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

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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 (or a few) 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 U.S. sulfur market and the global carbon market that may eventually develop beyond the Kyoto Protocol.

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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. This design was used in the US sulfur dioxide trading programme\(^1\) but global trading proposals to dealing with carbon dioxide emissions share similar characteristics. 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.\(^2\) 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.\(^3\) 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\(^4\) — and a competitive fringe of many small polluting agents.\(^5\) 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

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\(^1\)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).

\(^2\)We provided premialiry discussion of the problem in Liski-Montero (2005a) and Liski-Montero (2006a).

\(^3\)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).

\(^4\)In Section 4.3 we explain the changes (or no changes) to our equilibrium path from replacing the large firm by a few large firms.

\(^5\)The properties of the perfectly competitive equilibrium path are well understood (e.g., Rubin, 1996).
buyer or a seller of permits in the market, which, in turn, may affect how and to what 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.\textsuperscript{6} 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 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.

We then illustrate the use of our theory with two applications: the existing sulfur market created by the U.S. Acid Rain Program in 1990, and the global carbon market that may eventually develop beyond the Kyoto Protocol. 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

\textsuperscript{6}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.
as heavy borrowers of permits during and after 2000, rules out, according to our theory, market power coming from the initial allocations of permits. The carbon application, on the other hand, is much more limited in scope since we do not know yet the type of regulatory institutions that will succeed the Kyoto Protocol in the multinational efforts to stabilize carbon emissions and concentrations. Nevertheless, we ask, as an illustrative exercise, to what extent the proportions used in the Kyoto Protocol to allocate permits among the more developed countries may create market-power problems in an eventual global carbon market beyond Kyoto.

The theoretical result that the equilibrium is competitive as soon as the allocation implies a net buyer position for the large agent is an instance of the Coase conjecture (Coase, 1972; Bulow, 1982), although the setting is different from what Coase initially considered. The large agent would like to depress prices by committing to a moderate purchase plan but cannot credibly do so equilibrium, and is therefore forced to behave competitively. It is of some general interest that the seminal works of Coase and Hotelling can be combined to organize our thinking of how pollution permit markets work. In our framework, the permit allocation to the large agent determines whether the equilibrium is in the domain of Coase or Hotelling. Intuitively, the large agent has two uses for its permit stock—sales revenue maximization and compliance cost minimization—and when its allocation is sufficiently abundant it has enough permits for both purposes. 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). When the large agent’s endowment is reduced 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.8

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

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, long-run market power, the presence of two or more large agents and alternative market structures (e.g., forward contracting) are in Section 4. The applications to sulfur and carbon trading are in Section 5. Final remarks are in Section 6.

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 \( I \) denote a continuum of heterogeneous pollution sources. Each source \( i \in I \) is characterized by a permit allocation \( a_i^t \geq 0 \), unrestricted emissions \( u_i^t \geq 0 \), and a strictly convex abatement cost function \( c_i(q_i^t) \), where \( q_i^t \geq 0 \) is abatement.

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8While it has been long recognized that an exhaustible-resource buyer faces a dynamic inconsistency problem (see, e.g., Karp and Newbery 1993), the conditions for the Coase conjecture in the resource model have not been well understood. Hörner and Kamien (2004) show that the commitment solutions of the durable-good monopoly and exhaustible-resource monopoly are equivalent. The result of the current paper led us to investigate the general equivalence of the subgame-perfect solutions of the two models (Liski-Montero 2008). With the help of this other paper, we can link our result to the previous literature (see Section 3.2.).

9Firm’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.
share a common discount rate $r > 0$ per unit of time. We introduce the model in continuous time. 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, we assume that the aggregate allocation is generous only at $t = 0$ 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, $u_t = u > a$. 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 Hotelling equilibrium for a depletable stock market. First, trading across firms implies that at all times $t$ marginal costs equal the price,

$$p_t = c'_i(q^i_t), \forall i \in I.$$  

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 future use. 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

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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 essence of the results obtained from the basic model.

11 Again, this will be relaxed in Section 4.

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 market power will be exercised, as we will discuss in detail below.
equilibrium exhaustion time. Then, $T$ is such that (1) holds for all $t$, and

$$dp_t/dt = rp_t, \ 0 \leq t < T,$$

$$q_T = u - a,$$

$$s_0 = \int_0^T (u - a - q_t) dt.$$  \hfill (2)

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.

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 $I$ and call it the large agent. The remaining agents $i \in I$ 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

$$u - a = (u^m + u^f) - (a^m + a^f) > 0.$$  \hfill (3)

The fringe’s aggregate cost is denoted by $c_f(q^f_t)$, which gives the minimum cost of achieving the total abatement $q^f_t$ by sources in $I$. This cost function is strictly convex, as well as the cost for the large agent, denoted by $c_m(q^m_t)$.

We look for a subgame-perfect equilibrium in the game between the large polluter and the fringe. Such a game is best introduced in discrete time so that the timing and strategies become perfectly clear but, for ease of exposition, we explain the equilibrium in continuous time in the main text. The discrete time set up is in the Appendix and the full discrete-time analysis in our working paper.

At each point $t$, all agents observe the stock holdings of both the large polluter, $s^m_t$, and the fringe, $s^f_t$. We simplify the permits market clearing process by letting the large agent to announce first its spot sales of permits at $t$, which we denote by $x^m_t > 0$ ($< 0$, if the large agent is buying permits).\footnote{Without the Stackelberg timing for $x^m_t$ 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} Having observed stocks $s^m_t$ and $s^f_t$ and the large
agent’s sales $x_i^m$, fringe members form rational expectations about future supplies by the large agent and make their abatement decision $q_i^f$ as to clear the market at a price $p_t$. In equilibrium $p_t$ is such that

$$x_i^f = -x_i^m, \quad p_t = c_i'(q_i^f) \quad \text{and} \quad dp_t/dt \leq rp_t,$$

(5)
i.e., the price not only eliminates arbitrage possibilities across fringe firms at $t$, $p_t = c_i'(q_i^f) = c_i'(q_i^f), \forall i$, but also across periods. If some of the fringe stock is left for the future, then the latter arbitrage condition in (5) holds as an equality. The fringe stock evolves according to

$$ds_i^f/dt = a^f - u^f + q_i^f - x_i^f.$$

(6)
We can assume that the fringe does not observe $q_i^m$ before abating at $t$, so the decisions on abatement are simultaneous, although the timing with respect to abatement is not essential for the results.\(^{14}\)

At each $t$ and given stocks $(s_i^m, s_i^f)$, the large agent chooses $x_i^m$ and decides on $q_i^m$ knowing that the fringe can correctly replicate the large agent’s problem in future subgames. Equilibrium choice $(x_i^m, q_i^m)$ at each $t$ solves

$$\max \int_t^\infty \{ p_\tau x_\tau^m - c_m(q_\tau^m) \} e^{-r(\tau-t)} d\tau$$

(7)
subject to

$$ds_i^m/dt = a_i^m - v_i^m + q_i^m - x_i^m,$$

(8)
and (5)-(6).

