Unfortunately, PROCEFF does not have records on inspection activities for the entire period or source-level data.

2.2. Natural gas adoption, environmental policy and fuel prices

Natural gas started to be imported from Argentina in 1997 by a private company, METROGAS. Even its introduction to the whole city is yet not completed; it has been available in most of the communes of Santiago since 1998.

Table 3 shows the pattern of switching followed by boilers (distinguishing between the overall rate of switching by industrial and residential boilers and the rate of switching by large boilers within each group) and bakery ovens from 1998 to 2005. Unfortunately, industrial processes are excluded from the analysis since there is no identification variable that allows following them through time.

Industrial boilers started to switch to natural gas earlier, while residential boilers began to switch heavily after 2000. Since then, the rate of switching of residential boilers increased quickly, exceeding industrial boilers at the end of the period. Within each group, large boilers switched earlier and the rate of switching slightly exceeded the overall rate at the end of the period. On the other hand, just 12.5% of the bakery ovens switched to natural gas and the rate of switching is very flat along the period.

At a first sight, both environmental policies seem quite correlated with the switching process. First, large boilers started switching earlier, suggesting some facet of the tradable permit program encouraged this process. Second, the lag of the relative importance of stationary sources in the pre-emergency list is clearly correlated with their pattern of switching. The switching rate of industrial boilers took off between 1998 and 1999, after they became the group most affected by this policy. The same happened with residential boilers, which started to switch heavily in 2000, while bakery ovens which were not very affected did not switch very much. However, since natural gas was the cheapest clean fuel available, there is also room for relative fuel prices being the main driver explaining the switching. In fact, in most cases, switching to natural gas reduced production costs because of the lower cost per unit of energy. Additionally, since the natural gas supplier METROGAS used a non-linear pricing scheme to offer volume discounts, switching was more profitable to large sources using more fuel. Table 4 shows some statistics about the relative fuel expenditure in 1998 for a sample of industrial boilers, residential boilers, and bakery ovens, and for a sample of fuels used previously for most stationary sources.

Table 3
Rate of switching to natural gas.

Year	Industrial boilers				Residential boilers					
	Overall		Large boilers		Overall		Large boilers		Bakery ovens	
	N	Switching Rate	N	Switching Rate	N	Switching Rate	N	Switching Rate	N	Switching Rate
1998	612	4.7%	504	9.9%	1018	0.0%	79	9.9%	505	0.2%
1999	620	18.8%	442	25.4%	1225	1.7%	74	30.5%	613	0.7%
2000	660	24.7%	449	30.1%	1706	20.6%	85	37.5%	660	1.7%
2001	643	33.4%	414	42.3%	1809	41.8%	81	50.3%	860	5.7%
2002	644	39.6%	433	47.6%	1916	53.8%	80	59.0%	945	7.4%
2003	641	41.3%	446	52.0%	2011	57.7%	75	62.9%	1031	8.2%
2004	624	45.0%	451	56.1%	2109	61.7%	75	66.5%	1127	10.1%
2005	636	42.6%	445	52.8%	2890	58.8%	74	69.2%	1168	12.5%

Source: elaborated from data provided by PROCEFF and METROGAS.

For each previous fuel, the relative expenditure was calculated as the ratio between the expenditure in energy in 1998, using that fuel and the expenditure if it were burning natural gas.

Even though the fuel expenditure using diesel No. 5 was lower, this fuel did not allow sources to meet the environmental regulation because of the high level of PM_{10} concentration it produced. Therefore, after its introduction, natural gas became the cheapest clean fuel available.

The next section introduces the methodology used to disentangle the role of environmental regulations and fuel prices driving the switching to natural gas.

