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MARKET POWER IN AN EXHAUSTIBLE RESOURCE MARKET: THE CASE OF STORABLE POLLUTION PERMITS*

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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 an agent, or a group of agents, in a position to exercise market power. A large seller of permits exercises market power no differently than a large supplier of an exhaustible resource. However, whenever the large agent's endowment falls short of his efficient endowment – allocation profile that would exactly cover his emissions along the perfectly competitive path – market power is greatly mitigated by a commitment problem, much like in a durable-goods monopoly. We illustrate our theory with two applications: the US sulphur market and the international carbon market that may eventually develop beyond the Kyoto Protocol.

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 of storing today's unused permits for use in later periods. This design was used in the US sulphur dioxide trading programme[1] but global trading proposals to deal with carbon dioxide emissions share similar characteristics. In anticipation of a tighter emissions limit, it is in the firms' own interest to store permits from 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 gives 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 article we study the

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1 As documented by Ellerman and Montero (2007), during the first five years of the US Acid Rain Program constituting Phase I (1995–9) only 26.4 million of the 38.1 million permits (i.e., allowances) distributed were used to cover sulphur dioxide emissions. The remaining 11.7 million allowances were saved and have been gradually consumed during Phase II (2000 and beyond).

2 We provide a preliminary discussion of the problem in Liski and Montero (2006*a*).

3 Already in the very early programmes such as the US lead phasedown trading programme and the US EPA trading programme firms were allowed to store permits under the so-called 'banking' provisions – provisions that were extensively used (Tietenberg, 2006).

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 – and a competitive fringe of many small polluting agents.[4] Agents receive free a very generous allocation of permits for a few periods and then an allocation equal, on aggregate, to the long-term emissions goal established by the regulation. We are interested in studying how the exercise of market power changes as we vary the initial distribution of the overall allocation among the different parties. Depending on individual permit endowments and relative costs of pollution abatement, the large agent can be either a buyer or a seller of permits in the market, which, in turn, may affect how and to what extent he distorts prices away from perfectly competitive levels.

Existing literature provides little guidance on how individual endowments relate to market power in a dynamic setting with storable endowments.[5] Agents in our model not only decide on how to sell the stock over time, as in any conventional exhaustible resource market, but also on 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. We find that the equilibrium can be described by a simple dichotomy. When the large agent's intertemporal endowment (i.e., profile of annual endowments) is above his efficient allocation (i.e., the allocation profile that would cover his total emissions along the perfectly competitive path), the large agent becomes a net seller of permits in the market and exercises market power no differently than a large supplier of a conventional exhaustible resource (Salant, 1976).[6] On the other hand, when the large agent's intertemporal endowment is below his efficient allocation, the large agent becomes a buyer of permits and the exercise of market power follows a logic similar in spirit to that in a durable-goods monopoly (Coase, 1972). Any effort to depress prices requires the large agent to delay purchases and, hence, to move away from his own compliance-cost minimisation. This costly distortion, which the seller does not face, severely limits the scope for market power and thus the overall distortion in the market.[7]

We then illustrate the use of our theory with two applications: the existing sulphur market created by the US Acid Rain Program in 1990, and the international carbon market that may eventually develop beyond the Kyoto Protocol. For the sulphur application, we use publicly available data on sulphur 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., 1995–9. The fact that these players, taken either individually or as a cohesive group, appear as heavy borrowers of permits during and after 2000, practically rules out, according to our theory, market power coming from the initial allocation of

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

[5] In the context of static permit trading (i.e., one-period market), Hahn (1984) shows that market power vanishes when the large agent's initial allocation is exactly equal to his 'efficient allocation' (i.e., emissions under perfect competition).

[6] Our approach is very different from Salant's in that we view firms as coming to the market in each period instead of making a one-time quantity-path announcement at the beginning of the game. There is a large theoretical literature after Salant (1976), including, among others, Newbery (1981) and Lewis and Schmalensee (1982). For a survey see Karp and Newbery (1993).

[7] While it has been long recognised that an exhaustible-resource buyer faces a dynamic inconsistency problem (Maskin and Newbery, 1990; Karp and Newbery, 1993), the conditions for the Coase conjecture in the resource model have not been well understood (Liski and Montero, 2009). We develop this point further in subsection 2.2.