3 Characterization of the Equilibrium

3.1 Equilibrium solution

It is natural to consider first what happens in the long run, i.e., when both stocks $s_0^m$ and $s_0^f$ 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 want to assume away market power coming from extreme annual allocations.

\(^{14}\)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 $x_i^m$ but also for $q_i^m$ does not change the results.
that determine the long-run trading positions. It is clear that this source of market power can be ruled out by assuming efficient annual allocations $a^{m*}$ and $a^{f*}$ satisfying

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

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, $c'_f(q'_f) - x^{m*}_t c''_f(q'_f) = c'_m(q'_m)$ holds whenever $x^{m*}_t = 0$.

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 $q_t = q^{m*}_t + q^{f*}_t$ satisfies both $c'_f(q^{f*}_t) = c'_m(q^{m*}_t)$ and the Hotelling conditions (2)-(4) ensuring efficient stock depletion. Since we shall show that the share $s^{m*}_0$ 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

$$s^{m*}_0 = \int_0^T (u^m - q^{m*}_t - a^{m*}) dt$$

$$s^{f*}_0 = \int_0^T (u^f - q^{f*}_t - a^{f*}) dt,$$

where the pair $(q^{m*}_t, q^{f*}_t)_{t \geq 0}$ is the socially 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 time points 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

\[\text{alternatively, we can assume that the long-run emissions goal is sufficiently tight that the long-run equilibrium price is fully governed by the price of backstop technologies, denoted by } \bar{p}. \text{ This seems to be a reasonable assumption for the carbon market and perhaps so for the sulfur market after recent announcements of much tighter limits for 2010 and beyond. In any case, we allow for long-run market power in Section 4. The relevant question there is the following: how large can the transitory stock be without creating market power that is additional to that coming from the annual allocations.} \]
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. Right after the fringe stock is exhausted, denoted by \(T^f\), the manipulated price grows at a lower rate. As a monopoly stockholder, the large agent is now 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 future uses, prices must be equal in present value, implying that the market-clearing abatement for the fringe must satisfy

\[
dc_f(q^f_t)/dt = rc_f(q^f_t) \quad \text{for all } 0 \leq t < T^f.\tag{10}
\]

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
\[
d[c_f^t(q_f^t) - x_m^t c_f^t(q_f^t)]/dt = r[c_f^t(q_f^t) - x_m^t c_f^t(q_f^t)] \tag{11}
\]

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,

\[
dc_m^t(q_m^t)/dt = rc_m^t(q_m^t) \tag{12}
\]

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,

\[
c_f^t(q_f^t) - x_m^t c_f^t(q_f^t) = c_m^t(q_m^t) \tag{13}
\]

must hold for all \(t\).

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

**Proposition 1** If \(s_m^0 > s_m^{0*}\), then subgame-perfect equilibrium has the above properties and satisfies the conditions (10)-(13).

**Proof.** See the Appendix. ■

The equilibrium is found by solving the commitment solution, where the large agent commits to a path \((x_i^t, q_i^t)_{t \geq 0}\) at time \(t = 0\), and showing that this solution identifies the subgame-perfect equilibrium path. The equilibrium determines, for any given remaining stocks \((s_i^t, s_f^t)\), the of time periods it takes for the large agent and fringe to sell their stocks such that at each time the stocks and the large agent’s optimal actions are as previously anticipated. For initial stocks \((s_i^0, s_f^0)\), the time period 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 equilibrium exhaustion times change, but the equilibrium is still characterized as above.

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 the Appendix. ■

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 some \( t' < T \) (some time point before exhaustion) that is large enough to imply a permit holding in excess of its own demand, then the spot market at \( t' \) rationally anticipates this, leading to a price satisfying

\[
dp_t / dt = r p_t > r [c'_f(q_T^f) - x_T^m c''_f(q_T^f)].
\]

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 marginal revenue an instant later. This argument holds for any number of periods before the overall stock exhaustion, implying that, if a subgame-perfect path starts with \( s_0^m \leq s_0^{m*} \), 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 \( t = T \), because of the option to store, no fringe member is willing to sell at a price below \( \bar{p} \) 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 2. 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 at all times, which is what happens in reality, \( p^{**} \)
and $c'_m$ are not time consistent (i.e., they 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 2 HERE ***

3.2 Connections to durable goods and exhaustible resources

The time-inconsistency problem of our large agent is similar to that of a durable-good monopolist (Coase, 1972; Bulow, 1982). The connection between exhaustible resources (the permit stock in our case) and durable-goods has been long recognized (see, e.g., Karp and Newbery 1993). Hörner and Kamien (2004) show that the commitment solutions to the durable-good monopoly and exhaustible-resource monopsony are formally equivalent, but Liski and Montero (2009) were the first to recognize the differences in the subgame-perfect solutions of the two problems.

For durable goods, the stock is the consumer population already served, and, if the consumer valuation declines with the stock, the low-valuation consumers are expected to be served at some point. This creates a consumer incentive to wait, and is the reason why the commitment solution is not subgame perfect. Then, if consumers are patient enough, the conjecture says that the monopoly will have to sell at competitive price. For exhaustible resources, the value changing with the stock is the resource extraction cost. The conjecture then says that sellers can wait that the high-cost sellers’ enter the market, and thereby force the buyer to pay his choke valuation for the resource. In both cases, in this argument, the conjecture requires that market valuations change with the stock (consumer valuation or producer cost).

Our result contradicts the above reasoning for the conjecture: the cost of extracting the resource (i.e., cost of selling permits from the stock) is zero and hence does not change with the size of the stock. In this sense, the reason for the Coase conjecture in our case is not the same as in the original Coase argument. This brings us to the heart of the difference between the durable-good and exhaustible-resource models. The analog

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16Note that the abatement cost has nothing to do with extraction costs. From the abatement cost we can derive the buyer’s utility from consumption, so it defines the buyer’s flow valuation for the good.
of zero extraction cost in the durable-good model is a constant consumer valuation. In this case, the Coase conjecture does not arise in the standard durable-good model, but it still arises in the corresponding exhaustible-resource model, as our result suggests. We explore this difference in Liski-Montero (2009) and find that it follows from the difference in the nature of the good traded. The durable-good remains in the market even when production ceases, and therefore the market cannot resist paying the final rental value for the good.\textsuperscript{17} In contrast, the exhaustible resource is perishable, and there is no analog of the secondary market. It is now the strategic agent rather than the market who cannot resist paying his final choke valuation for the last units. The difference in the nature of good tilts the subgame-perfect bargaining power in exactly opposite ways in the two models, even though the commitment solutions are the same.

A final comment: 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 \textit{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.

\section*{4 Extensions}

\subsection*{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, \( (a_t, u_t)_{t \geq 0} \),\textsuperscript{18} such that the reduction target \( u_t - a_t \) changes over time.