3. Methodology

Switching to natural gas offered several benefits to sources. First, the lower level of emissions produced with this fuel allowed large boilers to reduce the number of emission permits used. Second, it allowed non-large boilers to reach the concentration standard since the natural gas' emissions concentration was lower than the standard at any time. Third, it allowed both large boilers and non-large boilers to leave the contingency program since the natural gas' emissions concentration was lower than the critical threshold at any time. Finally, it reduced the cost of required energy due to the differences in the market prices of gas.

Let X_t^i be the amount of fuel used by a representative firm using the fuel i and releasing e_t^i units of emissions at time t. Emissions produced with natural gas are denoted as e_t^{NG}. Let p_t be the market price of the emission permits, z_t^{NG} the market price of the natural gas, $\boldsymbol{z}_t$ be the vector of prices of the remaining fuels, r the intertemporal discount rate, and W^{NG} be the investment required to acquire the capital input necessary to burn natural gas. Let the variable PERMIT denote if the source was included in the trading program (taking a value equal to 1 for large boilers and zero otherwise) and d_t to indicate if the source was included in the contingency program at the time t or not (taking a value equal to 1 if it was included and zero otherwise). Let the variable s_t indicate whether a non-large boiler reached the concentration standard at time t or not (taking a value equal to 1 if it did not reach the standard and zero otherwise). Finally, let us assume that critical episodes occurred with probability μ_t and that for a representative source the cost of being closed at the time t corresponds to L_t, while the cost of not reaching the concentration standard is F_t.

If each source is a profit maximizer, it chooses to switch to natural gas when the cost of delaying the switch equals the benefit. Then, the following arbitrage condition must hold:

$$\text{PERMIT}{*}p_t{*}\left(e_t^i - e_t^{NG}\right) + (1 - \text{PERMIT}){*}s_t{*}F_t + \mu_t{*}d_t{*}L_t + X_t^i\left(z_t^i - z_t^{NG}\right) = r{*}W^{NG}. \quad (1)$$

Thus, large boilers would switch to natural gas insofar as the saving due to the reduction in the use of emission permits plus the expected benefit from avoiding the shutdown, plus any gain in the energy expenditure compensate the opportunity cost of the required investment. Non-large boilers would switch insofar as the expected benefit from avoiding a shutdown and the standard concentration plus the gains in the energy expenditure compensate the opportunity cost.

A hazard model was used to estimate how the variation of environmental regulations and fuel prices modified the decision to switch. For each firm, the hazard function is defined as the probability of switching to natural gas at time t, given that it has not switched yet (Kiefer, 1988). Formally:

$$h(t,x_t,\beta) = \frac{f(t,x_t,\beta)}{1 - F(t,x_t,\beta)}, \quad (2)$$

where the behavior of the hazard function depends on the distributional assumptions for the cumulative distribution function $F(t,x_t,\beta)$ and probability density $f(t,x_t,\beta)$, as along the way the set of explanatory variables x_t changes over time. The parameters β can be estimated using maximum likelihood.

Since spell lengths are observed only at intervals of a year and the experiment is not long enough to assume a continuous approximation, the two leading discrete distributions are explored—the logistic and the complementary log–log.[4] Both specifications separate the effects of explanatory variables on the hazard rate into two components: a baseline hazard rate which is a function of time, $c(t)$, and a function of the covariates $\beta' x_t$ that captures any difference between sources. Let $z(t) = c(t) + \beta' x_t$ be the hazard rate for a

Table 4
Fuel expenditure and the switching.

Fuel expenditure and the switching					
Previous fuel	PM_{10} concentration	No. of sources that switched	Relative fuel Expenditure expenditure in 1998		
			Industrial boilers	Residential boiler	Bakery ovens
Diesel No. 5	78[a]	20	0.69	0.60	0.60
Diesel No. 2	30	958	2.19	1.92	1.91
Kerosene	30	16	1.90	1.66	1.66
Liquified gas	15	99	2.32	2.03	2.03
City gas	15	70	3.01	2.64	2.63
New users[b]	15	1391	1.00	1.00	1.00
N		2554			

Source: elaborated from data provided by PROCEFF and METROGAS.
[a] Estimated from a sample of sources using Diesel No. 5 in 1998.
[b] New users that started operations burning natural gas.