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 stabilise 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 international carbon market beyond Kyoto.

Although understanding the effect of endowment allocations on the performance of a dynamic permit market is our main motivation, it is worth emphasising 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 potentially a dominant agent in the oil market needs a significant fraction of the overall oil stock before being able to exercise market power.

The rest of the article is organised as follows. The model is presented in Section 1. The characterisation of the properties of our equilibrium solution are in Section 2. 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 3. The applications to sulphur and carbon trading are in Section 4. Final remarks are in Section 5.

1. The Model

We consider pollution regulations that become tighter over time. Let t denote continuous time and $\mathcal{I}$ a continuum of heterogenous pollution sources. Each source $i \in \mathcal{I}$ is characterised by a (grandfathered) tradable-permit allocation over time $a_t^i \geq 0$, unrestricted emissions $u_t^i \geq 0$,[8] and a strictly convex abatement cost function $c_i(q_t^i)$, where $q_t^i \geq 0$ is abatement. Sources share a common discount rate $r > 0$ per unit of time. During the first years of the regulation the aggregate allocation a_t is relatively generous (either because the allocation is high or unrestricted emissions are low or both) but ultimately binding such that $u_t - a_t > 0$, where u_t denotes aggregate unrestricted emissions (we omit index i from aggregate variables). Without loss of generality,[9] we assume that firms receive, on aggregate, a stock allocation of s_0 at $t = 0$ and a constant flow $a_t = a$ thereafter, so a represents the long-run emissions limit (which could be zero as in the US lead phasedown programme). Aggregate unrestricted emissions are also assumed to be constant over time, i.e., $u_t = u > a$ for all t.[10]

Let us first study the benchmark case of perfect competition. For this benchmark we do not have to specify how the stock and flow endowments are allocated among agents. The following conditions must hold in equilibrium. First, trading across firms in any given period results in marginal costs equal price, that is,

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

[9] In subsection 3.1 we allow for trends in allocations and unrestricted emissions. In particular, there can be multiple periods of generous allocations leading to savings and endogenous accumulation of the stock to be drawn down when the annual allocations decline. Permits will also be saved and accumulated if unrestricted emissions sufficiently grow, that is, if marginal abatement costs grow faster than the interest rate in the absence of saving. None of these extensions change the essense of the results obtained from the basic model.

[10] Again, this will be relaxed in subsection 3.1.

$$p_t = c_i'(q_t^i) \tag{1}$$

for all i and t. Second, since holding permits across periods allows parties to arbitrate any price difference over time, equilibrium prices are equal in present value as long as some of the permit stock is left for future use. Exactly how long it takes to exhaust the initial stock depends on both the stringency of the long-run reduction target $u - a > 0$ and the size of the initial stock s_0. Denoting by T the (equilibrium) time of exhaustion, in equilibrium must also hold

$$\mathrm{d}p_t/\mathrm{d}t = rp_t, \text{ for } 0 \leq t < T, \tag{2}$$

$$q_T = u - a, \tag{3}$$

$$s_0 = \int_0^T (u - a - q_t)\, \mathrm{d}t. \tag{4}$$

The above 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 equalise marginal costs across space, the Hotelling conditions ensure that firms reach the ultimate reduction target gradually so that marginal abatement costs are equalised in present value during the transition period.[11]

We are interested in understanding how the presence of a large agent moves us away from the perfectly competitive equilibrium. To this end, we isolate one agent (or a coherent group of agents), denoted by the index m, from $\mathcal{I}$ and call him the large or strategic agent. The remaining agents $i \in \mathcal{I}$ form a group that acts 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 flow allocations a^m and a^f are constants, as well as the unrestricted emissions u^m and u^f, and still satisfying

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

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

We look for a Markovian subgame-perfect equilibrium in the game between the large polluter and the fringe. Such a game is best introduced in discrete time (see the Appendix), so that the timing and strategies become perfectly clear. However, to facilitate the exposition, we proceed below in continuous time, i.e., we describe the equilibrium using differential methods.

[11] 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 moves to some exogenously given substitute supply (i.e., backstop technology) in the long run. This implies that long-run market power is a possibility in the permit market, which, if exercised, affects the equilibrium during the depletion phase. Second, the per-period 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.