\textsuperscript{17}The secondary market implies that the good can be further sold or rented. This is consistent with Coase’s original idea, and explicitly assumed in, e.g., Stokey (1981), Bulow (1982), and Kahn (1986).

\textsuperscript{18}We continue assuming that \( (a_t, u_t)_{t \geq 0} \) is known with certainty. Uncertainty would provide an addi-
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.\footnote{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.} 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.\footnote{Obviously, the same description applies irrespective of whether savings start at }t=0\text{ or at some later point }t>0,\text{ 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.}

Although the stock available is now endogenously accumulated, each agent’s efficient share of the stock at }t\text{ can be defined almost as before: it is a stock holding at }t\text{ 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 }\left(a^m_t, u^m_t\right)_{t\geq0}\text{ and }\left(a^f_t, u^f_t\right)_{t\geq0}\text{. Then, the large agent’s efficient share of the stock at }t\text{ is just enough to cover the large agent’s future own net demand:}

\begin{equation*}
    s^m_t = \int_t^T (u^m_{\tau} - q^m_{\tau} - a^m_{\tau}) d\tau,
\end{equation*}

where }q^m_{\tau}\text{ denotes the socially efficient abatement path for the large agent. On the other hand, the socially efficient stock holdings, which are denoted by

\begin{equation*}
    \hat{s}^m_t = \int_0^t (a^m_{\tau} - u^m_{\tau} + q^m_{\tau}) d\tau,
\end{equation*}

will typically differ from }s^m_t\text{. It can nevertheless be established:}

\begin{proposition}
\text{If }\hat{s}^m_t \leq s^m_t \text{ for all }t, \text{ the subgame-perfect equilibrium is efficient.}
\end{proposition}

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 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.
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

$$\int_0^T a_t^m dt \leq \int_0^T (u_t^m - q_t^{m*}) dt,$$

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 3 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 (14) 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 Figure 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 3, 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, 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 3.22

*** INSERT FIGURE 3 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 price of permits is fully governed by the price of backstop technologies (see (9) 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.

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 4. 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

\[ ^{21}\text{In all existing and proposed market designs firms are not allowed to "borrow" permits from far-term allocations to cover near-term emissions (Tietenberg, 2006).} \]

\[ ^{22}\text{Although not necessarily related to the market power reasons discussed here, it is interesting to note that swap trading is commonly used in the US sulfur market (see Ellerman et al., 2000).} \]
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. 4 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 4 HERE ***

The second relevant case is that of long-run monopsony power, which is illustrated in Figure 5. 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 $c'_m(q^m_t)$ 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 5 HERE ***
4.3 Multiple large agents

We now discuss how the characterization of the equilibrium presented in Section 5 changes as we consider two or more large (strategic) firms sharing the market with the fringe of competitive firms. To simplify the exposition consider just two strategic firms and denote them by \( i \) and \( j \). Notation and the timing of the game are as before: at the beginning of period \( t \) and having observed the stock vector \((s_i^t, s_j^t, s_f^t)\), strategic firms simultaneously announce their spot sales/purchases \( x_i^t \) and \( x_j^t \); based on these announcements and the stock vector, fringe firms clear the spot market by setting, on aggregate, \( x_f^t = -x_i^t - x_j^t \).

Unlike in the basic model with a single strategic player, here we require the fringe to be sufficiently large as to clear the market for any possible equilibrium pair \((x_i^t, x_j^t)\).\(^{23}\)

Neglect for the moment any long-run market power and focus exclusively on market power during the depletion of the stocks (we will come back to long-run market power at the end of the section). Depending on the initial share of the stock and firms’ costs, there are three cases to consider: (i) both strategic firms are on the demand side of the market, (ii) both firms are on the supply side; and (iii) firm \( i \) is on the supply side and \( j \) is on the demand side. Note that unless \( i \) and \( j \) are identical in all respects (i.e., allocations and abatement costs), case (iii) will always arise at some point along the depletion path. The first case does not deserve further analysis: Proposition 2 holds for any number of strategic buyers. For the study of cases (ii) and (iii) we will rely on a two-period analysis, which will provide us with all the relevant results for our discussion (you may think of these two periods as the last two periods of the transitory phase before entering the long-run equilibrium phase). We have relegated most of the technical analysis to the Appendix, so below we concentrate on the main results.

Consider first case (ii). There are two periods \( t = 1, 2 \) and initial stock holdings such that \( s_1^i, s_1^j > 0 \) and \( s_1^f = 0 \). We find that spot actions for \( i = i, j \) are described by conditions

\[
\begin{align*}
    c_i'(q_i^2) - x_i^2 c_i''(q_i^2) - c_i'(q_i^2) &= 0 \\
    c_j'(q_j^1) - x_j^1 c_j''(q_j^1) - c_j'(q_j^1) &= 0
\end{align*}
\]

One may thus argue that the two strategic sellers behave, at least qualitatively, no

\(^{23}\)If the fringe were too small we would have to rely on a different equilibrium concept, for example, like the one proposed by Hendricks and McAfee (2007) for the case in which the market is populated exclusively by large buyers and sellers. See Yates and Malueg (2009) for an application to pollution permit markets.
differently than a single-large seller in that they all equalize marginal revenues to marginal costs in each period. However, there are interesting intertemporal implications. Recall that storage can be seen as an investment allowing the agent to sell more in the future. Because spot sales are strategic substitutes, it is not surprising that competition between the strategic agents leads to more conservative stock depletion than in the presence of only one firm (i.e., when \( i \) is assumed to behave strategically and \( j \) is taken as part of the fringe). Thus, the strategic interaction leads both firms to behave more conservatively today (i.e., leaving more stock for tomorrow) by both selling less and abating more. Intuitively, firms behave this way in an attempt to capture larger market share in the future.

Let us now turn to case (iii) by making \( s_j^1 = 0 \), while maintaining \( s_i^1 > 0 \) and \( s_f^1 = 0 \). Before discussing the case it is instructive to explain what happens in a static context where the strategic seller, \( i \), and the strategic buyer, \( j \), share the market with the competitive fringe for a single period. To counteract \( j \)'s buying power \( i \) will sell less (abate less) relative to the case in which \( j \) behaves competitively (i.e., is part of the fringe). Likewise, firm \( j \) will counteract \( i \)'s selling power by buying less (abating more) than if the stock were in competitive hands. The equilibrium price will tend to move closer to competitive levels and eventually may coincide with its perfectly competitive level if buyer and selling powers exactly cancel out. The same strategic forces are present in a dynamic context but with quite different implications for equilibrium prices. The presence of an strategic buyer makes firm \( i \) to lower the rate at which it sells its stock over time. In terms of our general model, this reaction will unambiguously translate into a less competitive price path (i.e., wider gap between \( p_t \) and \( \delta p_{t+1} \)) extending even further the depletion phase. This can be readily seen with our two period model. Rearrange equation (39) in the Appendix to obtain

\[
c_f'(q^1) - \delta c_f'(q^2) = x_1 c_f''(q^1) - \delta x_2 c_f''(q^2) - \delta x_2 c_f''(q^2) \frac{\partial x_2^j}{\partial s_2^j} \tag{15}
\]

When \( j \) is negligible (i.e., \( \partial x_2^j / \partial s_2^j = 0 \)), we arrive precisely at the equilibrium condition for the single strategic seller where, as we know from the basic model, \( c_f'(q^1) = p_1 > \delta p_2 = \delta c_f'(q^2) \). As \( j \) grows larger, the gap \( c_f'(q^1) - \delta c_f'(q^2) \) increases in equilibrium since we are adding a positive term (recall that \( \partial x_2^j / \partial s_2^j < 0 \)).