[4] The complementary log–log specification is a discrete representation of a continuous time–proportional hazard model while the logistic model was primarily developed for data that is intrinsically discrete.

representative source in year *t*. Then, the shapes of the logistic and complementary log–log time hazard functions correspond to:

$$h^{\text{Logistic}}(t,x_t,\beta) = [1 + \exp(-z(t))]^{-1} \quad (3)$$
$$h^{\text{CLog-Log}}(t,x_t,\beta) = 1 - \exp[\exp(z(t))].$$

The model estimated assumes a non-parametric baseline $c(t)$, creating duration interval-specific dummy variables, one for each spell year at risk. This approach was chosen because it allows the data to reflect any shock occurred in a particular year. This is quite relevant in the natural gas case, since Chile has faced restrictions over the quantity of gas that can be imported from Argentina since 2004.

The dependent variable NATURAL GAS_t indicates whether a source is using natural gas at each point in time within sample or not, having a value equal to 1 if the source is using natural gas at the time t and zero otherwise.

3.1. Independent variables

To capture the impact of environmental policies, the following variables are included:

3.1.1. Permit

This is a dummy variable that takes a value of 1 if the source is regulated through the tradable permit system and zero otherwise. This coefficient is expected to be positive and statistically significant since large boilers could reduce the use of emission permits by switching.[5]

3.1.2. Number of Shutdowns_{t-1}

This variable captures the impacts of critical episodes. It equals the number of days that the sources included on either in the pre-emergency or emergency list, or both, had to close during the previous year due to these regulations:

$$\text{NUMBER OF SHUTDOWNS}_{t-1} = \text{PRE}-\text{EMERGENCY}_{t-1} \quad (4)$$
$$*\text{NUMBER OF PRE}-\text{EMERGENCIES}_{t-1}+\text{EMERGENCY}_{t-1}$$
$$*\text{NUMBER OF EMERGENCIES}_{t-1}.$$

The lagged value of the variable is used, since this should be the best guess available to sources deciding whether or not to switch to natural gas at the beginning of each interval at risk.[6] This coefficient is expected to be positive and statistically significant since more shutdowns increase the economic benefits from switching.

Notice that the variables PERMIT and NUMBER OF SHUTDOWNS_{t-1} should pick up any effect that the tradable permit system and the contingency program had beyond the concentration standard.

3.1.3. Fuel expenditure gap_{-t}

Switching fuels affects production costs since each fuel entails a different per unit energy cost, either because of differences in fuel price or in the quantity required to generate the same level of production. In addition, METROGAS combines an average per cubic meter fee that decreases with volume with a fixed charge that increases with it. To capture all these dimensions, a relative expenditure variable was constructed, by source per year, considering the fuel the source was previously using. For any source previously using the fuel *i*, the relative expenditure at *t* corresponds to the ratio between the expenditure in energy using fuel *i* and the expenditure, if it were burning natural gas in that particular year, as it is detailed in the following formula:

$$\text{Fuel Expenditure Gap}_t^i = \frac{\text{Energy Expenditure}_t^i}{\text{Energy Expenditure}_t^{\text{NG}}} \quad (5)$$
$$= \frac{z_t^i * X_t^i}{z_t^{\text{NG}}(X_t^{\text{NG}}) * X_t^{\text{NG}} + \text{Fixed Charge}_t(X_t^{\text{NG}})},$$

where X^i cubic meters of fuel *i* and X^{NG} cubic meters are required to produce the same output. The expenditure in gas is equal to the price of that fuel for that level of consumption $z_t^{\text{NG}}(X_t^{\text{NG}})$ times the level of consumption plus the fixed charge, which also depends on the volume of natural gas used by the source $\textit{Fixed Charge}_t(X_t^{\text{NG}})$.[7] Due to data limitations, the analysis focused on those sources previously using diesel No. 5, diesel No. 2, liquified gas, kerosene, and city gas. Fuel Expenditure Gap is expected to be positive and statistically significant.