At each point t, all agents observe the stock holdings of both the large polluter, s_t^m, and the fringe, s_t^f. We simplify the market clearing process by letting the large agent announce first his spot sales at t, which we denote by $x_t^m > 0$ ($x_t^m < 0$ if the large agent is buying permits).[12] Having observed stocks s_t^m and s_t^f and the large agent's spot transaction x_t^m, fringe members form rational expectations about future supplies by the large agent and make their abatement decision q_t^f as to clear the market at price p_t. In equilibrium, p_t is such that

$$x_t^f = -x_t^m, p_t = c_f'(q_t^f) \text{ and } \mathrm{d}p_t/\mathrm{d}t \leq rp_t. \tag{5}$$

Note that as long as the fringe is holding a stock, arbitrage implies $\mathrm{d}p_t/\mathrm{d}t = rp_t$. The fringe's stock evolves according to

$$\mathrm{d}s_t^f/\mathrm{d}t = a^f - u^f + q_t^f - x_t^f. \tag{6}$$

At any t and given stocks (s_t^m, s_t^f), the large agent chooses x_t^m and q_t^m so as to maximise profits but knowing that the fringe can correctly replicate his problem in future subgames.[13] Hence, the equilibrium path that starts at the subgame in t, i.e., $(x_\tau^m, q_\tau^m)_{\tau \geq t}$, generates a payoff to the large agent equal to

$$\int_t^\infty \left[p_\tau x_\tau^m - c_m(q_\tau^m)\right] \mathrm{e}^{-r(\tau - t)} \mathrm{d}\tau \tag{7}$$

while satisfying

$$\mathrm{d}s_\tau^m/\mathrm{d}\tau = a_\tau^m - u_\tau^m + q_\tau^m - x_\tau^m, \tag{8}$$

(5) and (6) for all $\tau \geq t$.

2. Characterisation of the Equilibrium

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 depleted. Since our main motivation is to consider the link between permit stocks and market power, we want first to assume away market power coming from extreme flow allocations that determine the long-run trading positions. This source of market power can be ruled out by assuming efficient flow allocations a^{m*} and a^{f*} that satisfy[14]

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

[13] In the discrete-time version in the Appendix, we assume that the fringe decides on q_t^f before observing q_t^m, so the decisions on abatement are simultaneous. Not observing abatement is realistic because this information becomes publicly available only at the closing of the period as firms redeem permits to cover their emissions of that period. Assuming the Stackelberg timing not only for x_t^m but also for q_t^m does not substantially change the results.

[14] Alternatively, we can assume that the long-run emissions goal is sufficiently tight that the long-run equilibrium price is fully governed by the price of backstop technologies, denoted by $\bar{p}$. This seems to 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 subsection 3.2. 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 flow allocations.

$$\bar{p} = c_f'(q_t^f = u^f - a^{f*}) = c_m'(q_t^m = u^m - a^{m*}). \tag{9}$$

Under this allocation, the large agent chooses not to trade in the long-run because the marginal revenue from selling one unit is exactly equal to its opportunity cost (Hahn, 1984).

Having defined the efficient flow allocations, a^{m*} and a^{f*}, it is natural to define next the efficient stock allocations: endowments that allow the large agent and the fringe to follow perfectly competitive (i.e., socially efficient) abatement paths along the stock depletion phase without any trade of permits. We denote the efficient stock allocations by s_0^{m*} and s_0^{f*} and define them explicitly for future reference.

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

$$s_0^{m*} = \int_0^{T^*} (u^m - q_t^{m*} - a^{m*})\mathrm{d}t$$

$$s_0^{f*} = \int_0^{T^*} (u^f - q_t^{f*} - a^{f*})\mathrm{d}t,$$

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

We shall show that the share s_0^{m*} is the critical stock determining the type of market manipulation: seller power if $s_0^m > s_0^{m*}$ and buyer power if $s_0^m < s_0^{m*}$. Irrespective of how the overall stock is divided initially, it is clear it will be exhausted in finite time. Furthermore, the equilibrium path must necessarily follow one of these three possible paths depending on the trading position of the large agent (T^m and T^f are the equilibrium exhaustion times for the large agent and the fringe, respectively):

(*i*) all agents, large and small, hold permits until the overall stock is exhausted ($T^m = T^f$);
(*ii*) the small agents deplete their stocks first ($T^m > T^f$); or
(*iii*) the large agent depletes his stock first ($T^m < T^f$).

