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Market power in an exhaustible resource market: The case of storable pollution permits

Matti Liski and Juan-Pablo Montero*

Jan 15, 2008

Abstract

Motivated by the structure of existing pollution permit markets, we study the equilibrium path that results from allocating an initial stock of storable permits to a large polluting agent and a competitive fringe. A large agent selling permits in the market exercises market power no differently than a large supplier of an exhaustible resource. However, whenever the large agent's endowment falls short of its efficient endowment —allocation profile that would exactly cover its emissions along the perfectly competitive path— the market power problem disappears, much like in a durable-good monopoly. We illustrate our theory with two applications: the carbon market that may eventually develop under the Kyoto Protocol and beyond and the US sulfur market.

JEL classification: L51; Q28.

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1 Introduction

Markets for trading pollution rights or permits have attracted increasing attention in the last two decades. A common feature in most existing and proposed market designs is the future tightening of emission limits accompanied by firms' possibility to store today's unused permits for use in later periods. The US sulfur dioxide trading program with its two distinct phases is a salient example but global trading proposals to dealing with carbon dioxide emissions share similar characteristics.[1] In anticipation of a tighter emission limit, it is in the firms' own interest to store permits from the early permit allocations and build up a stock of permits that can then be gradually consumed until reaching the long-run emissions limit. This build-up and gradual consumption of a stock of permits give rise to a dynamic market that shares many, but not all, of the properties of a conventional exhaustible-resource market (Hotelling, 1931).

As with many other commodity markets, permit markets have not been immune to market power concerns (e.g., Hahn, 1984; Tietenberg, 2006). Following Hahn (1984), there is substantial theoretical literature studying market power problems in a static context but none in the dynamic context we just described. This is problematic because static markets, i.e., markets in which permits must be consumed in the same period for which they are issued, are rather the exception.[2] In this paper we study the properties of the equilibrium path of a dynamic permit market in which there is a large polluting agent —that can be either a firm, country or cohesive cartel[3]— and a competitive fringe of many small polluting agents.[4] Agents receive for free a very generous allocation of permits for a few periods and then a allocation equal, in aggregate, to the long-term emissions goal established by the regulation. We are interested in studying how the exercise of market power by the large firm changes as we vary the initial distribution of the overall allocation among the different parties. Depending on individual permit endowments and relative costs of pollution abatement, the large agent can be either a buyer or a seller of permits in the market, which, in turn, may affect how and to what

[1] As documented by Ellerman and Montero (2007), during the first five years of the U.S. Acid Rain Program constituting Phase I (1995-99) only 26.4 million of the 38.1 million permits (i.e., allowances) distributed were used to cover sulfur dioxide emissions. The remaining 11.65 million allowances were saved and have been gradually consumed during Phase II (2000 and beyond).

[2] Already in the very early programs like the U.S. lead phasedown trading program and the U.S. EPA trading program firms were allowed to store permits under the so-called "banking" provisions – provisions that were extensively used (Tietenberg, 2006).

[3] In the concluding section we explain the changes (or no changes) to our equilibrium path from replacing the large firm by a few large non-cooperative firms.

[4] The properties of the perfectly competitive equilibrium path are well understood (e.g., Rubin, 1996).

extent it distorts prices away from perfectly competitive levels.

Existing literature provides little guidance on how individual endowments relate to market power in a dynamic setting with storable endowments.[5] Agents in our model not only decide on how to sell the stock over time, as in any conventional exhaustible resource market, but also how to consume it as to cover their own emissions. In addition, since permits can be stored at no cost agents are free to either deplete or build up their own stocks. Despite all these complications, we find a simple result: an intertemporal endowment (i.e., profile of annual endowments) to the large agent results in no market power as long it is equal or below the large agent's "efficient allocation", i.e., the allocation profile that would cover its total emissions along the perfectly competitive path. When the large agent's intertemporal endowment is above its efficient allocation, it exercises market power by restricting its supply of permits to the market and by abating less than what is socially optimal. There are important policy implications from these results. The first is that allocations to early years that exceed the large agent's current needs (i.e., emissions) do not necessarily lead to market power problems if allocations to later years are below future (expected) needs. The second implication is that any redistribution of permits from the large agent to small agents will unambiguously make the exercise of market power less likely. This is in sharp contrast with predictions from static models where such redistribution of permits could result in an increase of market power; for example, by moving from no market power to monopsony power. Closely related to the second implication is that our results would make a stronger case for auctioning off the permits instead of allocating them for free. This will necessarily make the large agent a buyer of permits.

The properties of our subgame-perfect equilibrium can be best understood by recognizing that the large agent has two opposing objectives —revenue maximization and compliance cost minimization— and at the same time it faces a fringe of competitive agents with rational expectations that force it to follow a subgame-perfect path. The opposing objectives problem arises because our large firm must decide on two variables at each point in time: how many permits to bring to (or buy from) the spot market and how much stock to leave for subsequent periods, or equivalently, how many permits to use for its own compliance. Fringe members clear the spot market and decide their

[5] In the context of static permit trading (i.e., one-period market), Hahn (1984) shows that market power vanishes when the permit allocation of the large agent is exactly equal to its "efficient allocation" (i.e., its emissions under perfectly competitive pricing). Hence, an allocation different than the efficient allocation results in either monopoly or monopsony power.

remaining stocks based on what they (correctly) believe the market development will be.

Thus, the large agent seeks, on the one hand, to maximize revenues from permits sales, which is achieved by a sales policy that equalizes marginal revenue across periods. On the other hand, the large agent seeks to minimize its own compliance cost, i.e., the cost of gradually reaching the long-run emissions limit. In an effort to equalize marginal costs across periods, this second objective commands some own demand for permits. When the large agent has the entire permit stock as endowment, we obtain the monopoly solution with initial prices above efficient levels but gradually declining in present value terms. In this case, fringe members are not willing to store permits which eliminates any commitment problem the large agent may have.

It is more realistic, however, that competitive agents hold some fraction of the stock, which necessarily implies an initial storage period by the competitive agents. Such agents are willing to hold stock in early periods when prices are high, thereby free-riding on the large agent's market power. As long as the large agent's holding is above its efficient allocation, it will have no problems in solving the two-dimensional objective of intertemporal revenue maximization and cost minimization in a credible (i.e., subgame-perfect) manner. Furthermore, the way the large agent exercises market power gives rise to an equilibrium path analogous to the path for an exhaustible resource with a large supplier (e.g., Salant, 1976).[6] When the large agent's endowment converges to its efficient allocation, the revenue maximization objective drops out and the agent stops trading with the rest of the market; it only uses its stock to minimize costs while reaching the long-run emissions target.

When the large agent's stock falls below its efficient allocation, and hence, becomes a net buyer in the market, it has no means of credibly committing to a purchasing path that would keep prices below their competitive levels throughout. Any effort to depress prices below competitive levels would make fringe members to maintain a larger stock in response to their (correct) expectation of a later appreciation of permits. And such off-equilibrium effort would be suboptimal for the large agent, i.e., it is not the large agent's best response to fringe members' rational expectations.[7]

Although understanding the effect of endowment allocations on the performance of a

[6] Note that our approach is very different from Salant's in that we view firms as coming to the market in each period instead of making a one-time quantity-path announcement at the beginning of the game. There is a large theoretical literature after Salant (1976), including, among others, Newbery (1981), Schmalensee and Lewis (1980), Gilbert (1978). For a survey see Karp and Newbery (1993).

[7] Note that the depletable nature of the permit stocks makes this time-inconsistency problem faced by the large agent similar to that of a durable-good monopolist (Coase, 1972; Bulow, 1982).

dynamic permit market is our main motivation, it is worth emphasizing that the properties of our equilibrium solution apply equally well to any conventional exhaustible resource market in which the large agent is in both sides of the market. Our results imply, for example, that a dominant agent in the oil market needs potentially a significant fraction of the overall oil stock before being able to exercise market power.

We then illustrate our theoretical results with two applications: the carbon market that may eventually develop under the Kyoto Protocol and beyond and the existing sulfur market of the US Acid Rain Program. Our intention with these applications is not to test for market power *per se*, which would require to have or estimate marginal abatement cost curves, but to explore to what extent the permit allocations in these trading programs depart from our condition for efficiency. Motivated by the widespread concern about Russia's ability to exercise market power,[8] in the carbon application we show how such ability greatly diminishes when countries affected by the Protocol are expected to store a significant fraction of early permits in anticipation of tighter emission constraints and higher prices in later periods. The reason is that Russia would not only hold a large stock, which is built during the first periods, but would also consume a large amount during later periods.

For the sulfur application, we use publicly available data on sulfur dioxide emissions and permit allocations to track down the actual compliance paths of the four largest players in the market, which together account for 43% of the permits allocated during the generous-allocation years, i.e., 1995-1999. The fact that these players, taken either individually or as a cohesive group, appear as heavy borrowers of permits during and after 2000 rules out, according to our theory, market power coming from the initial allocations.

The rest of the paper is organized as follows. The model is presented in Section 2. The characterization of the properties of our equilibrium solution are in Section 3. Extensions of the basic model that account for trends in permit allocations and emissions and long-run market power are in Section 4. The applications to carbon and sulfur trading are in Section 5. Final remarks are in Section 6.

[8] Even if Russia decides to distribute its carbon quota among its domestic firms, it would be relatively straightforward for Russia to act as cohesive unit in the global market, in regard to the exercise of market power, by levying an permits export tax.

2 The Model

We are interested in pollution regulations that become tighter over time. A flexible way to achieve such a tightening is to use tradable pollution permits whose aggregate allocation is declining over time. When permits are storable, i.e., unused permits can be saved and used in any later period, a competitive permit market will allocate permits not only across firms but also intertemporally such that the realized time path of reductions is the least cost adjustment path to the regulatory target.

We start by defining the competitive benchmark model of such a dynamic market. Let $\mathcal{I}$ denote a continuum of heterogenous pollution sources. Each source $i \in \mathcal{I}$ is characterized by a permit allocation $a_t^i \geq 0$, unrestricted emissions $u_t^i \geq 0$,[9] and a strictly convex abatement cost function $c_i(q_t^i)$, where $q_t^i \geq 0$ is abatement. Sources also share a common discount factor $\delta \in (0, 1)$ per regulatory period $t = 0, 1, 2, ...$ (a regulatory period is typically a year). The aggregate allocation a_t is initially generous but ultimately binding such that $u_t - a_t > 0$, where u_t denotes the aggregate unrestricted emissions (no index i for the aggregate variables). Without loss of generality,[10] we assume that the aggregate allocation is generous only in the first period $t = 0$ and constant thereafter:

$$a_t = \begin{cases} s_0 + a \text{ for } t = 0 \\ a \text{ for } t > 0, \end{cases}$$

where $s_0 > 0$ is the initial 'stock' allocation of permits that introduces the intertemporal gradualism into polluters' compliance strategies. Note that $a \geq 0$ is the long-run emissions limit (which could be zero as in the U.S. lead phasedown program). Assume for the moment that none of the stockholders is large; thus, we do not have to specify how the stock is allocated among agents. Aggregate unrestricted emissions are assumed to be constant over time, $u_t = u > a$.[11] While the first period reduction requirement may or may not be binding, we assume that s_0 is large enough to induce savings of permits.

Let us now describe the competitive equilibrium, which is not too different from a

[9] A firm's unrestricted emissions — also known as baseline emissions or business as usual emissions — are the emissions that the firm would have emitted in the absence of environmental regulation.

[10] In Section 4, we allow for trends in allocations and unrestricted emissions. In particular, there can be multiple periods of generous allocations leading to savings and endogenous accumulation of the stock to be drawn down when the annual allocations decline. Permits will also be saved and accumulated if unrestricted emissions sufficiently grow, that is, if marginal abatement costs grow faster than the interest rate in the absence of saving. None of these extensions change the essense of the results obtained from the basic model.

[11] Again, this will be relaxed in Section 4.

