EconomiX
http://economix.u-paris10.fr/

Document de Travail
Working Paper
2007-18

A differential game of intertemporal emissions trading with market power

---

Julien CHEVALLIER

UMR 7166 CNRS

Université Paris X-Nanterre
Maison Max Weber (bâtiments K et G)
200, Avenue de la République
92001 NANTERRE CEDEX

Tél et Fax : 33.(0)1.40.97.59.07
Email : secretariat-economix@u-paris10.fr

Université Paris X Nanterre

A Differential Game of Intertemporal Emissions Trading with Market Power

Julien Chevallier* †

1^{st} version: November, 2006 ; this version: June, 2007

Abstract

In international emissions trading schemes such as the Kyoto Protocol and the European Union Emissions Trading Scheme, the sub-optimal negotiation of the cap with respect to total pollution minimization leads us to critically examine the proposition that generous allocation of grandfathered permits by the regulator based on recent emissions might pave the way for dominant positions.

Stemming from this politically given market imperfection, this paper develops a differential Stackelberg game with two types of non-cooperative agents: a large potentially dominant agent and a competitive fringe whose size are exogenously determined. The strategic interactions are modelled on an intra-industry permits markets where agents can freely bank and borrow permits.

This paper contributes to the debate on initial permits allocation and market power by focusing on the effects of allowing banking and borrowing. A documented appraisal on whether or not such provisions should be included is frequently overlooked by the debate to introduce the permits market itself among other environmental regulation tools. Results are presented under perfect information.

JEL Codes: C73, L11, Q52

Keywords: emissions trading, banking borrowing, market power.

---

[*] EconomiX, University of Paris 10. <jchevall@u-paris10.fr> Department of Economics, Office G-507, 200 avenue de la Republique, 92001 Nanterre Cedex, France. Tel: +33 (0)1.40.97.59.36 Fax: +33 (0)1.40.97.77.84.

[†] Acknowledgements: I wish to thank Pr. G. Rotillon, Pr. P.A. Jouvet (University of Paris 10), Pr. E.D Ellerman (MIT) and Pr. O. Godard (Ecole Polytechnique) for discussions on this topic, as well as participants to the Seminar on Emissions Trading (University of Paris 1, 2006), the 4th Workshop "Permit Trading in Different Applications" (University of Halle Wittenberg, Germany, 2006), the EconomiX "Environment" Session (University of Paris 10, 2007) and the 24th Applied Microeconomics Conference (University of Fribourg, Switzerland, 2007) for useful comments. Special thanks to S. Bridji (University of Paris 10) for his ongoing support on this paper. The usual disclaimer applies.

1 Introduction

What happens on a tradable permits market when distortions occur as a consequence of the inital allocation? Whereas Hahn (1984) contributed first to this debate by demonstrating the non neutrality of permits allocation for an agent able to exert market power[1] in a static context and concerning the spatial exchange of permits only, this paper addresses the critical aspect of initial permits allocation in a dynamic context and concerning intertemporal emissions trading. Theoretical analyses remain scarce in this domain, even if the properties of banking (i.e. the ability to stock permits for future use) and borrowing (i.e. the ability to borrow permits from future periods) have been detailed. In a continuous time model under certainty, Rubin (1996) shows that an intertemporal equilibrium exists on a permits market from the viewpoint of the regulator and the firm, and that banking and borrowing allow firms to smooth emissions. Under uncertainty, Schennach (2000) shows the permits price may rise at a rate less than the discount rate and new public information may cause jumps in the price and emissions paths, among other major contributions.

This article builds on the intertemporal emissions trading literature with market imperfections. It aims at filling the gap in the literature between the pros and cons of authorizing banking and borrowing in permit trading programs, a topic which is typically not enough debated when deciding to adopt such an environmental regulation system. Against this background, it attempts to shed some light on the ability of a large agent to move dynamic markets when permits are grandfathered.

Liski & Montero (2005b) study the effect of market power on the equilibrium of a permits market by introducing a large potentially dominant and a competitive fringe. Based upon two cases, their analysis reveals first that the large agent might manipulate the market by banking allowances when it owns all the stock of permits and second when the fringe receives all the stock of permits, the large agent has an incentive to exchange permits at the competitive price and to build a permits bank for the next period. While previous papers restricted their analysis to banking only[2], both banking and borrowing are allowed without restrictions in a continuous time setting.

The model brings to the regulatory economics literature a realistic description of relationships between agents on a tradable permits market with information asymmetry. As Liski & Montero (2005b) did not impose a particular game structure, I adopt a Stackelberg game structure that allows to deal with strategic interactions between two types of agents: a leader with an informational advantage associated to a large agent, and a follower

---

[1] For an exhaustive literature review on permits trading and market power, see Petrakis & Xepapadeas (2003).

[2] This was mainly due to the fact that no major international agreement on greenhouse gases allows borrowing to a full extent to date (personal contacts with M. Liski).

associated to a competitive fringe.

The market imperfection arises from the free distribution of permits on the basis of past emissions, while the product market is assumed to remain competitive[3]. I explicitly include the Hotelling conditions[4] that must apply if permits are considered as an exhaustible resource.

The paper unfolds as follows: first, I describe the institutional environment of current permit trading programs, namely the Kyoto Protocol (KP) and the European Union Emissions Trading Scheme (EU ETS); second I derive in a benchmark case an expression for market power; third I develop the differential Stackelberg game.

2 Description of the Institutional Environment

In this section, I describe how the model hinges on critical design issues of existing international emissions trading schemes, namely the KP and the EU ETS. I also attempt to provide a balanced picture of the EU ETS and KP market power concerns.

2.1 The Kyoto Protocol

The question of the Kyoto Protocol as an "unfinished business" is often evoked. Very heterogenous sectors were included under the same regulation, which could be detrimental to find the right method to allocate permits depending on price elasticities between sectors.

The intra-industry structure adopted in this paper may be seen as a simplification of the KP. Yet it may propose useful policy recommendations when dealing with such an international scheme. In what follows, I focus on the negotiation phase, the special case of Russia and the prospective use of banking and borrowing.

2.1.1 Negotiation phase

Since there exists no historical data for carbon emission reduction cost, it may prove particularly difficult to induce a cost-effective allocation of the initial quotas to participating countries. In the context of the KP, the case of countries supplied with allocations in excess of their actual needs has been coined as *Hot Air* in the literature[5]. The distribution of a large number of permits to Former Soviet Union (FSU) and Eastern Europe countries (Russia, the Ukraine forming two thirds) may be seen indeed as an imperfection

---

[3] For the distinction between permits market and industry structure imperfections, see Sartzetakis (1997) and Sartzetakis (2004)

[4] Namely the exhaustion and terminal conditions.

[5] See Baron (1999), Burniaux (1999), Bernard *et al.* (2003), Bohringer & Loshel (2003), Holtsmark (2003).

of the KP, as those countries were given generous allocations to foster agreement during the first phase (2008-2012). Market power concerns arise as industrial firms may benefit from the gap between their initial permits allocation (based on 1990 production levels) and their real emission needs in 2008 (after a period of recession), and the use of these permits surpluses remains unclear. If a pure monopoly emerges, a single seller may price its ouput at a higher level than its marginal cost of production. Under international emissions trading, the case of relatively large buyers or cartels exerting market power sounds more relevant[6].

This situation emerged as a conflict between the internal and the external consistency of the permits market:

- the *internal* consistency refers to the situation where agents freely receive or bid for permits according to their real needs. The regulator may be interested however in distributing more permits to a country than strictly needed (according to business as usual emissions or a benchmark for instance) in order to ensure participation to the permits market[7]. As a consequence, one agent may achieve a dominant position which in turns threatens the efficiency of the permits market itself.