3.2. Control variables

3.2.1. Size

The variable FLOW RATE_t is the rate at which emissions are discharged through a duct or stack and it is used as a proxy for size, since it is strongly correlated with the size of the combustion process. However, it is also strongly correlated with the type of policy instrument, since those sources which discharge their emissions at a rate higher than 1000 m^3/h are regulated through the tradable permit program. To disentangle the effect of size from the regulatory effect, five FLOW RATE_t dummy variables were created to reduce the correlation between both variables. The dummies are defined as follows: FLOW RATE_t^1 takes a value equal to 1 if the source discharged its emissions at a rate lower than 500 m^3/h and zero otherwise; FLOW RATE_t^2 takes a value equal to 1 if the source discharged its emissions at a rate of 500–1200 m^3/h and zero otherwise; FLOW RATE_t^3 takes a value equal to 1 if the rate varies between 1200 and 1900 m^3/h and zero otherwise; FLOW RATE_t^4 takes a value equal to 1 if the rate varies between 1900 and 3500 m^3/h and zero otherwise. Finally, FLOW RATE_t^5 takes a value of 1 if the rate is higher than 3500 m^3/h and zero otherwise. All these coefficients are expected to be positive and statistically significant.

3.2.2. Previous change

Those sources that switched to cleaner non-natural gas fuels before the arrival of natural gas could be less prone to switching again since they faced fewer regulatory restrictions than those using dirtier fuels. In addition, there could be opportunity costs created by the previous switch. The dummy variable PREVIOUS CHANGE takes account of this effect. It takes a value equal to 1 if the source switched to a cleaner non-natural gas fuel before the natural gas arrival and zero otherwise. This coefficient is expected to be negative and statistically significant.

[5] To give account of the impacts of the tradable permit system, the variable DELTA EMISSONS_t was also intended. It corresponds to the difference between the emissions produced by the fuel in use and the emissions produced by natural gas. However, the estimation results of the hazard model using such a variable did not change.

[6] The variables $\text{PRE-EMERGENCY}_{t-1}$ and EMERGENCY_{t-1} were also intended. $\text{PRE-EMERGENCY}_{t-1}$ was a dummy variable equal to 1 if the source was included in the pre-emergency list the previous year and zero otherwise. EMERGENCY_{t-1} was a dummy variable equal to 1 if the source was included in the pre-emergency list the previous year and zero otherwise. The estimation results of the hazard model using such variables did not change. But NUMBER OF SHUTDOWNS_{t-1} was preferred, since it was more meaningful in terms of the economic decision.

[7] In the data set, energy consumption is expressed in kilograms by hour. The consumption by month by source was determined by multiplying the original variable times the number of hours a source works everyday and times the number of days that it works every month. Then, it was transformed into square meters (m^3) of fuel divided by the density of each fuel. After that, the physical consumption was expressed in money and the relative price was calculated.

3.2.3. Equipment

Sources could also reduce their emissions installing end-of-pipe technologies, such as filters, electrostatic precipitators, cyclones, or scrubbers. However, in the sample, this was a very unusual alternative. The dummy variable EQUIPMENT is included to capture any effect that the availability of abatement technologies could have on the switching probability.

3.2.4. Bakery ovens effect

The main reason to include this variable is to capture the role of the Association of Bakery Owners, INDUPAN, which at the beginning of the 1990s encouraged its members to switch from wood to light oil. To support this, INDUPAN signed agreements with suppliers of the technology required to burn light oil and with a light oil company (Shell), offering discounted prices to its members. These measures were not offered again to promote the switch to natural gas. Thus, this coefficient is expected to be negative and statistically significant.