Hotelling equilibrium for a depletable stock market.[12] First, trading across firms implies that in all periods t marginal costs equal the price,

$$p_t = c_i'(q_t^i), \forall i \in \mathcal{I}. \tag{1}$$

Second, since holding permits across periods prevents arbitrage over time, equilibrium prices are equal in present value as long as some of the permit stock is left for the next period, $s_{t+1} > 0$. Exactly how long it takes to exhaust the initial stock depends on the stringency of the long-run reduction target $u - a > 0$, and the size of the initial stock s_0. Let T be the equilibrium exhaustion period. Then, T is the largest integer satisfying (1) for all t, and

$$\begin{aligned} p_t &= \delta p_{t+1}, \; 0 \leq t < T & (2)\\ q_T &\leq q_{T+1} = u - a & (3)\\ s_0 &= \sum\nolimits_{t=0}^{T} (u - a - q_t). & (4) \end{aligned}$$

These are the three Hotelling conditions that in exhaustible-resource theory are called the arbitrage, terminal, and exhaustion conditions, respectively. Thus, while (1) ensures that polluters equalize marginal costs across space, the Hotelling conditions ensure that firms reach the ultimate reduction target gradually so that marginal abatement costs are equalized in present value during the transition. Note that the terminal condition can also be written as

$$p_T \geq \delta p_{T+1},$$

where the inequality follows because of the discrete time; in general, stock s_0 cannot be divided between discrete time periods such that the boundary condition holds as an equality (when the length of the time period is made shorter, the gap $p_T - \delta p_{T+1}$ vanishes). Throughout this paper, we mean to model situations where the stock is large relative to the period length so that the competitive equilibrium prices are almost continuous in

[12] While we will discuss the differences between dynamic permit markets and exhaustible-resource markets, it might be useful to note two main differences here. First, the permit market still exists after the exhaustion of the excessive initial allocations while a typical exhaustible-resource market vanishes in the long run. This implies that long-run market power is a possibility in the permit market, which, if exercised, affects the depletion period equilibrium. Second, the annual demand for permits is a derived demand by the same parties that hold the stocks whereas the demand in an exhaustible-resource market comes from third parties. This affects the way the market power will be exercised, as we will discuss in detail below.

present value between T and $T+1$.[13]

We are interested in the effect of market power on this type of equilibrium. To this end, we isolate one agent, denoted by the index m, from $\mathcal{I}$ and call it the large agent. The remaining agents $i \in \mathcal{I}$ are studied as a single competitive unit, called the fringe, for which we will use the index f. In particular, the stock allocation for the large agent, $s_0^m = s_0 - s_0^f$, is now large compared to the holdings of any of the other fringe members. The annual allocations a^m and a^f are constants, as well as the unrestricted emissions u^m and u^f, and still satisfying

$$u - a = (u^m + u^f) - (a^m + a^f) > 0.$$

The fringe's aggregate cost is denoted by $c_f(q_t^f)$, which gives the minimum cost of achieving the total abatement q_t^f by sources in $\mathcal{I}$. This cost function is strictly convex, as well as the cost for the large agent, denoted by $c_m(q_t^m)$.

We look for a subgame-perfect equilibrium for the following game between the large polluter and the fringe. At the beginning of each period $t = 0, 1, 2, \ldots$ all agents observe the stock holdings of both the large polluter, s_t^m, and the fringe, s_t^f. We simplify the permits market clearing process by letting the large agent to announce first its spot sales of permits for period t, which we denote by $x_t^m > 0$ (< 0, if the large agent is buying permits).[14] Having observed stocks s_t^m and s_t^f and the large agent's sales x_t^m, fringe members form rational expectations about future supplies by the large agent and make their abatement decision q_t^f as to clear the market, i.e., $x_t^f = -x_t^m$, at a price p_t. In equilibrium p_t is such that it not only eliminates arbitrage possibilities across fringe firms at t, $p_t = c_f'(q_t^f)$, but also across periods, $p_t = \delta p_{t+1}$, as long as some of the fringe stock is left for the next period, that is

$$s_{t+1}^f = s_t^f + a^f - u^f + q_t^f - x_t^f > 0.$$

[13] To give the reader an idea why we are emphasizing this potential last period jump in present-value prices, we note that we will be making efficiency statements where it is important that the dominant agent in the market does not have much scope in moving the last period price. If the integer problem discussed above is severe, market power will be built into the model through the discrete time formulation that creates the last period problem. But when the stock is large relative to the period length (i.e., the stock is consumed over a span of several periods), the integer problem vanishes and with that any market power associated to this source.

[14] Without the Stackelberg timing for x_t^m we would have to specify a trading mechanism for clearing the spot market. In a typical exhaustible-resource market the problem does not arise since buyers are third party consumers.

It is clear that the fringe abatement strategy depends on the observable triple (x_t^m, s_t^m, s_t^f), so we will write $q_t^f = q^f(x_t^m, s_t^m, s_t^f)$. Note that we assume that the fringe does not observe q_t^m before abating at t, so the decisions on abatement are simultaneous.[15]

At each t and given stocks (s_t^m, s_t^f), the large agent chooses x_t^m and decides on q_t^m knowing that the fringe can correctly replicate the large agent's problem in the subgame starting at $t+1$. Let $V^m(s_t^m, s_t^f)$ denote the large agent's payoff given (s_t^m, s_t^f). Then, the equilibrium strategy $\{x^m(s_t^m, s_t^f), q^m(s_t^m, s_t^f)\}$, which we will find by backward induction, must solve

$$V^m(s_t^m, s_t^f) = \max_{\{x_t^m, q_t^m\}} \{p_t x_t^m - c_m(q_t^m) + \delta V^m(s_{t+1}^m, s_{t+1}^f)\} \tag{5}$$

where

$$\begin{aligned} s_{t+1}^m &= s_t^m + a_t^m - u_t^m + q_t^m - x_t^m, & (6)\\ s_{t+1}^f &= s_t^f + a_t^f - u_t^f + q_t^f - x_t^f, & (7)\\ x_t^f &= -x_t^m & (8)\\ q_t^f &= q^f(x_t^m, s_t^m, s_t^f), & (9)\\ p_t &= c_f'(q_t^f), & (10) \end{aligned}$$

and $q^f(x_t^m, s_t^m, s_t^f)$ is the fringe equilibrium strategy. While individual $i \in \mathcal{I}$ takes the equilibrium path $\{x_\tau^m, s_\tau^m, s_\tau^f\}_{\tau \geq t}$ as given, aggregate q_t^f for all $i \in \mathcal{I}$ can be solved from the allocation problem that minimizes the present-value compliance cost for the nonstrategic fringe as a whole. Letting $C^f(x_t^m, s_t^m, s_t^f)$ denote this cost aggregate given the observed triple (x_t^m, s_t^m, s_t^f), we can find $q^f(x_t^m, s_t^m, s_t^f)$ from

$$C^f(x_t^m, s_t^m, s_t^f) = \min_{q_t^f} \{c_f(q_t^f) + \delta C^f(\tilde{x}_{t+1}^m, \tilde{s}_{t+1}^m, s_{t+1}^f)\} \tag{11}$$

where $\tilde{x}_{t+1}^m$ and $\tilde{s}_{t+1}^m$ are taken as given by equilibrium expectations. Although fringe members do not directly observe the large agent's abatement q_t^m, they form (rational) expectations about the large agent's optimal abatement $q_t^m = q^m(s_t^m, s_t^f)$, which together with x_t^m is then used in (6) to predict the large agent's next period stock $\tilde{s}_{t+1}^m$. The expectation of $\tilde{s}_{t+1}^m$ is thus independent of what fringe members are choosing for q_t^f. In

[15] Note that not observing abatement q is most realistic because this information becomes publicly available only at the closing of the period as firms redeem permits to cover their emissions during that period. Assuming the Stackelberg timing not only for x_t^m but also for q_t^m does not change the results (Appendices A-B can be readily extended to cover this case).

contrast, the expectation of $\tilde{x}^m_{t+1}$ must be such that solving q^f_t and s^f_{t+1} from (11) and (7) fulfills this expectation, that is, $\tilde{x}^m_{t+1} = x^m(s^m_{t+1}, s^f_{t+1})$. In this way current actions are consistent with the next period subgame that the fringe members are rationally expecting. This resource-allocation problem is the appropriate objective for the nonstrategic fringe, because whenever market abatement solves (11) with equilibrium expectations, no individual $i \in \mathcal{I}$ can save on compliance costs by rearranging its plans.[16]

3 Characterization of the Equilibrium

We solve the game by backward induction, so it is natural to consider first what happens in the long run, i.e., when both stocks s^m_0 and s^f_0 have been consumed. Since our main motivation is to consider how large can be the transitory permit stock for an individual polluter without leading to market power problems, we do not want to assume market power through extreme annual allocations that determine the long-run trading positions. It is clear that market power after the depletion of the stocks can be ruled out by assuming efficient annual allocations a^{m*} and a^{f*} satisfying[17]

$$\bar{p} = c'_f(q^f_t = u^f - a^{f*}) = c'_m(q^m_t = u^m - a^{m*}). \tag{12}$$

Under this allocation the large agent chooses not to trade in the long-run equilibrium because the marginal revenue from the first sales is exactly equal to opportunity cost of selling. In other words, $c'_f(q^f_t) - x^m_t c''_f(q^f_t) = c'_m(q^m_t)$ holds when $x^m_t = 0$.

Having defined the efficient annual allocations, a^{m*} and a^{f*}, it is natural to define next the efficient stock allocations which have the same conceptual meaning as the efficient annual allocations: these endowments are such that no trading is needed for efficiency during the stock depletion phase. We denote the efficient stock allocations by s^{m*}_0 and s^{f*}_0. Then, if the large agent and the fringe choose socially efficient abatement strategies for all $t \geq 0$, their consumption shares of the given overall stock s_0 are exactly s^{m*}_0 and s^{f*}_0. The socially efficient abatement pair $\{q^{m*}_t, q^{f*}_t\}_{t\geq 0}$ is such that $q_t = q^{m*}_t + q^{f*}_t$

[16] We emphasize that (11) characterizes efficient resource allocation, constrained by the leader's behavior, without any strategic influence on the equilibrium path.

[17] Alternatively, we can assume that the long-run emissions goal is sufficiently tight that the long-run equilibrium price is fully governed by the price of backstop technologies, denoted by $\bar{p}$. This seems to a be a reasonable assumption for the carbon market and perhaps so for the sulfur market after recent announcements of much tighter limits for 2010 and beyond. In any case, we allow for long-run market power in Section 4. The relevant question there is the following: how large can the transitory stock be without creating market power that is additional to that coming from the annual allocations.

satisfies both $c_f'(q_t^{f*}) = c_m'(q_t^{m*})$ and the Hotelling conditions (2)-(4) ensuring efficient stock depletion. Since we shall show that the share s_0^{m*} is the critical stock needed for market manipulation, we define it here explicitly for future reference.

Definition 1 *Efficient consumption shares of the initial stock, s_0, are defined by*

$$\begin{aligned} s_0^{m*} &= \sum\nolimits_{t=0}^{T}(u^m - q_t^{m*} - a^{m*}) \\ s_0^{f*} &= \sum\nolimits_{t=0}^{T}(u^f - q_t^{f*} - a^{f*}), \end{aligned}$$

where the pair $\{q_t^{m*}, q_t^{f*}\}_{t\geq 0}$ defines the efficient abatement path.

Let us now assume some division of the stock $(s^m, s^f) \neq (s^{m*}, s^{f*})$ and consider how the large agent might move the market. It is clear that the stock will be exhausted at some point; let T^m and T^f denote the (endogenous) exhaustion periods for the large agent and the fringe, respectively (in equilibrium these will depend on the remaining stocks). There are three possibilities: (i) all agents, large and small, hold permits until the overall stock is exhausted ($T^m = T^f$); (ii) the large agent depletes its stock first ($T^m < T^f$); or (iii) the small agents deplete their stocks first ($T^m > T^f$). In the first two cases, the fringe arbitrage implies that market prices are equal in present-value throughout the equilibrium. Only the last case is consistent with an outcome where the large agent can implement a noncompetitive shape for the price path. In what follows, we will show that the manipulated equilibrium looks like the one in Figure 1, where the large agent acts as a seller for permits throughout the equilibrium.