- the *external* consistency of the permits market is linked to the broader debate of climate change as the purchase of a "global public good"[8]. This altruistic view embodies the notions of "Burden Sharing" or "common but differentiated responsibilities"[9] attached to the KP, whereby developed countries agree to spend a higher income share on fighting climate change than developing countries[10].

Those conflicting views undermine the negotiation of the cap, which is fixed at a suboptimal level compared to what would be needed to minimize the total damage to the environment. Greenhouse gases (GHG) emission targets under the KP represents a mere 5% reduction below 1990 levels. Now if early movers like EU countries are willing to ratchet down the cap, little progress can be achieved without luring in major players like the USA, India

---

[6] One could symmetrically evoke the case of monopsony power whereby large buyers would lower the permit price from its level under perfect competition. Yet outlooks for the KP do not match this perspective. Indeed, market power is more likely to come from sellers than from buyers.

[7] Such negotiation with Russia was determinant for the KP to enter into force on 16/02/05

[8] See Guesnerie (2006).

[9] See Muller (2002).

[10] Note that the implicit assumptions of the existence of such an Environmental Kuznets Curve (the environment is a superior good and environmental regulation becomes stricter through time at higher levels of GDP per capita) is left out of the debate.

and China. Thus, many difficulties arise to pierce the "veil of uncertainty" around international negotiation[11].

Uncertainty also affects the nature and the size of individual market participants. As Klepper & Peterson (2005)[12] put it:"*The Kyoto Protocol and its related decisions do not explicitly state who is actually supposed to be trading. Probably we will observe both government and firm trading. Under the former, market power might indeed become a relevant issue*". Therefore, the risk of market power is higher if governments are trading large amounts of permits in a centralised manner.

The fact that the creation of a permits market gives some countries the opportunity to draw a financial advantage without a direct environmental gain (i.e. in the absence of effective emissions abatement) may be puzzling. Yet as stated by Maeda (2003)[13], "*[this debate] seems misguided because it focuses on the political importance of the issue, rather than addressing it from an economic perspective.*" That is why in this paper I investigate how permit price manipulation strategies may entail additional economic costs to achieve the same level of abatement as under perfect competition.

Overall, the hypothesis that generous allocations that broaden the scope of a cap-and-trade program might also give birth to dominant positions shall not be neglected. This leads me to comment in depth the case of Russia.

2.1.2 Will Russia be a net seller of permits?

Russia seems the best example to investigate potential market power within the KP according to Korppoo *et al.* (2006)[14]: "*Given the collapse of its emissions in the course of its economic transition, Russia is the country with by far the largest potential surplus of emission allowances for sale under the Kyoto international trading mechanisms. It is also generally considered to be the country with the greatest potential for continuing emission-reducing improvements in energy efficiency. Indeed, in the first commitment period under the Kyoto Protocol it could be described as the Saudi Arabia of the emerging carbon market, with the potential to try to manipulate the market through strategic decisions as to when and how it releases it surplus - if there are buyers willing to deal.*"

Empirical evidence gathered by Grubb (2004), Liski & Montero (2005a)[15] and Korppoo *et al.* (2006) suggests Russia will be a net seller of allowances during the first phase of the KP. Different projections for Russian CO_2 emissions and surplus are detailed in Tables 1 and 2.

The key finding in Table 1 is that under all scenarios Russia would meet

---

[11] See Kolstad (2005).

[12] p.207

[13] p.295

[14] p.2

[15] Based on the MIT-EPPA database that aggregates FSU countries.

Source	Year of Estimate	Percentage of 1990 Levels	Period
Ellerman & Decaux[a]	1998	73	2010
Russian Energy Strategy	2000	76-93	2012
Loschel & Zhang[b]	2002	83,6	2010
IEA[c] World Energy Outlook	2004	72	2008-2012
CEPA[d]	2004	75	2008-2012

Table 1: A Survey of Projections for Russian Carbon Dioxide Emissions. *Source*: adapted from Ellerman & Decaux (1998), Loschel & Zhang (2002) and Korpoo et al. (2006)

---

[a] Scenario with Annex B Trading.

[b] Scenario assuming trading without the US.

[c] International Energy Agency.

[d] Cambridge Economic Policy Associates. Scenario with a 2% energy intensity reduction.

Source	Year of Estimate	Size of the surplus[a]	Period
Ellerman & Decaux	1998	111[b]	2010
Loschel & Zhang[c]	2002	157,8	2010
Russian Ministry of Economic Development and Trade[d]	2003	408-545	2008-2012
Russian Forecast to the UNFCCC[e]	2003	456-913	2008-2012
CEPA	2004	400	2008-2012
Klepper-Peterson	2005	410	2010
Bohringer et al.	2006	246[f]	2008-2012

Table 2: A Survey of Projections for Russia's Surplus under the KP. *Source*: author

---

[a] In million tonnes of carbon equivalent (MtCe).

[b] $MtCO_2$

[c] scenario assuming only Russia exercises monopoly power

[d] adapted from Korpoo et al. (2005)

[e] adapted from Korpoo et al. (2005)

[f] $MtCO_2$

its Kyoto targets, as its CO_2 emissions projections consistently hit below 1990 levels. The room for interpretation of Table 2 is limited by the wide variation in surplus estimates with a lowest value of 111 $MtCO_2$ found by Decaux & Ellerman (1998) and, as expressed above, by the current absence of clearly defined international trading rules to monetize such a surplus.

Further projections regarding Russia's own energy demand *after* the first period of the KP are neeeded to determine whether Russian industrial firms might actually benefit from their *Hot Air*. Besides, the treatment of *Hot Air* needs to be supplemented by considerations about a potential "leakage"[16] of emissions to other regions that are not covered by the KP and by additional allowances from the Clean Development Mechanism or Joint Implementation[17] that might compete with Russian allowances[18].

2.1.3 Prospective use of banking and borrowing in the KP

This section offers a description of the possible use of banking borrowing in the KP. On the one hand, provisions on banking are explicited by Klepper & Peterson (2005)[19]: "*Assigned Amount Units (AAUs) resulting from the Kyoto commitment can be banked without a time constraint. Credits from Joint Implementation (JI) or Clean Development Mechanism (CDM) can be banked up to a limit of , respectively, 2.5% and 5% of a Party's initial assigned amount. Sink credits can not be banked*".

On the other hand, implicit provisions on borrowing may be found in the United Nations Framework Convention on Climate Change (UNFCCC (2000)) report[20]. As explained by Newell *et al.* (2005)[21]: "*International climate policy discussions have implicitly included borrowing within possible consequences for noncompliance under the Kyoto Protocol, through the payback of excess tons with a penalty (i.e., interest).*" This penalty could be fixed to 40% of additional emissions reduction for the next period of the Kyoto Protocol despite uncertainties regarding the enforcement of this particular provision. This question is adressed in depth by Alberola & Chevallier (2007).

---

[16] As documented by Decaux & Ellerman (1998) (pp.15-16), the net effect of potential market power associated to *Hot Air* depends on the compensating emissions that might "leak" to regions unconstrained by the KP.

[17] Conservative estimates range from a lower bound of $800 MtCO_2$ according to UKERC (2006) to an upper bound of $1000 MtCO_2$ according to Point Carbon.

[18] As Baron (1999) put it, trading based on projects may reduce the risk of market power or shift it to other regions which already host a large number of CDM projects like China.