3.3. Data

Data employed was recorded by the Point Sources Emission Control Program (PROCEFF) and includes information from more than 5000 sources from industrial boilers, residential boilers, and bakery ovens over 11 years (1995–2005).

The standard procedure to estimate discrete hazard models required re-organizing the data set so that for each source there were as many rows as there were intervals at risk of the event occurring for each source (Jenkins, 2004). Then, the panel was turned from one row of data per source to another in which each source contributed T_i rows, where T_i is the number of years i was at risk of switching. For a source that switched to natural gas, T_i corresponds to the time until the switch. If a source never switched, it corresponds to the time the source survived in the experiment. However, it cannot be expected that sources switch to natural gas if this fuel was not available. Thus, the number of years at risk of sources switching, that were located in communes where natural gas was available after 1998, starts to be considered from the date at which natural gas entered that commune.[8]

Table 5 presents summary statistics of the covariates for the whole sample and for sub-samples of industrial boilers, residential boilers and bakery ovens that switched and did not switch to natural gas. As it can be seen in Table 5, the tradable system program seems strongly correlated with the switching of industrial boilers, but it is not correlated with the switching of residential boilers. In any sub-sample, there is a positive correlation between the lag of the number of shutdowns and the switch, and between the fuel expenditure gap and the switch.

Table 5
Summary statistics.

Variable	Overall	Industrial boilers		Residential boilers		Bakery ovens	
		Switched	Did not switch	Switched	Did not switch	Switched	Did not switch
	Mean	Mean		Mean		Mean	
NGt	0.11	0.07		0.18		0.03	
Permit	0.12	0.61	0.32	0.05	0.07		
Number of Shutdowns$_{t-1}$	1.96	1.95	1.90	3.40	2.56	1.28	0.70
Fuel Expenditure$_t$	1.92	2.14	2.01	1.95	1.83	2.04	1.91
Flow Rate$_t^1$	0.72	0.16	0.45	0.71	0.76	0.96	0.93
Flow Rate$_t^2$	0.20	0.34	0.32	0.27	0.19	0.02	0.06
Flow Rate$_t^3$	0.03	0.16	0.10	0.01	0.02	0.01	0.00
Flow Rate$_t^4$	0.03	0.20	0.09	0.01	0.02	0.01	0.00
Flow Rate$_t^5$	0.02	0.14	0.05	0.00	0.01	0.00	0.00
Previous Change	0.19	0.14	0.37	0.01	0.14	0.02	0.26
Equipment$_t$	0.01	0.02	0.01	0.00	0.00	0.02	0.02
Baseline							
Dummy1998	0.10	0.26	0.10	0.11	0.08	0.12	0.07
Dummy1999	0.11	0.23	0.11	0.15	0.09	0.13	0.09
Dummy2000	0.14	0.18	0.12	0.23	0.12	0.18	0.11
Dummy2001	0.13	0.14	0.13	0.16	0.12	0.16	0.12
Dummy2002	0.13	0.08	0.13	0.10	0.14	0.13	0.15
Dummy2003	0.11	0.04	0.13	0.06	0.13	0.10	0.13
Dummy2004	0.12	0.03	0.14	0.04	0.14	0.11	0.16
Dummy2005	0.15	0.03	0.15	0.14	0.17	0.07	0.16
T	6.44	3.57	7.61	3.54	7.26	3.58	7.03
N	15284	3545		7459		4280	

4. Results

Table 6 displays the results under the complementary log–log specification. However, the results are robust to various distributional assumptions. The results reported are not the estimated values of the coefficients, but the marginal effects of the covariates (distinguishing among the marginal effects for the whole sample and the marginal effects by sub-samples of industrial boilers, residential boilers and bakery ovens). The mean probability of switching for each sub-sample is obtained when all continuous variables are evaluated at their mean and the dummy variables are equal to zero. The marginal effect of each dummy variable is obtained as the difference between the probability obtained when that variable takes a value equal to 1 and the mean probability of switching. For continuous variables, the marginal effect is calculated as the impact on the mean probability of increasing them by 10%.