In Figure 1, the manipulated price is initially higher than the competitive price (denoted by p^*) and grows at the rate of interest as long as the fringe is holding some stock. After the fringe period of exhaustion, denoted by T^f, the manipulated price grows at a lower rate because the large agent is the monopoly stockholder equalizing marginal revenues rather than prices in present value until the end of the storage period, T^m. The exercise of market power implies extended overall exhaustion time, $T^m > T$, where T is the socially optimal exhaustion period for the overall stock s_0, as defined by conditions (2)-(4). Thus, the large agent manipulates the market by saving too much of the stock, which shifts the initial abatement burden towards the fringe and leads to initially higher prices.

*** INSERT FIGURE 1 HERE OR BELOW ***

The equilibrium conditions that support this outcome are the following. First, as long as the fringe is saving some stock for the next period, $s_{t+1}^f > 0$, prices must be equal in present value, $p_t = \delta p_{t+1}$, implying that the market-clearing abatement for the fringe $q^f(x_t^m, s_t^m, s_t^f)$ must satisfy

$$p_t = c_f'(q_t^f) = \delta c_f'(q_{t+1}^f) \text{ for all } 0 \leq t < T^f. \tag{13}$$

Second, the large agent's equilibrium strategy is such that the gain from selling a marginal permit should be the same in present value for different periods. In this context, however, it is not obvious what is the appropriate marginal revenue concept, since the large agent is selling to other stockholders who adjust their storage decisions in response to sales. Nevertheless, the storage response will not change the principle that the present-value marginal gain from selling should be the same for all periods. Because in any period after the fringe exhaustion this gain is just the marginal revenue without the storage response, it must be the case that the subgame-perfect equilibrium gain from selling a marginal unit at any $t < T^f$ is equal, in present value, to the marginal revenue from sales at any $t > T^f$. The condition that ensures this indifference is the following

$$c_f'(q_t^f) - x_t^m c_f''(q_t^f) = \delta[c_f'(q_{t+1}^f) - x_{t+1}^m c_f''(q_{t+1}^f)] \tag{14}$$

for all $0 \leq t < T^m$.

Third, the large agent must not only achieve revenue maximization but also compliance cost minimization which is obtained by equalizing present-value marginal costs and, therefore,

$$c_m'(q_t^m) = \delta c_m'(q_{t+1}^m) \tag{15}$$

must hold for all $0 \leq t < T^m$. Finally, the large agent's strategy in equilibrium must be such that the gain from selling a marginal permit equals the opportunity cost of selling, that is,

$$c_f'(q_t^f) - x_t^m c_f''(q_t^f) = c_m'(q_t^m) \tag{16}$$

must hold for all t.

We can now state the condition for the above equilibrium outcome.

Proposition 1 *If $s_0^m > s_0^{m*}$, then subgame-perfect equilibrium has the above properties and satisfies the conditions (13)-(16).*

Proof. See Appendix A. ■

The proof is based on standard backward induction arguments. It determines for any given remaining stocks (s_t^m, s_t^f) the number of periods (stages) it takes for the large agent and fringe to sell their stocks such that at each stage the stocks and the large agent's optimal actions are as previously anticipated. For initial stocks (s_0^m, s_0^f), the number of stages is T^f for the fringe and T^m for the large agent. If for some reason the stocks go off the equilibrium path, the number of stages needed for stock depletion change, but the equilibrium is still characterized as above.

Before characterizing the equilibrium for $s_0^m \leq s_0^{*m}$, we need to discuss why and how the fringe storage response shows up in the equilibrium conditions. To this end, note that the marginal revenue for the large agent is

$$MR_t = p_t + x_t^m \frac{\partial p_t}{\partial q_t^f} \frac{\partial q_t^f}{\partial x_t^m} = c_f'(q_t^f) + x_t^m c_f''(q_t^f) \frac{\partial q_t^f}{\partial x_t^m} \tag{17}$$

where, in general, $\partial q_t^f / \partial x_t^m > -1$, if $s_{t+1}^f > 0$. This follows since the fringe's response to an increase in supply is to allocate more of its stock to the next period. Using (5), the first-order condition for sales, x_t^m, equates the marginal revenues and the opportunity cost of selling

$$\begin{aligned} MR_t \quad = \quad & \underbrace{-\delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^m} \frac{\partial s_{t+1}^m}{\partial x_t^m}}_{=c_m'(q_t^m)} \\ & \underbrace{-\delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^f} \left[\frac{\partial s_{t+1}^f}{\partial q_t^f} \frac{\partial q_t^f}{\partial x_t^m} + \frac{\partial s_{t+1}^f}{\partial x_t^m} \right]}_{=\Delta_t}. \end{aligned} \tag{18}$$

The first term on the RHS is the opportunity cost from not being able to use the sold permits for own compliance, which equals the marginal abatement cost. The second term is the opportunity cost from the fringe storage response, which is also positive but drops out as soon as the fringe exhausts its stock.[18] In Figure 2 we show the marginal revenue and the full opportunity cost. Note that because $c_m'(q_t^m)$ grows at the rate of interest, the net marginal revenue $MR_t - \Delta_t$ is also growing at this rate. Because of the fringe storage response, the large agent's sales become fungible across spot markets as long as the fringe is holding a stock, implying that selling a marginal unit today is like selling this unit to the fringe exhaustion period. But that period is the first period

[18] The term $[\frac{\partial s_{t+1}^f}{\partial q_t^f} \frac{\partial q_t^f}{\partial x_t^m} + \frac{\partial s_{t+1}^f}{\partial x_t^m}]$ is zero for $t \geq T^f$, because $\frac{\partial s_{t+1}^f}{\partial q_t^f} = 1 = \frac{\partial s_{t+1}^f}{\partial x_t^m}$ and $\frac{\partial q_t^f}{\partial x_t^m} = -1$.

without the storage response and, therefore, $\partial q^f_{T^f}/\partial x^m_{T^f} = -1$ and expression (16) must hold at T^f. Since the large agent is indifferent between putting a marginal unit on the market today $t < T^f$ or at $t = T^f$, both sides of the expression must grow at the rate of interest. Hence, the stated equilibrium conditions must hold.

*** INSERT FIGURE 2 HERE OR BELOW ***

The above description of market power is qualitatively consistent with Salant (1976) who considered a large oil seller facing a competitive fringe. However, when the large agent's allocation falls below the efficient share this connection is broken.

Proposition 2 *If $s^m_0 \leq s^{m*}_0$, the subgame-perfect depletion path is efficient.*

Proof. See Appendix B. ■

This result is central to our applications below. It follows, first, because one-shot deviations through large purchases that move the price above the competitive level are not profitable and, second, because the fringe arbitrage prevents the large agent from depressing the price through restricted purchases. Moving the price up is not profitable since the fringe is free-riding on the market power that the large agent seeks to achieve through large purchases; the gains from monopolizing the market spill over to the fringe asset values through the increase in the spot price, while the cost from materializing the price increase is borne by the large agent only. Formally, if the large agent makes a purchase at $T-1$ (one period before exhaustion) that is large enough to imply a permit holding in excess of its own demand at T, then the spot market at $T-1$ rationally anticipates this, leading to a price satisfying

$$p_{T-1} = \delta p_T > \delta[c'_f(q^f_T) - x^m_T c''_f(q^f_T)].$$

The equality is due to fringe arbitrage. It implies that the large agent is paying more for the permits than the marginal gain from sales, given by the discounted marginal revenue from market $t = T$. This argument holds for any number of periods before the overall stock exhaustion, implying that, if a subgame-perfect path starts with $s^m_0 \leq s^{m*}_0$, the large agent's share of the stock remains below the efficient share at any subsequent stage.

The large agent cannot depress the price as a large monopsonistic buyer either. At the last period $t = T$, because of the option to store, no fringe member is willing to sell at a price below $\delta\bar{p}$ where $\bar{p}$ is the price after the stock exhaustion (which is competitive). This argument applies to any period before exhaustion where the large agent's holding does not cover its future own demand along the equilibrium path; the fringe anticipates that reducing purchases today increases the need to buy more in later periods, which leads to more storage and, thereby, offsets the effect on the current spot price.

Further intuition for Proposition 2 can be provided with the aid of Figure 3. The perfectly competitive price path is denoted by p^*. Ask now, what would be the optimal purchase path for the large agent if it could fully commit to it at time $t = 0$? Since letting the large agent choose a spot purchase path is equivalent to letting it go to the spot market for a one-time stock purchase at time $t = 0$, conventional monopsony arguments would show that the large agent's optimal one-time stock purchase is strictly smaller than its purchases along the competitive path p^*. The new equilibrium price path would be p^{**} and the fringe's stock would be exhausted at $T^{**} > T$. The large agent, on the other hand, would move along c'_m and its own stock would be exhausted at $T^m < T^{**}$ (recall that all three paths p^*, p^{**} and c'_m rise at the rate of interest). But in our original game where players come to the spot market period after period, which is what happens in reality, p^{**} and c'_m are not time consistent (i.e., violate subgame perfection). The easiest way to see this is by observing that at time T^m the large agent would like to make additional purchases, which would drive prices up. Since fringe members anticipate and arbitrate this price jump the actual equilibrium path would lie somewhere between p^{**} and p^* (and c'_m closer to p^*). But the large agent has the opportunity to move not twice but in each and every period, so the only time-consistent path is the perfectly competitive path p^*.

*** INSERT FIGURE 3 HERE ***

The time-inconsistency problem of our large agent is similar to that of a durable-good monopolist (Coase, 1972; Bulow, 1982). But unlike the durable-good monopolist, it is not clear to us how our large agent can escape from the Coase conjecture. The existence of the backstop price $\bar{p}$ together with the fact the stocks are in the hands of the fringe rule out the construction of punishment strategies *a la* Ausubel and Deneckere (1987) and Gul (1987) that could support the monopsony path. Fringe's rational expectations cannot support a price path that never reaches $\bar{p}$ but approaches it asymptotically.

4 Extensions

4.1 Trends in allocations and emissions

In most cases the transitory compliance flexibility is not created by a one-time allocation of a large stock of permits but rather by a stream of generous annual allocations, as in the U.S. Acid Rain Program (see footnote 1). In a carbon market, the emissions constraint is likely to become tighter in the future not only due to lower allocations but also to significantly higher unrestricted emissions prompted by economic growth. This is particularly so for economies in transition and developing countries whose annual permits may well cover current emission but not those in the future as economic growth takes place.

To cover these situations, let us now consider aggregate allocation and unrestricted emission sequences, $\{a_t, u_t\}_{t\geq 0}$,[19] such that the reduction target $u_t - a_t$ changes over time in a way that makes it attractive for firms to first save and build up a stock of permits and then draw it down as the reduction targets become tighter.[20] As long as the market is leaving some stock for the next period, the efficient equilibrium is characterized by the Hotelling conditions, with the exhaustion condition replaced by the requirement that aggregate permit savings are equal to the stock consumption during the stock-depletion phase.[21]

Although the stock available is now endogenously accumulated, each agent's efficient share of the stock at t can be defined almost as before: it is a stock holding at t that just covers the agent's future consumption net of the agent's own savings. Let us now consider the efficient shares for the large agent and fringe, facing reduction targets given by $\{a_t^m, u_t^m\}_{t\geq 0}$ and $\{a_t^f, u_t^f\}_{t\geq 0}$. Then, the large agent's efficient share of the stock at t

[19] We continue assuming that $\{a_t, u_t\}_{t\geq 0}$ is known with certainty. Uncertainty would provide an additional storage motive, besides the one coming from tightening targets, as in standard commodity storage models (Williams and Wright, 1991). It seems to us that uncertainty may exacerbate the exercise of market power, but the full analysis and the effect on the critical holding needed for market power is beyond the scope of this paper.

[20] If the reduction target increases because of economic growth, as in climate change, it is perhaps not clear why the marginal costs should ever level off. However, the targets will also induce technical change, implying that abatement costs will also change over time (see, e.g., Goulder and Mathai, 2000). While we do not explicitly include this effect, it is clear that the presence of technical change will limit the permit storage motive.

