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Pollution Permit Systems and Firm Dynamics: Does the Allocation Scheme Matter?

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Evangelina Dardati†

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Abstract

Most cap-and-trade systems allocate permits for free. However, they differ dependent on whether closing plants and new entrants get free permits. Free permits do not have any impact on the static problem of a plant but they affect the dynamics. I use a dynamic model with heterogeneous firms to quantify the effect on exit/entry, investment and welfare of different allocation rules. I adapt the model to the electricity sector, add a cap-and-trade regulation and equilibrium conditions for the pollution market. I calibrate the model with data from the power plants participating in the US SO2 program and quantify the effects of two allocation schemes: The US SO_2 case, in which closing plants keep their permits and new entrants do not get any of them; The EU-ETS case, in which plants lose permits upon exit and new entrants get allowances. If the US switched to the EU-ETS allocation scheme, the price of output would be 1.5% lower, the price of permits 7.6% higher, and there could be a distribution of dirtier and less productive plants. Consumers are better off if the US switched to the EU-ETS system (higher output), while producers are better off with the US SO_2 system (higher profits).

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1 Introduction

Pollution permit systems or cap-and-trade programs are becoming a popular policy to regulate activities that affect the environment. The government fixes an upper bound of emissions; issues pollution permits and allocates them to the firms. They can trade them between each other and, at the end of the period, they have to back up each unit of emission with a permit. Most of the programs allocate the permits for free. However, they differ with respect to the rules for closing plants and new entrants. The first big cap-and-trade initiative began in 1995 in the US to control sulfur dioxide emissions from the fossil-fuel power plants (US SO_2). Plants keep the permits forever, even if they close, and new entrants do not get free permits. The European Union implemented the EU Emission Trading Scheme (EU-ETS) in 2005 to control carbon dioxide emissions (CO_2). Each member state (MS) is responsible for allocating allowances in their country. Unlike the US, most of the MS chose to give permits to new entrants while closing firms lose the right to keep them.[1]

The purpose of this paper is to quantify the effects on exit, entry, investment and welfare of alternative allocation schemes for closing plants and new entrants. Free permits do not have any impact on the static problem of a plant; the opportunity cost of producing output is the same, regardless of free permits. However, they affect the dynamic decisions with welfare and efficiency implications. I introduce a Hopenhayn (1992) type of model to study the problem of a power plant that has to choose between staying or exiting the industry, and whether or not it should invest in a new and cleaner boiler. I add another market to that model: the pollution market. Plants produce and have to back up emissions with pollution

[1] Some MS used a different allocation rule, similar to the one used in the US SO_2. However, since most MS decided not give permits to closing plants and give permits new entrants I will call it EU-ETS to simplify the exposition.

permits. When they exit or invest in new boilers they can either keep the permits (US SO_2) or lose them (EU-ETS). In the EU-ETS case, the permit allocation distorts the exit and investment decision: plants have incentives to stay longer in the market and to delay investment. In the model, potential entrants can pay a fixed cost and enter the industry. The value of entry is different depending on whether they get free permits (EU-ETS) or not (US SO_2). This has consequences on the price of output, price of permits and entry rate. The fact that new entrants get permits makes the equilibrium price of output lower, while the entry rate is higher. However, a higher entry rate also implies a higher exit rate. The final effect on exit, entry, investment and prices is ambiguous.

I add heterogeneity on two dimensions: plants differ on productivity levels and on the age of their boiler. More productive plants produce more. Older boilers are dirtier and more likely to fail. I work with a competitive stationary equilibrium. In equilibrium, decision rules are optimal, the state reproduces each period and the price of output and the price of permits adjust such that both markets clear. In the case of the permit market, the supply is the cap fixed by the government. The demand of permits depends on output and the polluting technology. I calibrate the model with US SO_2 data before the regulation took place. I quantify the dynamic effects of the introduction of the cap-and-trade program. In a counterfactual, I ask what would happen if the US switched to a EU-ETS allocation type, and quantify the effects on the new equilibrium and welfare.

Most of the literature on permit allocation focuses on the differences between auctions, historical-based allocation and updating[2] (Goulder et al (1999), Jensen and Ramussen (2000), Sterner and Muller (2006), among many others). Historical-based allocation is the most common way to allocate allowances. In the US SO_2 program and in the EU-ETS, at least 95% of the allowances are given out for

[2]Plants get allowances for free, based on current or future measures of output or emissions

free while just a 5% are auctioned. Only a few papers consider historical-based allocation and the alternative policies regarding closing plants and new entrants. Ahman et al (2007) addresses the ways in which the rules for new entrants and closing plants can create distortions to entry, exit and investment. Ellerman (2008) is the first to model the effects of those policies. Within a comparative statics framework he studies if capital adjusts in the long run depending whether the firm gets permits or not. He finds that provisions for new entrants create over-capacity, but the effect on emission markets is ambiguous. My paper differs because I work in a dynamic framework with endogenous exit and entry. I interact the permits and output market and solve for the equilibrium prices. Both the price of permits and the price of output are endogenous in my model. To analyze how permits affect the industry distribution, I add heterogeneity in productivity and in their emissions. Finally, I take the model to the data.

I also contribute to the literature on the dynamic effects of environmental regulation. Ryan (2006) uses an Ericson and Pakes (1995) framework to study environmental regulation in the cement sector. Cullen (2008) uses a dynamic model to study the response of electricity producers to a carbon tax. Heutel (2009) uses a dynamic model to study the perverse effect of grandfathering in the Clean Air Act of 1970 on the electric power generating industry. None of these papers models a pollution permit system.

I calibrate the model with power plants participating in the US SO_2 market before the regulation took place. Then, I quantify the effect of the introduction of the cap-and-trade program. The regulation increases the marginal cost of the plants, increasing the equilibrium price of output by 5.3%. Emissions decrease through two channels: the decrease in the output level (-2%) and the change in the distributions of plants. The dirtiest and most unproductive plants have to leave the industry because they cannot longer comply with the regulation. The

exit rate increases from 0.7% to 2.7%. Also, plants invest and leave the industry earlier, comparing to the case with no regulation. In the new equilibrium, the average age is 27% lower and the average emission rate is 43% lower, while the average productivity is 5% higher.

How does the equilibrium change with the EU-ETS allocation? In this case, exit is 7% lower due to the distortion, while investment remains almost the same. Plants delay the exit and investment decision. The average age of exiting and investing are 1.4% and 4.9% higher, respectively. The fact that new entrants get permits implies a higher value of entry, a 1.5% lower price of output and 0.5% higher output. The average age and average emission rate are 3.6% and 3.4% higher than in the US SO_2, respectively, while the average productivity is 0.5% lower.

With respect to the welfare implications, consumer surplus is 29% lower in the US SO_2 (higher price of output) but producer surplus is 24% higher (higher price of output, lower price of permits). Which allocation is better? That depends on how much weight we put to consumers and producers. The EU-ETS allocation has higher consumer welfare and lower producer welfare. It could be a good way to protect consumers from the increase in the price of output after the regulation. However, the cost is the distortion in the exit and investment decision that implies a distribution with dirtier and less productive plants.

The paper is organized as follows. Section 2 introduces the model. In section 3, I explain the data and give some background on the US Acid Rain Program. In section 4, I explain how I solve and calibrate the model. In section 5, I analyze and discuss the results. Finally, section 6 concludes.

2 The Model

In this section, I introduce a dynamic model related to Hopenhayn (1992) to study the decision of the power plants. My model differs because I adapt it to the electricity sector, add an investment choice and a pollution market that is regulated with a a cap-and-trade program.

2.1 The Environment

A continuum of plants produce an homogenous output Q (electricity), time is discrete defined by $t = 1, 2, 3....$ The output of each plant q is given by the technology $q = zF(f)$ where z is a productivity shock, $F(f)$ is the production function and f is fuel. I assume $F(f)$ to be a strictly concave and twice continuously differentiable function on f. The productivity shock follows a Markov process and it is independent across plants.