2.1. *Seller Power*

Like in any monopoly, seller power leads to excessive saving of the stock, thereby shifting the initial abatement burden towards the fringe, and forcing the small agents deplete their stocks first, $T^m > T^f$ (case (*ii*) above). The resulting equilibrium path is shown in Figure 1, where the manipulated price is initially higher than the competitive price p_t^*. The price grows at the rate of interest as long as the fringe is holding some stock, $t \leq T^f$, but, thereafter, the price grows at a lower rate, because the large agent is now equalising marginal revenues rather than prices in present value until the end of the storage period T^m. Note that $T^m > T^*$, where T^* is the socially optimal exhaustion period for the overall stock s_0.

The equilibrium conditions that support this outcome are the following. First, as long as the fringe is holding some stock, prices must be equal in present value, implying that the fringe's market-clearing abatement must satisfy

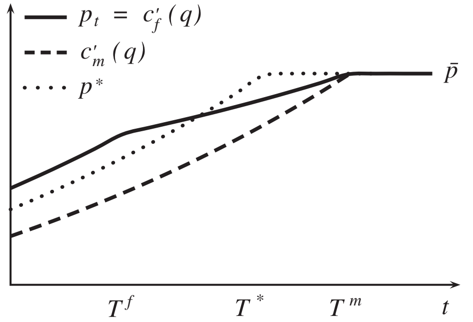

Fig. 1. *Equilibrium Under Seller Power:* $s^m > s^{m*}$

$$\mathrm{d}c'_f(q_t^f)/\mathrm{d}t = rc'_f(q_t^f) \text{ for all } 0 \leq t < T^f. \tag{10}$$

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.[15] The condition that ensures this indifference is

$$\mathrm{d}[c'_f(q_t^f) - x_t^m c''_f(q_t^f)]/\mathrm{d}t = r[c'_f(q_t^f) - x_t^m c''_f(q_t^f)] \tag{11}$$

for all $0 \leq t < T^m$. Note that $c'_f(q_t^f) - x_t^m c''_f(q_t^f)$ is the equilibrium marginal revenue from sales to the fringe at time t.

Third, the large agent must not only achieve revenue maximisation but also compliance cost minimisation which is obtained by equalising present-value marginal costs; hence,

$$\mathrm{d}c'_m(q_t^m)/\mathrm{d}t = rc'_m(q_t^m) \tag{12}$$

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

$$c'_f(q_t^f) - x_t^m c''_f(q_t^f) = c'_m(q_t^m) \tag{13}$$

must hold for all t.

Proposition 1. *If* $s_0^m > s_0^{m*}$ *then conditions* (10)–(13) *describe a subgame-perfect equilibrium.*

Proof. See the Appendix.

For future reference, it is important to note that the equilibrium path is identical to the seller's commitment solution; indeed, the equilibrium can be computed by first

[15] 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, in subgame-perfect equilibrium, that the gain from selling a marginal unit at any $t < T^f$ is equal, in present value, to the marginal revenue from sales at any $t > T^f$.

finding the large agent's commitment path and then showing that he does not want to deviate from it. The above description of market power is qualitatively consistent with Salant (1976) who considered a large seller of oil facing a competitive fringe. However, when the large agent's allocation falls below the efficient share this connection is broken. We turn to this case now.

2.2. *Buyer Power*

When the large agent has a stock exactly equal to the efficient share of the overall stock, $s_0^m = s_0^{m*}$, conditions (10)-(13) identify the socially efficient depletion path with $x_t^m = 0$ for all *t*, and $T^m = T^f = T^*$. But when $s_0^m < s_0^{m*}$, the large agent's holding falls short of what he needs for minimising compliance costs. For if the large agent does not purchase permits from the fringe but consumes only from his own stock s_0^m, he runs out of permits before the fringe does, implying both that $T^m < T^f$ and that $c_m'(q_t^m)$ exceeds the market price at $t = T^m$. This cannot hold in equilibrium, so the large agent must necessarily become a buyer whenever $s_0^m < s_0^{m*}$.

