Pollution permits, Strategic Trading and Dynamic Technology Adoption

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Regulation through transferable emissions

- The main idea behind transferable emission permits is **to create a market** for pollution rights.
- A pollution right simply represents a permit that consists of a unit (pound, ton, etc.) of a specific pollutant.
- Transferable permits operates on the basis of the following postulates:
  1. It is possible to obtain a **legally sanctioned right** to pollute.
  2. These rights (permits) are **clearly defined**.
  3. The total number of permits and the initial distribution of the total permits among the various polluters are **assigned by government agencies**.
  4. Polluters emitting in excess of their allowances are subject to a **stiff monetary penalty**.
  5. Pollution permits are **freely transferable**. That is, they can be freely traded in the marketplace.

Adoption of low pollution–emitting technologies

- A key consideration when **choosing a policy** is the **incentives** it provides to regulated agents to **invest** in new technologies or **adopt** alternative, low pollution–emitting technologies;
- In most of the cases, the adoption of low pollution–emitting technologies **permanently** reduces future emissions.
- This has clear consequences on the **future needs of permits** and, more importantly, on the **future incentives** to adopt new technologies.
- Most of the current literature neglects the impact of **aggregate reductions** on the *allowances supply*.
- Including this in the analysis would showcase an **individual firm's incentives** to adopt low pollution–emitting technology.

Positioning in the existing literature

- Biglaiser et al. [1995] show that under a system of tradable permits, technology adoption is **distorted** because individual regulated companies may have a **significant effect** on the **aggregate supply** of permits.
- They, however, **assume** that companies are **price–takers**, and do not investigate the impact on the incentives for technology adoption of strategic exchanges of permits.
- As shown by Kennedy and Laplante [1999], **under imperfect competition** standard results might have to be revised.
- In this paper we determine the firms' optimal **compliance strategy** (permit trading and timing of the technology adoption) when companies are not price takers.

The paper in a nutshell

- This paper examines a pollution–constrained economy, where it is assumed that the **regulator** does **not anticipate** the adoption of new technology.
- The regulator sets an **optimal** and **credible** policy by committing to the **type** of policy instrument and its **level**, $\{N(t), P\}$, for a sufficiently long period of time, T.
- Regulated firms can determine their **compliance strategies** by choosing between investment in low pollution–emitting technologies and trading emission permits.
- The firms' emissions are **technology-specific** and are subject to **economic shocks**.
- The adoption of new technologies is assumed to **affect** only the amount of **pollution** emitted for given output or input, and does not otherwise affect production.

Approach and contributions of the paper

We use a game–theoretical approach to model the formation of permit prices and investigate how the policy levels affect 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* policy that **restores the dynamic incentives** to invest in low pollution–emitting technologies.

The subjects in the model

- 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 **stochastic emission profiles**, as well as by the costs of abatement **investments**.
- A regulator whose intention is to control pollution and promote the adoption of low pollution–emitting technologies.
  - The regulator identifies an **optimal** and **credible** emission reduction **target**, the overall **length** of the commitment **period** and the **enforcement structure**.
  - The regulator (cannot) 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).
- **At time t=0** the regulator issues each firm i a **number** $N^i(t)$ of emission permits for each future period $t \in [0, T-1]$.

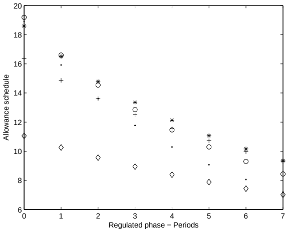


Figure: We assume the stream of permits is decreasing and corresponds to the parametric family $N^i(t;\alpha,\beta) = \beta(t+1)^{-\alpha}$. Example of allocation path to 5 regulated firms for 8 periods.

- There is a per unit **penalty**, P, for excess emissions.

Firms characterization: pollution emissions

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

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

  Here $h \in \{o, n\}$ denotes whether or not the firm is operating under the **old** or **new** technology, $u_h^i(t) > d_h^i(t) > 1$, and $u_o^i(t) > u_n^i(t)$ and $d_o^i(t) > d_n^i(t)$ (more below).

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

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

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**.
- Adoption of the new technology affects only the amount of pollution emitted for given output or input, and **does not** otherwise **affect production**.
- Firm i must **spend** C^i if it wishes to change its pollution emission profile.
- The future value of the investment is computed using an interest rate $r > 0$, which we assume remains **constant** throughout the phase.