The mean probability of switching for the whole sample is equal to 9.82% (first column of Table 6). PERMIT and NUMBER OF SHUTDOWNS$_{t-1}$ have the expected signs, although surprisingly, none affects the likelihood of switching statistically. On the opposite, FUEL EXPENDITURE GAP$_t$ is positive and statistically significant, suggesting the existence of important cost advantages of switching to natural gas. In fact, a 10% increase of the fuel expenditure raised the mean probability by 2.59%. Considering that the price of natural gas was almost half the price of all other clean fuels, this implied a total effect equal to 25.9%.

The estimations show that the bigger sources (FLOW RATE$_t^3$, FLOW RATE$_t^4$ and FLOW RATE$_t^5$) were more likely to switch to natural gas. For example, belonging to the biggest sources (FLOW RATE$_t^5$) increased this probability almost 24%. On the contrary, to have switched to another cleaner non-natural gas fuel (PREVIOUS CHANGE) decreases the probability of change by almost 7%. In the meantime, to have abatement equipment (EQUIPMENT) at one's disposal affects the switching probability positively but not significantly.

The results are consistent with a significant fixed effect that indicates that being a bakery oven decreases the probability of switching by 7.65%. This suggests that regardless of the rest of the variables considered in the analysis, bakery ovens switched less, probably because of the incentives granted by INDUPAN.

The results also indicate that from 2002 onwards the stationary sources began to switch at a lower rate. One possible explanation for this is that the dummies captured some sort of vintage effect. Since the sources that did not switch (probably since they did not see enough benefits from the switch) are those that remained in the sample longer, the negative coefficients show that each year the adoption was less probable for them. This situation can also be related to the natural gas crisis that began in 2004 due to the restrictions imposed by the Argentine government on the quantity of gas that could be imported by Chile. Clearly, the crisis reduced the incentives to switch, given the uncertainty about its availability.

[8] Consider the case of a source that existed in 1998, but only had gas available in 2000 and switched to gas in 2003. For this source, T equals 3.

Table 6
Results.

Marginal effect (%) with *p* value in parenthesis						
Variable	Overall	Industrial boilers	Residential boilers	Bakery ovens	New industrial boilers	New residential boilers
Permit	1.38	2.91	0.92		0.50	0.82
	(0.43)	(0.11)	(0.65)		(0.76)	(0.73)
No. of Shutdowns$_{t-1}$	0.15	0.36	−0.02	0.00	0.02	−0.03
Fuel	2.59	3.85	2.13	0.54	0.82	1.16
Expenditure Gap$_t$	(0.00)*	(0.00)*	(0.00)*	(0.03)**	(0.00)*	(0.00)*
Flow Rate$_t^2$	0.99	5.60	0.03	−2.27	4.29	0.00
	(0.91)	(0.00)	(0.97)	(0.20)	(0.01)*	(0.99)
Flow Rate$_t^3$	3.96	12.18	−4.49	22.69	17.86	−4.37
	(0.12)	(0.00)*	(0.11)	(0.03)**	(0.00)	(0.21)
Flow Rate$_t^4$	9.85	18.1	2.52		23.10	−0.14
	(0.00)*	(0.00)*	(0.49)		(0.00)*	(0.97)
Flow Rate$_t^5$	23.8	34.11	0.71		43.19	3.10
	(0.00)*	(0.00)*	(0.12)		(0.00)*	(0.68)
Previous Change	−7.06	−3.55	−6.14	−2.84	−2.90	−6.64
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*
Equipment$_t$	4.32	3.15	2.86	1.52	0.00	0.00
	(0.23)	(0.29)	(0.55)	(0.70)	(0.03)**	(0.49)
Bakery ovens	−7.65					
	(0.00)*					
Year 1999	1.28	−0.87	3.64	−0.29	1.00	4.27
	(0.25)	(0.35)	(0.1)***	(0.84)	(0.39)	(0.01)*
Year 2000	1.16	−3.11	6.69	−0.25	−1.06	7.37
	(0.34)	(0.00)*	(0.00)*	(0.87)	(0.37)	(0.00)*
Year 2001	0.91	−2.69	6.60	−10.65	−0.95	7.15
	(0.47)	(0.00)*	(0.00)*	(0.42)	(0.43)	(0.00)*
Year 2002	−3.38	−4.06	0.57	−2.32	−2.32	0.66
	(0.00)*	(0.00)*	(0.67)	(0.03)**	(0.03)**	(0.65)
Year 2003	−6.67	−4.90	−3.85	−2.18	−3.15	−3.93
	(0.00)*	(0.00)*	(0.01)*	(0.05)**	(0.01)*	(0.00)*
Year 2004	−7.67	−5.63	−5.12	−2.22	−4.33	−5.28
	(0.00)*	(0.00)*	(0.00)*	(0.02)**	(0.00)*	(0.00)*
Year 2005	−9.59	−5.90	−7.60		−4.21	−7.69
	(0.00)*	(0.00)*	(0.00)*		(0.00)*	(0.00)*
Mean probability of switching	9.82	5.91	7.64	3.12	4.49	7.83
N	14724	3208	6771	3932	2709	6698
Log likelihood	−2616.31	−636.67	−1673.3	−236.85	−483.29	−1651.27