Figure 2 depicts the equilibrium path in the presence of buyer power. As long as the buyer is holding stock ($t < T^m$), he can minimise costs, i.e., present-value marginal costs are equalised as expressed in condition (12). Any abatement path $c_m'(q_t^m)$ that does not satisfy this requirement but leads to exhaustion at T^m leaves room for the buyer to improve upon it without interacting with the market. Therefore, $c_m'(q_t^m)$ must grow at the rate of interest as long as $s_t^m > 0$.

The second equilibrium condition is (10), i.e., the permit price must grow at the rate of interest to the very end of the exhaustion of the overall stock, which takes place when the fringe runs out of the stock at $t = T^f$. We must have that $T^m \leq T^f$, because otherwise the equilibrium would be in the domain of the seller-power case. Indeed, this inequality is strict, $T^m < T^f$, since the buyer will be able to distort the equilibrium by delaying the overall exhaustion time, which leads to lower present-value purchasing costs ($T^m = T^f$ would imply efficiency by conditions (10) and (12)). This is depicted in Figure 2, where the equilibrium price path lies below the buyer's marginal cost for all $t < T^f$ (the efficient price path is the dotted line).

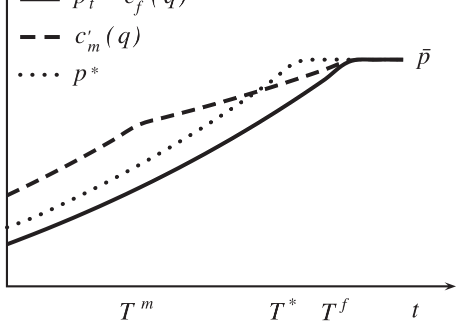

Fig. 2. *Equilibrium Under Buyer Power:* $s^m < s^{m*}$

The gap between the marginal cost and price, $c'_m(q^m_t) - p_t$, declines in the final part of the equilibrium, i.e., when $T^m < t < T^f$. Here the buyer has no stock of his own, so he buys from the fringe's. In the Appendix, we derive the following condition describing the buyer's equilibrium cost and benefit from reducing purchases by one marginal unit:

$$c'_m(q^m_t) = p_t + \frac{rp_t X_t}{u^f_t - a^f_t - q^f_t + x^f_t}, \tag{14}$$

where $T^m < t < T^f$, X_t is the large agent's total remaining purchases from time t on along the equilibrium path, and $u^f_t - a^f_t - q^f_t + x^f_t = -\mathrm{d}s^f_t/\mathrm{d}t > 0$.

The left-hand side of (14) reflects the cost of reducing purchases by a marginal unit. The first term in the right-hand side of (14) is the saving from not buying that unit and the second term is the gain from lower prices for the remaining purchases. In continuous time, a marginal reduction in today's purchase leads to a marginal delay in the arrival of the long-run equilibrium which, in turn, depresses the equilibrium price by rp_t. This leads to a total purchase cost reduction of rp_tX_t that divided by $-\mathrm{d}s^f_t/\mathrm{d}t$ gives the marginal gain. To understand why this term is divided by $-\mathrm{d}s^f_t/\mathrm{d}t$ and not simply by the actual purchase x^f_t, note that the fringe stock is 'lost' at this rate, so delaying the arrival of the long-run equilibrium becomes less effective the faster the fringe's own usage of the stock is (i.e., the larger $u^f_t - a^f_t - q^f_t$ is). If the fringe is not polluting at all $(u^f_t - a^f_t - q^f_t = 0)$, the buyer could delay the arrival of the long-run equilibrium in one marginal unit of time, i.e., $\mathrm{d}t$, by just refraining from buying x^f_t. But since the fringe is also using permits for compliance, the large agent must make an extra effort to effectively postpone the arrival of the long-run equilibrium in one period; he must save x^f_t plus $u^f_t - a^f_t - q^f_t$.

We can now complete the description of the equilibrium. As depicted in Figure 2, the buyer's marginal cost is increasing at rate r up to T^m, and it remains higher than the equilibrium price, which grows at rate r to the very end of the depletion phase at T^f (note that $T^m = 0$ when $s^m_0 = 0$). The fringe is willing to sell at lower prices because the buyer can credibly delay consumption according to (14) after his own exhaustion, i.e., during $T^m < t < T^f$.

