Pollution permits, Strategic Trading and Dynamic Technology Adoption

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Aim of the paper

This work takes a game–theoretical approach for modeling the generation of allowance prices and its impact on the incentive to adopt new technology under a transferable permits system.

The contribution of the paper is threefold:

1. To investigate the **strategic trading behavior** of market participants that underpins the allowance price formation.
2. To study the **incentive to adopt** low pollution–emitting technologies in a **dynamic** setup.
3. To propose and implement a criterion for the selection of a **self–financing** (cost-neutral) policy that restores the dynamic incentives to invest in low pollution–emitting technologies.

The players

- A group of (risk averse) firms ($\mathbb{I} = 1, ..., m$), which operate in a pollution–constrained economy under a transferable permits system.
  - Firms are **not** price takers on the permit market.
  - Firms can **adopt** low pollution–emitting production **technologies** and **exchange permits**.
  - Firms are characterized by their **pollution emission profiles** before and after adoption of new technologies, as well as by the **costs** of such **investments**.

- A regulator whose intention is to control pollution and promote the adoption of low pollution–emitting technologies by implementing a credible policy.
  - The regulator chooses a **credible** emission reduction **target**, the overall **length** of the commitment **period** and the **enforcement structure**.
  - The regulator does **not anticipate** the adoption of new technologies.

The structure of the policy

- The regulated **phase** consists of T **periods** (we write $[0, T]$ for the former and $[t, t+1]$ for each of the latter).
- The regulator issues each firm i a **number** $N^i(t)$ of emission permits at the beginning of each period.

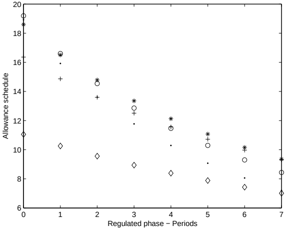


Figure: We assume the stream of permits is decreasing and corresponds to the parametric family $N^i(t; \alpha, \beta) = \beta(t+1)^{-\alpha}$. Example of allocation path to 5 regulated firms for 8 periods.

- For each unit of pollutant not offset by a permit, firm i must pay a **penalty**, P.

Firms characterization: pollution emissions

- We denote the cumulative emissions of firm i up to time t by $Q(t)$, which is modeled by

$$Q^i_h(t+1) = \begin{cases} u^i_h(t) \cdot Q^i(t), & \text{with probability } q(t). \\ d^i_h(t) \cdot Q^i(t), & \text{with probability } 1 - q(t), \end{cases}$$

  Here $h \in \{o, n\}$ denotes whether or not the firm is operating under the **old** or **new** technology, $u^i_h(t) > d^i_h(t) > 1$, and $u^i_o(t) > u^i_n(t)$ and $d^i_o(t) > d^i_n(t)$ (more below).

- The firms' emissions are subject to **economic shocks** and their current **technology status**.

- Demand for a firm's products is contingent on phenomena that are beyond its grasp (a widespread crisis, for example). Therefore, $u^i_h(t)$ and $d^i_h(t)$ -state of the economy- are **exogenous**.

Adoption of new technology

Each firm has the alternative to adopt low pollution–emissions technology. In particular, we assume:

- Decisions to adopt technology over the period $[t, t+1]$ are made at time t, and they come into effect **instantaneously**.
- The investment in the new technology occurs only once during the phase, and it is **non–reversible**.
- Firm i must **spend** C^i if it wishes to change its pollution emission profile.

Graphical representation of firms' emissions

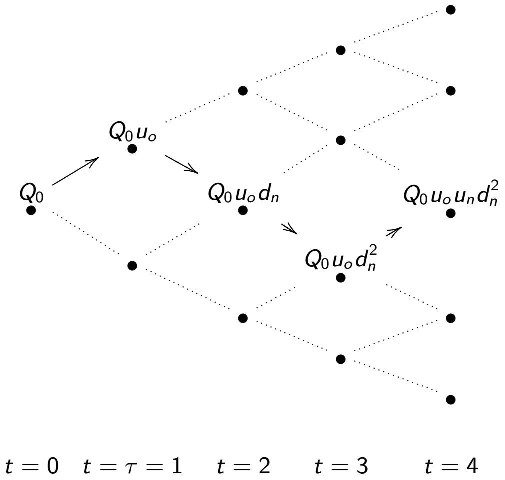


Figure: A possible evolution of a firm's cumulative emissions in a four–period long phase, where the firm adopts the new technology at time $t = 1$.