* Significant at 1%.
** Significant at 5%.
*** Significant at 10%.

Although most of the results remain the same when the model is estimated by sub-samples of industrial boilers, residential boilers, and bakery ovens (second, third and fourth columns of Table 6), there is an interesting difference is the significance of environmental regulation. While the effects of the tradable permit program remained insignificant for both types of boilers, the contingency program did statistically increase the switching probability of industrial boilers. However, the marginal effect is very small. A 10% increase in the number of days that an industrial boiler had to shutdown the previous year increased the mean probability of switching by just 0.36%.

In spite of its magnitude, the previous result suggests the existence of differences in the impact of the number of shutdowns, either due to differences in the cost of being closed or differences in the probability of being closed.[9] With regards to the last point, in the analysis about the switching decision, it is assumed that the probability of being closed during a bad quality episode is equal to 1. However, if sources are not forced to shutdown, the economic incentives of the regulation disappear. The results seem to support such an idea. The lack of effect of the contingency program for some stationary sources appears to be strongly related to the lack of monitoring efforts. Indeed, while the probability of being inspected was high for industrial boilers, it decreased for the rest, given that residential boilers were more prone to be inspected than bakery ovens. Unfortunately, data to test such a hypothesis more carefully it is not available.

Again, there is an important role played by the lower price of natural gas to encourage the switch. Its impact is much more significant for industrial boilers, as it increased the mean probability by 38.5%, instead of 21.3% and 5.4% for residential boilers and bakery ovens, respectively.

The effect of size is also more important for industrial boilers. Belonging to the group of the biggest industrial boilers (FLOW RATE$_t^5$) increased the switching probability by 34.11%. In the meantime, belonging to the group of the biggest bakery ovens (FLOW RATE$_t^3$) increased the switching probability by 22.69%. Residential boilers seem to have switched at the same rate, regardless of size.

The effect of a previous switch is higher for residential boilers, accounting for a 6.14% decrease in the probability of switching. Finally, the results by sub-samples show a significant decrease in the switching rate of all sources from 2003 on, probably reflecting the natural gas crisis, and from 2000 on for industrial boilers, which may be related to the vintage effect suggested previously.