[21] Obviously, the same description applies irrespective of whether savings start at $t = 0$ or at some later point $t > 0$, or, perhaps, at many distinct points in time. The last case is a possibility if the trading program has multiple distinct stages of tightening targets such that the stages are relatively far apart, i.e., one storage period may end before the next one starts.

is just enough to cover the large agent's future own net demand:

$$s_t^{m*} = \sum\nolimits_{\tau=t}^{T} (u_\tau^m - q_\tau^{m*} - a_\tau^m),$$

where q_τ^{m*} denotes the socially efficient abatement path for the large agent. On the other hand, the socially efficient stock holdings, which are denoted by

$$\hat{s}_t^m = \sum\nolimits_{\tau=0}^{t} (a_\tau^m - u_\tau^m + q_\tau^{m*}),$$

will typically differ from s_t^{m*}. It can nevertheless be established:

Proposition 3 *If $\hat{s}_t^m \leq s_t^{m*}$ for all t, the subgame-perfect equilibrium is efficient.*

The formal proof follows the steps of the proof of Proposition 2 and is therefore omitted. During the stock draw-down phase it is clear that we can directly follow the reasoning of Proposition 2 because it does not make any difference whether the market participants' permit holdings were obtained through savings or initial stock allocations. Since, by $\hat{s}_t^m \leq s_t^{m*}$, the large agent needs to be a net buyer in the market to cover its own future demand, we can consider two cases as in Proposition 2. First, the large agent cannot depress the price path down from the efficient path through restricted purchases (and increased own abatement) because of the fringe arbitrage; the fringe can store permits and make sure that its asset values do not go below the long-run competitive price in present value. Second, the large agent cannot profitably make one-shot purchases large enough to monopolize the market such that the large agent would be a seller at some later point; the market would more than fully appropriate the gains from such an attempt. As a result, the large agent will in equilibrium trade quantities that allow cost-effective compliance but do not move the market away from perfect competition. This same argument holds for dates at which the market is accumulating the aggregate stock, because the argument does not depend on whether the large agent is a net saver or user at t.

The implications of Proposition 3 can be illustrated with the following two cases. Consider first the case in which the large agent's cumulated efficient savings $\hat{s}_t^m$ are non-negative for all t. Then, it suffices to check at date $t = 0$ that the large agent's cumulative allocation does not exceed the cumulative emissions. That is, if it holds that

$$\sum\nolimits_{t=0}^{T} a_t^m \leq \sum\nolimits_{t=0}^{T} (u_t^m - q_t^{m*}), \tag{19}$$

then, it is the case that $\hat{s}_t^m \leq s_t^{m*}$ holds throughout the subgame-perfect equilibrium.

Consider now the case depicted in Figure 4 which shows the time paths for the large agent's allocation and socially efficient emissions. Suppose that the areas in the figure are such that $B - A = C$, which implies that (19) holds as an equality at $t = 0$. Suppose next that the market has indeed followed the efficient path from $t = 0$ to $t = t'$. This requires the large agent to buy permits in the market in an amount equal to area A. At $t = t'$, however, Proposition 3 cannot continue holding because $B > C$. In other words, assuming efficiency up to $t = t'$ implies that the equilibrium of the continuation game at $t = t'$ is not competitive but characterized as in Proposition 1. Therefore, the equilibrium path starting at $t = 0$ must have the shape of the noncompetitive path depicted in Fig. 1.

It is easy to see that moving to the less competitive equilibrium only benefits the fringe but not the large agent. The large agent is forced to be a net buyer in subgame-perfect equilibrium (it follows a lower marginal abatement path). In other words, market power shifts the emission path $u_t^m - q_t^m$ to the right as shown in Figure 4, whereas in the competitive equilibrium net purchases are zero, i.e., $B - A = C$. It then follows directly from Proposition 2 that the net purchase is not profitable: the large agent buys permits at higher than competitive prices and then sells them, on average, at lower prices. Thus the gains from market manipulation spill over to fringe asset values.

Although using future allocations for current compliance is ruled out by regulatory design,[22] the large agent can restore the competitive solution as a subgame-perfect equilibrium by swapping part of its far-term allocations for near-term allocations of competitive agents. To be more precise, the large agent would need to swap at the least an amount equal to area A in Figure 4.[23]

*** INSERT FIGURE 4 HERE ***

4.2 Long-run market power

So far we have considered that after exhaustion of the overall stock firms follow perfect competition. This is the result of assuming either that the large agent's long-run permit allocation is close to its long-run competitive emissions or that the long-run equilibrium

[22] In all existing and proposed market designs firms are not allowed to "borrow" permits from far-term allocatios to cover near-term emissions (Tietenberg, 2006).

[23] Although not necessarily related to the market power reasons discussed here, it is interesting to note that swap trading is commonly used in the US sulfur market (see Ellerman et al., 2000).

price of permits is fully governed by the price of backstop technologies (see (12) and footnote 18). While the long-run perfect competition assumption is reasonable for both of our applications below, it is still interesting to explore the implications of long-run market power on the evolution of the permits stock. Since long-run market power is intimately related to the large agent's long-run annual allocation relative to its emissions, it should be possible to make a distinction between the market power attributable to the long-run annual allocations and the transitory market power attributable to the stock allocations.[24]

The first relevant case is that of long-run monopoly power, which following the equilibrium conditions of Propositions 1 and 2 is illustrated in Figure 5. For clarity, we assume that long-run allocations are constants. Then, the long-run market power coming from an annual allocation $a^m > a^{m*}$ implies a higher than competitive price $p^m > p^*$. Whether there is any further transitory market power coming from the stock allocation depends, as in previous sections, on the large agent's share of the transitory stock. The equilibrium without transitory market power is characterized by a competitive storage period with a distorted terminal price at $p^m > p^*$, where the ending time is denoted by T_0^f to reflect the fact that the fringe is holding a stock to the very end of the storage period. This path is depicted in Fig. 5 as p_0^m. The critical stock is defined by this path as the holding that just covers the large agent's own compliance needs without any spot trading additional to that prevailing after the stock exhaustion. Note that the overall stock is depleted faster than what is socially optimal, $T_0^f < T$, because the long-run monopoly power allows the large agent to commit to consuming more than the efficient share of the available overall allocation.

The transitory market power, that arises for holdings above the critical level, leads to an equilibrium price path p_1^m with a familiar shape. This path reaches price p^m at $t = T^m$, which can be smaller or larger than T depending on whether the long-run shortening effect is greater or smaller than the transitory extending effect.

*** INSERT FIGURE 5 HERE ***

The second relevant case is that of long-run monopsony power, which is illustrated in

[24]Note that in the presence of long-run market power we may no longer treat the stock depletion game as a strictly finite-horizon game for the case in which the large agent is not a single firm but a cartel of two or more firms. One could argue, for example, that the (subgame-perfect) threat of falling into the (long-run) noncooperative equilibrium may even allow firms to sustain monoposony power during the stock depletion phase.

Figure 6. Here, the equilibrium path without transitory market power, which is denoted by p_0^m, stays below the socially efficient path throughout ending at $p^m < p^*$. The time of overall stock depletion is extended, i.e., $T_0^f > T$, because the long-run monopsonist restricts purchases and is thereby able to depress the price level throughout the equilibrium. Again, this path defines the critical stock for the transitory market power as the holding that allows compliance cost minimization without adding to the long-run trading activity. Quite interestingly, for stockholdings above this critical level, the large agent has more than its own need during the transition, so that the agent is first a seller of permits but later on becomes a buyer of permits. The price path with transitory market power is denoted by p_1^m which ends at $t = T^m$ and intersects the marginal cost $c_m'(q_t^m)$ at the point where $x_t^m = 0$, so that this intersection identifies the precise moment at which the large agent start coming to the market to buy permits (while continue consuming from its own stock). Note the transitory motive to keep marginal net revenues equalized in present value extends the overall depletion period further in addition to the extension coming from the long-run monopsony power and, therefore, T^m is unambiguously greater than T.

*** INSERT FIGURE 6 HERE ***

5 Applications

We illustrate the use of our theoretical results with two very different applications: the carbon market that may eventually develop under the Kyoto Protocol and beyond and the existing sulfur market of the U.S. Acid Rain Program of the 1990 Clean Air Act Amendments (CAAA).

5.1 Carbon trading

Motivated by the widespread concern about Russia's ability to exercise market power (e.g., Bernard et al., 2003; Manne and Richels, 2001; Hagem and Westskog, 1998), the purpose of this first application is to illustrate the use of our theory to explore whether and to what extent Russia's ability to manipulate the carbon market is ameliorated when we take into consideration the possibility of storing today's permits for future use. It should be clear that we are not providing a test of market-power *per se*, but only necessary conditions for the created trading institution to be efficient.

Except for the permit allocations established by the Kyoto Protocol for the period 2008-2012, the data we used in this exercise come from work done at the MIT Joint Program on the Science and Policy of Global Change. Since the computable general equilibrium model developed by MIT — known as the MIT-EPPA model (Babiker et al., 2001) — aggregates all Former Soviet Union (FSU) countries into one region, we take the FSU region as our large agent. Unrestricted emissions for years 2010-2050 and different Kyoto regions come from the MIT-EPPA runs reported in Bernard et al. (2003).[25] Marginal cost curves are borrowed from Ellerman and Decaux (1998). Carbon permit prices are capped by the existence of backstop technologies available at prices in the range of $400-500 per ton of carbon (all prices are 1995 prices). Following the approach of Bernard et al. (2003), we also allow for some voluntary participation from countries outside the Kyoto Protocol. Under the Protocol's Clean Development Mechanism (CDM) these countries can engage in emission reduction projects generating additional supply of carbon permits to the market.[26] Finally, we adopt the commonly used discount rate of 5% (e.g., Jacoby et al., 1999).

Let us first consider market equilibrium outcomes when the Kyoto commitment period, 2008-2012, is taken in isolation from future commitment periods (results are presented only for 2010, which is taken as the representative year for this five-year period). The first row of Table 1 presents expected unrestricted emissions, i.e., emissions in the absence of regulation. The next two rows show, respectively, the perfectly competitive equilibrium solution and the outcome when FSU exercises maximum market power. FSU emissions in perfect competition are 75% of its permit allocation, which is an indication of potential for market power. In implementing the market-power outcome FSU abates no emissions and restricts its supply of hot air (permits above unrestricted emissions) in 18 million tons of carbon (mtC) from its total of 186 mtC almost doubling the equilibrium price.

*** INSERT TABLE 1 HERE OR BELOW ***

[25] We thank John Reilly of MIT for sharing the background data of this paper with us. Besides FSU, the remaining Kyoto regions of the MIT-EPPA model are Japan (JPN), The European Union (EEC), other OECD nations including Australia, Canada and New Zeland (OOE), and Eastern European economies in transition (EET). For more details see Babiker et al. (2001).

[26] Unless otherwise indicated we use $\alpha = 300$ for the supply coefficient in the CDM equation of Bernard et al. (2003). We cap CDM credits at 1000 million tons of carbon (mtC) to keep them close to the total allocation of Kyoto regions other than the FSU's. Note that CDM credits can be interpreted more generally as the inclusion of non-Kyoto countries into binding commitments as their income per capita increase.

Let us now extend the regulatory window beyond Kyoto while keeping the same permit trading regulatory approach. In addition to the above data assumptions, we need to make assumptions on Post-Kyoto permit allocations/endowments. We simplify this speculative exercise by borrowing from the discussion in Jacoby et al. (1999), where one can envision that countries accepting binding commitments will see their future permits allocations declining at some rate between 1 and 2% per year until they reach some minimum level that we believe should not be much lower than 50%.[27]

We consider two different allocations. In the first case we let the permit allocation of Kyoto regions to remain equal to the Kyoto allocation for the next two commitment periods and then decline at an annual rate of 2% for the remaining periods (following the Kyoto design, post-Kyoto commitment periods are also taken as five-year periods). Table 2 presents the perfectly competitive path for such allocations. The stock of permits is totally exhausted at year 2050 when carbon prices approach backstop technology prices around 450 \$/tC. Since FSU's cumulative emissions over 2010-2050 are equal to its cumulative allocation of permits during that time, the competitive path is, according to our theory, the equilibrium path.

*** INSERT TABLE 2 HERE OR BELOW ***

Despite the equilibrium path of Table 2 does not exhibit market power, it is important to understand that agents' subgame perfect equilibrium strategies do impose restrictions on the maximum amount of stock-holdings that the large agent can have at any point in time before constituting a (costly) deviation. Such amounts are the efficient shares s_t^{m*} identified in Section 4.1 and are shown in the penultimate column of Table 2. Note that because FSU cumulative emissions are equal to its cumulative allocation, its stock-holdings $\hat{s}_t^m$ coincide with the efficient shares at all times. Obviously, FSU can sell part or all of its stock $\hat{s}_t^m$ in the market without altering the competitive equilibrium.