In the production process, plants pollute. Emissions are regulated with a cap-and-trade program. Each plant denoted by i owns a single boiler[3] that is the emission unit. All plants have an emission rate function denoted by $g(a_t)$ that depends positively on the age of the boiler and it is strictly convex. The emission rate function can take two types: low and high. The low type is cleaner than the high type such that $g^l(a_t) > g^h(a_t)$. For a given age, the high type emits more than the low type.

Every period, the government issues a aggregate fixed amount of permits. It distributes them to each boiler at no cost. I assume each incumbent boiler gets the same amount of permits. Plants can trade the allowances between each other and at the end of the period they have to back up each unit of emission with a permit. There is no banking or borrowing: plants have to use the permits the same period

[3] A boiler is the device that heats the input to then produce electricity.

they were issued. I assume no strategic behavior between plants, which behave competitively in the output and the permit market.

The plant faces two marginal costs: one for the fuel and the other for buying the pollution permits. Additionally, every period they are in the market, they pay a fixed cost of producing (FC). The fixed cost allows for exit. If it did not exist, plants would produce zero and wait for better productivity shocks.

I assume that each boiler lives up to T periods. The state of a plant in each period can be described by the productivity z, the age of the boiler denoted by a and the amount of free permits that they get every period ω. The 3 variables take discrete values such that $z \epsilon \mathbb{Z}$, $a \epsilon \mathbb{A}$ and $\omega \epsilon \{0, \overline{e}\}$. Boilers can either get a positive and fixed amount of permits $\overline{e}$ or no permits.

In every period, plants observe prices, produce electricity and earn profits in the spot market. Profits depend on the plant state, on the prices and on the emission type. I denote profits by $\pi(z_t, a_t, \omega_t; \mathbf{p})$ where $\mathbf{p} = (p, p^f, p^e)$ is the price vector, p is the price of output, p^f is the price of fuel and p^e is the price of permits.

The model allows for exit and entry. Incumbent plants observe a scrap value ϕ and decide to stay or exit the industry. If the plant decides to stay, it can spend d units of output and invest in a new boiler. The new unit emits less. Also, new units are more reliable, they have a lower probability of failing. Once a boiler fails, the plant dies and become useless. The probability of failing is increasing in the boiler age. A plant with an older boiler is more likely to become obsolete.

In each period, there's a pool of potential entrants that can pay a fixed cost of entry c_e and draw their initial state from a distribution. Entrants start to earn profits the period after they enter.

The timing of the model is:

- Incumbents observe current state and prices, they produce and get profits $\pi(z_t, a_t, \omega_t; \mathbf{p})$.

- Incumbents observe scrap value and decide whether to stay or exit. If they stay, they decided whether to invest in a new boiler.
- Potential entrants observe current state of the industry and decide whether to enter.
- Plants exit and get scrap values, new entrants pay fixed cost, take a draw from the distribution and enter.
- The state moves to the next period and everything starts over.

I work with a stationary equilibrium. In a steady state, some plants are exiting, some plants are replacing boilers, and new plants are entering. However, the aggregate variables remain constant. The steady state equilibrium implies a distribution by age, size and emission type.

I work in a competitive environment. I take the model to data using the US electricity market. This could be a restrictive assumption given that there is evidence that the electricity generation is not a perfectly competitive sector [Wolak (2003); Borenstein, Bushnell and Wolak (2002); Joskow and Kahn (2003)]. However, in order to keep things simple, I take the power plants as my units of analysis and abstract from the strategic interdependence or the coordination among power plants that belong to the same firm or utility, or boilers that belong to the same power plant. I work with aggregate data from the sector; market power is more likely to be concentrated in some states, while others show a more competitive behavior. Adding market power could also imply restricting my analysis to a single region with evidence of market power. In that case, I should take the price of permits as given (the cap-and-trade is for the entire US) and could not study the equilibrium effects in the permits market, which does not show evidence of market power. So, I assume that both the output and permits market are competitive and study the interaction between them.

I assume that each plant has a single boiler. Table 2 in the data section shows that plants have, on average, 2.8 boilers. I treat each boiler separately. Another assumption of my model is that plants can either replace a boiler or exit the industry. In the data, 85% of the plants that stop using a boiler either exit the industry or replace it with a new one, and I focus on those decisions only. I do not consider the decision of a plant to add an extra boiler. A plant invests in a new boiler to replace an old one.

Another important assumption is that investment does not add capacity to the plant. Power plant capacity is increased by buying generators. I do not model the decision to buy generators. I focus on the decision to obtain a new boiler because this is the emission unit subject to the regulation. I assume that investment does not improve its productivity, either. I did not find evidence in the data that new boilers improve the plant's productivity.[4] In my model, investment makes boilers more reliable (they have a lower probability of failing) and cleaner (they pollute less per level of output).

I assume younger boilers are cleaner. Figure 2 from the data section shows a positive relationship between the age of the boiler and its level of emissions. Plants with younger boilers are also more reliable. They are less likely to die. I make this assumption because emissions are not the only reason why a plant might invest in a new boiler (before any regulation they would still replace boilers as they aged). I add that assumption to capture the fact that plants tend to replace boilers as they get older. I assume boilers live up to T years. In the data, I observe no boiler older than 75 years old. Note that in my model, boilers have a finite life but plants do not. They can replace boilers and continue to operate for an infinite period of

[4] To do that, first I computed total factor productivity (TFP) for each plant using the Levinshon and Petrin (2003) method and compared the productivity for plants before and after a new boiler was added. I did not find a significant difference in the productivity measure.

time.

In the data, I observe heterogeneity in emissions and size. In my model, I add heterogeneity in size by assuming that plants have different productivity levels. More productive plants produce more. Finally, I assume that the emission rate of the boiler depends on its age and type. Because of the improvement in technology newer boilers emit less. However, I do not observe all units of the same age to have the same emission rate function. Other factors (e.g. type of plant (gas or coal), how close the plant is to a low-sulfur coal mine, if they have a scrubber, etc.) also influence the amount of pollution. I capture some of this heterogeneity by adding two types of emission rate functions: the low and the high emitter.

2.2 Equilibrium

2.2.1 Static problem

Each period, each incumbent plant decides how much fuel f to use to produce the quantity q and emissions e. Total emissions depend on the quantity of fuel and on the emission rate function. The static problem of a plant i of emission type j where $j = h, l$ in period t is:

$$\begin{aligned} max_f \quad & \{\pi_t^{i,j} = p_t \times q_t^i - p_t^f \times f_t^i - p_t^e(f_t^i \times g^j(a_t^i) - \omega) - p_t \times FC\} \\ s.t. \quad & q_t^i \leq z_t^i F(f_t^i) \end{aligned} \tag{1}$$

The problem has an interior solution. The first order condition is:

$$p_t \times z_t^i \frac{dF}{df_t^i} - p^f - p^e \times g^j(a_t^i) = 0$$

Let $f^*(z, a; \mathbf{p})$ be the solution to this problem. It depends on z, a and the prices. The optimal fuel f^* is increasing in p and z and decreasing in p^f, p^e and a. The

plant produces more when the output price is higher, and less when marginal costs are higher. Given f^*, I compute each plant's output. Even if the amount of free permits ($p^e\omega$) enters the profit function, they do not have any impact in the static problem of the plant. The optimal f^* is independent on the amount of free permits. Since plants can buy or sell the permits, the opportunity cost of polluting is the same, regardless of the free permits. However, they do have effects in the dynamic decision.

Also, note that the emissions depend indirectly on the productivity of the plant. A more productive plant that uses less fuel per unit of output will emit less than an unproductive plant, all else equal. If there was no regulation, the third term of the equation would not exist and the optimal output would be higher (costs would be lower). The policy creates and incentive to reduce output regardless of how the permits are allocated.[5] A way to comply with the regulation would be to reduce output, thus reducing emissions.