[19] p.295

[20] paragraph II.XV

[21] p.149

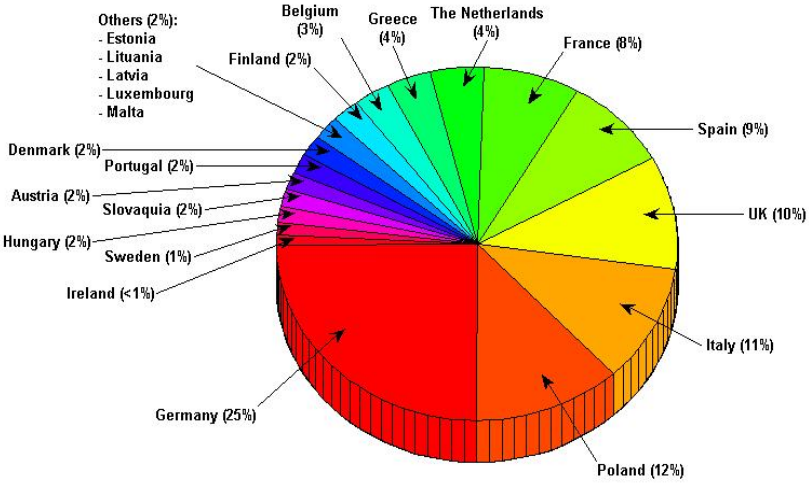

Figure 1: EU ETS National Allocation Plans - Phase 1 (2005-2007) *Source*: CITL (2007) and CDC (2006)

2.2 The European Union Emissions Trading Scheme

Here I draw comments on two critical aspects of the EU ETS. First, I deal with possible design flaws in the allocation of permits that might pave the way for dominant positions during the first phase. Second, I provide an overview of the prospective use of banking and borrowing.

2.2.1 Over-allocation or relative success?

The EU ETS gently constrains emissions (8% reduction for EU-15) so as to start with a low carbon price. Yet the debate has shifted toward a possible over-allocation of permits during the first phase. The production decisions of private actors are under scrutiny: do permits surpluses constitute a relative success (i.e. firms have reduced their emissions above projected levels) or an imperfection in the design of the system?

Figure 1 represents the repartition of 2005 European Union Allowance Units (EUAs in million tonnes of CO_2) among countries, where Germany, Poland, Italy, UK and Spain stand out as the most important actors by totalling about two thirds of the total allowances. Data is taken from CDC (2006)[22] and the Community Independent Transaction Log administered by

---

[22] *Tendances Carbone* is published by the French Caisse des Depots and is available at <http://www.caissedesdepots.fr/>, accessed on November, 2006.

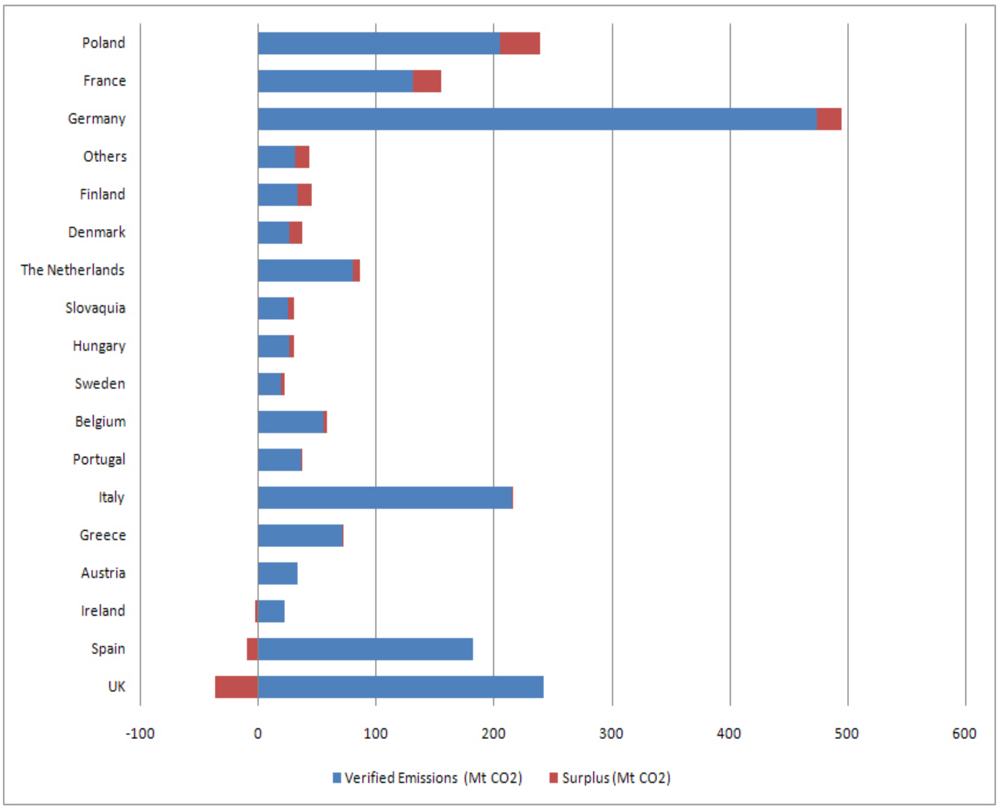

Figure 2: Potential for Market Power by Country (in absolute terms) *Source*: CITL (2007) and CDC (2006)

the European Commission[23]. While it is not our goal to comment on the structure of the European carbon market here, it seems interesting to look at the possible surplus those countries were endowed with.

Figure 2 depicts the 2005 reported emissions and, if any, the size of the surplus. The sum of the two bars is equivalent to the 2005 allocation of permits for a given country. Its main finding lies in the fact that most countries seemed to favor generous allocations during the first phase of the EU ETS[24]. Surpluses also reflect in a limited amount reserves for new entrants, which are included in the data used.

Figure 3 takes a closer look at the allowances surpluses in percentage

---

[23] available at <http://ec.europa.eu/environment/ets/>, accessed on June, 2007

[24] Apart from the EU ETS, there is a need to be cautious here with the notions of "over allocating" and conversely "under-allocating" permits depending on the country. Their meaning depends on the reference point (business as usual plus some abatement for instance). If other trading schemes implement per capita distribution for instance, it may appear less relevant to talk about "over allocation".

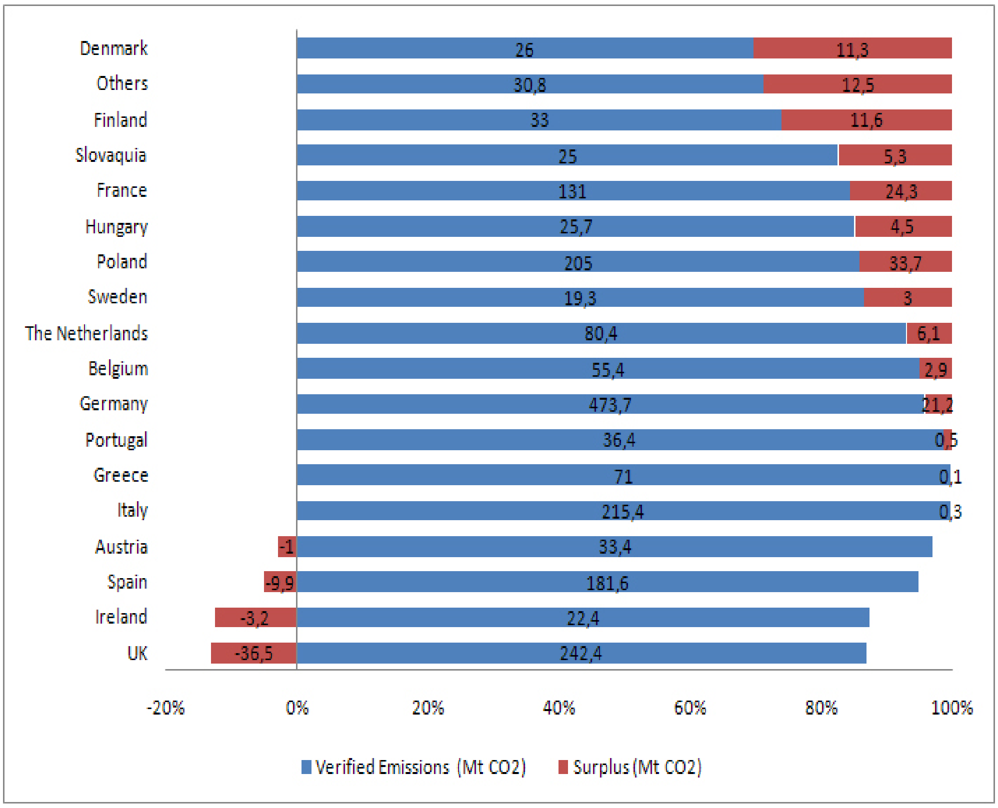

Figure 3: Potential for Market Power by Country (in percentage)
Source: CITL (2007) and CDC (2006)