Nevertheless, the question remains: why did the tradable permit system not encourage the switching to natural gas? Since it is quite difficult to disentangle the impacts of the tradable permit program from the size, I looked for another way to identify the effect of tradable permit program. For that, the hazard model was estimated for the sub-

[9] In a series of interviews, PROCEFF's workers mentioned that residential boilers could avoid the cost of the shutdowns by moving the combustion process to the night previous to the start of the shutdown. So, even though residential boilers were significantly affected by contingencies, the benefits of avoiding shutdowns were not enough to drive the decision to switch. Unfortunately, I do not have data to prove such a hypothesis.

sample of new industrial and residential boilers—that is, the sub-sample of boilers installed after 1992. Since new large boilers had to fully offset their emissions by buying emission permits from the existing large boilers, they could benefit the most from reducing the use of emission permits. Thereby, PERMIT is expected to be positive and statistically significant when only this sub-sample of new boilers is considered. The fifth and sixth columns of Table 6 show the results. As can be seen, the tradable permit program did not speed up the switch to natural gas from new large boilers either.

Why did the tradable permit system not encourage the switching to natural gas? The reasons behind its lack of effect seem correlated with the implementation of the program. As was mentioned in Section 3, since the environmental authority lacked good historical records on emissions by large boilers, they over-allocated permits, producing a very significant excess of supply in spite of regulatory changes that have reduced the stock. The aggregate excess of supply must have produced a very low permit price of equilibrium, making the benefits from reducing the use of emission permits insignificant when compared to the savings from fuel consumption. Unfortunately, there is no information about permit prices to verify this hypothesis more carefully.

An additional explanation is provided by Palacios and Chávez (2005). According to the authors, the enforcement design used has not been able to induce high compliance levels because of a combination of monetary penalties that are not clearly defined and actual sanctions that are not automatically implemented but are decided on a case-by-case basis. As a consequence, the program has failed to provide enough incentives for firms to assume a high degree of compliance.

5. Conclusions

What can we learn from the process of switching to natural gas in Santiago? Basically, that when it is time to undertake technological change, firms are quite responsive to changes in relative prices. If the environmental regulatory institutions are weak and they have limited capabilities to monitor and enforce environmental regulations, indirect regulations might stand a better chance of being effective promoting environmental targets. In fact, the large response of the rate of switching to the lower price of natural gas in Santiago—although not technically environmental taxation—supports the use of taxes on non-clean fuels. Despite they do not create incentives to abate emissions per se; they might create incentives to use cleaner fuels and to reduce emissions.

An important advantage of the use of fuel taxes in less developed countries is the ease of administration (Sterner, 1996 and Blackman and Harrington, 2000). First, because consumption of fuel is usually much easier to monitor than emissions. Second, because they operate through government tax collection institutions that are more established and effective than environmental regulatory institutions. These two aspects seem quite correlated to the success of the implicit tax on “non-natural gas fuels” and to the failure of quantity policies in Santiago. Lack of reliable baseline data, lack of expertise with environmental regulations, short supply of resources for environmental protection and lack of monitoring and enforcement are among the reasons that explain the poor performance of the tradable permit program and the contingencies program. On the other hand, the effective pricing strategy of METROGAS speeded up the pattern of switching and induced a major improvement in air quality within a few years.

Fuel taxes might involve also some disadvantages. They may affect non-targeted activities and they may have distributional impacts if they have a more severe impact on poor households than on rich ones. These issues may be solved by using tax revenues to finance new expenditures which benefit poorer households or exempting certain activities and consumers from the tax. However, the last approach should be considered carefully since it may encourage the creation of black markets for the taxed fuels.

Summarizing, Santiago's experience shows us that the challenges of designing successful environmental programs in less developed countries should not be underestimated and that fuel taxes might be an appropriate policy option when institutional constraints on direct regulation prevent the effectiveness of such policies. This is not to say that indirect regulations are the only efficient and effective approach for less developing countries. Environmental management capabilities can be increased through time as well as the set of policies to choose from.

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