2.2.2 Dynamic problem

Every period, incumbent plants choose to stay or exit the industry. If a plant exits, it gets a scrap value ϕ. If it stays, it chooses whether to invest in a new boiler. New units cost d, are cleaner and have a lower probability of failing. Since new units are cleaner, the plant pollutes less per unit of output, which reduces the cost of buying pollution permits.

The probability of failing is an increasing function of age denoted by $\delta(a)$. I assume that the productivity shock z follows a Markov process drawn from a know distribution. Each plant also has an emission type that does not change over time.

[5]This applies if permits are distributed through auction or historical-based allocation. If the allocation depends on current output there would be more production [Sterner and Muller (2006)].

The productivity and the emission type are specific to the plant. The age is specific to the boiler. I do not allow the plant to choose the type of unit when they invest.

I assume two different cases for the permit allocation:

1. Plants get permits forever, even if they exit. New entrants do not get any permits. I will call this the *US* SO_2 *case*.

2. Plants get permits until they exit or scrap their units. New entrants get permits. I will call this *EU-ETS case*.

Let χ and I be the exit and investment strategy of the plant. They take value 1 if the plant exits ($\chi = 1$) or invests ($I = 1$) and 0 otherwise. Let primes denote future values. If the plant does not invest, it will be a year older in the following period, it will get another productivity shock that will depend on the shock today and will get the same amount of permits $\bar{e}$ from the previous period and the same emission function type. If the plant fails, in the US SO_2 case it still get the stream of permits in perpetuity. So, the value function for a plant of emission type j that stays in the industry and does not invest in a new boiler is:

$$
\begin{aligned}
V^N(z, a, \bar{e}; \mathbf{p}) &= max\{\pi(z, a, \bar{e}; \mathbf{p}) + ... \\
&\quad (1 - \delta(a+1))\beta E_{z'/z} V(z', a+1, \bar{e}; \mathbf{p}') + ... \\
&\quad \delta(a+1)(\phi + p^e \times \bar{e}(1 + 1/r))\}
\end{aligned}
$$

The difference with the EU-ETS case is that if the plant fails it will get the scrap value but not the permits. In this case, the value function of not investing is:

$$
\begin{aligned}
V^N(z, a, \bar{e}; \mathbf{p}) &= max\{\pi(z, a, \bar{e}; \mathbf{p}) + ... \\
&\quad (1 - \delta(a+1))\beta E_{z'/z} V(z', a+1, \bar{e}; \mathbf{p}') + ... \\
&\quad \delta(a+1)\phi\}
\end{aligned}
$$

The value of investing in a new unit is also different for the two cases. In the first case, permits are forever, regardless of what the plant does. In the second case,

plants lose the permits when they scrap the old boiler. In both cases, the plant has a new productivity draw and the age of the unit goes to one. The value function of a plant of emission type j that invests in a new boiler for US SO_2 is:

$$\begin{aligned} V^I(z,a,\overline{e};\mathbf{p}) &= max\{\pi(z,a,\overline{e};\mathbf{p}) - p \times d + ... \\ & (1-\delta(1))\beta E_{z'/z} V(z',1,\overline{e};\mathbf{p}') + ... \\ & \delta(1)(\phi + p^e \times \overline{e}(1+1/r))\} \end{aligned}$$

The difference with the EU-ETS is that once the plant invests in a new boiler, it cannot keep the permits anymore. Therefore, the value function in this case is:

$$\begin{aligned} V^I(z,a,\overline{e};\mathbf{p}) &= max\{\pi(z,a,\overline{e};\mathbf{p}) - p \times d + ... \\ & (1-\delta(1))\beta E_{z'/z} V(z',1,0;\mathbf{p}') + ... \\ & \delta(1)\phi\} \end{aligned}$$

Note that for the EU-ETS case, the fact that the plant does not get permits when they invest in a new unit distorts the investment decision. It has an incentive to keep the unit longer in order to keep the permits. This distortion does not exist in the US SO_2 case. Free permits do not matter for the investment choice.

The value function for a plant that stays in the industry is:

$$V^s(z,a,\overline{e};\mathbf{p}) = max[V^N(z,a,\overline{e};\mathbf{p}), V^I(z,a,\overline{e};\mathbf{p})] \tag{2}$$

Finally, a plant stays if the value V^s is higher than the scrap value. In the US SO_2, they also get the stream of permits in perpetuity, namely:

$$V(z,a,\overline{e};\mathbf{p}) = max[V^s(z,a,\overline{e};\mathbf{p}), \phi + p^e \times \overline{e}(1+1/r)] \tag{3}$$

For the other case the last term $p^e \times \overline{e}(1+1/r)$ is zero since they do not keep the permits upon exit. In the EU-ETS, a plant does not keep the permits when closing. There is an incentive to stay longer in business. If the plant does not

get free permits upon closure or for a new investment, it distorts the exit and investment decision. That distortion does not exist for the US SO_2 case. Exit and investment are lower in the EU-ETS case.

Incumbents make three decisions: the amount of fuel and the two dynamic choices: stay/exit and investment. The first is a static decision and do not depend on the free amount of permits. For the US SO_2, plants make the dynamic decisions taking into account their productivity shocks, age and the emission type. In the EU-ETS case, they also take into account the amount of free permits. If they leave or invest in a new boiler, they lose them. Free permits matter.

Also, there's a pool of ex-ante potential entrants. Upon entry, they draw an initial endowment of z_t and an emission type from the time invariant and known distributions z and v, respectively. They start a new plant with age 1. For the US SO_2, they do not get free permits. Let ϵ be the entry strategy such that it takes value 1 if the plant enters and 0 otherwise. The value of entry is:

$$V^e(\mathbf{p}) = \beta EV(z', 1, 0; \mathbf{p}') - p \times c_e$$

For the EU-ETS, new entrants get an endowment of permits. The value function for them is:

$$V^e(\mathbf{p}) = \beta EV(z', 1, \overline{e}; \mathbf{p}') - p \times c_e$$

When the new entrants get permits, the value of entry is higher than when they do not get free permits (or, what is similar, the fixed cost of entry is lower). This has two consequences: the first is that the equilibrium price of output has to be lower; the second effect is a higher entry rate and, therefore, a higher exit rate. The lower fixed cost of entry reduces the barriers to entry, more plants enter and there is more selection: more plants have to exit. The new plants are cleaner, so more entry implies also more incentives to invest in new units. So, investment and exit are higher in this case. This effect is opposite to the one created by the distortion

of not giving permits to closing plants. The final effect on exit and investment is ambiguous.

2.2.3 Definition of Equilibrium

I work with a stationary equilibrium. The price of output and the price of permits are constant. The price of fuel is given and is exogenous to the model. Aggregate variables remain unchanged through time. However, even if aggregate variables are constant, in each period there are plants investing, unproductive plants exiting and new plants entering the industry. Let M be the entry rate. The state of a plant in a given period can be described by (z_t, a_t, ω). I denote $\mu(z_t, a_t, \omega)$ the measure of plants with state (z_t, a_t, ω). The aggregate state of the industry μ is the distribution of the state variable for all plants. The state in the following period is denoted by μ' and $T(\mu, M; \mathbf{p}) = \mu'$ is the transition from μ to μ'.

The demand for output is defined by an inverse demand function $P(Q^d)$. The supply depends on the distribution of plants in the industry defined by:

$$Q^s(\mu, M; \mathbf{p}) = \int q^*(z_t, a_t, \omega) d\mu(z_t, a_t, \omega) + M \int q^*(z_t, 1, \omega) dz dv$$

Plants have to back up each unit of emission with a permit. For every period, the total demand of permits PP^d equals total emissions:

$$\begin{aligned} PP^d(\mu, M; \mathbf{p}) = \int f^*(z_t, a_t, \omega) \times g_t(a_t) d\mu(z_t, a_t, \omega) + ... \\ M \int f^*(z_t, 1, \omega) \times g_t^i(1) dz dv \end{aligned}$$

The supply of permits corresponds to the total amount of permits that the government issues every period. The price of permits is endogenous and clears the permit market.