We conclude this section with a brief discussion on the possibility for the strategic firms to sustain collusion. If we also allow for long-run market power we may no longer treat the stock depletion game as a strictly finite-horizon game. Related to Gul (1987),
one could argue that the (subgame-perfect) threat of falling into the (long-run) noncooperative equilibrium may even allow strategic buyers to sustain monopsony profits during the stock depletion phase.

4.4 Alternative market structures

It is natural to focus on the spot market transactions when the objective to understand the primitive determinants of permit valuations over time. However, in view of the different type of market transactions that we observe in the U.S. sulfur market—see, for example, Ellerman et al. (2000)—, it is natural to ask whether and how our equilibrium description would change if we extended the scope of the market to cover forward transactions. The demand for forward transactions typically arises due to the need to share risk among market participants, but it is well known that oligopolistic firms can also choose to enter the forward market due to strategic reasons (Allaz and Vila, 1993). Forward contracting of production provides a commitment to a future market share, but leads to a prisoners' dilemma type of situation where firms end up behaving more competitively than without forward markets.

The procompetitive effect of Allaz and Vila cannot be directly applied to a dynamic market such as the pollution permit market considered here. Liski and Montero (2006b) show that the existence of forward markets increases the scope for collusive outcomes in an oligopolistic setting (i.e., two or more large firms), if the traded good is reproducible and interaction is repeated over time. For an exhaustible-resource market a different result follows: oligopolistic equilibrium becomes competitive very quickly without a possibility of collusion when forward market interactions are rapid, although asymmetries in stockholdings can help firms to avoid the procompetitive effect coming from contracting (Liski and Montero 2008).

These results are of direct use in the dynamic permit market, but the conclusion depends on further characteristics of the permit market. The long-run market interaction, after the exhaustion of the stock, can in principle continue forever, and, in this case, 'deep' markets in the form of forward trading may help to sustain collusion as suggested by the theory. However, if the long-run equilibrium is covered by a backstop technology (see fn. 3.1), the permit-stock can be seen as an exhaustible resource, and the market deepening should have only a procompetitive effect on the equilibrium path.

For policy design, the forward market has the implication that if market manipulation is a concern, it makes sense to require sufficient forward sales of permit stocks. In par-
ticular, this can eliminate the potential collusion working through forward markets, and, even when collusion is not concern, oligopolistic interaction becomes more competitive, the greater is the degree of contract coverage of sales.

5 Applications

We illustrate the use of our theory with two applications: the sulfur market of the U.S. Acid Rain Program of the 1990 Clean Air Act Amendments (CAAAA) and the carbon market that may eventually develop with and beyond the Kyoto Protocol.

5.1 Sulfur trading

The market for sulfur dioxide (SO$_2$) emissions has been operating since the early 90s; right after the 1990 CAAA allocated allowances/permits to electric utility units for the next 30 years in designated electronic accounts. We can then 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 have or 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 and later 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 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

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24For details in market design and performance see Ellerman et al. (2000) and Joskow et al. (1998).
group, are assumed to be the four largest permit-stock holding companies—American Electric Power, Southern Company, FirstEnergy\textsuperscript{25} 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.\textsuperscript{26} 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.\textsuperscript{27} 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 significant surplus of permits by 1999 that may be indicative of possible market power problems,\textsuperscript{28} 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.

\textbf{*** INSERT TABLE 1 HERE OR BELOW ***}

\textsuperscript{25}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.

\textsuperscript{26}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.

\textsuperscript{27}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.

\textsuperscript{28}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.
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, 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. 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 of removing up to 95% of SO₂ emissions.

5.2 Carbon trading

The carbon application differs from the previous application in significant ways. First and most importantly, we do not know yet the type of regulatory institutions—including policy instruments and participants—that will succeed the Kyoto Protocol in the multinational efforts to stabilize carbon emissions and concentrations in the atmosphere. At this point all we know is that regardless of the regulatory mechanism adoted, there will be a long transition period of a few decades between now and the time of stabilization. But if this transition period is governed by a Kyoto-type market mechanism, then, the global carbon market that will eventually develop will share many of the characteristics

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29 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.

30 The same argument applies if the overall stock is expected to be depleted much earlier, say, in 2009.
of our model. First, firms will have strong incentives to store permits from earlier allocations in an effort to smooth the increase in abatement costs that is required to stabilize emissions in the long-run; and second, there will be large players, i.e., countries or group of countries, with ability to manipulate market prices if it is in their best interest to do so.\textsuperscript{31}

Even when a country member ends up allocating its permits quota to its domestic firms, which can then be freely traded in the global market, the country can simultaneously resort to alternative domestic policies to "coordinate" the actions of its domestics firms very much like a large agent in our model. For example, a country that wants to exercise downward pressure on prices can set a domestic subsidy on cleaner but more expensive technologies (e.g., some of the renewable energies), and thus, reducing the country’s aggregate demand for permits in the global market. On the other hand, a country that wants to exercise upward pressure on prices can levy a tariff on permit exports, and thus, depressing the country’s aggregate supply of permits. As with the subsidy, it would be hard to argue against this latter measure if the resulting revenues are aimed at financing R&D on cleaner technologies.\textsuperscript{32} In any case, the interesting question is under what circumstances a large country would find in its own interest to implement domestic policies of such kind. Or alternatively put, having observed the implementation of such policies to what extent one can tell apart whether they are driven by market power considerations or by other domestic forces.

Our theory can help us to start framing these and related questions. We illustrate now the use of the theory with a simple exercise that does not require extending the model to incorporate many of the elements that would prove relevant in a more comprehensive analysis (e.g., timing and scope of developing countries’ participation, treatment of carbon sequestration, etc.). For the same reason our exercise is purely illustrative and by no means looks for policy recommendations. In this simple exercise we ask to what extent the proportions used in the Kyoto Protocol to allocate permits among Annex I (i.e., more developed) countries may create market-power problems in a global carbon market that would go well beyond Kyoto. Using the country classification of the MIT’s CGE climate policy model (Babiker et al., 2008) and considering all greenhouse gases (GHG) at their carbon dioxide equivalent (CO\textsubscript{2}-e), the fist three columns of Table 2 show

\textsuperscript{31}We are certainly not the first to argue that large countries such as Russia and the U.S. can have a substantial effect on prices. See, for example, Bernard et al. (2003), Manne and Richels (2001), and Hagem and Westskog (1998).