Realized net pollution emissions

Emissions are **verified** at the end of each period. Compliance requires firms to **completely offset** their emissions either using allocated permits or purchasing permits on the exchange.

- $\Delta Q^i_{\varsigma,h}(t+1)$ denotes the pollution emissions over $[t, t+1]$ under the economy state ς and technology h for firm i-th.
- The realization of the $\Delta Q^i_{\varsigma,h}(t+1) - N^i(t)$'s determines the firms' positions in the permits market.
  - If $\Delta Q^i_{\varsigma,h}(t+1) - N^i(t) > 0$ than the firm *must* **purchase** permits in the market or **pay the penalty** P.
  - If $\Delta Q^i_{\varsigma,h}(t+1) - N^i(t) < 0$ than the firm *can* **offer** the permits in the exchange **for a profit**.
- Trading takes place at the end of each period.

Realized vs. expected net pollution emissions

- $\Delta Q^i_{\varsigma}(t+1) - N^i(t)$'s determines the **realized** firms' positions in the permits market.
- $x_i(t+1,h) := \mathbb{E}[\Delta Q^i(t+1,h) - N^i(t)]$ represents firms' **expected** emissions. These quantities 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,

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

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

The regulator's objective - cap emissions

Before proceeding with the analysis of the generation of prices and the technology adoption, we stress that the following policy levels have been optimally chosen at time $t = 0$:

1. The **allocation of allowances** $\{N^i(t)\}$, i.e. $\alpha_i(t), \beta_i(t)$;
2. The **penalty** level P.
3. The **length** of the phase T;

The regulator's aim is to spur technology adoption by **controlling emission** via emission permits. We observe how these policy levels interact with the **incentive** for technology adoption through time.

Generation of allowance prices

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

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

and, consistent with Seifert et al. [2008], Chesney and Taschini [2011], and Carmona et al. [2009] we define the permit price Π

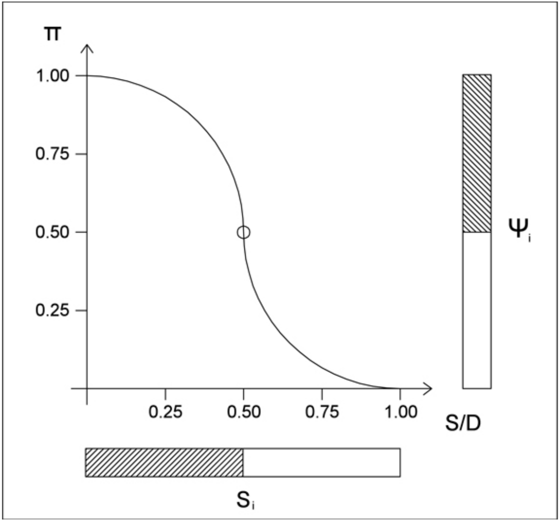
$$\Pi(t+1,h) := P \cdot \eta_{\mathcal{R}(t+1,h)}\Big(-\frac{\mathcal{S}(t+1,h)}{\mathcal{D}(t+1,h)}\Big)$$

where P is the penalty level and $\eta_{\mathcal{R}}$ is a (reaction) function $\eta_a : [0,a] \longrightarrow [0,1]$

$$\eta_a(x) := \begin{cases} \exp\left\{\frac{x^2}{x^2-a^2}\right\}, & \text{if } x \in [0,a), \\ 0, & \text{otherwise.} \end{cases}$$

- By construction $0 \leq \Pi(t+1,h) \leq P$.

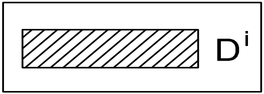
Graphical representation of allowance prices



Aggregate demand and supply

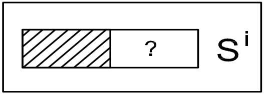
Aggregate demand

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.



Example: the first phase of the EU ETS

Figure: Spot price of the EU Allowance Unit from 2005 until 2008 on the European Climate Exchange (ECX).

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.
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 ${}^*\mathcal{S}(t+1, h) = \sum_{i \in m_s} {}^*x^i(t+1, h)$, and ${}^*x^i(t+1, h)$ are the best responses.