Definition 1 *A stationary competitive equilibrium is a list* $p^*, p^e, f^*, Q^*, M^*, \mu^*, I^*, X^*$ *such that:*

1. *Given prices* $\boldsymbol{p}^*$*, decision rules are optimal.*

    - f^* *maximizes (1)*
    - I^* *maximizes (2)*
    - X^* *maximizes (3)*

2. *Aggregate demand is equal to aggregate supply.*

$$Q^d(p^*) = Q^s(\mu^*, M^*, \boldsymbol{p}^*)$$

3. *Demand of permits is equal to supply of permits.*

$$PP^s = PP^d(\mu^*, M^*, \boldsymbol{p}^*)$$

4. *The state is reproduced in each period.*

$$T(\mu^*, M^*, \boldsymbol{p}^*) = \mu^*$$

5. *The free entry condition is satisfied.*

$$\beta EV^e(\boldsymbol{p}^*) \leq p \times c_e$$

    with equality if the number of entrants is positive.

The first part of the definition states that decision rules are optimal. The optimal amount of fuel solves the static problem. The investment and exit decision rules give the maximum value for staying, investing or exiting the industry. The demand of output has to be equal to the supply of output. The price of output adjusts such that the output market clears. The demand of permits has to be equal to the supply of them. The price of permits adjusts such that the permits market clears. The distribution reproduces itself every period. In equilibrium, the size, age and emission type invariant distribution does not change trough time. Finally, the free

entry condition has to hold with equality if the number of entrants is positive. If $\beta EV^e(p^*) < p^* \times c_e$ then there would be no entry. If $\beta EV^e(p^*) > p^* \times c_e$ plants would enter, lowering the price until both terms are equal. I assume an equilibrium with positive entry. Therefore, in equilibrium the entry condition holds with equality.

Now, suppose new entrants get permits. The value of entry is higher. This can also be interpreted as a lower fixed cost of entry. That means that $\beta EV^e(p^*) > p^* \times c_e$ and, as more plants enter, the price of output decreases to restore the equality. The quantity is determined for the demand function. Thus, a lower price means also lower aggregate quantity. Giving permits to new entrants implies lower price of output and higher output.

To sum up the effects of the free permits on the dynamic model: Not giving permits to closing plants or new investment distorts the exit and investment decision. (Exit and investment would be lower.) Giving permits to new entrants makes the value of entry higher and has two effects. First, the equilibrium price of output is lower. Second, it implies higher entry and therefore, higher exit and investment. The final results on those variables are ambiguous. A quantification is useful.

The explanation of how to solve the model and the computational algorithm are in the Appendix.

3 Background and Data

3.1 Acid Rain Program: Background

The Acid Rain Program, instituted under the 1990 Clean Air Act Amendments, established a pollution permit system to regulate SO_2 emissions in the electricity generation sector. The program affects coal, gas and oil plants, and it has consti-

tuted the biggest pollution permit system implemented in the US until now. In it, power plants have units called boilers, which are the emission units subject to the regulations. The boilers are devices which heat the fuel which is then converted into electricity. The government issues a fixed amount of permits every year. It distributes the permits to boilers at no cost. Units can trade permits between each other. At the end of the year, they have to back each ton of SO_2 with a permit. The program started in 1995 and had two phases. The first, from 1995 to 1999, included only the 263 dirtiest units (110 power plants, "Table A" plants). The second phase began in 2000 and included every unit with capacity higher than 20 Mega Watts (MW), around 2000 units. Also, in the second phase, the cap was set to 9.5 million tons. In 2010, a new cap was set at 8.95 million tons.

Every year, units get a fixed amount of permits that do not change while the units stay in business. The allocation of permits depends on past output and emissions. Bigger, dirtier units receive more allowances. The rule for allocating permits is as follows:

- From 1995-1999 (first phase), the EPA (Environmental Protection Agency) allocated allowances at an emission rate of 2.5 pounds of SO2/mmBtu of heat input, multiplied by the unit's baseline mmBtu (the average fuel consumed from 1985 through 1987)
- In the second phase (from 2000), the EPA allocated allowances at an emission rate of 1.2 pounds of SO2/mmBtu of heat input, multiplied by the unit's baseline.

Every boiler gets permits according to that rule and the plants keep them forever, even if the boiler exits the industry. New plants that began operating after 1995 do not get any free allowances. They have to purchase all of them in the market. The Act also set aside a reserve of allowances. Existing units that promote demand-side

energy conservation or install renewable energy generation are eligible to receive permits from the reserve.[6]

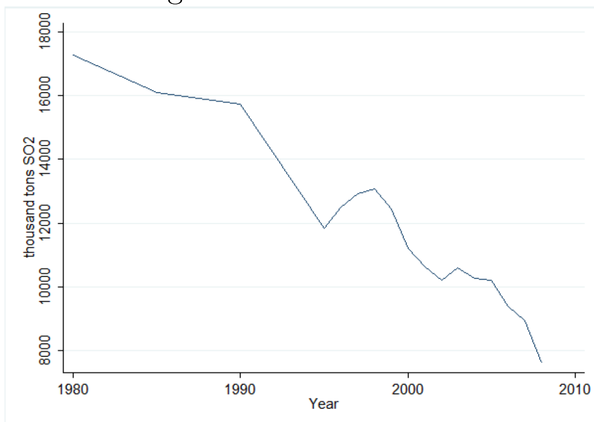
Plants can reduce their SO_2 emission in several ways. They can invest in flue gas desulfurization units (FGD) called scrubbers, which remove up to the 90% of SO_2. However, these devices are extremely expensive, and just a few plants have adopted them. Plants can also use low-sulfur coal instead of high-sulfur coal. However, transportation costs for coal are high. For a plant that is located near a high-sulfur coal mine, it could be more expensive to use the cleaner coal.

One of the most important characteristics of a tradable permit system (as opposed to command and control policies wherein a plant must meet standards) is that it leads to an efficient outcome when units are heterogeneous. In the case of the power plants, they are heterogeneous in many dimensions. Plants differ considerably in size. There is also heterogeneity with respect to how clean they are. In particular, gas plants are cleaner than coal plants. Also, as I noted before, location is one important source of heterogeneity. The cap-and-trade program internalizes all these heterogeneity issues. Assuming that all units have the same amount of permits, a plant with high (low) marginal cost of abatement will be a net buyer (seller) of permits. Therefore, this regulation constitutes an important improvement for cost reduction with respect to the standards that were used before [Carlson, et al (2000)].

The Acid Rain Program was very successful in terms of absolute level of SO_2 emissions. Figure 1 shows its trend during the last decades.

[6] http://www.epa.gov/airmarkets/progsregs/arp/basic.html

Figure 1: SO2 Emissions



3.2 Data

I use data from Data and Maps[7] from the EPA. Data are on compliance, allowances allocated, traded and used every year. I also have data on characteristics of units and plants [emission, output (electric generation), heat input (fuel consumption), type of fuel used, phase of the program, maximum heat input capacity of the plant, and their operation status (retired or operating)]. I complemented the data with information from EGRID[8] (primary fuel for each unit) and Form EIA-860 (generation capacity). I have data for the years 1995 to 2009 after the regulation and from 1980, 1985 and 1990 before the regulation. Also, I use the form EIA-423 for information regarding the cost of fuel.

The data from Data and Maps before 1990 only includes the units that participated in the Acid Rain Program. Therefore, it does not include units that retired before 1990. To complement this information, I hand collected generator level data from the "Inventory of Power Plants in the United States" from 1982 to 1990. Unfortunately, these reports do not include information on heat input (fuel consumption) or emissions. I imputed the values for heat input. To do the

[7] http://camddataandmaps.epa.gov/gdm/

[8] http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

imputation, I did yearly regressions of heat input on capacity, type of fuel, the interaction of capacity and type of fuel, and state, using the available data from the units that participated in the Acid Rain Program. Then, I imputed the values of heat input for the retired units that I added to the sample. As the data from the "Inventory of Power Plants in the United States" is at the generator rather than the boiler level and given that most generators are related to a single boiler, I use information on the retired generating units rather than boilers for the years previous to 1990.