Consider now a relatively more generous allocation for FSU. In particular, let the future permits allocations of Kyoto regions decline by 1% instead of 2% and reduce the CDM supply coefficient by half. Table 3 presents the perfectly competitive path. Since FSU's cumulative permits over the period 2010-2050 are now above its cumulative emissions, the actual equilibrium path (not shown) should in principle depart from the competitive path with initial prices above the competitive ones. Based on our theory

[27] At least this is consistent with recent announcements by different countries. For example, the UK government has set the target of cutting CO2 emissions to 60% below 1990 levels by 2050. For more go to http://www.dti.gov.uk/energy/whitepaper/index.shtml.

(Proposition 3), however, there is a simple way to restore competitive pricing: by requiring FSU to always keep its current permit stock $\hat{s}_t^m$ at or below its efficient level s_t^{m*}. As can be inferred from the s_t^{m*} figures in the penultimate column of Table 3, these stock-holding limits will only be binding during the first three commitment periods. Note also that since stock-holdings cannot go negative by construction, the negative numbers of the first two commitment periods must be interpreted as zero stock-holdings during that time.

*** INSERT TABLE 3 HERE ***

An alternative way to eliminate market-power is by requiring the large agent to dispose part of its permit allocation by taking short positions in the forward market. In any case, when market power is believed to be a problem, our theoretical results should prove useful in understanding how the imposition of stock-holding or forward-contracting requirements can make an early generous allocation of permits be fully compatible with competitive behavior. This seems to be particularly relevant for discussions on how to incorporate large developing countries such as China under a global carbon trading regime.

5.2 Sulfur trading

Our second application differs from the carbon application in important ways. Unlike the carbon market, the market for sulfur dioxide (SO_2) emissions has been operating since the early 90s; right after 1990 CAAA allocated allowances/permits to electric utility units for the next 30 years in designated electronic accounts.[28] So, we can make use of agents' actual behaviors, as opposed to hypothetical ones, to check whether our necessary condition for market manipulation holds or not. Note that our exercise is by no means a test for market power; for that we would need either to have or to estimate marginal abatement cost curves.

The data we use for our exercise, which is publicly available, comprises electric utility units' annual SO_2 emissions and allowance allocations from 1995 — the first year of compliance with SO_2 limits — through 2003. We purposefully exclude 2004 numbers because of the four-fold increase in SO_2 allowance prices during 2004-05 in response to the proposed implementation of the Clean Air Interstate Rule, which would effectively

[28] For details in market design and performance see Ellerman et al. (2000) and Joskow et al. (1998).

lower the SO_2 limits established in the original regulatory design by two-thirds in two steps beginning in 2010. Although this recent price increase provides further evidence that in anticipation of tighter limits firms do respond by building up extra stocks (or by depleting existing stocks less intensively), we concentrate on firms' behavior under the original regulatory design where we have nine years of data and can therefore, make reasonable projections as needed. The long-term emissions goal under the original design is slightly above 9 million tons of SO_2.

Following our theory, the exercise consists in identifying potential strategic players and checking whether or not the necessary condition for market manipulation (that initial allocations be above perfectly competitive emissions, i.e., $s_0^m > s_0^{m*}$) holds. The potential strategic players in our analysis, acting either individually or as a cohesive group, are assumed to be the four largest permit-stock holding companies — American Electric Power, Southern Company, FirstEnergy[29] and Allegheny Power — that together account for 42.5% of the permits allocated during Phase I of the Acid Rain Program, i.e., 1995-1999, which corresponds to the "generous-allocation" phase.[30] While s_0^m is readily obtained from agents' cumulative permit allocations, calculating s_0^{m*} would seem to require a more elaborate procedure based, perhaps, on some abatement cost estimates. But unlike the carbon application, this is not necessarily so because we have actual emissions data.

Table 4 presents a summary of compliance paths for the two largest strategic players, the Group of Four, as well as for all firms. The noticeable discontinuities in 2000 — the first year of Phase II — are due to both a significant decrease in permit allocations and the entry of a large number of previously unregulated sources.[31] Precisely because of this discontinuity in the regulatory design firms had incentives to build a large stock of permits during Phase I, which reached an aggregate peak of 11.65 million allowance by the end of 1999. Although strategic players, either individually or as a group, present a

[29]Note that FirstEnergy was the result of mergers in 1997 and 2001 but for the purpose of this analysis we make the conservative assumption that all mergers were consummated by 1995.

[30]Their individual shares of Phase I permits are 13.2, 13.5, 9.3 and 6.5%, respectively. The next permit-stock holder is Union Electric Co. with 4.2% of the permits. Neither was Tennessee Valley Authority (TVA), which received 9.2% of Phase I permits, considered as part of the potential strategic players for the simple reason that it is a federal corporation that reports to the U.S. Congress. Even if we add these two companies to the group, forming a coalition with 56% of the market, our conclusions remain unaltered because at the time of the exhaustion of the overall stock TVA shows a deficit of permits while Union Electric a mild surplus.

[31]Some of these unregulated sources voluntarily opted in earlier into Phase I and received permits under the so-called Substitution Provision. Since with very few exceptions opt-in sources have helped utilities to increase their permit stocks (Montero, 1999), for the purpose of our analysis we treat these sources (with their emissions and allocations) as Phase I sources.

significant surplus of permits by 1999 that may be indicative of possible market power problems,[32] it is also true that these players are rapidly depleting their stocks from the simple fact that their annual emissions are above their annual permit allocations. By 2003, the last year for which we have actual emissions, the stock of the Group of Four is already reduced to 1.11 million allowances while the aggregate stock is still significant at 6.47 million allowances.

*** INSERT TABLE 4 HERE OR BELOW ***

Taking a linear extrapolation of aggregate emissions from its 2003 level of 10.60 million tons to the long-run emissions limit of 9.12 million tons, we project the aggregate stock of permits to be depleted by 2012, which is very much in line with the more elaborated projections of Ellerman and Montero (2007). Assuming that the share of emissions for the projected years is the same as during 2000-2003,[33] the numbers in the last row of Table 4 show that the compliance paths followed by the potential strategic players, taken either individually or collectively, are, according to our theory, consistent with perfect competition.[34] As established by Propositions 2 and 3, a necessary condition for a large agent, whether a firm or a cartel, to exercise market power is that of being a net seller of permits. But the net sellers in this market are many of the smaller players, not the large players.

Our focus has been on transitory market power, i.e., market power during the evolution of the permit stock. Looking at long-run market power, as discussed in Section 4.2, is not feasible without having data on actual long-run behavior. We believe, however, long-run market power to be less of a problem because large players' long-run allocations are greatly reduced in relative terms. The largest player (Southern Company) receives less than 8% of the total allocation and the Group of Four only 23%. Any larger coalition of players would be hard to imagine. Moreover, it is quite possible that the long-run market equilibrium would have been dictated by the price of scrubbing technologies capable

[32] In reality their actual stocks may be larger or smaller than these figures depending on firms' market trading activity. Our theoretical predictions, however, are independent of trading activity as long as it is observed, which in this particular case can be done with the aid of the U.S. EPA allowance tracking system. We will come back to the issue of imperfect observability in the concluding section.

[33] This is a reasonable assumption in the sense that the extra reduction needed to reach the long-run limit is moderate and not much larger than the reduction that has already taken place in Phase II. In addition, since we know that all firms move along their marginal cost curves at the (common) discount rate regardless of the exercise of market power, their emission shares should not vary much if we believe their marginal cost curves have similar curvatures in the relevant range.

[34] The same argument applies if the overall stock is expected to be depleted much earlier, say, in 2009.

of removing up to 95% of SO_2 emissions.

6 Concluding Remarks

We developed a model of a market for storable pollution permits in which a large polluting agent and a fringe of small agents gradually consume a stock of permits until they reach a long-run emissions limit. We characterized the properties of the subgame-perfect equilibrium for different permit allocations and found the conditions under which the large agent fails to exercise any degree of market power. The latter occurs when the large agent's intertemporal permits endowment is equal or below its efficient allocation (i.e., the allocation profile that would cover its total emissions along the perfectly competitive path). When the endowment is above the efficient allocation, the large agent exercises market power very much like a large supplier of an exhaustible resource. At least three policy implications come out from these results. The first is that allocations to early years that exceed the large agent's current emissions do not necessarily lead to market power problems if allocations to later years are below future needs (this was the case in the sulfur application). The second implication is that any redistribution of permits from the large agent to small agents will unambiguously make the exercise of market power less likely (some of this was discussed in the carbon application). Closely related to the latter, a third implication is that our results make a stronger case for auctioning off permits instead of allocating them for free (as considered throughout the paper). Assuming that there is an after-auction market where firms can exchange permits, any attempt by the large agent to depress auction prices would be arbitrated by the small fringe players —bidding demand schedules above their true marginal costs— in anticipation to the large agent's incentives to buy additional permits in the after market.[35]

In view of the different type of market transactions that we observe in the US sulfur market (see Ellerman et al., 2000), it is natural to ask whether and how our equilibrium solution would change if we extend agents' action space to stock and forward transactions. Since stock transactions are observable (as spot transactions are), allowing agents to trade large chunk of permits does not introduce any changes in our equilibrium solution. Our definition of spot transaction implicitly allows for this interpretation. The same does not apply to forward trading, however. A large agent with an initial stock large enough

[35] Note that uniform price auctions can suffer from under pricing even for a large number of small bidders (Wilson, 1979).

to move the market wants to avoid forward transactions.[36] By selling part of its stock forward, the large agent introduces a time-inconsistency problem that makes it worse off. Fringe members correctly anticipate that right after the large agent has committed part of its stock forward, the continuation game becomes more competitive (Liski and Montero, 2006a).[37]

Our model also assumes that agents' stock-holdings are observable at the beginning of each period. While the EPA allowance tracking system may significantly facilitate keeping track of agents' stock-holdings in the US sulfur market,[38] it is still interesting to ask what would happen to our equilibrium solution if we let stock-holdings be somewhat private information (or alternatively, assume that large stockholders can use third parties, e.g., brokers, to hide their identities). Lewis and Schmalensee (1982) have already identified this incomplete information problem for a conventional nonrenewable resource market where agents' reserves are only imperfectly observed. They argue that Salant's (1976) solution no longer holds: the large agent could increase profits (above Salant's) by covertly producing either more or less than its Salant equilibrium output. We see the exact same problems affecting our equilibrium solution. Unfortunately, Lewis and Schmalensee (1976) do not offer much insight as to what the new equilibrium conditions might look like. We think this is an interesting topic for future research.

Uncertainty is another ingredient absent in our model. This may be particularly relevant for the carbon application that shows time-horizons of several decades. There are multiple sources of uncertainty related to different aspects of the problem such as technology innovation, economic growth, future permit allocations, timing and extent of participation of non-Kyoto countries, etc. How these uncertainties, acting either individually or collectively, could affect the essence of our equilibrium solution is not immediately obvious to us because of the irreversibility associated to the build-up and depletion of the permits stock. Tackling these issues may require to put together the strategic elements found in this paper with those of the literature of investment under uncertainty (e.g., Dixit and Pindyck, 1994).

Although we have only formally considered the case of a single large agent, we do

[36] Even in the absence of uncertainty it is possible that agents in oligopolistic markets get engaged in forward trading for pure strategic reasons (Allaz and Vila, 1993; Liski and Montero, 2006b).

[37] If the large agent is a cartel of firms, one could argue that firms may need to resort to forward trading in order to sustain tacit collusion. But if anything, we suspect that this should be done through long positions, i.e., by buying forward contracts (Liski and Montero, 2006b).

[38] For a description of the EPA tracking system go to http://www.epa.gov/airmarkets/tracking/.

not see how our results would qualitatively change with two or more large firms.[39] Large permit sellers do not face any commitment problems, so their marginal costs will be below prices and their marginal revenues equalized in present value terms along the equilibrium path. On the other hand, large permit buyers continue facing the same commitment problem than the single buyer did, so in equilibrium their marginal costs must be equal to prices throughout the equilibrium path.