Proposition 2. *If* $0 \le s^m_0 < s^{m*}_0$, *then the above description corresponds to a subgame-perfect equilibrium.*

Proof. See the Appendix.

Unlike the seller, the buyer cannot implement his first best: he would like to commit to a single large purchase, leading to a lower price than described above (discussed in detail in the next Section), but he faces a time-inconsistency problem similar to that of a durable-goods monopolist (Coase, 1972; Bulow, 1982). The connection between exhaustible resources (stock of permits in our case) and durable goods has been long recognised (Maskin and Newbery, 1990; Karp and Newbery, 1993). In fact, Hörner and Kamien (2004) show that the *commitment* solutions of the durable-goods monopoly and the exhaustible-resource monopsony are formally equivalent. But Liski and Montero (2009) were the first to recognise the differences in the *subgame-perfect solutions* of the two problems.

For durable goods, the stock is the consumer population already served. And if consumers' valuations decline with the stock, high-valuation consumers have incentives to wait for lower prices as lower-valuation consumers are expected to be served in the future at lower prices. This makes the commitment solution to violate subgame perfection. If, in addition, sales are arbitrarily frequent, the Coase conjecture says that the durable-goods monopolist is forced to sell at the lowest valuation almost instantly. For exhaustible resources, the value changing with the stock is the cost of extracting the resource from the ground. The conjecture for the resource monopsony would then read as follows: low-cost sellers would rather wait for high-cost sellers to enter the market, thereby, forcing the buyer to raise prices to the high-cost level almost instantly. In both cases, the conjecture requires market valuations (either consumer valuation or producer cost) to change with the stock.

In our case, there is no extraction cost,[16] and hence, it would seem that the commitment problem suggested by the durable-goods analogy is absent. However, Liski and Montero (2009) show that the existence of a choke price is what creates the buyer's commitment problem. The equilibrium condition (14) describing the buyer's purchases is equivalent to the equilibrium consumption rule derived for the exhaustible-resource monopsony in Liski and Montero (2009). However, the scope for market power is considerably reduced here for two reasons specific to the pollution context:

(*i*) the presence of many small polluting agents that free-ride on the large agent's effort to depress permit prices (i.e., the seller side is also consuming from the remaining stock), and

(*ii*) the substantial costs the large agent may incur from postponing the arrival of the long-run equilibrium. For exhaustible resources, if the buyer 'dies' with the exhaustion of the resource, there are no costs for the buyer in delaying his death (indeed, he will do so indefinitely). Conversely, the polluting buyer continues operating in the long-run, so his costs are the forgone long-run profits.

2.3. *Welfare Comparison: A Numerical Exercise*

We now develop a numerical exercise to illustrate how the market dynamics introduced by the stock allocations bring about a sharp distinction between the seller and buyer power; something that does not arise in a static context (Hahn, 1984). The large agent and the fringe are identical in all respects but in stock allocations. We assume linear marginal costs, $c'_m(q) = c'_f(q) = q$, and constant unrestricted emissions, $u^f = u^m = 2$.[17] In each period $t \in [0,\infty)$, firms receive a flow allocation equal to $a^f = a^m = 1$. In addition to the flow allocations, firms receive an overall stock allocation at $t = 0$ of $s_0 = s_0^f + s_0^m = 5$. The (continuous-time) interest rate is $r = 0.1$. Note that in the long run, i.e., once stocks have been fully depleted, firms are in perfect competition

[16] Note that the abatement cost has nothing to do with extraction costs. Abatement costs allow us to derive the buyer's utility from consumption, so it defines the buyer's flow valuation for the good.

[17] Note that in Hahn's static model with linear marginal costs and symmetric counterfactuals, a given deviation from the efficient permit allocation leads to the same welfare loss independently of whether this deviation makes the large agent a seller or buyer (i.e, regardless of whether we are reallocating a given number of permits from the fringe to the large agent or vice versa).

($\bar{p} = q^f = q^m = 1$). The idea of the exercise is to compare the perfectly competitive path (that results from stock allocations $s_0^f = s_0^m = 2.5$) with the subgame perfect paths associated to two extreme stock allocations:

(*i*) pure monopsony ($s_0^m = 0$) and
(*ii*) pure monopoly ($s_0^m = 5$).