Table 1 shows summary statistics at the boiler level. Boilers are heterogeneous in their production level, their capacity as well as in their emissions. Mean age is 24.6 and the maximum is 75 years old.

Table 1: Summary statistics (Boiler level)

Variable	Mean	Std. Dev.	Min.	Max.	N
output (electricity)	965	1,474	0	38,722	31,501
so2 emissions (in tons)	4,525	10,345	0	211,998	45,465
fuel consumption (in GBTU)	9,483	13,927	0	125,334	45,481
max capacity heat (in MMBTU/h)	2,375	2,384	46	16,700	44,038
age	24.6	17.9	0	75	48,022
Years	1980-2009				

Table 2 shows summary statistics at the plant level. Plants have between one and 24 boilers. The average number of boilers is 2.82. In 2000, coal plants accounted for 80% of the total electricity generation, gas plants account for 15% and the rest corresponds to oil plants or others. The investment in gas plants increased the first years of the decade. In 2005, gas already accounted for 19% of the total production.[9] Gas units are on average smaller, explaining the decrease in mean capacity and output in the last few years.

Table 3 shows summary statistics per year at the boiler level. I define the

[9]Gas is a more expensive fuel compared to coal but it is cleaner.

Table 2: Summary statistics (Plant level)

Variable	Mean	Std. Dev.	Min.	Max.	N
Number of Boilers	2.82	1.83	1	16	16,912
Age	26.54	17.96	0	75	16,912
Capacity	6185	6952	0	50,100	16,912
Coal Plants					6,745
Gas Plants					8,708
Oil Plants					1,193
Others					53

emission rate as the total emission of a unit over its heat input (fuel consumption). Since the start of the program the emission rate is lower; plants are getting, on average, cleaner. Mean age is decreasing because the entry rate is higher than the exit rate (table 4), the market is expanding. New units are on average smaller, explaining the lower average capacity and output level. Since new boilers do not get free permits, the mean number of allocated allowances is lower in the last years.

Table 4 shows summary statistics of exit and entry of boilers by year. I separate those boilers of an incumbent plant which exits (the plant stays in business), and the boilers that exit because the plant itself is exiting. Same with entry, I separate new boilers of incumbent plants or new plants. This distinction is important for the model, in particular for the exit. Exit is higher during in the years after the cap-and-trade program was implemented. The new regulation increased the marginal costs of production because units started to pay for permits. The least productive and dirtier units could no longer afford to comply with the regulation and had to exit.

Figure 2 shows the relationship between the average emission rate and the age. The average emission rate is increasing with age. This could be due to an age effect (boilers get dirtier when time goes by because of depreciation) or a vintage effect (newer boilers have a cleaner technology so they emit, on average, less). The time

Table 3: Summary statistics by year (Boiler level)

Year	**Total Obs**	**Capacity MMBtu/h**	**Age**	**Emission rate SO_2/MMBtu**	**Allocation**	**Output GWh**
1980	1839	2,395	19.38	.00088	0	—
1985	1841	2,687	22.41	.00078	0	—
1990	1762	2,895	26.37	.00072	0	—
1995	2069	2,813	29.30	.00067	3,987	—
1996	1969	2,782	29.39	.00051	4,032	—
1997	1973	2,767	29.94	.00049	3,458	1,266,229
1998	1994	2,748	30.66	.00048	3,383	1,303,145
1999	2074	2,680	30.60	.00045	3,235	1,272,617
2000	2304	2,531	28.62	.00036	4,152	1,178,351
2001	2737	2,319	25.02	.00031	3,332	993,994
2002	3127	2,193	22.73	.00025	2,904	871,901
2003	3377	2,158	21.86	.00024	2,677	836,075
2004	3422	2,161	21.84	.00023	2,622	851,514
2005	3460	2,158	21.98	.00021	2,588	884,171
2006	3464	2,157	22.41	.00019	2,630	862,223
2007	3488	2,151	22.91	.00017	2,611	882,825
2008	3548	2,165	23.19	.00016	2,566	846,295
2009	3409	—	23.52	.00016	2,666	—

Table 4: Boilers: Exit and Entry

Year	Total		Incumbent Plant		Exiting Plant	New Plant
	exit	entry	exit	entry	exit	entry
1980	91	60	57	60	34	0
1985	104	93	77	44	27	49
1990	9	22	8	12	1	10
1995	175	203	97	70	78	133
1996	29	39	24	20	5	19
1997	12	19	1	3	11	16
1998	11	20	6	4	5	16
1999	8	73	3	18	5	55
2000	1	227	1	49	0	178
2001	11	434	11	86	0	348
2002	15	401	11	78	4	323
2003	52	265	30	60	22	205
2004	47	95	27	28	20	67
2005	52	84	15	27	37	57
2006	28	61	15	27	13	34
2007	30	50	7	17	23	33
2008	139	89	67	48	72	41
2009	24	11	15	9	9	2

series variation within a boiler is much lower than the between variation across boilers, so the positive relation showed in the graph is more likely to be due to a vintage effect. I observe a decrease in the emission rate for ages above 58. Most of the units exit before that age. There are very few observations beyond this age (around 10 coal plants and five gas plants older than 58 years old).

Figure 2: Average emissions and age

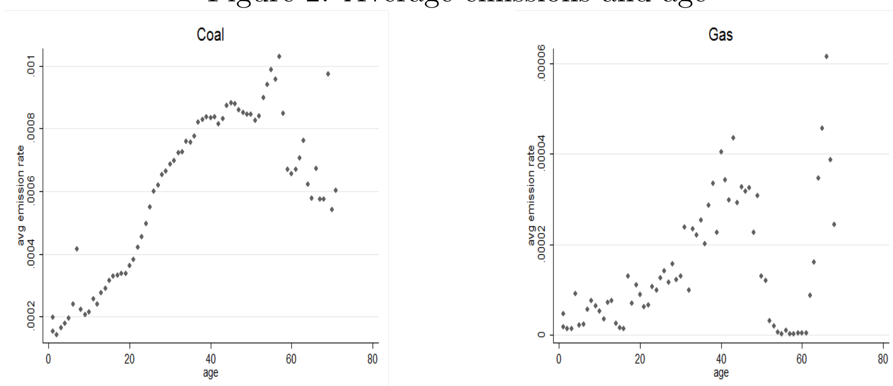


Table 5 shows the pairwise correlation between the main variables. The emission rate is positively correlated with output and fuel consumption. Output and fuel consumption are very highly correlated (fuel is the main input for electricity production). Older and bigger plants are dirtier. Due to the rule for allocation, permits allocated are highly correlated with fuel consumption and emission rate.

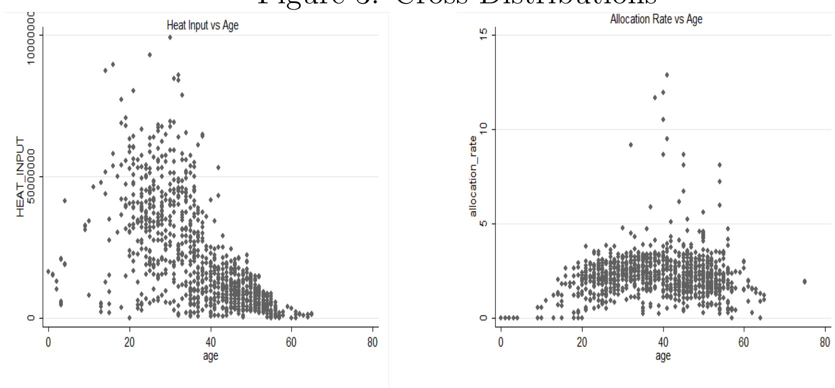
Table 5: Cross-correlation table

Variables	emission rate	age	output	fuel consumption	capacity	permits allocated
emission rate	1.000					
age	0.5089	1.000				
output	0.245	0.1353	1.000			
fuel consumption	0.2408	0.1412	0.9801	1.000		
capacity	0.1531	0.1047	0.8539	0.8705	1.000	
permits allocated	0.3433	0.1954	0.6675	0.6751	0.6186	1.000

The correlations with the variable permits allocated are with data after 2000, when the program was fully implemented.