\textsuperscript{32}This opens up a new question not addressed in our model which is how a large agent would decide on R&D investments along with abatement and permit transactions.
baseline emissions (i.e., emissions in the absence of regulation) for year 2010 and Kyoto allocations for the different Annex I regions/countries. Baseline emissions are obtained from MIT’s model (Morris et al., 2008) and Kyoto allocations are computed using the latest data from the web site of the United Nations Framework Convention on Climate Change (www.unfccc.int).

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

Based on Hahn’s (1984) static framework, it is clear, for example, that regardless of its abatement cost function, FSU would restrict its supply of permits in an effort to increase prices above competitive levels. According to our theory, however, FSU would find it advantageous to do so only if its allocation profile during the transition period falls below its perfectly competitive emissions path. Babiker et al. (2008) report the perfectly competitive emissions path that would stabilize world GHG emissions by 2050.33

The following columns of Table 2 present cumulative baseline GHG emissions and cumulative emissions along the competitive path for the period 2010-2050 and for the different countries/regions.34 Assuming that participation in this global carbon market is restricted to Annex I countries — low-cost abatement opportunities from the developing world are brought to the carbon market through alternative but equally efficient institutions —, the numbers in Table 2 suggest that FSU would certainly benefit from manipulating today’s prices if it expects its future share of permits to remain at its Kyoto level (24%). Conversely, if the FSU allocation share is expected to drop closer to 18% in the future, not only the FSU would find it disadvantageous to move today’s prices but so would the U.S. — even when the latter expects to get an allocation well below its efficient level. According to our theory, a large agent on the buyer-side would have a credible (i.e., subgame perfect) incentive to move prices only when there is a large agent on the seller-side exercising monopoly power (i.e., with an allocation profile above its perfectly competitive path).35 Interestingly, Europe, acting as a cohesive unit, would have no incentives to manipulate prices if it expects to keep its Kyoto share.

33 Babiker et al.’s (2008) recursive path show equilibrium prices starting at 17 US$ per ton of CO₂-e in 2010 and rising 4% per year.
34 We use world emissions from Babiker et al.’s (2008) recursive path. Region and country emissions are computed using data from Morris et al. (2008).
35 Note from (15) that when the large (potential) seller is not coming the market, i.e., \( x_1^i = x_2^i = 0 \), prices go up at the rate of interest.
6 Concluding Remarks

We developed a model of a market for storable pollution permits in which a (or a few) 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.36

Our model 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,37 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).

One can view our sulfur application as one of the few attempts at empirically studying market power in pollution permit trading, 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.

Finally, the theory applied in this paper could also be applied to other exhaustible-resource markets, including the world market for oil. In the oil market, one could perhaps estimate countries efficient own demand and reservoir developments to identify their future positions in this market, and in this way find the countries or regions with highest potential for being in the dominant position today or in the future. The theory suggests that expected future changes in demand infrastructure or reservoir recoveries should

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38 Kolstad and Wolak (2003) is another attempt.
influence market performance today.

7 Appendix

7.1 Proof of Proposition 1

We introduce the game first in discrete time to make the extensive form clear. At the beginning of each period $t = 0, 1, 2, \ldots$ all agents observe the stock holdings of both the large polluter, $s^m_t$, and the fringe, $s^f_t$. Having observed stocks $s^m_t$ and $s^f_t$ and the large agent’s sales $x^m_t$, fringe members form rational expectations about future supplies by the large agent and make their abatement decision $q^f_t$ as to clear the market, i.e., $x^f_t = -x^m_t$, at a price $p_t$. It is clear that the fringe abatement strategy depends on the observable triple $(x^m_t, s^m_t, s^f_t)$, so we will write $q^f_t = q^f(x^m_t, s^m_t, s^f_t)$. Note that we assume that the fringe does not observe $q^m_t$ before abating at $t$, so the decisions on abatement are simultaneous (but this is not essential for the results).

At each $t$ and given stocks $(s^m_t, s^f_t)$, the large agent chooses $x^m_t$ and decides on $q^m_t$ knowing that the fringe can correctly replicate the large agent’s problem in the subgame starting at $t + 1$. Let $V^m(s^m_t, s^f_t)$ denote the large agent’s payoff given $(s^m_t, s^f_t)$. Let $\delta = e^{-r\Delta}$ be the discount factor associated with the discount rate $r$ and period length $\Delta = 1$. Then, the equilibrium strategy $\{x^m(s^m_t, s^f_t), q^m(s^m_t, s^f_t)\}$, which we will find by backward induction, must solve

$$V^m(s^m_t, s^f_t) = \max_{\{x^m_t, q^m_t\}} \{p_t x^m_t - c_m(q^m_t) + \delta V^m(s^m_{t+1}, s^f_{t+1})\} \quad (16)$$

where

$$s^m_{t+1} = s^m_t + a^m_t - u^m_t + q^m_t - x^m_t, \quad (17)$$

$$s^f_{t+1} = s^f_t + a^f_t - u^f_t + q^f_t - x^f_t, \quad (18)$$

$$x^f_t = -x^m_t \quad (19)$$

$$q^f_t = q^f(x^m_t, s^m_t, s^f_t), \quad (20)$$

$$p_t = c^f_f(q^f_t), \quad (21)$$

and $q^f(x^m_t, s^m_t, s^f_t)$ is the fringe equilibrium strategy. While individual $i \in I$ takes the equilibrium path $\{x^m_t, s^m_t, s^f_t\}^{t \geq t}$ as given, aggregate $q^f_t$ for all $i \in I$ can be solved from the allocation problem that minimizes the present-value compliance cost for the nonstrategic
fringe as a whole. Letting $C_f(x^m_t, s^m_t, s^f_t)$ denote this cost aggregate given the observed triple $(x^m_t, s^m_t, s^f_t)$, we can find $q^f(x^m_t, s^m_t, s^f_t)$ from

$$C_f(x^m_t, s^m_t, s^f_t) = \min_{q^f_t} \{ c_f(q^f_t) + \delta C_f(\tilde{x}^m_{t+1}, \tilde{s}^m_{t+1}, \tilde{s}^f_{t+1}) \} \quad (22)$$

where $\tilde{x}^m_{t+1}$ and $\tilde{s}^m_{t+1}$ are taken as given by equilibrium expectations. Although fringe members do not directly observe the large agent’s abatement $q^m_t$, they form (rational) expectations about the large agent’s optimal abatement $\tilde{q}^m_t = q^m(s^m_t, s^f_t)$, which together with $x^m_t$ is then used in (8) to predict the large agent’s next period stock $\tilde{s}^m_{t+1}$. The expectation of $\tilde{s}^m_{t+1}$ is thus independent of what fringe members are choosing for $q^f_t$. In contrast, the expectation of $\tilde{x}^m_{t+1}$ must be such that solving $q^f_t$ and $s^f_t$ from (22) and (18) 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 (22) with equilibrium expectations, no individual $i \in I$ can save on compliance costs by rearranging its plans.$^{39}$