of the allocation. It reflects a wide variety of cases among market participants as a bulk of countries (Poland, France, Finland, Denmark, Slovaquia, Hungary) was able to build a permits surplus above 15%, while others (UK, Ireland) are short of permits by more than 15%.

The biggest player, Germany does not seem to be in a position to exert market power with less than 5% excess allowances. The surplus of Poland need not be overstated either since the use of 10% of allowances is missing in the CITL. Portugal, Greece, Italy and Austria form a group of countries where the regulator strived to allocate optimally. On the contrary, stricter emissions reductions were enforced in the case of the UK, Ireland and Spain.

How could one explain those contrasting patterns in actual emissions for EU ETS participants in 2005? Part of the answer may be found in the decision making process within each National Allocation Plan (NAP). Godard (2003) and Godard (2005) describe the logic behind the French NAP when allocating shares of recent emissions baselines: non-electric utilities were supplied with their projected need in permits, while electric utilities were more constrained. This situation may be justified by the perceived abatement potential of the electricity industry, but it reveals overall the necessary arbitrages to be made due to sector heterogeneity and a stringent cap.

As long as governments continue to allocate allowances to existing facilities based on historic emissions, the scheme is flawed by a perverse "updating" incentive (Grubb & Neuhoff (2006), p.8). Firms have indeed an incentive to delay early action in abatement technologies since higher emissions today will be rewarded with bigger allocations in future periods.

Buchner & Ellerman (2006) provide a first empirical assessment of the EU ETS allocation process based on 2005 emissions data. They estimate a slight over-allocatation of 4% during the first period of allocation, while there are strong signs that some emissions abatement measures have occurred. But the analysis is not straightforward since "*a long position is not* per se *evidence of over-allocation*"[25]. The difference between 2005 allocation and verified emissions suggests too many allowances were allocated, but the benchmark against which this conclusion is reached may be biased by insufficient data reporting on emissions before 2005 and by a lack of comparability at the EU-wide level. Firms may also be long because of differences in marginal abatement costs or in expectations (regarding economic activity, energy prices, etc.) under uncertainty.

Due to a lack of data availability from 2004 onwards, it appears difficult to provide a more precise characterization of the room for market power at the sectoral level. For French installations subject to the Directive 2003/87/CE, an estimation based on 1,402 installations totalling 185,3 $MtCO_2$ taken from

---

[25] p.2

the Register for Polluting Emissions (iREP)[26] reveals almost 50% of permits were distributed to four players, and the first ten permits holder sum up to 60% of permits allocation.

Ongoing research by De Perthuis et al.[27] points out a strong concentration of EU ETS installations, with 10% of 4019 installations in surplus representing 75% of the total surplus (totalling 145 Mt) and 2% of installations representing 2% of the surplus.

Each of this big players might exert a dominant position on its own sector if permits are distributed freely based on recent emissions, as modelled in this paper.

2.2.2 Prospective use of banking and borrowing in the EU ETS

Member states have allowed banking and borrowing without restriction within each compliance period. But the possibility to carry over EUAs from 2005-2007 to 2008-2012 has been restricted, even by France and Poland who allowed it to a certain extent in the first place[28]. A more detailed analysis of the consequences of banning banking from one period to another on the permits price and firms behaviour may be found in Alberola & Chevallier (2007).

This section provided an overview of two major tradable permits market along with their allocation methodology. It revealed a wide range of opportunities for strategic behaviour in the design of international permit trading regimes. The presence of countries with large permits holdings increases the probability of price manipulation and the risk of efficiency loss in the allocation of abatement efforts between countries. This background information is used as the basis for the modelling of a differential game with hierarchical play in the paper.

3 The Model

This section details the features of the model. First, I explain the design of the cap-and-trade program. Second, I examine the industry and information structures. Third, I define an intertemporal emissions trading constraint. Fourth, I express the Hotelling conditions. Finally, I explicit the properties of the abatement cost function.

---

[26] The iREP is monitored by the Minister of the Environment and displays public information at <http://www.pollutionsindustrielles.ecologie.gouv.fr/IREP/index.php> (accessed on November, 24th 2006).

[27] Workshop "Evaluation of the EU ETS", April 2007, Caisse des Dépôts, Paris

[28] Permits that were bought cannot be banked. Besides, only "green" firms that have effectively reduced emissions may bank allowances in Poland.

3.1 Design of the Cap-and-Trade Program

The regulator sets a cap $\overline{E}$ on emissions of a given pollutant that corresponds to a specific environmental goal. The fix endowment is therefore exogenous to the model, and may be broken down into individual permits allocation $\overline{e}_i$ mandatory for each agent i.

Agents are further decomposed into two types:

1. agent $[i = 1]$ is a large polluting agent, who is initially allocated a large number of permits;
2. agents $[i = 2, \ldots N]$ aggregate many small polluting agent, who are assumed to be comparatively smaller permits-holders, and belong to the competitive fringe.

An agent may be either a country, a firm or a cartel[29]. The competitive market price is determined by fringe agents' abatement costs.

The market imperfection arises during the free permits distribution on the basis of recent emissions[30]. The premise of the paper is that the large agent may be able to exert market power. I do not include the effects of allowing a safety valve[31] in the model.

3.2 Industry Structure

This partial equilibrium model features an intra-industry permit market in a single good economy. I tend to neglect the interaction with the output market.

Market power is defined by Burniaux (1999)[32] as "*the capacity of a firm / country to influence the transaction price of traded permits* " (referred to as a "cost minimising manipulation"). Thus, I do not address exclusionary

---

[29] For instance, within the KP permits may be exchanged party-to-party, but also firm-to-firm if Annex B members delegate this ability to private actors. In the third case, collusive behaviours may appear either between parties or between firms. (Liski & Montero (2005b))

[30] See Ellerman & Parsons (2006) for a review concerning the use of projections, benchmarking and intensity targets. While it is beyond the scope of this paper to study the relative merits of grandfathering and auctioning, theoretical analyses stress the superiority of auctioning as in Jouvet *et al.* (2005). In the view of the Public Choice Theory, free allocation of permits may also be seen by some firms as a means to extract more permits as a scarcity rent, and therefore lobbying takes place. But it is also imposes liabilities on firms that will be reflected in their balance sheets. As highlighted by Raymond (1996), initial permits allocation reveals social norms embedded by newly created permits. The free distribution of permits may be seen as an entitlement over an environmental resource. As conceptions evolve and auctioning might become predominant, the question arises whether the probability of achieving a dominant position will increase or decrease.

[31] A safety valve may be defined as an hybrid instrument to limit the cost of capping emissions at some target level whereby the regulator offers to sell permits in whatever quantity at a pre-determined price.

[32] p.2

manipulation strategies[33] that occur when the dominant agent uses its market power on the permits market to raise entry barriers or exclude agents on the output market.