Figure 3 shows the scatter plots for some of the main variable pairs. The first panel shows allocation rate versus age. Older plants get all the permits while new ones do not get any. The second panel shows heat input vs. age, as the unit gets older, the usage decreases until finally they exit.

Figure 3: Cross Distributions



4 Estimation

In this section, I solve and calibrate the structural model before the new environmental regulation was implemented. I use data from the power plants which participated in the US SO_2 market for the years 1980, 1985 and 1990. The implicit assumption of doing this is that the economy was in a steady state. I recover the cost parameters and then I add the cap-and-trade system to study the new steady state.

I assume the following functional forms:

- Demand $\Rightarrow P(Q) = A \times Q^{\gamma}$
- Production $\Rightarrow y = z \times f^{\theta}$
- Emission rate $\Rightarrow e = V \times (1 - \rho^{a})$ for l, h

- Probability of failing $\Rightarrow (1 - \delta^a)$

Several papers estimate the elasticity of demand for electricity (Paul, Myers and Palmer (2009), Bernestein and Griffin (2005)). I assume the previous functional form for the demand function so I can use those estimates from previous literatures for γ. I use the estimate of Paul, Myers and Palmer (2009) of -0.36. This estimate is consistent with previous literature and corresponds to the national, annual average long-run price elasticity across all customers classes. I calibrate the parameter A such that the output market clears when the exit rate is equal to the entry rate.

I assume a Cobb-Douglas functional form for the production function. I estimate θ using a Simulated Method of Moments (SMM) estimation that I explain below.

The emission rate function is such that emissions increase when the boiler ages. I estimate its parameters using reduced form estimation and define the high-emission type as coal plants and the low-emission type for gas. I estimate V and ρ with a non-linear least squares (NLS) regression, controlling for capacity and for scrubber. Table 8 shows the results of the regression.

The functional form for the probability of failing depends positively on the age. A higher value of δ implies that the older the boiler, the higher the probability it fails and becomes obsolete. I estimate δ by SMM.

For the size, I divide the data in five bins depending on the fuel consumption. For each size, there is an optimal amount of fuel consumption (f^*) that is the result of the profit maximization. I assume that the fuel consumption that I observe in the data is the optimal. That is, plants are maximizing profits. From the first order conditions, I have the information on f^* and prices, so I solve for z. Table 6 shows the distribution.

To compute the transition matrix (the probability to go from a state to another),

Table 6: Fuel Consumption

million MMBTU	Share	Productivity (z)	State
0 - 15	75.57	550,542	1
15 - 30	13.12	1,361,544	2
30 - 45	6.63	2,074,332	3
45 - 60	2.63	2,737,260	4
> 60	2.06	3,055,714	5

I calculate from the data the likelihood to go from a state to another. Table 7 shows the transition matrix. Each row is the probability of going to state j given that the plant is on state i. The Markov process is persistent. It is more likely to stay in the same state than to move to a different one. For example, if a plant is in state 1 it is more likely to stay there (probability of staying is 0.953). The probability of moving to state 2 is 0.042 and the farther away the state, the lower the probability of moving there. The persistency of the process and the fixed cost of producing are key elements to allow for exit. The last raw is the invariant distribution, and I use it for the productivity distribution of the new entrants.

Table 7: Transition Matrix

	1	2	3	4	5
1	0.953	0.042	0.003	0.001	0
2	0.247	0.590	0.154	0.007	0.002
3	0.016	0.234	0.633	0.117	0
4	0	0.015	0.338	0.554	0.092
5	0	0	0.077	0.308	0.615
invariant distribution	0.723	0.131	0.098	0.038	0.01

I set the maximum lifetime of a boiler to 75 years (I do not observe in the data boilers older than that). That means that $\delta(T) = 1$. The period of time of the data is yearly, so I set the discount factor β to 0.95. I set the scrap value ϕ equal

to zero. I assume that old boilers are obsolete and they cannot be used for other purposes.

I obtain fuel prices p_f from Form-423 from the EIA. This form has information about the quantity and cost of fuel each plant purchased. I use a quantity weighted average for the years 1980 to 1990. I set the price of output to 4.69 to match the average price of electricity to the average price of the period 1980-1990.[10] I set the cost of entry c_e such that it satisfies the entry condition with price of output equal to 4.69.

Table 8 summarizes the values that I use for the estimation.

Table 8: Calibration

		Value	**Source**
T	lifetime of a boiler	75	data
β	discount factor	.95	previous literature
c_e	cost of entry	713,782,668	set it st value of entry equals zero
ϕ	scrap value	0	
p^f	price of fuel	3.34 (dls/MMbtu)	average 1980-90 (EIA-423)
p	price of output	4.69 (dls/mwh)	average 1980-90
A	demand function	41,980,924	set it st output mkt in equ with entry rate from data
γ	demand elasticity	-0.36	Paul, Myers and Palmer (2009)
V_l	emission function	.0000328	reduced form estimation
		(6.41e-06)	
ρ_l	emission function	.9654	reduce form estimation
		(.113251)	
V_h	emission function	.001001	reduced form estimation
		(.0000172)	
ρ_h	emission function	.9552691	reduce form estimation
		(.0023464)	

The remaining parameters are δ (prob failing), FC (Fixed Cost) and d (Investment Cost) and θ. I estimate them using SMM. In this procedure, for a set

[10]There is no information for wholesale prices prior to 1995 so I use prices for industrial consumers. They take the electricity at higher voltages; it does not need to be stepped down. These factors make the price of power for industrial customers closer to the wholesale price of electricity.

of parameters to be estimated, one obtains a set of moments from the model, compares them to the equivalent moments from the data, and then chooses the parameters such that the difference between the simulated model and data moments is as low as possible. Formally, let M_D be a vector of data moments. Let $M(u,\Theta)_S$ be a vector of simulated moments that depends on the set of parameters Θ and the shock u. For a given Θ and a draw of the shock the industry equilibrium is solved. This is done S times. So, $M(u,\Theta)_S = \frac{1}{S}\sum_{s=1}^{S} M(\Theta)_S$.

The simulated method of moments minimizes the distance between the simulated moments and the moments from data such that:

$$\widehat{\Theta}_S(W) = min_{\Theta}[M_D - M(\Theta)_S]' W [M_D - M(\Theta)_S]$$

where W is the weighting matrix.

Table 9 shows the moments that I use for the estimation. I use the identity matrix for the weighting matrix. With respect to identification, with the average age of plants that exit I identify the FC, and with the average age of plants that replace boilers, I identify the cost of investment. I identify the parameter θ with the average size of plants. Finally, I use the share of young, middle and old plants to identify the probability of failing. Having a higher share of older plants implies that the probability of surviving is higher.

Table 9: Data Moments

Average Age of plants that exit	38
Average Age of plants that replace boilers	38.5
Average Size (MMBtu)	10,063,600
Share of young plants (1-25)	.568
Share of middle age plants (26-50)	0.424
Share of old plants (>50)	.008

Table 10 shows the results from the estimation. The cost parameters parameters are in terms of the yearly production of a plant of a middle level productivity

($z = 3$). That means, a plant with productivity $z = 3$ has to pay around 26% of its yearly production in fixed costs. The cost of investment is the production of a year, while the cost of entry of a new plant represents about 4.7% times the production of a year. Lower productivity plants find more difficult to pay the fixed cost and will be more likely to exit.