Using the above structure we can prove both Propositions 1-2 by backward induction. For Proposition 1, where $s^{m*}_0 > s^m_0$, we can show the result slightly more concisely by proceeding directly to continuous time (the discrete-time backward induction derivation is in the working paper Liski-Montero, 2005). The reason is that when $s^{m*}_0 > s^m_0$ the large seller faces no commitment problems, and commitment solution is easy to describe in continuous time (the discrete-time strategies exhibit exactly the same properties). The conjectured equilibrium has two parts: the time interval $[0, T^f]$ where the fringe is active, and the interval $[T^f, T^m]$ where the large agent is a monopoly. We describe first the monopoly solution by assuming $s^f_0 = 0$. We assume that the monopoly can commit to path $(x^m_t, q^m_t)_{t \geq 0}$ at $t = 0$, and then argue that the path found this way is the subgame-perfect path. Hence, given $s^{m}_0 > 0$ and $s^f_0 = 0$, the permit-stock monopoly solves

$$\max_{(x^m_t, q^m_t)_{t \geq 0}} \int_0^\infty \{ p_t x^m_t - c_m(q^m_t) \} e^{-rt} dt$$

$$ds^m_t/dt = a^m_t - u^m_t + q^m_t - x^m_t$$

$$p_t = c_f(u^f - a^f - x^m_t)$$

$^{39}$We emphasize that (22) characterizes efficient resource allocation, constrained by the leader’s behavior, without any strategic influence on the equilibrium path.
where \( u^f - a^f - x^m_t \) is what the fringe needs to abate when \( x^m_t \) is offered to the market. To save on notation, we denote the marginal revenue by

\[
MR_t = c'_f(u^f - a^f - x^m_t) + x^m_t \frac{\partial c'_f(u^f - a^f - x^m_t)}{\partial x^m_t}.
\]

Let \( \lambda_t \) denote the current-value shadow price of the stock \( s^m_t \). Then, the interior first-order conditions are \( MR_t = \lambda_t \), \( c'_m(q^m_t) = \lambda_t \), and \( d\lambda_t/dt = r\lambda_t \). Combing gives

\[
\begin{align*}
MR_t &= c'_m(q^m_t) \\
\frac{dMR_t}{dt} &= rMR_t \\
\frac{dc'_m(q^m_t)}{dt} &= rc'_m(q^m_t),
\end{align*}
\]

which are the conditions discussed in the text. Note that

\[
\begin{align*}
MR_t &= p_t[1 + \frac{1}{\varepsilon_t}] \\
\varepsilon_t &= \frac{[\frac{dc'_f(q^f)}{dq^f} x^m_p]}{p} - 1 = -\frac{dx p}{dp x},
\end{align*}
\]

where \( \varepsilon_t \) is the demand elasticity (defined to be positive). Since \( \varepsilon_t \) increases over time, it follows that

\[
\frac{dMR_t}{dt} = r > \frac{dp_t}{dt}.
\]

From this we can conclude that the competitive agents do not save permits for future uses along the monopolist’s first best solution. The monopolist then faces no commitment problem; we can write the solution as a stock-dependent rule without changing the equilibrium path. For this same reason, the Hotelling monopoly (1931) faces no commitment problems.

Consider then the situation where the fringe has some stock \( s^f_0 > 0 \), but has still less than the efficient share \( s^f_0 < s^f_0^* \), i.e., \( s^m_0 > s^m_0 \). We proceed as before, i.e., assume that the large agent can commit to path \((x^m_t, q^m_t)_{t \geq 0}\) at \( t = 0 \), and then argue that the path found this way is the subgame-perfect path. After announcing \((x^m_t, q^m_t)_{t \geq 0}\), the large agent understands that the arbitrage will imply \( dp_t/dt = rp_t \) as long as \( s^f_t > 0 \). Integrating gives

\[
p_t = p_0 e^{rt} \text{ for } t \leq T^f.
\]
The large agent’s objective can then be written as

\[
\max \{ p_0 \int_0^{T_f} x_t^m dt - \int_0^{T_m} c_m(q_t^m)e^{-rt} dt \}, \text{ or }
\]

\[
\max \{ p_0 X^m - \int_0^{T_m} c_m(q_t^m)e^{-rt} dt \},
\]

where \( X^m \) is the total amount sold to the market by the large agent. We can thus express the optimal sales condition as

\[
\frac{\partial p_0}{\partial X^m} X^m + p_0 = e^{-rT_f} MR_{T_f}
\]

where the RHS is the discounted marginal revenue from the monopoly phase. Since \( MR_t \) grows at rate \( r \) for \( T_f \leq t \leq T_m \), condition (26) says that the large agent receives the same discounted marginal revenue from all \( t \leq T_m \). In particular, condition (26) holds if the agent implements the total sale \( X^m \) by choosing \((x_t^m)_{T_f > t > 0}\) to satisfy (24). The equilibrium conditions are then (23)-(25) plus the fringe arbitrage condition. Note that if \( s_0^{m*} = s_0^m \), the socially optimal path \((q_t^{m*}, q_t^f)_{t \geq 0}\) with \( X^m = 0 \) satisfies the conditions for the commitment solution. If \( s_0^{m*} > s_0^m \), the solution requires \( 0 < T_f < T_m \), and these numbers are found by using the stock-exhaustion conditions together with first-order conditions.

The path identified this way (and discussed in more detail in the text) is the subgame-perfect path if the agent implements the total sale \( X^m \) by choosing \((x_t^m)_{T_f > t \geq 0}\) to satisfy (24). In this case, the stocks \((s_t^m, s_t^f)_{t \geq 0}\) develop along the equilibrium path such that the analog of condition (26) evaluated at any future point \( t \leq T_f \) continues to hold: the large agent has no reason revise the plan. In contrast, if the total sale \( X^m \) was made at \( t = 0 \), the stocks would go off the subgame-equilibrium path. The path defined in this way is consistent and the supporting strategies can be written as state-dependent rules without influencing the path. In our working paper Liski-Montero (2005), we do this for a discrete-time version of the model.

### 7.2 Proof of Proposition 2

We prove the result by backward induction, so we switch to discrete time and then let the period length vanish. The idea of the proof is the following. The buyer cannot extend the stock-depletion path from the socially optimal length for such a path. Doing so would increase the own marginal abatement cost above the choke price for permits which is
what the buyer needs to pay due to market arbitrage. The distortion in the price path is then limited to what can be done in the last period where the stock is exhausted. When the period length vanishes, so does the distortion and the deviation from social optimum.