3.3 Information Structure

I model a differential game[34] played in continuous time where all players have the possibility of influencing the rate of change of the permits bank through the choice of their current actions. It is therefore assumed that they adopt a Markovian strategy.

The common knowledge includes the fact that all players need to comply to the environmental constraint exogenously set by the regulator. The game unfolds in two steps. First, I derive the follower's reaction function to any action announced by the leader through fringe agents' cost minimization problem at the competitive price. Second, I observe how the leader might exercise market power as large agent integrates the reaction function into his own cost minimization problem, and decides how to adjust his emissions level. I hold all other parameters constant[35].

3.4 Intertemporal Emissions Trading

Agents may bank and borrow permits without restrictions. Let $B_i(t)$ be the permits bank, with $B_i(t) > 0$ in case of banking and $B_i(t) < 0$ in case of borrowing.

Any change in the permits bank is equal to the difference between $\overline{e}_i(t)$ and $e_i(t)$, respectively agent's i permits allocation and his emission level at time t. The banking and borrowing constraint may be written as:

$$\dot{B}_i(t) = \overline{e}_i(t) - e_i(t) \tag{1}$$

with $B_i(0) = 0$ as an initial condition.

3.5 Hotelling Conditions

Notwithstanding differences between a permit and an exhaustible resource[36], it is assumed in the literature that the Hotelling conditions for exhaustible

---

[33] See Misiolek & Elder (1989).

[34] See Dockner *et al.* (2000) for an overview of differential games.

[35] For instance, agents do not incur information costs.

[36] According to Liski & Montero (2006) (p.3), the following differences may be highlighted. First, in a permits market with banking, the market may remain after the exhaustion of the bank; while the market of a non-renewable resource vanishes after the last unit extraction. Second, permits extraction and storage costs are equal to zero; while those costs are generally positive for a non-renewable resource. Third, the demand for an extra permit usually comes from a derived demand of other firms that also hold permits; while the demand for an extra unit of a non-renewable resource comes more often from a derived demand of another actor (e.g., a consumer).

resources must apply on a permits market. Consequently, the terminal and exhaustion conditions are detailed below.

3.5.1 Terminal Condition

Let $[0,T]$ be the continuous time planning horizon[37]. At time T, cumulated emissions must be equal to the sum of each agent's depollution objective and therefore to the global cap $\overline{E}$ set by the regulator[38]:

$$\int_0^T \sum_{i=1}^{N} e_i(t)\mathrm{d}t = \sum_{i=1}^{N} \overline{e}_i = \overline{E} \tag{2}$$

3.5.2 Exhaustion Condition

At time T, there is no more permit in the bank (either stocked or borrowed):

$$\sum_{i=1}^{N} B_i(T) = 0 \tag{3}$$

Those conditions ensure that agents gradually meet their depollution objective so that the marginal cost of depollution is equalized in present value over the time period, and the permits bank clears in the end.

There is typically a truncation problem at the end of the period:

- if $B_i(T) > 0$, surplus allowances are worthless and agents are wasting permits;
- if $B_i(T) < 0$, agents need to pay a penalty[39].

3.6 Abatement Cost Function

Let $C_i[e_i(t)]$ be the abatement cost function[40] incurred by agent i in order to comply with his permits allocation $\overline{e}_i$. $C_i[e_i(t)]$ is defined on $\Re$ in $\Re$ continuous and is of class $C^2[0;T]$, i.e. twice continuously differentiable. The

---

[37] This planning period seems appropriate for a theoretical study of intertemporal emissions trading. Alternative time settings including distinct phases may be found in Montero & Ellerman (1998), Schennach (2000) or Ellerman & Montero (2002), but they reflect the specific requirements of the *Acid Rain Program* (USA).

[38] See also Leiby & Rubin (2001), p. 231.

[39] For instance, the penalty is equal to 40€ and 100€ per unit plus a compensating allowance for the first two periods of the EU ETS, and can add up to 40% of additional emissions during the first period of the Kyoto Protocol.

[40] Compared to a situation where profits are unconstrained, abatement costs appear in order to meet the emission cap $\overline{e}_i$.

classical assumption[41] of strictly increasing abatement costs leads $C_i[e_i(t)]$ to be convex, with $C_i'[e_i(t)] < 0$ and $C_i''[e_i(t)] > 0$. I can set $C_i[e_i(0)] = 0$.

Agent's i marginal abatement costs (MAC) are associated with a one-unit reduction from his emission level e_i at time t and are noted $-C_i'[e_i(t)] > 0$. At the equilibrium of a permits market in a static framework[42], price-taking agents adjust emissions until the aggregated MAC is equal to the price P at time t:

$$P_t = -C_i'[e_i(t)] \tag{4}$$

Thus, at the equilibrium, there is no free-lunch for price-taking agents.

4 Benchmark Case

In what follows, the dominant agent sets the price at the level which corresponds to the maximization of the difference between revenues from permits sales and its abatement costs. All other agents behave as price takers, i.e. they minimize their abatement and trading costs given the permit price set by the dominant agent. I want to evaluate how the dominant agent will set the permit price higher and abate less (or sell fewer permits) compared to the competitive solution.

I develop a benchmark case where by assumption the large agent receives all the stock of permits. Both types of agent need to comply to the environmental constraint by adjusting their emissions level and trading permits. In this setting, fringe agents' emissions come from trading with the large agent. The expression of market power may be derived straightforward when the large agent directly integrates the competitive price into his maximization program.

4.1 Optimization program

The large agent minimizes its abatement costs with respect to total emissions and behaves as follows:

$$\begin{cases} \min_{e_1,e_2,\ldots,e_N} \displaystyle\int_0^T e^{-rt}\Big\{C_1[e_1(t)] + P_t\ [e_1(t) - \overline{e}_1(t)]\Big\}\ \mathrm{d}t \\ \displaystyle\int_0^T e_1(t)\ \mathrm{d}t = \overline{E} - \int_0^T \sum_{i=2}^{N} e_i(t)\ \mathrm{d}t \\ P_t = -C_i'[e_i(t)]\ \forall i = 2, \ldots, N \\ [e_1(t) - \overline{e}_1(t)] = \displaystyle\sum_{i=2}^{N} e_i(t) \end{cases}$$

---

[41] Stated first by Montgomery (1972). The conditions given by Leiby & Rubin (2001) include the output $q(t)$ where $C_i[q_i(t), e_i(t), t]$ is strongly convex with $C_i'[q_i(t)] > 0$ and $C_i''[q_i(t)] > 0$. Properties of non-convex abatement cost functions may be found in Godby (2000).