Firms' investment decision

- Technology adoption is determined **endogenously** and it depends on the **(uncertain) future supply** and **demand** of permits.
- The incentives for a firm in permit excess hinge on the firm's **potential profits**, i.e. on the ability to sell unused permits for a high price.
- The incentives for a firm in the need for permits depend on the firm's **potentially avoided penalty costs**, i.e. on its ability to reduce emissions by the use of new technologies.
- To quantify these amounts, each firm computes its corresponding expected payoff for the remainder of the regulated phase, which shall be denoted by $[t_0, T]$, 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**.

The technology matrix

- We define

$$\mathcal{O}(t_0) := \{ i \in \mathbb{I} \mid \mu^i(t_0 - 1) = \mu^i_o(t_0 - 1) \}.$$

  which represents the set of firms that have not changed technology up to time $t_0 - 1$;

- We consider the set $\mathcal{M}(t_0)$ of matrices of dimension $\#\mathcal{O}(t_0) x (T - t_0)$, where each row contains a single 1 and the rest of its entries are 0's.

$$\text{This firm adopts at time } t = t_0 \longrightarrow \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 1 \end{pmatrix}$$

Technology matrix and associated payoffs

- We distinguish between firms that adopt the new technology

$$\mathcal{M}_n^i(t_0) := \{M \in \mathcal{M}(t_0) \mid M(i,0) = 1\},$$

and firms that decide to wait at time t_0

$$\mathcal{M}_o^i(t_0) := \{M \in \mathcal{M}(t_0) \mid M(i,0) = 0\}.$$

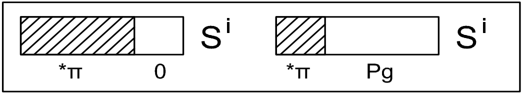
- For $k \in \{o, n\}$, we define the **payoffs vector** associated to $\mathcal{M}_k^i(t_0)$ as

$$\Upsilon^i(t_0, k) := \left(1/\#\mathcal{M}_k^i(t_0)\right) \sum_{j=1}^{\#\mathcal{M}_k^i(t_0)} U^i\left(\mathcal{V}_k^i(t_0)\right).$$

where $\mathcal{V}_k^i(t_0)$ represents the future profits under technology k. **If** $\Upsilon^i(t_0, n) \geq \Upsilon^i(t_0, o)$, then firm i **adopts** the low–emitting technology at time t_0, **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 introduce a **price support** instrument.
- We introduce a free–of–charge option contract (EC4P) that is written on the final holdings of permits and it is **contingent** on the technology status.
- At maturity, this contract **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* $t \in [0, T]$:

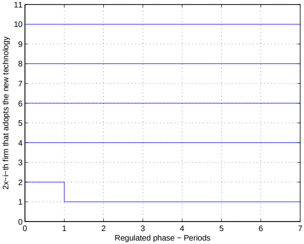
$$^4\Pi^*(t+1, h) \geq \Pi^*(t+1, h).$$

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

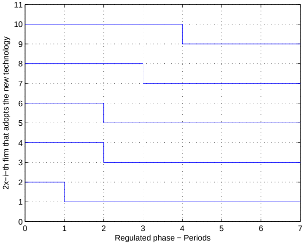
$$^4\phi^i(t+1, h) \geq \phi^i(t+1, h).$$

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

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

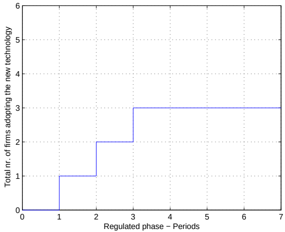


(a) Firm–wise technological adoption without EC4P

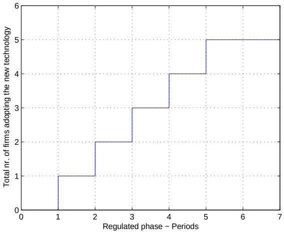


(b) Firm–wise technological adoption with EC4P

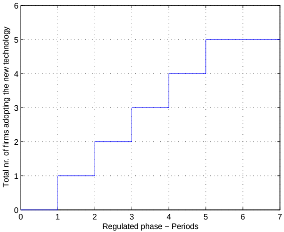
Controlling also the timing of the adoption