Finally, one can view our sulfur application as one of the few attempts at empirically studying market power in pollution permit trading,[40] but it is important to emphasize that we do not provide a formal test of market power (a test comparing prices and marginal abatement costs) in part because we do not have reliable estimates of marginal cost curves. Our exercise simply showed that the initial allocations of permits to the large firms made these firms net buyers in the market, ruling out any exercise of market power according to our theory. We nevertheless think it is an interesting area for future research estimating marginal cost curves from publicly available data such as prices and emissions and then comparing those cost figures to actual prices. Notice that finding evidence of market power (i.e., departure from marginal cost pricing) under such a test would open up an entirely new set of theoretical questions as to what could explain the presence of market power beyond that attributed to the initial allocation of permits.

Appendix A: Proof of Proposition 1

Proof. The proof has two main parts. First, we show that working backwards from the large agent's exhaustion date T^m to the fringe exhaustion date T^f, and finally to initial time $t = 0$, leads to equilibrium conditions (13)-(16). Second, we show that conditions (13)-(16) pin down unique T^m and T^f such that $T^m > T^f$ if $s_0^m > s_0^{m*}$.

First part. The large agent's problem starting at the fringe exhaustion date T^f is a monopoly decision problem whose solution maximizes the value $V^m(s^m_{T^f}, s^f_{T^f})$ which was defined in (5) and is restated here for convenience

$$V^m(s_t^m, s_t^f) = \max_{\{x_t^m, q_t^m\}} \{p_t x_t^m - c_m(q_t^m) + \delta V^m(s_{t+1}^m, s_{t+1}^f)\}. \tag{20}$$

[39] They may change if we introduce collusion considerations.
[40] Kolstad and Wolak (2003) is another attempt.

At any stage $t \in \{T^f, ..., T^m - 1\}$, the optimal choice for x_t^m and q_t^m must satisfy

$$\begin{aligned} c_f'(q_t^f) + x_t^m c_f''(q_t^f)\frac{\partial q_t^f}{\partial x_t^m} + \delta\frac{\partial V^m(s_{t+1}^m, 0)}{\partial s_{t+1}^m}\frac{\partial s_{t+1}^m}{\partial x_t^m} &= 0 \\ -c_m'(q_t^m) + \delta\frac{\partial V^m(s_{t+1}^m, 0)}{\partial s_{t+1}^m}\frac{\partial s_{t+1}^m}{\partial q_t^m} &= 0. \end{aligned}$$

Note that since the fringe is not storing permits, its response to sales satisfies $\partial q_t^f/\partial x_t^m = -1$ (see (7) with $s_{t+1}^f = 0$). This together with $\partial s_{t+1}^m/\partial x_t^m = -1$ and $\partial s_{t+1}^m/\partial q_t^m = 1$ implies that the first-order conditions can be combined to yield

$$c_f'(q_t^f) - x_t^m c_f''(q_t^f) = c_m'(q_t^m), \tag{21}$$

which is the condition (16) in the text. Applying the envelope theorem to (20) shows that for any $t \in \{T^f, ..., T^m - 1\}$,

$$\frac{\partial V^m(s_t^m, 0)}{\partial s_t^m} = \delta\frac{\partial V^m(s_{t+1}^m, 0)}{\partial s_{t+1}^m}. \tag{22}$$

For $t = T^m$, we must have

$$\begin{aligned} \frac{\partial V^m(s_{T^m}^m, 0)}{\partial s_{T^m}^m} &= c_f'(q_{T^m}^f) - x_{T^m}^m c_f''(q_{T^m}^f) \\ &= c_m'(q_{T^m}^m) \\ &\geq \delta c_m'(u^m - a^m). \end{aligned} \tag{23}$$

The first equality follows from the fact that T^m is the last sales date. The second equality ensures that the opportunity costs of selling or using permits must be equal. The inequality in (23) ensures that the monopoly is willing to exhaust at T^m rather than saving some permits to $T^m + 1$. Combining (22) and (23) implies that the conditions (14)-(15), stated in the text, hold for all $t \in \{T^f, ..., T^m - 1\}$.

The following Lemma states the relevant information needed about the monopoly phase for the analysis of subgames preceding the fringe exit.

Lemma 1 *Suppose T^f is the fringe exhaustion date in the subgame-perfect equilibrium.*

Then, the large agent's value function at T^f satisfies

$$\frac{\partial V^m(s^m_{T^f}, s^f_{T^f})}{\partial s^m_{T^f}} = c'_f(q^f_{T^f}) - x^m_{T^f} c''_f(q^f_{T^f}) \tag{24}$$

$$\frac{\partial V^m(s^m_{T^f}, s^f_{T^f})}{\partial s^f_{T^f}} = -x^m_{T^f} c''_f(q^f_{T^f}). \tag{25}$$

Proof. The first equality follows from (22) and (23). The second follows by applying the Envelope Theorem to $V^m(s^m_{T^f}, s^f_{T^f})$ and using the fact that $s^f_{T^f+1} = 0$. ■

The next Lemma builds upon Lemma 1 to derive an equilibrium condition that will readily lead to the verification of the conditions characterizing the subgame-perfect equilibrium path.

Lemma 2 *Let $t \in \{0, ..., T^f - 1\}$ be some date such that the fringe is holding a stock for the next period in the subgame-perfect equilibrium. Then, the following must hold:*

$$c'_f(q^f_t) + x^m_t c''_f(q^f_t)\frac{\partial q^f_t}{\partial x^m_t} = \delta[c'_f(q^f_{t+1}) + x^m_{t+1} c''_f(q^f_{t+1})\frac{\partial s^f_{t+1}}{\partial q^f_t}\frac{\partial q^f_t}{\partial x^m_t}]. \tag{26}$$

Proof. Sales at any $t \in \{0, ..., T^f - 1\}$ must satisfy

$$\begin{aligned} & c'_f(q^f_t) + x^m_t c''_f(q^f_t)\frac{\partial q^f_t}{\partial x^m_t} \\ & +\delta\frac{\partial V^m(s^m_{t+1}, s^f_{t+1})}{\partial s^m_{t+1}}\frac{\partial s^m_{t+1}}{\partial x^m_t} \\ & +\delta\frac{\partial V^m(s^m_{t+1}, s^f_{t+1})}{\partial s^f_{t+1}}[\frac{\partial s^f_{t+1}}{\partial q^f_t}\frac{\partial q^f_t}{\partial x^m_t} + \frac{\partial s^f_{t+1}}{\partial x^m_t}] = 0. \end{aligned} \tag{27}$$

In particular, at $t = T^f - 1$, first-order condition (27) leads to (26) by Lemma 1. By the fact that the fringe is holding permits between $T^f - 1$ and T^f, we have

$$p_{T^f-1} = c'_f(q^f_{T^f-1}) = \delta c'_f(q^f_{T^f}) = \delta p_{T^f}, \tag{28}$$

which together with (26) implies

$$x^m_{T^f-1} c''_f(q^f_{T^f-1}) = \delta x^m_{T^f} c''_f(q^f_{T^f}). \tag{29}$$

Next we again apply the envelope theorem to (20) at $t < T^f$ to obtain

$$\frac{\partial V^m(s_t^m, s_t^f)}{\partial s_t^m} = \{x_t^m c_f''(q_t^f) + \delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^f} \frac{\partial s_{t+1}^f}{\partial q_t^f}\} \frac{\partial q_t^f}{\partial s_t^m} + \delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^m} \frac{\partial s_{t+1}^m}{\partial s_t^m} \tag{30}$$

and

$$\frac{\partial V^m(s_t^m, s_t^f)}{\partial s_t^f} = \{x_t^m c_f''(q_t^f) + \delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^f} \frac{\partial s_{t+1}^f}{\partial q_t^f}\} \frac{\partial q_t^f}{\partial s_t^f} + \delta \frac{\partial V^m(s_{t+1}^m, s_{t+1}^f)}{\partial s_{t+1}^f} \frac{\partial s_{t+1}^f}{\partial s_t^f}. \tag{31}$$

Consider now these expressions at $t = T^f - 1$. Using (25) of Lemma 1 together with (29), implies

$$\frac{\partial V^m(s_{T^f-1}^m, s_{T^f-1}^f)}{\partial s_{T^f-1}^m} = \delta \frac{\partial V^m(s_{T^f}^m, s_{T^f}^f)}{\partial s_{T^f}^m} \tag{32}$$

$$\frac{\partial V^m(s_{T^f-1}^m, s_{T^f-1}^f)}{\partial s_{T^f-1}^f} = \delta \frac{\partial V^m(s_{T^f}^m, s_{T^f}^f)}{\partial s_{T^f}^f}. \tag{33}$$

We have now enough material for the recursion establishing (26) for all $t < T^f$. At $t = T^f - 2$, the first-order condition (27) for $x_{T^f-2}^m$ can be written, using (32)-(33), as follows:

$$c_f'(q_{T^f-2}^f) + x_{T^f-2}^m c_f''(q_{T^f-2}^f) \frac{\partial q_{T^f-2}^f}{\partial x_{T^f-2}^m} + \delta^2 [c_f'(q_{T^f}^f) - x_{T^f}^m c_f''(q_{T^f})] \frac{\partial s_{T^f-1}^m}{\partial x_{T^f-2}^m} + \delta^2 [-x_{T^f}^m c_f''(q_{T^f})] [\frac{\partial s_{T^f-1}^f}{\partial q_{T^f-2}^f} \frac{\partial q_{T^f-2}^f}{\partial x_{T^f-2}^m} + \frac{\partial s_{T^f-1}^f}{\partial x_{T^f-2}^m}] = 0$$

which, by (28) and (29), shows that (26) holds between $T^f - 2$ and $T^f - 1$. Repeating the above steps for all periods $T^f - k$ with $k > 2$ completes the proof. ■

We can now complete the first part of the proof. The fringe arbitrage condition

$p_t = \delta p_{t+1}$ and Lemma 2 imply that

$$x_t^m c_f''(q_t^f) = \delta x_{t+1}^m c_f''(q_{t+1}^f) \tag{34}$$

holds for all $t \in \{0, ..., T^f - 1\}$. Therefore, we have

$$c_f'(q_t^f) - x_t^m c_f''(q_t^f) = \delta[c_f'(q_{t+1}^f) - x_{t+1}^m c_f''(q_{t+1}^f)]$$

for all $t \in \{0, ..., T^f - 1\}$, which is the condition (14) in the text. The rest of the equilibrium conditions follow from the arguments given for the monopoly phase ($t \geq T^f$).

Second Part. We explain next that, if $s_0^m > s_0^{m*}$, conditions (13)-(16) provide enough information to pin down unique time periods T^f and T^m such that $T^m > T^f$. For ease of exposition, let us first consider the case $s_0^f = 0$. Then, condition (13) drops out, and we only need to solve the difference equation (15) (x_t^m will be chosen to satisfy eq. (16), so eq. (14) will automatically hold, given the path for q_t^m). We can find the initial value q_0^m and terminal time T^m ($T^f = 0$ by $s_0^f = 0$) using the boundary condition

$$q_{T^m}^m \leq q_{T^m+1}^m = u^m - a^{m*},$$

and the stock exhaustion condition

$$s_0^m = \sum\nolimits_{t=0}^{T^m} (u^m - a^{m*} - q_t^m + x_t^m).$$

Consider now the case $s_0^f > 0$. The solution is found as above but we have to solve two difference equations, (13) and (15); again, x_t^m is defined through (16). There are now four unknowns: q_0^m, q_0^f, T^m, and T^f. We can use

$$q_{T^f}^f \leq q_{T^f+1}^f$$

as an additional boundary condition and

$$s_0^f = \sum\nolimits_{t=0}^{T^f} (u^f - a^{f*} - q_t^f - x_t^m)$$

as an additional exhaustion condition.

To complete the proof we need to demonstrate that the above solution has the following property

$$s_0^m > s_0^{m*} \Longrightarrow T^m > T^f. \tag{35}$$

Note that

$$s_0^m = s_0 \Longrightarrow T^m > T^f = 0, \quad (36)$$
$$s_0^m = s_0^{m*} \Longrightarrow T^m = T^f = T, \quad (37)$$

where $s_0^m = s_0$ is the monopoly case and $s_0^m = s_0^{m*}$ is the efficient share (T is the competitive exhaustion time). From (36), it is clear that property (35) holds if s_0^m is close to the monopoly share. Property (37) follows since the system (13)-(16) has a unique solution with $x_t^m = 0$ and $T^m = T^f = T$ if the large agent's share of the stock equals the efficient share, $s_0^m = s_0^{m*}$.