[42] See Hahn (1984).

where the expression $[e_1(t) - \overline{e}_1(t)]$ represents the number of permits bought (> 0) or sold (< 0). I replace the value of P_t and $[e_1(t) - \overline{e}_1(t)]$ in the objective function and form the Lagrangean with $e_1(t)$ and $e_i(t)$ as control variables, and $\lambda(t)$ as a multiplier:

$$\begin{aligned} L = \quad & \int_0^T e^{-rt} \left\{ C_1[e_1(t)] - C_i'[e_i(t)] \sum_{i=2}^{N} e_i(t) \right\} \mathrm{d}t \\ & + \lambda(t) \left[\overline{E} - \int_0^T e_1(t)\mathrm{d}t - \int_0^T \sum_{i=2}^{N} e_i(t)\mathrm{d}t \right] \end{aligned}$$

The first-order conditions are:

$$\begin{aligned} \frac{\partial L}{\partial e_1(t)} &= C_1'[e_1(t)] - \lambda(t) = 0 \\ \frac{\partial L}{\partial e_i(t)} &= -C_i''[e_i(t)] \sum_{i=2}^{N} e_i(t) \ - C_i'[e_i(t)] - \lambda(t) = 0 \end{aligned}$$

Replacing $\lambda(t) = C_1'[e_1(t)]$ in the second equation and rearranging terms, I get:

$$-C_i''[e_i(t)] \sum_{i=2}^{N} e_i(t) \ - C_i'[e_i(t)] - C_1'[e_1(t)] = 0$$

$$-C_1'[e_1(t)] = C_i''[e_i(t)] \sum_{i=2}^{N} e_i(t) \ + C_i'[e_i(t)]$$

$$-C_1'[e_1(t)] = C_i'[e_i(t)] \left[1 + \frac{C_i''}{C_i'} \sum_{i=2}^{N} e_i(t) \right]$$

$$-C_1'[e_1(t)] = P(t) \ \left[1 + \varepsilon_i \sum_{i=2}^{N} e_i(t) \right]$$

The large agent's MAC is equal to the competitive permits price plus an element of price distortion ε_i defined as fringe agents' elasticity:

$$\varepsilon_i = \frac{C_i''(e_i)}{C_i'(e_i)} = \frac{\dfrac{\mathrm{d}C_i'}{\mathrm{d}e_i}}{\dfrac{\mathrm{d}C_i}{\mathrm{d}e_i}} = \frac{\mathrm{d}C_i'}{\mathrm{d}e_i} \frac{\mathrm{d}e_i}{\mathrm{d}C_i} = \frac{\mathrm{d}C_i'}{\mathrm{d}C_i}$$

Thus, permits price manipulation results in higher total abatement costs than under perfect competition. Next, I explicit this market power condition.

4.2 Market Power Condition

In this setting, market power is function of fringe agents' elasticity and of the large agent's number of permits:

$$\varepsilon_i \sum_{i=2}^{N} e_i(t) = \varepsilon_i \; [e_1(t) - \overline{e}_1(t)] \tag{5}$$

Due to the convexity assumption, fringe agents' elasticity is negative, and reveals the possibility for the leader to affect negatively fringe agents' behaviour. The large agent's MAC is *lower* than under perfect competition. Since he enjoys a dominant position and has the ability to influence the permits price, the large agent may be characterized overall as a net gainer and fringe agents as net losers.

5 Fringe Agents' Reaction Function

The first step of the game consists in forming the strategy of the fringe. Fringe agents choose their optimal emissions level according to the possibility to bank and borrow permits in constraint (1). The cost minimization program may be written as follows:

$$\begin{cases} \min\limits_{e_i} \displaystyle\int_0^T e^{-rt} \left\{ C_i[e_i(t)] + P(t) \; [e_i(t) - \overline{e}_i(t)] \right\} \mathrm{d}t \\ \dot{B}_i(t) = \overline{e}_i(t) - e_i(t) \\ B_i(0) = 0 \\ C_i[e_i(0)] = 0 \end{cases}$$

I write the corresponding current-value Hamiltonian and first-order optimality conditions:

$$H(B_i(t), e_i(t), \lambda(t), t) = \{C_i[e_i(t)] + P(t) \; [e_i(t) - \overline{e}_i(t)]\} - \lambda(t)[\overline{e}_i(t) - e_i(t)]$$

$$\frac{\partial H}{\partial e_i(t)} = 0 : \; P(t) = -C_i'[e_i(t)] + \lambda(t) \tag{6}$$

$$\dot{B}_i(t) = \frac{\partial H}{\partial \lambda(t)} = 0 : \dot{B}_i(t) = \overline{e}_i(t) - e_i(t) \tag{7}$$

$$\dot{\lambda}(t) - r\lambda(t) = -\frac{\partial H}{\partial B_i(t)} = 0, \; \lambda(T)B_i(T) = 0 \tag{8}$$

It can be infered from (8) that $\lambda(t) = \lambda(0)e^{rt}$. The transversality condition (8) is required to meet the exhaustion condition (3), i.e. to reflect the idea that the bank has no scrap value at the end of the period. I can distinguish several cases:

- if $B_i(T) > 0$ or $B_i(T) < 0$, then $\lambda(T) = 0, \lambda(t) = 0$: when fringe agents have a net banking or borrowing position at the end of the period, the reaction function is equal to the static equilibrium condition (4) where fringe agents equalize their MAC with the permits price. As stated earlier, surplus allowances are worthless and agents need to pay a penalty in case of net borrowing;
- if $\lambda(T) > 0$, then $B_i(T) = 0$ and $\lambda(t) > 0$: when the constraint on λ is binding, this implies a positive shadow price for units in the bank that is cleared. The reaction function is equal to (6);
- if $\lambda(T) < 0$, then $B_i(T) = 0$ and $\lambda(t) < 0$: this would imply a negative shadow price for units in the bank when it is cleared. Since this result is not in accordance with the specific purpose of a cap-and-trade program, I do not further comment this case.

I have therefore highlighted two possible forms of fringe agents' reaction function depending on a net banking/borrowing position or to a positive value of the co-state variable.

In the second step of the game, I turn to the large agent's behaviour and to how he integrates the two possible cases of reaction function into his own optimization program.

6 Behaviour of the Large Agent

6.1 Optimization program

The large agent adjusts strategically his optimal emissions levels according to its initial allocation $\overline{e}_1$ as expressed by (2) and the banking borrowing constraint (1). The cost minimization program for agent $[i = 1]$ is:

$$\begin{cases} \min\limits_{e_1} \displaystyle\int_0^T e^{-rt} \left\{ C_1[e_1(t)] + P_t \; [e_1(t) - \overline{e}_1(t)] \right\} \, \mathrm{d}t \\ \dot{B}_1(t) = \overline{e}_1(t) - e_1(t) \\ \overline{E} = \displaystyle\int_0^T e_1(t)\mathrm{d}t + \int_0^T \sum_{i=2}^{N} e_i(t)\mathrm{d}t \\ B_1(0) = 0 \\ C_1[e_1(0)] = 0 \end{cases}$$

6.2 First case

Replacing P_t by (4), the large agent's optimization program becomes:

$$\begin{cases} \displaystyle\min_{e_1} \int_0^T e^{-rt} \left\{ C_1[e_1(t)] - C_i'[e_i(t)]\ [e_1(t) - \overline{e}_1(t)] \right\}\ \mathrm{d}t \\ \dot{B}_1(t) = \overline{e}_1(t) - e_1(t) \\ \displaystyle\overline{E} = \int_0^T e_1(t)\mathrm{d}t + \int_0^T \sum_{i=2}^{N} e_i(t)\mathrm{d}t \\ B_1(0) = 0 \\ C_1[e_1(0)] = 0 \end{cases}$$

Assuming fringe agents are homogenous, I write $\sum_{i=2}^{N} e_i(t) = (N-1)e_i(t)$ and replace the emissions constraint (2) into the objective function:

$$\begin{cases} \displaystyle\min_{e_1} \int_0^T e^{-rt} \left\{ C_1[e_1(t)] - C_i' \left[\frac{\overline{E} - e_1(t)}{N-1} \right]\ [e_1(t) - \overline{e}_1(t)] \right\}\ \mathrm{d}t \\ \dot{B}_1(t) = \overline{e}_1(t) - e_1(t) \\ B_1(0) = 0 \\ C_1[e_1(0)] = 0 \end{cases}$$

I form the corresponding current-value Hamiltonian with $e_1(t)$ as a control variable, $B_1(t)$ as a state variable, and $\mu(t)$ as a co-state variable:

$$H(B_1(t), e_1(t), \mu(t), t) =$$

$$C_1[e_1(t)] - C_i' \left[\frac{\overline{E} - e_1(t)}{N-1} \right]\ [e_1(t) - \overline{e}_1(t)] + \mu(t)[\overline{e}_1(t) - e_1(t)]$$