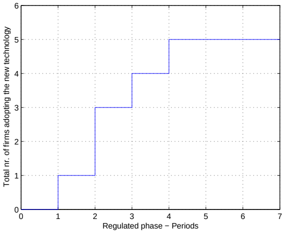
(c) Aggregate technology adoption for $P_g = 1.5$



(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

- The purpose of introducing this instrument is to have a contingent policy that allows to "control" permits supply and continue to **promote technology adoption**.
- This, however, comes **at the expense** of the payments to be made to firms that exercise their contracts.
- Yet, the regulator **collects funds** from the firms that make **penalty** payments, which may be used to (partially) cover the EC4Ps.
- We present a methodology to **assess the likelihood** that the collection of such payments renders the policy budget compatible, so-called *"self–financing"*, i.e. that tax–payers' funds are **not required** to cover the cost of its implementation.

Risk assessment of the cost of the policy

- Let X_I denote potential incomes, penalty payments, and let X_O denote potential outcomes, EC4Ps.
- We use value–at–risk to perform an analysis of **how plausible** it is that a policy turns out to be self–financing.
- For a given ρ, the assessment $\rho(X_I - X_O)$ provides a **measurement** of whether or not the permits system endowed with EC4Ps is self–financing.
- For fixed $\{T, \{N(t)\}\}$, the parameters P and P_g **completely determine** $\rho(X_I - X_O) =: f(P, P_g)$.
- This risk assessment is based on the previous examples and it is evaluated by performing Monte Carlo simulations of pollution emissions used to **approximate the PDFs** of $(X_I - X_O)$.

Value-at-risk of the contingent policy

$V@R_\rho(X_I - X_O)$				
	P_g			
ρ	1.5	2.5	3.5	4.5
0.10	-30.8	-274.6	-397.0	-704.5
0.05	-123.5	-344.6	-476.3	-798.1
0.01	-187.5	-424.9	-594.9	-944.7

Table: $V@R_\rho(X_I - X_O)$ for standard confidence levels $\rho = \{0.10; 0.05; 0.01\}$.

Numerical evaluation of the PDFs of $X_I - X_O$

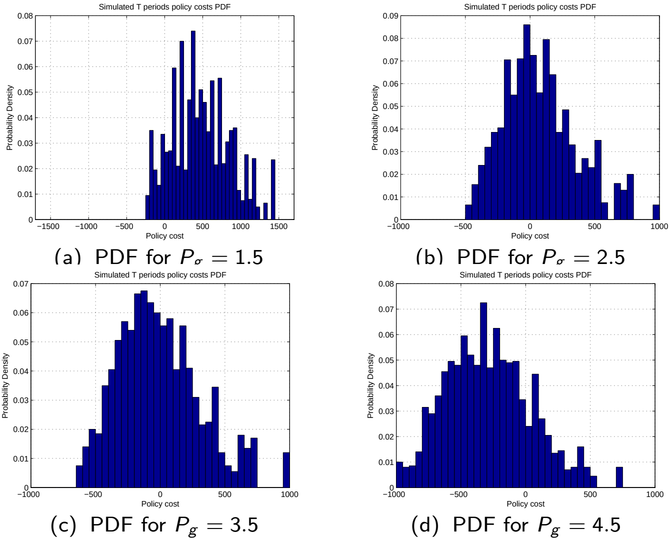


Figure: Probability density functions for different levels of P_g, $P = 10$.

Conclusions

In this paper:

1. Technology adoption and allowance price are generated **endogenously** and are inter–dependent.
2. It is shown that the non–cooperative permit trading game possesses a **pure–strategy** Nash equilibrium, where the allowance value **reflects** the level of **uncovered pollution** (demand), the level of **unused allowances** (supply), and the **technological status**.
3. These conditions are also satisfied when a **price support instrument**, which is contingent on the adoption of the new technology, is introduced.
4. Numerical investigation confirms that this policy generates a **floating price floor** for the allowances, and it maintains the dynamic incentive to invest.
5. Given that this policy comes at a cost, a **criterion for the selection** of a *"self-financing"* policy is proposed and implemented.

Disclaimer

Disclaimer 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**. In the numerical implementations, we compare the effect of different levels of P and P_g on the distribution of $X_I - X_O$ (and therefore on ρ), and simultaneously on the adoption of low pollution–emitting technologies. It might be the case that a choice of primitives that yields very rapid technology adoption of all firms is too socially costly. The analysis of such scenario is not undertaken in this paper.

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