Let \( \delta = e^{-r\Delta} \) be the discount factor associated with the discount rate \( r \) and period length \( \Delta > 0 \) that we keep fixed until the end of the proof. Let \( T \) denote the period in which it is socially efficient to consume the remaining stock \( s^m_T > 0 \). Assume that the large agent’s share of the stock is below the efficient share at \( T \), i.e., \( s^m_T \leq s^m_T \). We start working backwards from period \( T \), and show that \( s^m_T \) is consumed at \( T \) also in the game if \( s^m_T \leq s^m_T \). Recall that timing in each period is such that stocks \((s^m_t, s^f_t)\) are first observed, and then the large agent chooses \( x^m_t \), so that fringe is conditioning actions on the observed triple \((s^m_t, s^f_t, x^m_t)\).

By definition of \( s^m_T = s^m_T \),

\[
c'_f(q^f_T = u^f - a^f - s^f_T) = c'_m(q^m_T = u^m - a^m - s^m_T) = p^*_T \geq \delta \bar{p},
\]

where \( p^*_T \) is the socially efficient price and \( \bar{p} \) is the choke price. Thus, there is no trading and \( s^m_T \) is consumed at \( T \) if \( s^m_T = s^m_T \).

If \( s^m_T < s^m_T \), 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

\[
c'_f(q^f_T) - x^m_T c'_f(q^f_T) = c'_m(q^m_T) \geq p_T \geq \delta \bar{p},
\]

where \( q^f_T = u^f - a^f - s^f_T - x^m_T \) and \( q^m_T = u^m - a^m - s^m_T + x^m_T \). As \( x^m_T < 0 \), 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

\[
cespace
\begin{align*}
c'_f(q^f_T) & = \delta c'_f(q^f_{T+1}) \\
c'_m(q^m_T) & = \delta c'_m(q^m_{T+1})
\end{align*}
\]

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

\[ c'_m(q^m_{T+1}) \leq \bar{p}. \]  

(28)

Boundary (28) must hold since \( c'_m(q^m = u^m - a^m) = \bar{p} \) by definition and thus \( c'_m(q^m) > \bar{p} \) would imply \( q^m > u^m - a^m \), a contradiction with \( x^m < 0 \). Boundary (28) implies that all agents have marginal costs equal to or lower than \( \bar{p} \) in present value:

\[ c'_m(q^m_T) = \delta c'_m(q^m_{T+1}) < c'_f(q^f_T) = \delta c'_f(q^f_{T+1}) \leq \delta \bar{p}. \]

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 \( s^m_{T-1} > 0 \) in two periods. Assume \( s^m_{T-1} \leq s^m_{T-1} \). Again, by definition, \( s^m_{T-1} = s^*_m \) implies

\[ c'_f(q^f_{T-1} = u^f - a^f - s^f_{T-1} + s^f_{T}) = c'_m(q^m_{T-1} = u^m - a^m - s^m_{T-1} + s^m_{T}) = p^*_T = \delta p^*_T \geq \delta \bar{p} \]

If \( s^m_{T-1} < s^m_{T-1} \), there is again a need to buy as no trading would imply \( c'_f(q^f_{T-1}) = \delta c'_f(q^f_{T}) = c'_m(q^m_{T}) = \delta c'_m(q^m_{T}) \). Given \((s^m_{T-1},s^f_{T-1})\), the choice of \( x^m_{T-1} \) determines, by backward induction, the last period stocks through

\[ c'_f(q^f_{T-1}) = \delta c'_f(q^f_{T}) \]  

(29)

\[ c'_m(q^m_{T-1}) = \delta c'_m(q^m_{T}) \]  

(30)

\[ c'_f(q^f_T) - x^m_T c'_f(q^f_{T}) = c'_m(q^m_{T}). \]  

(31)

From the analysis of the last period \( T \), we know that (i) whatever stock \( s^m_T \leq s^m_{T-1} \) 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 \( s^m_{T-1} \).

The above reasoning can be repeated for any induction step \( T - k \) with \( s^m_{T-k} \leq s^m_{T-k} \). In particular, when \( k \) is large, the maximum distortion in the price level is

\[ \delta^k(p^*_T - \delta \bar{p}) \geq 0. \]

As period length vanishes, \( \Delta \rightarrow 0 \), difference between the last period price and choke
price disappears as well.

7.3 Multiple large firms

Consider case (ii) as described in the text. We proceed by backward induction. At \( t = 2 \) and for any given stock vector \((s^i_2, s^j_2)\), firm \( i = i, j \) solves

\[
\max_{x^i_2} p_2(x^i_2, x^j_2)x^i_2 - c_i(q^i_2)
\]

where \( q^i_2 = u^i - a^i - s^i_2 + x^i_2, \) \( p_2(x^i_2, x^j_2) = c'_f(q^i_2) \) and \( q^j_2 = u^j - a^j - x^i_2 - x^j_2 \). Solving the first-order condition (FOC)

\[
c'_f(q^i_2) - x^i_2 c''_f(q^i_2) - c'_i(q^i_2) = 0 \tag{32}
\]

for both \( i \) and \( j \), we obtain the subgame-perfect quantity \( x^i_2(s^i_2, s^j_2) \) and profit

\[
\pi^i_2(s^i_2, s^j_2) = p_2(x^i_2(s^i_2, s^j_2), x^j_2(s^j_2, s^j_2))x^i_2(s^i_2, s^j_2) - c_i(q^i_2) = x^i_2(s^i_2, s^j_2) - s^i_2 + u^i. \tag{33}
\]

At \( t = 1 \) firm \( i \) must decide on two independent variables, \( x^i_1 \) and \( q^i_1 \); hence, it solves

\[
\max_{x^i_1, q^i_1} p_1(x^i_1, x^j_1)x^i_1 - c_i(q^i_1) + \delta \pi^i_2(s^i_2, s^j_2)
\]

where \( p_1(x^i_1, x^j_1) = c'_f(q^i_1), q^i_1 = u^i - x^i_1 - x^j_1, \) \( \pi^i_2(s^i_2, s^j_2) \) is given by (33) and

\[
s^i_2 = s^i_1 - u^i + q^i_1 - x^i_1 \tag{34}
\]

The FOC’s for \( x^i_1 \) and \( q^i_1 \) are, respectively

\[
c'_f(q^i_1) - x^i_1 c''_f(q^i_1) + \delta \frac{\partial \pi^i_2}{\partial s^i_2} \frac{\partial s^i_2}{\partial x^i_1} = 0 \tag{35}
\]

\[
-c'_i(q^i_1) + \delta \frac{\partial \pi^i_2}{\partial s^i_2} \frac{\partial s^i_2}{\partial q^i_1} = 0 \tag{36}
\]

Since \( \partial s^i_2 / \partial q^i_1 = -\partial s^i_2 / \partial x^i_1 = 1 \), we obtain that in equilibrium

\[
c'_f(q^i_1) - x^i_1 c''_f(q^i_1) - c'_i(q^i_1) = 0 \tag{37}
\]

From looking at (32), (37) and (13), one may argue that the two strategic sellers behave,
at least qualitatively, no differently than a single-large seller in that they all equalize marginal revenues to marginal costs in each period.