Assuming the existence of an interior solution, necessary optimality conditions include:

$$\frac{\partial H}{\partial e_1(t)} = 0 :$$

$$C_1'[e_1(t)] + \frac{1}{N-1} C_i'' \left[\frac{\overline{E} - e_1(t)}{N-1} \right]\ [e_1(t) - \overline{e}_1(t)] - C_i' \left[\frac{\overline{E} - e_1(t)}{N-1} \right] - \mu(t) = 0 \tag{9}$$

$$\dot{B}_1(t) = \frac{\partial H}{\partial \mu(t)} = 0 :\ \dot{B}_1(t) = \overline{e}_1(t) - e_1(t) \tag{10}$$

$$\dot{\mu}(t) - r\mu(t) = -\frac{\partial H}{\partial B_1(t)} = 0,\ \mu(T)B_1(T) = 0 \tag{11}$$

With reference to the transversality condition (11), I conduct the same analysis as in the previous section:

- if $B_1(T) > 0$, then $\mu(T) = 0, \mu(t) = 0$ and $B_i(T) < 0$: net banking by the large agent at the end of the period is compensated by fringe agents's net borrowing;
- if $B_1(T) < 0$, then $\mu(T) = 0, \mu(t) = 0$ and $B_i(T) > 0$: net borrowing by the large agent in terminal period is compensated by fringe agents' net banking.

Both cases of net banking $B_1(T) > 0$ or borrowing $B_1(T) < 0$ by the large agent in terminal period imply $\mu(T) = 0$ and $\mu(t) = 0$. From eq.(9), it is possible to identify a price distortion condition analogous to the market power condition (5):

$$-C_1'[e_1(t)] = -C_i'\left[\frac{\overline{E} - e_1(t)}{N-1}\right]\left[1 + \frac{1}{N-1}\frac{C_i''}{C_i'}\left[e_1(t) - \overline{e}_1(t)\right]\right]$$

$$-C_1'[e_1(t)] = P(t)\left[1 + \frac{1}{N-1}\varepsilon_i\left[e_1(t) - \overline{e}_1(t)\right]\right]$$

On the left hand side of the equation, I have the large agent's MAC. On the right hand side, I recognize the price distortion as a function of fringe agents' elasticity and the large agent's permits endowment.

In either case where both agents have a net banking or borrowing position in terminal period, the large agent is able to affect negatively fringe agent's MAC through the number of permits he holds in excess of his emissions. This result is similar to the benchmark case where the large agent owns all the stock of permits.

Next, I examine the form of the solution for the second form of fringe agents' reaction function.

6.3 Second case

Replacing P_t by eq.(6), the large agent's optimization program becomes:

$$\begin{cases} \min\limits_{e_1} \displaystyle\int_0^T e^{-rt}\left\{C_1[e_1(t)] - \{C_i'[e_i(t)] + \lambda(t)\}\left[e_1(t) - \overline{e}_1(t)\right]\right\}\,\mathrm{d}t \\ \dot{B}_1(t) = \overline{e}_1(t) - e_1(t) \\ \overline{E} = \displaystyle\int_0^T e_1(t)\mathrm{d}t + \int_0^T \sum_{i=2}^{N} e_i(t)\mathrm{d}t \\ B_1(0) = 0 \\ C_1[e_1(0)] = 0 \end{cases}$$

The resolution method is the same as in the first case and the following comment arise:

- if $B_1(T) = 0$, then $\mu(T) > 0, \mu(t) > 0$ and $B_i(T) = 0$: in case both agents clear their permits bank at the end of the period, the shadow values of a unit in the bank is positive. Both values of $\mu(t)$ and $\lambda(t)$ are known. For the large agent, the shadow value of a unit of emission in the bank measures the marginal utility of the state at time t along the optimal trajectory. For fringe agents, $\lambda(t)$ reflects the highest hypothetical price at which they would be willing to pay for an additional permit at time t.

Rearranging as above and setting $\{B_i(T) = 0, B_1(T) = 0, \lambda(t) > 0, \mu(t) > 0\}$ yields:

$$-C_1'[e_1(t)] + \mu(t) = -C_i' \left[\frac{\overline{E} - e_1(t)}{N-1}\right] \left[1 + \frac{1}{N-1} \frac{C_i''}{C_i'} [e_1(t) - \overline{e}_1(t)]\right] - \lambda(t)$$

$$-C_1'[e_1(t)] + \mu(t) = P(t) \left[1 + \frac{1}{N-1} \varepsilon_i [e_1(t) - \overline{e}_1(t)]\right] - \lambda(t)$$

This condition means that when both agents clear their permits bank in terminal period, the large agent is still able to affect negatively fringe agent's MAC. I have therefore confirmed the possibility of strategic manipulation for both forms of fringe agents' reaction function.

However, the spectre of a large agent achieving a market power position may be averted by a careful design of the cap-and-trade program. As illustrated by the ongoing debate on the EU ETS NAPs, there is a need for further research to assess the best solution to allocate permis efficiently (be it through output-based methods, benchmarking, minimum price auctioning, etc.).

7 Conclusion

The description of the institutional environment on which the model hinges provided a balanced picture of market power concerns in existing international emissions trading schemes. As for the Kyoto Protocol, trading rules in the making and the key role played by projections preclude from reaching a definitive conclusion, but it seems overall difficult to move an international permits market in a dynamic context. A global conclusion concerning EU ETS market power concerns gears towards a prudent approach: if some firms have received more permits than projected, they might very well end up with a shortage of permits at the end of the first period because of an increase in emissions. The EU Commission is especially careful during the validation of NAPs about their stringency and to the fact that there will be no ex-post adjustment. Still, there are strong signs of concentration at the installation level. Both schemes allow full banking and borrowing intra-period.

To capture the distortions induced by initial allocation, I introduce a differential game where agents differ in terms of their exogenous permits endowment and adopt a Markovian strategy. The main result consists in a price distortion condition based on fringe agents' elasticity and the large agent's permits endowment that explains how the large agent is able to affect negatively fringe agents' marginal abatement costs. Some similarities have been underlined between a benchmark case where the large agent owns all the stock and the model with grandfathered permits: in both cases where agents either compensate their net banking/borrowing positions or clear their permits bank at the end of the period, it is possible to identify net losers (i.e., fringe agents) and a net gainer (i.e., the large agent) as the large agent benefits from a lower marginal abatement cost than under perfect competition.

Since the price set by the dominant agent directly depends on the amount of permits initially allocated to that agent, this paper contributes to the link between distributional aspects and overall efficiency of tradable permits markets. It extends Hahn (1984)'s analysis on market power in a dynamic framework and builds upon Liski & Montero (2005b) and Liski & Montero (2006) by modelling strategic interactions after a Stackelberg game and providing a full characterization of effects of unrestricted banking and borrowing.

But the spectre of market power need not be raised if the cap-and-trade program appears properly designed. The negotiation process of each NAP at the Member State level is typically an example of a manipulable rule whereby industries may conduct lobbying activities to extract more permits as a monopoly rent. With reference to the debate "rules vs. discretion" in monetary economics, this unhealthy lobbying by major industries calls for further research to ascertain the conditions under which it would be optimal to delegate the determination of the cap and the distribution of permits to an independent agency (Helm *et al.* (2003), Grubb & Neuhoff (2006)).

The model could be extended by the adoption of an intertemporal trading ratio specific to borrowing as discussed by Kling & Rubin (1997)[43], allowing for a better grasp of the possibilities offered by intertemporal emissions trading. It may also be interesting to look at another source of heterogeneity between agents, for instance based on their emissions reduction function.