Table 10: Results

d (investment cost)	1.1
FC	.26
δ	0.999
θ	0.1461
c^e	4.7

To check how well the model performed in Table 11, I compare the data with the model moments that I matched and in Table 12, I compare the unmatched moments.

Table 11: Model Fit (matched moments)

Moment	**Data**	**Model**
Price of Output	4.69	4.69
Average Age of plants that exit	38	50.5
Average Age of plants that replace boilers	38.5	44.7
Average Size (MMBtu)	10,063,600	15,049,700
Share of young plants (1-25)	.568	.636
Share of middle age plants (26-50)	0.424	.358
Share of old plants (>50)	.008	.006

The model does well matching moments, in particular the age distribution. In terms of the size distribution my model predicts a lower share of low productivity plants and therefore a higher average size. In terms of the exit rate and investment rate, my model predicts that the exit rate is higher than the investment rate, while

Table 12: Unmatched Moments

Moment	**Data**	**Model**
Exit Rate (%)	0.38	0.73
Investment Rate (%)	0.88	0.18
Average Age	21.95	21.13
Share 1	.752	0.709
Share 2	.156	0.135
Share 3	.067	0.104
Share 4	.021	0.041
Share 5	.004	0.011

the data shows the opposite. One reason for that could be that my model does not incorporate productive investment. In some way, exit and investment are substitutes in the model.

In the next section, I use the estimates of the model to add the environmental regulation and do experiments regarding the permit allocation rule for closing plants and new entrants.

5 Results

5.1 Introduction of the Regulation

In this section, I introduce the environmental regulation: a cap-and-trade program. The steps to add the regulation are as follows. First, I compute the total amount of emissions when they could freely emit before the regulation. I assume the government sets an upper bound of emissions, which is 56.4% of the previous emissions.[11] Second, to the static problem of the plant, I add a new marginal

[11]In the Acid Rain Program emissions were reduced from around 16 million in the eighties to 8.9 million in 2010.

cost, paying for pollution permits, that depends on the emission function of the plant. Also, I add a new equilibrium condition (total demand of permits has to be equal to the cap). I give the same quantity of permits to the plants, regardless of its productivity or age. Third, I start solving the new model assuming in the first iteration a price of permits of zero. With this price of permits, total demand of permits (which will be equal to the unregulated emissions) will be higher than the cap (which was set to 54.6% the total unregulated emissions). The price of permits will increase until the total demand of permits and the cap are equal. This implies a new steady state equilibrium with new prices, new decision rules and a new distribution.

Table 13 shows the results of the introduction of the cap-and-trade program. The regulation increases marginal costs. Whereas before, plants could emit freely, now they must back up each unit of pollution with a permit. Pollution permits become valuable. In the new equilibrium the price of permits is $189. The increase in the marginal cost means that the value of entry is lower (at the old output price, plants have lower profits). The price of output increases until the value of entry is zero again. Therefore, the first effect of the environmental regulation is an increase in the output price and a decrease in the output level. The output decreases by 2%. The demand for output is inelastic. This number would be much higher for a market where demand is more elastic. Total emissions are lower and the plant distribution changes. The average emission rate goes from 0.0055 to 0.0025. The exit rate increases. The dirtiest and most unproductive plants have to leave the industry; they cannot comply with the regulation and remain profitable. Also, plants invest and leave the industry earlier (average age of exit and investment is lower). So, the resulting distribution is composed of more productive, cleaner and younger plants.

Table 13: Introduction of C&T

	Before Regulation	US SO_2	△%
Total Emissions	100	54.6	-45.4
Price of Permits	0	131	–
Price of Output	4.69	4.93	5.3
Total Output	100	98.2	-2
Average Emission Rate (ems/input)	.0044	0.0025	-43
Average Age	21.13	15.33	-27
Exit Rate (%)	0.73	2.7	274
Investment Rate (%)	0.19	0.15	-15
Average age exit	44.7	22.2	-56
Average age investment	50.5	40.2	-10
Average productivity	934,783	982,174	5

5.2 Counterfactual

Table 14 show the new equilibrium if the US were to implement the EU-ETS allocation scheme, where plants lose permits when they exit or scrap their old units and new entrants get permits. As in this case new entrants get permits, the value of entry is higher.[12] In equilibrium, that means a lower price of output. Total output is higher. This result is consistent with Ellerman (2008), who finds that permits to new entrants create over-capacity. Note that in the US SO_2 case, the price of output increases for two reasons: the marginal cost increases and the value of entry decreases. In the EU-ETS, the marginal cost increases as well.

Due to the exit and investment distortion, plants have incentives to stay longer in the industry. The average age of exit and investment are 1.4% and 4.9% higher, respectively. Exit rate is 7% lower and investment is 3.3 lower. The average emission rate is 3.4% higher. The resulting distribution has older and less productive

[12]This would decrease the fixed costs of entry. Ellerman (2008) uses an example of a Danish

plants than with the US SO_2.

Table 14: US vs EU

	US SO_2	EU-ETS	$\triangle$%
Total Emissions	54.6	54.6	–
Price of Permits	131	140.8	7.6
Price of Output	4.94	4.86	-1.5
Total Output	98.2	98.7	0.5
Average Emission Rate (ems/input)	0.0025	.0026	3.4
Average Age	15.3	15.9	3.6

Figure 4: Size Distribution before and after regulation

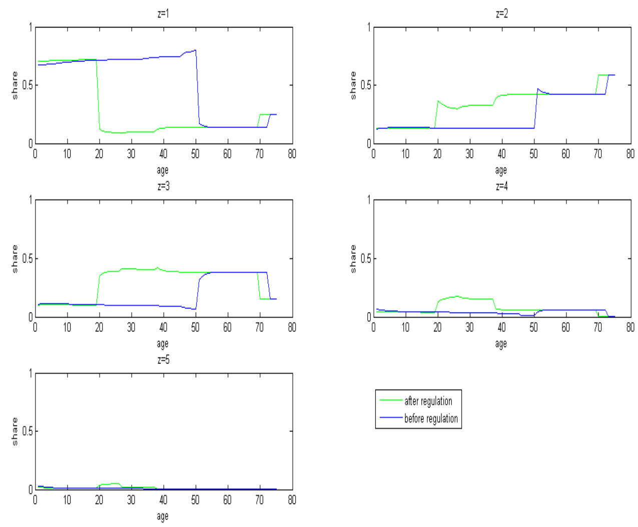
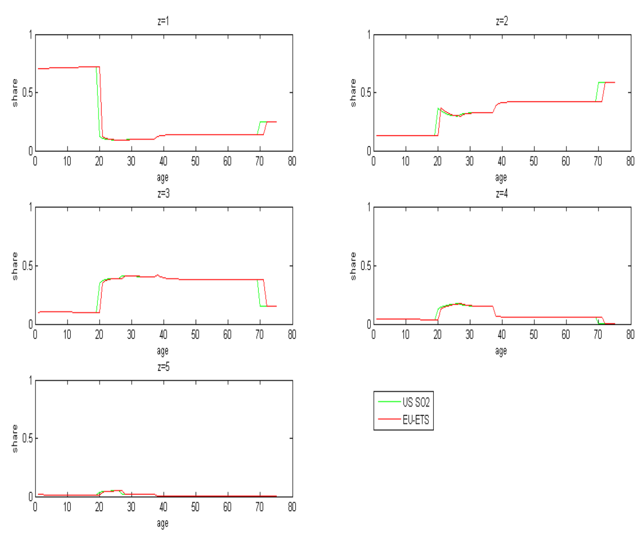
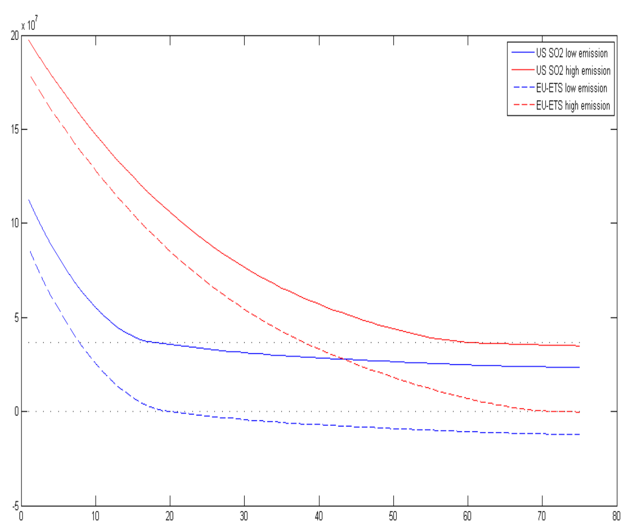