There are important intertemporal differences, however. From the envelope theorem, we know that

$$\frac{\partial \pi^i_f(s^i_2, s^j_2)}{\partial s^i_2} = x^i_2 \frac{\partial p^2}{\partial x^2_2} \frac{\partial x^i_2(s^i_2, s^j_2)}{\partial s^i_2} - c'_i(q^i_2) \frac{\partial q^i_2(x^i_2, s^j_2)}{\partial s^i_2}$$

(38)

Since $\frac{\partial q^i_2}{\partial s^i_2} = -1$ and $\frac{\partial p^2}{\partial x^2_2} = -c''_j(q^j_2)$, replacing (38) into (35) and (36), using (37) and rearranging we obtain

$$c'_i(q^i_1) - x^i_1 c''_i(q^i_1) + \delta x^j_2 c''_j(q^j_2) \frac{\partial x^j_2}{\partial s^i_2} = \delta [c'_j(q^j_2) - x^j_2 c''_j(q^j_2)]$$

(39)

$$c'_i(q^i_1) + \delta x^j_2 c''_j(q^j_2) \frac{\partial x^j_2}{\partial s^i_2} = \delta c'_i(q^i_2)$$

(40)

Clearly the equilibrium conditions above differ from those corresponding to the large seller, i.e., eqs. (11) and (12), respectively. Too see why is this, note first that when the large seller plays against the fringe, the first term on the right-hand-side of (38) is zero — fringe firms take prices as given— which leads to (11) and (12). In the presence of a strategic player, firm $i$ must also incorporate the effect that its current decisions have on tomorrow’s profits through $j$’s strategic reaction. The latter is captured by the strategic term $\delta x^j_2 c''_j \frac{\partial x^j_2}{\partial s^i_2}/\partial s^i_2 = -\delta x^j_2 [\partial p^2/\partial x^2_2][\partial x^j_2(s^i_2, s^j_2)/\partial s^i_2]$, which is negative since a larger second-period stock necessarily produces a contraction in $j$’s second-period sales.\(^\text{40}\)

More interestingly, this strategic interaction leads $i$ (and $j$) to behave more conservatively today (i.e., leaving more stock for tomorrow) by both selling less and abating more. As formally shown in (39), abating an extra unit today carries the additional benefit of increasing the stock available for tomorrow ($\partial s^i_2/\partial q^i_1 > 0$; see (34)), which induces $j$ to sell less tomorrow ($\partial x^j_2/\partial s^i_2 < 0$), which in turn, puts upward pressure on $p^2$ ($\partial p^2/\partial x^j_2 < 0$). The same logic explains why the strategic interaction in (40) makes $i$ to sell a bit less. Because of this strategic interaction marginal costs and marginal revenues will go up at

\(^\text{40}\)An expression for $\partial x^j_2(s^i_2, s^j_2)/\partial s^i_2$ can be obtained from total differentiating expression (37) with respect to $s^i_2$ for both $i$ and $j$ and then simultaneously solving for $\partial x^j_2(s^i_2, s^j_2)/\partial s^i_2$ and $\partial x^j_2(s^j_2, s^j_2)/\partial s^j_2$. If, for example, $c''_j(q^j_1) = 0$, then

$$\frac{\partial x^j_2(s^i_2, s^j_2)}{\partial s^i_2} = \frac{-c''_j c''_j}{3(c''_j)^2 + 2c''_j (c''_j + c''_j) + c''_j c''_j} < 0$$
a rate strictly lower than the interest rate in equilibrium. Overall, however, the two sellers will behave more competitively relative to a cartel compromising the two firms.

References


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41It is also worth commenting that the analogy between the large polluting seller and the large supplier of a conventional exhaustible resource (with no extraction costs or constant marginal costs) does no longer hold for the case of multiple strategic sellers. In the absence of extraction costs, marginal revenues continue growing at the rate of interest for the exhaustible-resource suppliers. The analogy can be reestablished if we let the exhaustible-resource suppliers have extraction costs dependent on the overall stock.


[23] Liski, M., and Juan-Pablo Montero (2005), Market power in an exhaustible resource market: The case of storable pollution permits, MIT-CEEPR working paper.


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: Evolution of largest holding companies’ compliance paths in the sulfur market

<table>
<thead>
<tr>
<th>Year</th>
<th>American Elec. Power</th>
<th>Southern Company</th>
<th>Group of Four</th>
<th>All firms</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Permits</td>
<td>Emissions</td>
<td>Permits</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td>1,194,410</td>
<td>739,322</td>
<td>1,079,502</td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td>1,182,429</td>
<td>926,215</td>
<td>1,079,085</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td>883,634</td>
<td>871,738</td>
<td>991,297</td>
</tr>
<tr>
<td>1999</td>
<td></td>
<td>883,634</td>
<td>723,589</td>
<td>991,297</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>663,514</td>
<td>1,136,095</td>
<td>734,464</td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td>663,514</td>
<td>979,653</td>
<td>734,464</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td>653,062</td>
<td>1,039,413</td>
<td>728,778</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td>653,062</td>
<td>1,017,878</td>
<td>728,778</td>
</tr>
</tbody>
</table>

TOTALS
Cumulative diff. 1999: 11,202,052

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

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

Table 2: Emissions and allocations in a global carbon market beyond Kyoto

<table>
<thead>
<tr>
<th>Region</th>
<th>Baseline emissions</th>
<th>Kyoto allocations</th>
<th>Kyoto share</th>
<th>Baseline emissions</th>
<th>Efficient path emissions</th>
<th>Efficient share</th>
</tr>
</thead>
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<tr>
<td>FSU</td>
<td>3.61</td>
<td>4.37</td>
<td>24%</td>
<td>219.45</td>
<td>131.59</td>
<td>18%</td>
</tr>
<tr>
<td>USA</td>
<td>7.68</td>
<td>5.71</td>
<td>32%</td>
<td>457.58</td>
<td>285.09</td>
<td>40%</td>
</tr>
<tr>
<td>EUR</td>
<td>5.11</td>
<td>4.00</td>
<td>22%</td>
<td>292.55</td>
<td>160.38</td>
<td>22%</td>
</tr>
<tr>
<td>Rest of Annex I</td>
<td>4.07</td>
<td>3.89</td>
<td>22%</td>
<td>232.37</td>
<td>143.48</td>
<td>20%</td>
</tr>
<tr>
<td>Total Annex I</td>
<td>20.47</td>
<td>17.96</td>
<td>100%</td>
<td>1201.95</td>
<td>720.55</td>
<td>100%</td>
</tr>
<tr>
<td>Total World</td>
<td>40.07</td>
<td>34.40</td>
<td></td>
<td>2527.77</td>
<td>1712.05</td>
<td></td>
</tr>
</tbody>
</table>

Notes: FSU = Former Soviet Union; EUR = European Union (EU-15) plus countries of the European Free Trade Area