We need to show that there exists small ε such that

$$s_0^m - s_0^{m*} = \varepsilon > 0 \Longrightarrow T^m > T^f. \quad (38)$$

For given ε, assume that the equilibrium satisfies $T^m = T^f = T$. This leads to a contraction since, by $\varepsilon > 0$, it is an option for the large agent to comply without trading, i.e., equalize marginal costs in present value by using permits from the stock s_0^m. But this implies that the large agent has not used ε when period $t = T$ arrives. Selling ε at $t = T$ leads to $p_T < \delta p_{T+1}$, which is the contradiction. Reoptimizing at the last period implies that it becomes optimal to extend the overall depletion period, $T^m > T^f$. ■

Appendix B: Proof of Proposition 2

Proof. The proof is by backward induction. Let T be a period such that it is socially efficient to consume the remaining stock $s_T > 0$ at T. Assume that the large agent's share of the stock is below the efficient share at T, i.e., $s_T^m \leq s_T^{m*}$. We start working backwards from period T, and show that s_T is consumed at T also in the game if $s_T^m \leq s_T^{m*}$.

By definition of $s_T^m = s_T^{m*}$,

$$c_f'(q_T^f = u^f - a^f - s_T^{f*}) = c_m'(q_T^m = u^m - a^m - s_T^{m*}) = p_T^* \geq \delta \bar{p},$$

where p_T^* is the efficient price and $\bar{p}$ is the choke price. Thus, there is no trading and s_T is consumed at T if $s_T^m = s_T^{m*}$.

If $s_T^m < s_T^{m*}$, the large agent needs to buy as no trading would imply $c_f'(q^f) < c_m'(q^m)$. Equalizing marginal revenues and costs within the period T gives

$$c_f'(q_T^f) - x_T^m c_f''(q_T^f) = c_m'(q_T^m) \geq p_T \geq \delta \bar{p}, \quad (39)$$

where $q_T^f = u^f - a^f - s_T^f - x_T^m$ and $q_T^m = u^m - a^m - s_T^m + x_T^m$. As $x_T^m < 0$, marginal revenue exceeds the price. This condition implies that the large agent depresses the equilibrium price closer to the discounted choke price:

$$p_T^* \geq p_T \geq \delta \bar{p}.$$

Indeed, we argue now that price p_T can be depressed at most to $p_T = \delta \bar{p}$. Suppose the contrary that $p_T < \delta \bar{p}$. Then, T would not be the last period of storage in the game, so that some permits are saved to $T+1$ and

$$\begin{aligned} c_f'(q_T^f) &= \delta c_f'(q_{T+1}^f) \\ c_m'(q_T^m) &= \delta c_m'(q_{T+1}^m) \end{aligned}$$

by the fringe arbitrage and the large agent's cost minimization. Marginal costs cannot exceed the choke price:

$$c_m'(q_{T+1}^m) \leq \bar{p}. \tag{40}$$

Boundary (40) must hold since $c_m'(q^m = u^m - a^m) = \bar{p}$ by definition and thus $c_m'(q^m) > \bar{p}$ would impy $q^m > u^m - a^m$, a contradiction with $x^m < 0$. Boundary (40) implies that all agents have marginal costs lower than $\bar{p}$ in present value:

$$c_f'(q_T^f) = \delta c_f'(q_{T+1}^f) < c_m'(q_T^m) = \delta c_m'(q_{T+1}^m) \leq \delta \bar{p}.$$

This implies that agents consume more than s_T which is the desired contradiction. Thus, if it is socially optimal to consume s_T in one period, monopsony power cannot extend the period of consumption.

Consider then period $T-1$ such that it is socially efficient to exhaust the remaining stock $s_{T-1} > 0$ in two periods. Assume $s_{T-1}^m \leq s_{T-1}^{m*}$. Again, by definition, $s_{T-1}^m = s_{T-1}^{m*}$ implies

$$c_f'(q_{T-1}^f = u^f - a^f - s_{T-1}^{f*} + s_T^{f*}) = c_m'(q_{T-1}^m = u^m - a^m - s_{T-1}^{m*} + s_T^{m*}) = p_{T-1}^* = \delta p_T^* \geq \delta \bar{p}$$

If $s_{T-1}^m < s_{T-1}^{m*}$, there is again a need to buy as no trading would imply $c_f'(q_{T-1}^f) = \delta c_f'(q_T^f) < c_m'(q_{T-1}^m) = \delta c_m'(q_T^m)$. Given (s_{T-1}^m, s_{T-1}^f), the choice of x_{T-1}^m determines, by backward induction, the last period stocks through

$$c_f'(q_{T-1}^f) = \delta c_f'(q_T^f) \quad (41)$$

$$c_m'(q_{T-1}^m) = \delta c_m'(q_T^m) \quad (42)$$

$$c_f'(q_T^f) - x_T^m c_f''(q_T^f) = c_m'(q_T^m). \quad (43)$$

From the analysis of the last period T, we know (i) whatever stock $s_T^m \leq s_T^{m*}$ is left to T the price is not depressed below $\delta\bar{p}$ and thus (ii) the number of periods of consumption is not altered. Thus, period $T-1$ choices in the game do not alter the socially optimal timing of exhaustion for s_{T-1}.

The above reasoning can be repeated for any induction step $T-k$ with $s_{T-k}^m \leq s_{T-k}^{m*}$. In particular, when k is large, the present-value efficiency loss

$$\delta^k(p_T^* - \delta\bar{p}) \geq -\delta^k x_T^m c_f''(q_T^f) \geq 0$$

becomes vanishingly small. ■

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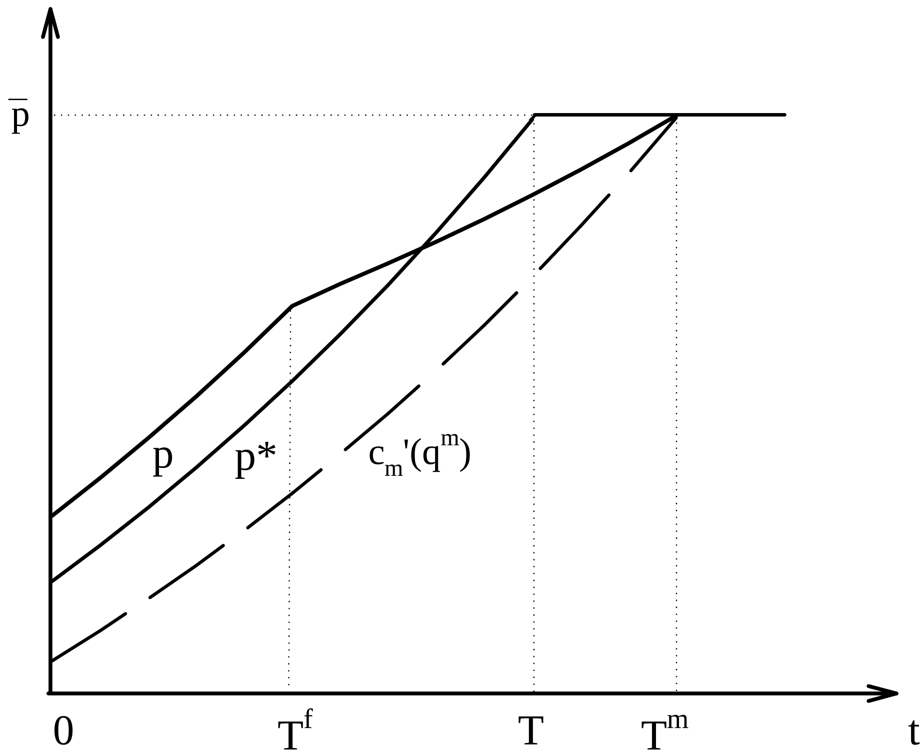