Realized vs. expected net pollution emissions

- $\Delta Q^i_h(t+1)$ denotes the pollution emissions over $[t, t+1]$.
- The realization of the $\Delta Q^i_h(t+1) - N^i(t)$'s determine the firms' positions in the permits market.
- Firms' expectations $x_i(t+1,h) := \mathbb{E}[\Delta Q^i(t+1,h) - N^i(t)]$ are used to make decisions regarding investments in the new technology, given technology status h.
- Let $s(t+1,h)$ and $d(t+1,h)$ be the supply and demand sides of the market (in terms of the firms expected positions), respectively.
- Then,

$$\mathcal{S}(t{+}1,h) := -\sum_{i\in s} x^i(t{+}1,h) \quad \text{and} \quad \mathcal{D}(t{+}1,h) := \sum_{i\in d} x^i(t{+}1,h)$$

represents the (expected) number of unused permits, i.e. the aggregate supply, and the (expected) number of nonoffset emissions, i.e. the aggregate demand.

Generation of allowance prices

- Prices are generated by "supply–and–demand". We define

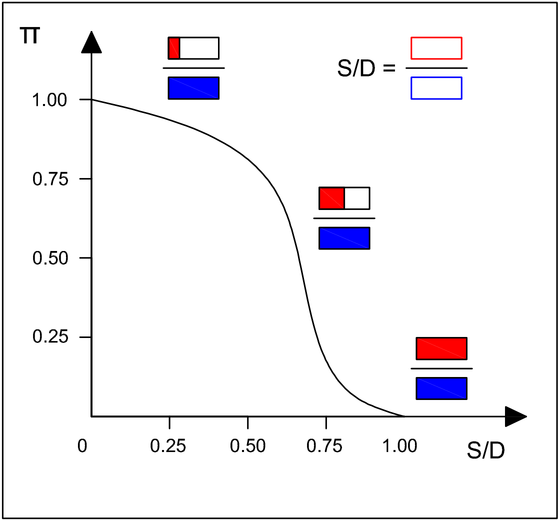
$$\mathcal{R}(t+1,h) := -\frac{\mathcal{S}(t+1,h)}{\mathcal{D}(t+1,h)},$$

the supply-demand ratio and, consistent with Seifert et al. [2008] and Chesney and Taschini [2009]

$$\Pi(t+1,h) := P \cdot \eta_{\mathcal{R}(t+1,h)}\Big(-\frac{\mathcal{S}(t+1,h)}{\mathcal{D}(t+1,h)}\Big)$$

where P is the penalty level and $\eta_{\mathcal{R}}$ is a non-linear function.

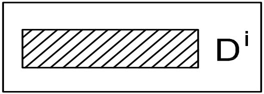
Graphical representation of allowance prices



Aggregate demand and supply

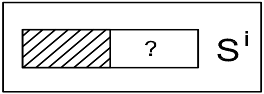
Aggregate demand

Firms in shortage of permits face severe penalties if they fail to deliver an amount of allowances equal to their emissions. So it is in the buyers' (d) best interest to offset all their emissions at **any price** lower than the penalty level P.



Aggregate supply

On the other hand, the lower the aggregate supply, $\mathcal{S}$, the higher the exchange value, Π. Therefore, it may very well be in the sellers' best interest to **reduce** the availability of permits and **increase** the allowance exchange value. In fact, there is a **trade–off** between offering a higher number of cheap permits, or less of them, but at a higher value.



Theorem: Non–cooperative game

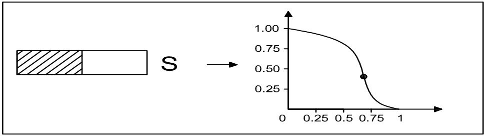
Let $-i$ represent all firms except i, and let firm i's payoff be

$$\Psi^i(x^i, x^{-i}) = x^i P \cdot \eta_{\mathcal{R}}\Big(-\frac{S^{-i}+x^i}{\mathcal{D}}\Big),$$

We construct an $m_s := \#s(t+1,h)$ (non–cooperative) game and show it possesses a **unique** pure–strategy Nash Equilibrium. Studying firms' **best responses** $({}^*x^i, {}^*x^{-i})$ we show that the *expected equilibrium exchange value* of an allowance, contingent on h is

$${}^*\Pi(t+1,h) = P \cdot \eta_{\mathcal{R}(t+1,h)}\Big(-\frac{{}^*\mathcal{S}(t+1,h)}{\mathcal{D}(t+1,h)}\Big)$$

where ${}^*\mathcal{S}(t+1,h) = \sum_{i\in m_s} {}^*x^i(t+1,h)$.