Figure 5: Size Distribution for US SO_2 and EU-ETS



type while the red ones correspond to the high type, for both the US SO_2 and the EU-ETS case. In the EU-ETS case, the scrap value is zero represented by the horizontal black dotted line in zero. In the US SO_2 the scrap value is the stream of permits forever, which is represented by the horizontal black dotted line with positive value. The graph shows that dirty plants will exit earlier regardless of the permits. There is only a year of difference between the two systems. Free permits are more important for the cleaner technology, the difference is nine years. The high emission type has higher marginal costs than the low type. Fixed costs and the free permits are lower relatively to the marginal cost of paying for emissions. So, when making the exit decision, the marginal costs of paying for permits are more important. The low emission type faces a lower marginal cost of paying for emissions and the free permits are relatively more important.

Figure 6: Value Function by Emission Technology (z=1)



In the case of investment, the decision is delayed up to two years depending on the emission type and the productivity level. The difference between the two technologies is not as pronounced as with exit. However, for higher productivity

bins, plants in the US SO_2 case invest a year earlier than with the EU-ETS for the high emission type and up to two years for the low emission type.

Table 15: Effects of Permits on Decision Rules: US vs EU

	High Emission		Low Emission	
	US SO_2	EU-ETS	US SO_2	EU-ETS
$z = 1$	I=never	I=never	I=never	I=never
	$x \geq 19$	$x \geq 20$	$x \geq 62$	$x \geq 73$
$z = 2$	$I \geq 75$	$I \geq 75$	$I \geq 75$	$I \geq 75$
	x=never	x=never	x=never	x=never
$z = 3$	$I \geq 69$	$I \geq 71$	$I \geq 74$	$I \geq 75$
	x=never	x=never	x=never	x=never
$z = 4$	$I \geq 37$	$I \geq 37$	$I \geq 43$	$I \geq 45$
	x=never	x=never	x=never	x=never
$z = 5$	$I \geq 26$	$I \geq 27$	$I \geq 32$	$I \geq 33$
	x=never	x=never	x=never	x=never

Corresponds to plants with permits

5.3 Distributive Analysis

The welfare definition I use has two components: consumer surplus and producer surplus. I do not take into account the change in welfare due to the emission reduction. In particular, I use the following definition:

$$welfare = \int_0^Q D(q)dq + \int \pi^*(z_t, a_t, \omega)d\mu(z_t, a_t, \omega)$$

Table 16 shows the change in welfare caused by the introduction of the regulation. The higher price implies a lower consumer surplus. Producer surplus increases. The increase in the price of output offsets the increase in the marginal costs, so on aggregate in the new equilibrium producers are better off. They are also compensated with the free permits. The total value of permit is $1,826,236$, however not all the permits belong to incumbents plants. On balance, after adding

the consumer and producer surpluses changes, total welfare increases by $312,472$.

Table 16: Welfare

	US SO_2
△consumer surplus	-5,904,164
△ producer surplus	4,390,400
Value permits	1,826,236
△ welfare w/o permits	-1,513,763
△ welfare w/permits	312,472

Table 17 shows the welfare implications of switching to the EU-ETS allocation scheme. In this case, consumers are better off because the price of output is not as high and the other case. Producers are worse off because the price of output is lower, and the price of permits is higher. Total welfare is higher. This result is important for policy evaluation. If the US were to give permits to new entrants and take them away from closing plants, then the cap-and-trade regulation would have a lower impact on the price of output. Consumers are better off and producers are worse off. Total welfare is higher but at the cost of having a steady state equilibrium with a higher emission rate and a distribution of dirtier and less productive plants. One relevant point is why total welfare is higher with the EU-ETS system, which is the one having distortion. Giving permits to new entrants is as lowering the fixed cost of entry. If we interpret the fixed cost of entry as a distortion (because it makes less firms to enter), then the system in the EU-ETS lowers that distortion. That is the reason why welfare is higher with the EU-ETS system even after distorting the entry and exit decision. It is important to keep in mind that these results hold for the model calibrated with US parameters.

Table 17: Welfare

	US SO_2	EU-ETS	Change (%)
△consumer surplus	-5,904,164	-4, 166,532	-29
△ producer surplus	4,390,400	3,365,863	-23
Value permits	1,826,236	1,965,106	7.6
△ welfare w/o permits	-1,513,763	-800,668	-47
△ welfare w/permits	312,472	1,164,437	272

6 Conclusion

In this paper, I quantify the effects on exit, entry, investment and welfare of different ways of allocating permits to closing plants and new entrants. I adapt a standard dynamic model to the electricity sector, add an investment choice and a pollution market regulated with a cap-and-trade program. I consider two systems: the US SO_2 case, where closing plants keep the free permits every period and new entrants do not get any for free; and the EU-ETS case, where plants that exit or replace boilers lose the free permits and new entrants get free allowances.

I calibrate the model with data from power plants participating in the US SO_2 program. Then, I introduce a cap-and-trade program, lowering emissions by almost half, and quantify the variables in the new equilibrium. I find that the price of output increases; exit rate increases and plants invest and exit at an earlier age. The new distribution has cleaner and more productive plants. I do a counterfactual experiment to quantify the difference in the equilibrium variables and welfare implications of the EU-ETS allocation. In this case, consumer surplus is higher because the equilibrium price of output is lower. However, the plants are on average dirtier and less productive.

My paper has some limitations. First, I work with a competitive environment and assume no regulation to power plants or utilities. I work with aggregate data and do not consider the differences and characteristics between different states.

I assume each power plant has a single boiler. This may be important for the EU-ETS allocation scheme. Plants lose permits when they scrap their boilers. I am not taking into account a scenario whereupon one of the units has permits and the plant considers getting another one to produce, while keeping the permits pertaining to the older one. This behavior may be another important source of distortions that I do not consider in this paper.

7 Appendix

Computational Algorithm

The algorithm to solve the model is the following:

- Given price of output and price of permits, solve for the decision rules through Value Function Iteration (see explanation below).
- Compute entry condition.
- Adjust price of output until entry condition is satisfied.
- Compute the invariant distribution and calculate aggregate demand and aggregate supply.
- Adjust the entry rate until the output market clears.
- Compute demand of permits, if demand of permits is different from the supply, adjust price of permits and restart.
- Do this until the demand equals the supply of permits.

The entry condition pins down the output price, and the output market equilibrium pins down the entry rate. Given the prices, the distribution and the entry conditions, I can compute the demand of permits. The supply of permits is fixed. The price of permits adjusts such that the permit markets clears.

Value Function Iteration

I solve for the decision rules using value function iteration (VFI). First, I assume functional forms and discretize the state space, as explained in the paper. For each state s, let $V(s)$ be the corresponding value function. I start with an initial guess, say $V_0(s)$ for every s. The value $V_1(s)$ is equal to the maximum of the profits for that period plus the discounted $EV_0(s)$. Using $V_1(s)$ I compute $V_2(s)$ and so

on. I iterate N times until $V_N(s)$ and $V_{N-1}(s)$ are close enough, for every s. In particular, I use $\mid V_N(s) - V_{N-1}(s) \mid < .005$, for every s, as the convergence criteria.

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