FIGURE 1: Manipulated equilibrium path

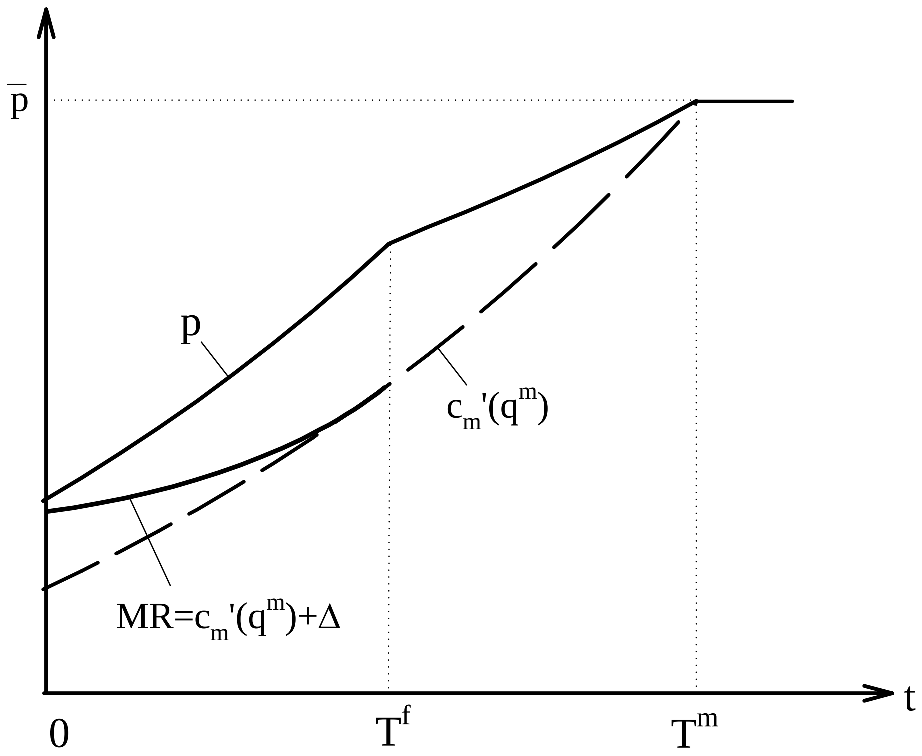

FIGURE 2: Market power and the storage response

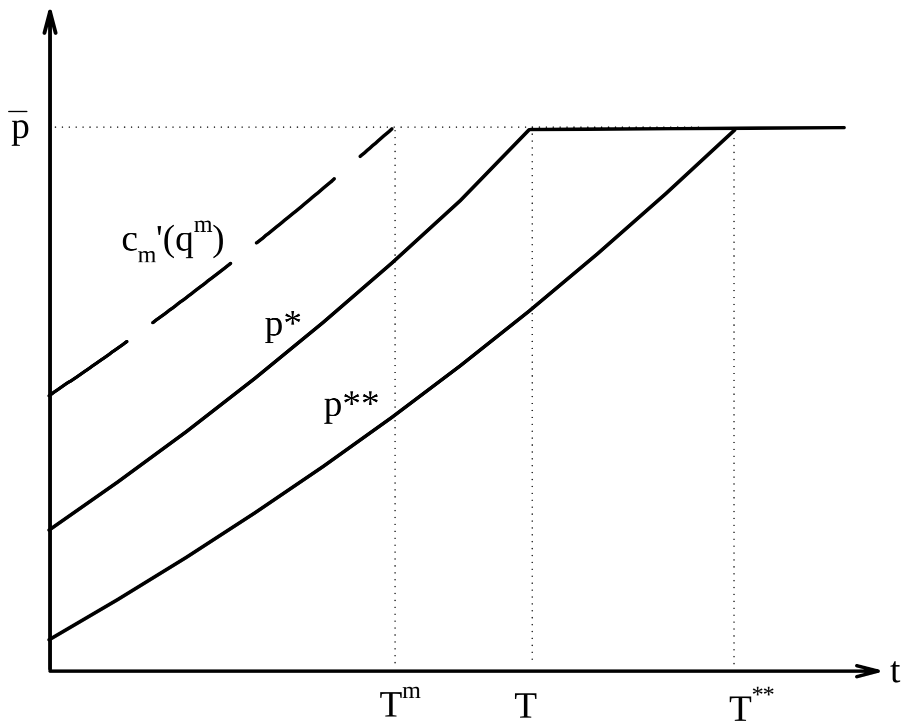

FIGURE 3: Equilibrium under a one-time stock purchase

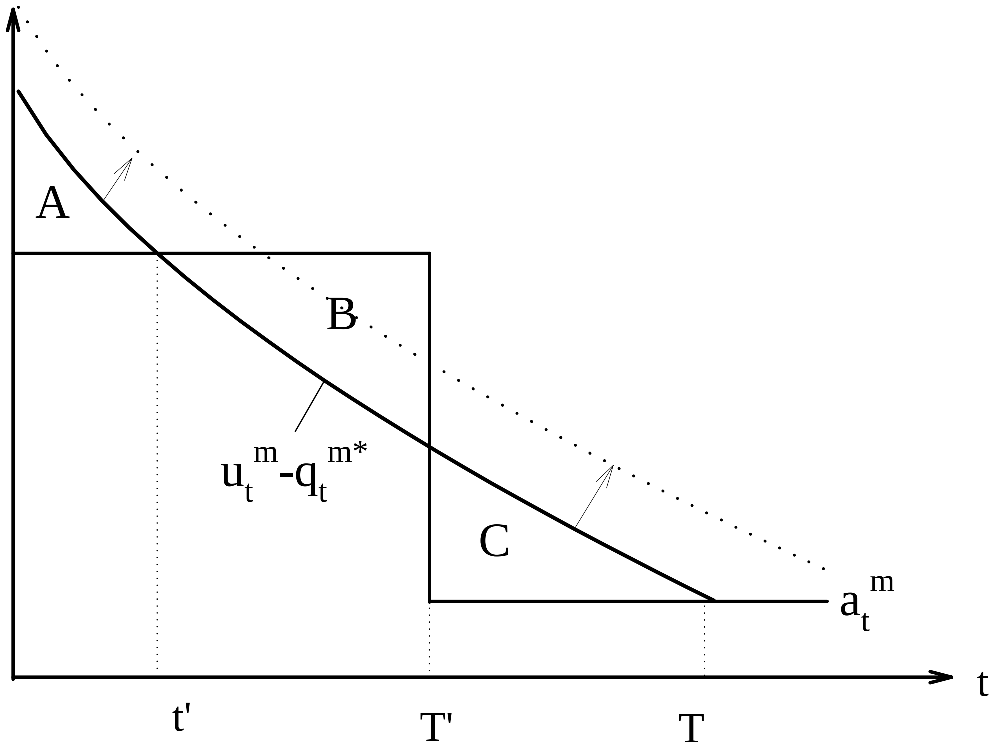

FIGURE 4: Allocation path that leads to unwanted market power

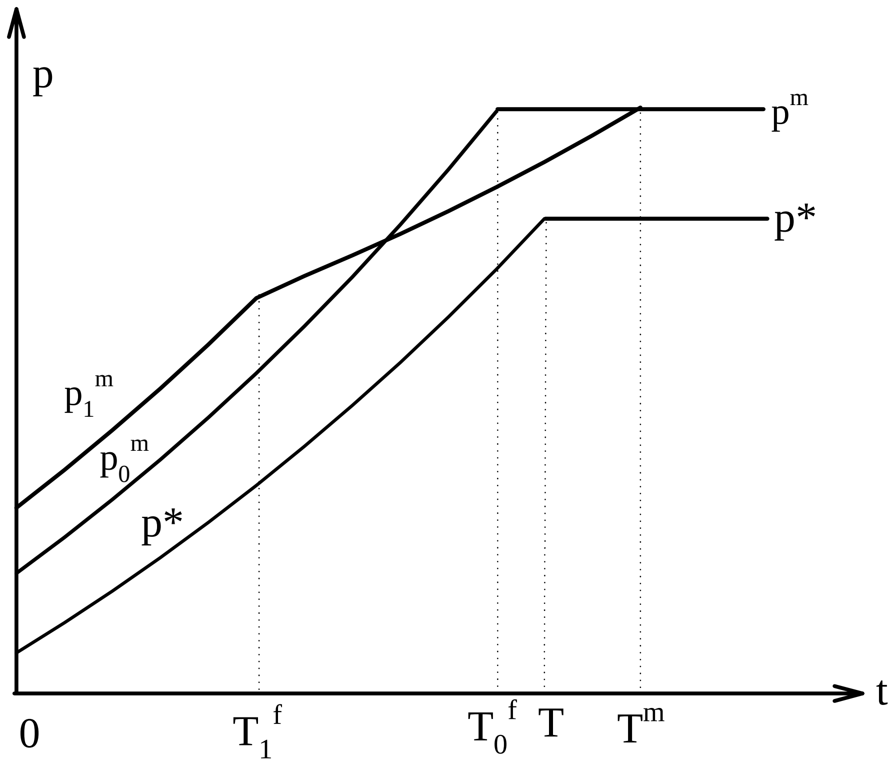

FIGURE 5: Long-run monopoly power

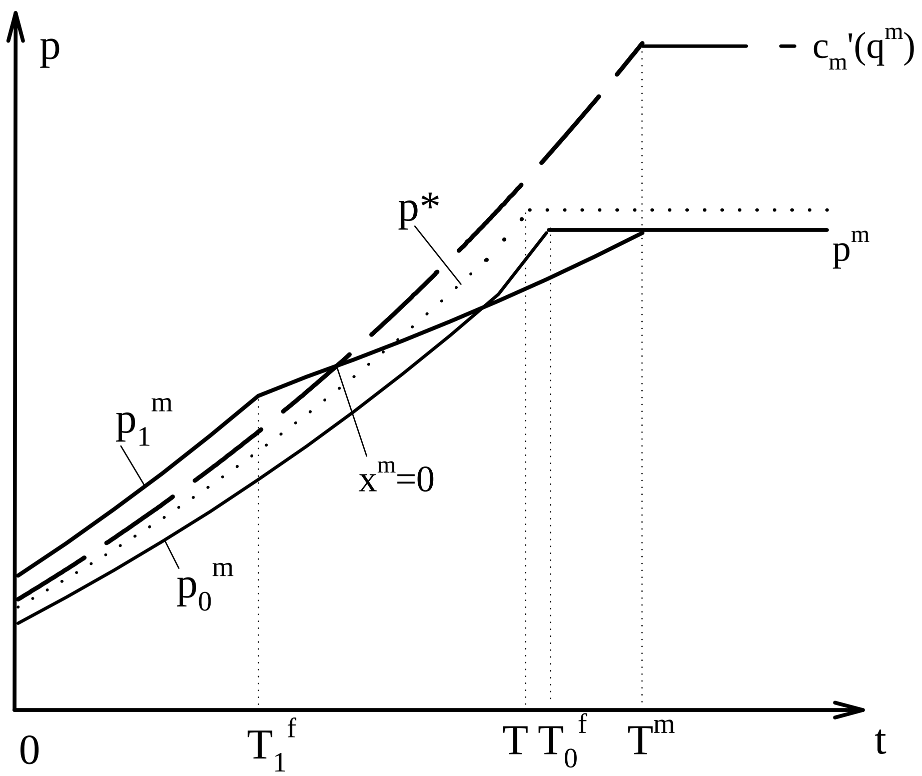

FIGURE 6: Long-run monopsony power

Table 1: Static equilibrium in 2010

	Prices ($/tC)	Emissions (mtC) OKR	FSU	Total	Permits (mtC) CDM	OKR	FSU	Total	FSU sales (mtC)
No regulation		2,153	818	2,970					
Perfect competition	11.0	2,027	749	2,776	100	1,672	1,004	2,776	255
Maximum market-power	20.1	1,975	818	2,793	135	1,672	1,004	2,811	168

OKR: other Kyoto regions; FSU: Former Soviet Union; CDM: Clean Development Mechanism.

Table 2: Perfectly competitive equilibrium path

Year	Prices ($/tC)	Annual Emissions (mtC) OKR	FSU	Total	Annual Permits (mtC) CDM	OKR	FSU	Total	Stocks (mtC) FSU (s_t^{m*})	Total
2010	62	1816	654	2,470	236	1,672	1,004	2,912	350	442
2015	79	1877	714	2,591	302	1,672	1,004	2,978	639	829
2020	101	1909	754	2,663	386	1,672	1,004	3,062	889	1,228
2025	129	1941	786	2,728	493	1,512	908	2,912	1,010	1,413
2030	164	1970	816	2,785	630	1,366	820	2,817	1,015	1,445
2035	210	2046	856	2,901	806	1,235	742	2,782	901	1,325
2040	268	2112	890	3,002	1,000	1,116	670	2,787	681	1,110
2045	342	2161	912	3,072	1,000	1,009	606	2,615	375	653
2050	436	2191	922	3,113	1,000	912	548	2,460	0	0
TOTALS		18,021	7,304	25,325	5,852	12,168	7,305	25,325		

OKR: other Kyoto regions; FSU: Former Soviet Union; CDM: Clean Development Mechanism.

Table 3: Perfectly competitive equilibrium path with stock-holding limits

Year	Prices ($/tC)	Annual Emissions (mtC) OKR	FSU	Total	Annual Permits (mtC) CDM	OKR	FSU	Total	Stocks (mtC) FSU (s_t^{m*})	Total
2010	66	1,805	650	2,455	121	1,672	1,004	2,798	-496	343
2015	84	1,865	709	2,574	155	1,672	1,004	2,831	-201	601
2020	107	1,895	748	2,643	198	1,672	1,004	2,875	54	832
2025	136	1,926	780	2,705	254	1,590	955	2,799	230	926
2030	174	1,952	808	2,760	324	1,512	908	2,744	330	910
2035	222	2,025	847	2,872	414	1,438	863	2,716	346	754
2040	283	2,089	880	2,969	529	1,368	821	2,718	287	503
2045	361	2,135	901	3,035	677	1,301	781	2,758	167	226
2050	461	2,161	910	3,071	865	1,237	743	2,845	0	0
TOTALS		17,851	7,233	25,084	3,538	13,463	8,083	25,084		

OKR: other Kyoto regions; FSU: Former Soviet Union; CDM: Clean Development Mechanism.

Table 4: Evolution of largest holding companies' compliance paths in the sulfur market

	American Elec. Power		**Southern Company**		**Group of Four**		**All firms**	
Year	Permits	Emissions	Permits	Emissions	Permits	Emissions	Permits	Emissions
1995	1,194,410	739,322	1,079,502	534,392	3,607,506	2,049,809	8,694,296	5,298,617
1996	1,182,429	926,215	1,079,085	565,097	3,591,282	2,259,687	8,271,366	5,433,351
1997	883,634	959,556	991,297	591,411	3,001,934	2,312,083	7,108,052	5,474,440
1998	883,634	871,738	991,297	642,093	3,001,728	2,229,636	7,033,671	5,298,498
1999	883,634	723,589	991,297	614,790	3,001,809	2,088,510	6,991,170	4,944,666
2000	663,514	1,136,095	734,464	1,048,296	2,121,591	3,307,858	9,714,830	11,202,052
2001	663,514	998,620	734,464	957,872	2,119,625	3,090,712	9,307,565	10,631,343
2002	663,514	979,653	734,464	959,338	2,119,625	3,059,693	9,282,297	10,175,057
2003	653,062	1,039,413	728,778	988,245	2,103,487	3,161,696	9,123,376	10,595,945
2004	653,062	1,017,878	728,778	969,568	2,103,487	3,096,652	9,123,376	10,432,326
…								
2012	653,062	890,164	728,778	847,915	2,103,487	2,708,114	9,123,376	9,123,376
TOTALS								
Cumulative by 1999	5,027,741	4,220,420	5,132,478	2,947,783	16,204,259	10,939,725	38,098,555	26,449,572
diff. 1999		807,321		2,184,695		5,264,534		11,648,983
Cumulative by 2003	7,671,345	8,374,201	8,064,648	6,901,534	24,668,587	23,559,684	75,526,623	69,053,969
diff. 2003		-702,856		1,163,114		1,108,903		6,472,654
Cumulative by 2012	13,548,903	16,960,388	14,623,650	15,080,208	43,599,970	49,681,131	157,637,007	157,054,629
diff. 2012		-3,411,485		-456,558		-6,081,161		582,378