Firms' investment decision

- The **incentive** to adopt the new technology depends on the firm's **potential profits** and **avoided penalty costs**.
- To quantify this amount, each firm computes its corresponding expected payoff for the remainder of the regulated phase, which shall be denoted by $[t, T]$, over all **possible technology scenarios**.
- A family of firm–specific and concave utility functions, Υ^i, is used to assess if the adoption of new technology at time t is **economically viable or not**.
- In order to model all the possible scenarios over the $[t, T]$ period, we consider the matrices of dimension $\#\mathcal{O}(t) \times (T - t)$, where each row contains a single 1 and the rest of its entries are 0's. Here $\#\mathcal{O}(t)$ is the set of firms that have not invested.

Technology adoption matrix

$$\text{this firm adopts at time } t \longrightarrow \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 1 \end{pmatrix}$$

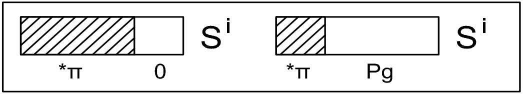
- We make the distinction between those matrices where firm i adopts the new technology at time t, $\mathcal{M}_n^i(t)$, and those where firm i has decided to wait, $\mathcal{M}_o^i(t)$.
- Each possible path matrix corresponds to a specific payoff.
- If $\Upsilon^i(t,n) \geq \Upsilon^i(t,o)$, where

$$\Upsilon^i(t,k) := \left(1/\#\mathcal{M}_k^i(t)\right) \sum_{j=1}^{\#\mathcal{M}_k^i(t)} U^i\left(\Psi_k^i(t)_j\right).$$

then firm i adopts the low–emitting technology at time t, otherwise it waits.

New policy: the contingent price support

- The **deterioration** of the economy or its **improvement** may provide incentives for the regulator to **adjust** the level of the policy, undermining its credibility.
- Following Laffont and Tirole [1996], we implement a price support instrument.
- We introduce a free–of–charge put–type option contract (EC4P) that is written on the final holdings of permits and **contingent** on the technology status.
- At maturity, the EC4P **guarantees** a per–permit amount, P_g.
- If firm i has adopted low pollution–emitting technology and it is in permits excess, then quantity x^i can be divided into ${}^e x^i$ and ${}^c x^i$.



[4] $\Psi^i\left({}^e x^i, {}^e x^{-i}\right) = P_g(x^i - {}^e x^i) + {}^e x^i P \cdot \eta_{\mathcal{R}}\left(-\frac{{}^e \mathcal{S}^{-i} + {}^e x^i}{\mathcal{D}}\right).$

Restore the incentive to adopt new technology

Proposition *Under identical primitives and identical triples* $\left(T, \{N^i(t)\}_{i\in\mathbb{I}}, P\right)$, *the following holds for all* $t \in [0, T]$:

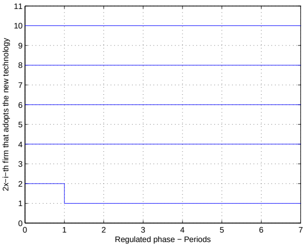
$$^4\Pi^*(t+1, h) \geq \Pi^*(t+1, h).$$

Remark By construction, if $i \in s(t+1, h)$, for any h we have that

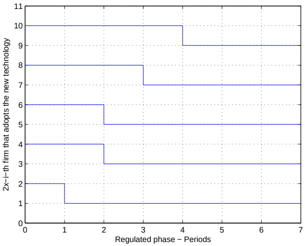
$$^4\phi^i(t+1, h) \geq \phi^i(t+1, h).$$