As a final comment, one could say a greater reliance on banking and limited borrowing (i.e. with a specific discounting factor) should be promoted to allow firms to smooth their emissions and take investment decisions in abatement technologies with a better capacity to react to the evolution of the carbon constraint over time.

---

[43] The adoption of a discount rate penalizing borrowing may remove some of the perverse incentives whereby agents concentrate emissions on early periods, which is not socially optimal.

References

Alberola, E., & Chevallier, J. 2007. *Banking Borrowing in the EU ETS: An Econometric Appraisal of the 2005-2007 Intertemporal Market.* Working Paper, EconomiX, University of Paris 10, France.

Baron, R. 1999. Market Power and Market Access in International GHG Emission Trading. *IEA Information Paper.* International Energy Agency, Energy and Environment Division.

Bernard, A., Paltsev, S., Reilly, J.M., Vielle, M., & Viguier, L. 2003. Russia's Role in the Kyoto Protocol. *MIT Joint Program on the Science of Policy and Global Change*, **98**.

Bohringer, C., & Loshel, A. 2003. Market Power and Hot Air in International Emissions Trading: the Impact of the US Withdrawal from the Kyoto Protocol. *Applied Economics*, **35**(6), 651–663.

Buchner, B., & Ellerman, E.D. 2006. *Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on 2005 Emissions Data.* FEEM Nota Di Lavoro 139.2996.

Burniaux, J.M. 1999. How important is market power in achieving Kyoto?: An assessment based on the GREEN model. *OECD Workshop on the "Economic Modelling of Climate Change"*, **13**.

CDC. 2006. *Note d'étude de la Mission Climat de la Caisse des Dépôts.* Number 8.

Decaux, A., & Ellerman, AD. 1998. *Analysis of Post-Kyoto CO2 Emissions Trading Using Marginal Abatement Curves.* MIT EPPR Report Number 40.

Dockner, E., Jorgensen, S., Long, N. Van, & Sorger, G. 2000. *Differential Games in Economics and Management Science.* Cambridge Universiy Press.

Ellerman, A.D., & Montero, J.P. 2002. The Temporal Efficiency of SO2 Emissions Trading. *CMI Working Paper*, **13**. Cambridge MIT Institute.

Ellerman, A.D., & Parsons, J. 2006. *Shortage, Inter-period Pricing, and Banking.* Tendances Carbone, Volume 5.

Godard, O. 2003. L'allocation initiale des quotas d'émission de CO2 aux entreprises à la lumière de l'analyse économique. *Cahier*, **2003**(008). Chaire Developpement Durable Ecole Polytechnique - EDF.

Godard, O. 2005. Politique de l'effet de serre: une évaluation du plan francais de quotas de CO2. *Revue Francaise d'Economie*, **19**(4), 147–186.

Godby, R.W. 2000. Market Power and Emissions Trading: Theory and Laboratory Results. *Pacific Economic Review*, **5**.

Grubb, M. 2004. Russian Energy and CO2 Emission Prospects: Evidence from Domestic Analyses and International Comparisons. *Briefing Note*. Royal Institute of International Affairs.

Grubb, M., & Neuhoff, K. 2006. Allocation and Competitiveness in the EU Emissions Trading Scheme: Policy Overview. *Climate Policy*, **6**, 7–30.

Guesnerie, R. 2006. *The design of post-Kyoto climate schemes : an introductory analytical assessment*. Working Paper PSE Number 2006-11.

Hahn, R.W. 1984. Market Power and Transferable Property Rights. *Quarterly Journal of Economics*, **99**, 753 – 765.

Helm, D., Hepburn, C., & Mash, R. 2003. Credible Carbon Policy. *Oxford Review of Economic Policy*, **19**(3), 438–450.

Holtsmark, B. 2003. Russian Behaviour in the Market for Permits under the Kyoto Protocol. *Climate Policy*, **3**, 399–415.

Jouvet, P.A., Michel, P., & Rotillon, G. 2005. Optimal Growth with Pollution: How to Use Pollution Permits? *Journal of Economic Dynamics and Control*, **29**, 1597–1609.

Klepper, G., & Peterson, S. 2005. Trading Hot Air. The Influence of Permit Allocation Rules, Market Power and the US Withdrawal from the Kyoto Protocol. *Environmental and Resource Economics*, **32**, 205–227.

Kling, C., & Rubin, J. 1997. Bankable Permits for the Control of Environmental Pollution. *Journal of Public Economics*, **64**, 101–115.

Kolstad, C.D. 2005. Piercing the Veil of Uncertainty in Transboundary Pollution Agreements. *Environmental and Resource Economics*, **31**, 21–34.

Korppoo, A., Karas, J., & Grubb, M. 2006. *Russia and the Kyoto Protocol: Opportunities and Challenges*. Royal institute of international affairs edn. Chatham House.

Leiby, P., & Rubin, J. 2001. Intertemporal Permit Trading for the Control of Greenhouse Gas Emissions. *Environmental and Resource Economics*, **19**, 229–256.

Liski, M., & Montero, J.P. 2005a. Market power in a storable-good market: Theory and Applications to Carbon and Sulfur Trading. *MIT CEEPR*, **16**.

Liski, M., & Montero, J.P. 2005b. A Note on Market Power in an Emissions Permit Market with Banking. *Environmental and Resource Economics*, **31**(2), 159–173. Special Issue.

Liski, M., & Montero, J.P. 2006. On Pollution Permit Banking and Market Power. *Journal of Regulatory Economics*, **29**(3), 283–302.

Maeda, A. 2003. The Emergence of Market Power in Emision Rights Markets: the Role of Initial Permit Distribution. *Journal of Regulatory Economics*.

Misiolek, W.S., & Elder, H.W. 1989. Exclusionary Manipulation of Markets for Pollution Rights. *Journal of Environmental Economics and Management*, **16**, 156–166.

Montero, J.P., & Ellerman, A.D. 1998. Explaining low sulfur dioxide allowance prices: the effect of expectation errors and irreversibility. *MIT CEEPR*, **98011**.

Montgomery, W.D. 1972. Markets in Licenses and Efficient Pollution Control Programs. *Journal of Economic Theory*, **5**, 395–418.

Muller, B. 2002. *Equity in Climate Change: The Great Divide*. Working Paper Number EV31, Oxford Institute for Energy Studies.

Newell, R., Pizer, W., & Zhang, J. 2005. Managing Permit Markets to Stabilize Prices. *Environmental and Resource Economics*, **31**, 133–157.

Petrakis, E., & Xepapadeas, A. 2003. Location decisions of a polluting firm and the time consistency of environmental policy. *Resource and Energy Economics*, **25**(2), 197–214.

Raymond, L. 1996. Private Rights in Public Resources: Equity and Property Allocation in Market-Based Environmental Policy. *Resources For The Future*.

Rubin, J. 1996. A model of Intertemporal Emission Trading, Banking, and Borrowing. *Journal of Environmental Economics and Management*, **31**, 269–286.

Sartzetakis, E.S. 1997. Tradeable Emission Permits Regulations in the Presence of Imperfectly Competitive Product Markets: Welfare Implications. *Environmental and Resource Economics*, **09**, 65–81.

Sartzetakis, E.S. 2004. On the Efficiency of Competitive Markets for Emission Permits. *Environmental and Resource Economics*, **27**, 01–19.

Schennach, S.M. 2000. The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments. *Journal of Environmental Economics and Management*, **40**, 189–210.

UKERC. 2006. *Implementing Kyoto - Does It All Add Up?* UK Energy Research Centre Workshop Report, March, University of Oxford.

UNFCCC. 2000. *Procedures and Mechanisms Relating to Compliance under the Kyoto Protocol: Note by the co-Chairmen of the Joint Working Group on Compliance, Bonn.* Report.