From previous Proposition, if $i \in d(t+1, h)$ then

$$^4\phi^i(t+1, h) \leq \phi^i(t+1, h).$$

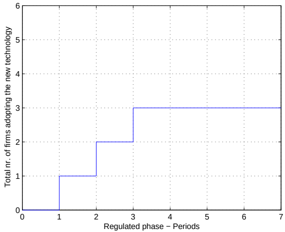


(a) Firm–wise technological adoption without EC4P

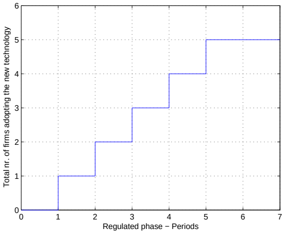


(b) Firm–wise technological adoption with EC4P

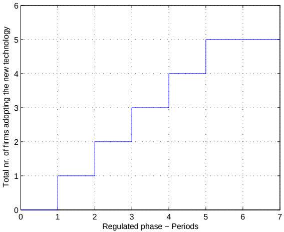
Controlling also the timing of the adoption



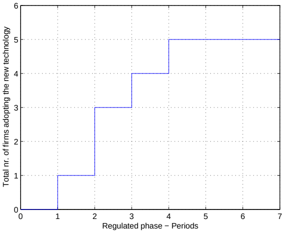
(c) Aggregate technology adoption for $P_g = 1.5$



(d) Aggregate technology adoption for $P_g = 2.5$



(e) Aggregate technology adoption for $P_g = 3.5$



(f) Aggregate technology adoption for $P_g = 4.5$

Risk assessment of the cost of the policy

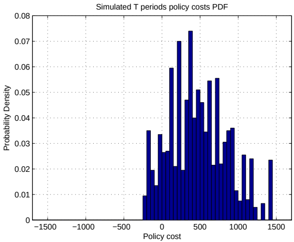
- Recalling that the penalty payments and EC4Ps generate potential cash incomes, X_I, and outcomes, X_O, we introduce the notion of *self–financing* policy.
- A policy is *self–financing* when tax-payers' funds are not required to cover the cost of its implementation. In our case, penalties cover the cost of payments of the EC4Ps.
- We propose a methodology to assess the **likelihood** that the collection of such payments, X_I, suffices to cover the chased EC4P, X_O.
- In particular, for fixed $\left\{T, \{N(t)\}\right\}$, the parameters P and P_g completely determine $(X_I - X_O)$,
- Such a methodology provides a **measure of the losses** the regulator might face when he chooses the penalty level P and the minimum price guarantee P_g for the EC4P.

Risk assessment of the cost of the policy

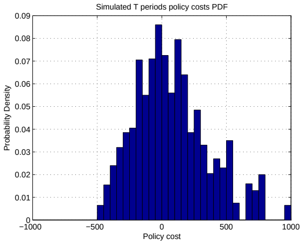
- So we assess **how risky** (how costly) this policy can be by comparing the effect of different levels of P and P_g on the distribution of $X_I - X_O$.
- This risk assessment is based on the previous examples and is evaluated by performing 2000 Monte Carlo simulations of pollution emissions to approximate the PDFs of $X_I - X_O$.

Remark Our main aim is to study the influence of the regulator's decisions on the **dynamic evolution** of the technological vector. On this same token, the introduction of a criterion to measure the likelihood of the policy being self–financing is not done in the spirit of minimizing social costs. It might be the case that a choice of primitives that yields very rapid technology adoption of all firms is too socially costly.

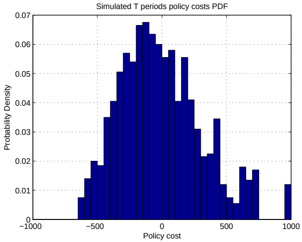
Numerical evaluation of the PDFs of $X_I - X_O$



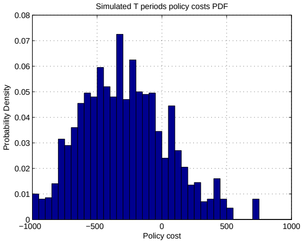
(a) PDF for $P_\sigma = 1.5$



(b) PDF for $P_\sigma = 2.5$



(c) PDF for $P_g = 3.5$



(d) PDF for $P_g = 4.5$

Figure: Probability density functions for different levels of P_g, $P = 10$.

References I

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