In carrying out the exercise, it is useful to start with the artificial assumption that the large agent is restricted to trade only once with the market at $t = 0$, i.e., there is a one-time stock transaction followed by no additional trading by the large agent. As in Figures 1 and 2, firms use their stocks after trading at $t = 0$ to minimise compliance costs, i.e., marginal costs grow at the rate of interest reaching eventually $\bar{p}$. In the monopsony case (*i*), the large agent buys 1.79 units of the overall stock at $t = 0$ leading to compliance paths ending at $T^m = 6.6$ and $T^f = 9.2$ (note that under perfect competition $T^* = 8.0$). In the monopoly solution (*ii*), the large agent sells only 1.44 units of his stock to the fringe and exhausts at $T^m = 9.8$, while the fringe exhausts earlier at $T^f = 5.9$. It is not surprising based on what we know from the static model, that the monopoly and monopsony solutions in this (artificial) one-shot game are almost a mirror of each other with similar welfare consequences.[18]

Let us now remove the one-time trading restriction and look for the true subgame-perfect equilibrium paths. As shown in the second row of Table 1, the buyer is only slightly able to depress the initial price p_0 from its competitive level of 0.449 to 0.429 and extend the overall exhaustion time T by only 6% (from 8.0 to 8.5). The buyer is clearly better off with the one-time trading restriction because that provides him with the commitment that does not exist in equilibrium. A good indication of this commitment problem is that the welfare loss – total abatement costs above those under perfect competition – is only 7%. Moving to the other extreme allocation, it is immediately clear that the monopoly seller greatly benefits from having removed the one-time trading restriction. It is more profitably for the seller to gradually sell permits to the fringe rather than selling everything at once. Relative to the perfectly competitive solution, we observe a considerable increase in both the initial price and the exhaustion time (55 and 19%, respectively). Not surprisingly, this leads to a significant welfare loss of 28%.[19] In sum, dynamics (the opportunity of gradually and frequently come to the market) helps the large seller but severely hurts the large buyer.

Table 1
Subgame-perfect Distortions Under Monopsony and Monopoly

Market structure	p_0	T	Welfare loss
Perfect competition	0.449	8.0	0%
Monopsony ($s_0^m = 0$)	0.429	8.5	7%
Monopoly ($s_0^m = s_0$)	0.694	9.5	28%

[18] The two solutions are not exactly the same because the price reaction function of the fringe is not linear in the stock as in the static case.

[19] Note that if marginal abatement cost were strictly convex, welfare differences between the (subgame perfect) monopoly and monopsony solutions would be even higher. See Hahn (1984) for a numerical example for the static case.

3. Extensions

3.1. *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 US 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.

It is not difficult to see that our analysis so far readily applies to cases in which the trading position of the large agent does not change over time. There can be more intricate situations, however, where the profile of permit endowments leads to both buyer and seller power during the equilibrium path. And there, the most interesting case is one in which the large agent's initial allocation is such that he starts buying permits in the market to later become a net seller. The case is depicted in Figure 3. The two solid lines correspond to the large agent's allocation profile (a_t^m) and his socially efficient emission path ($u_t^m - q_t^{m*}$). Assume further that the areas in the Figure are such that $B - A = C$, which implies that the large agent's cumulative allocation is exactly equal to his cumulative emissions along the efficient path.

Suppose for a moment that the market has indeed followed the efficient path from $t = 0$ to $t = t'$ (requiring the large agent to have bought a total of A permits in the market). But at $t = t'$, Proposition 1 indicates that the market can no longer follow the efficient path because $B > C$. Since the equilibrium of the continuation game at $t = t'$ suffers from seller power, the true equilibrium path starting at $t = 0$ must have a non-competitive shape. Note, however, that because the large agent is also able to exercise buyer power during the earlier periods – when he is short of permits – he is able to depress prices somewhat by buying less than A and delaying purchases beyond t'. But since buyer power is much less of a problem than seller power, prices at $t = 0$ are likely to be above competitive levels; although explicit results would require additional information.

The example above indicates that moving to a less competitive equilibrium may benefit the fringe but not the large agent: he may need to buy permits at higher than competitive prices to comply and then sell them, on average, at lower prices later on

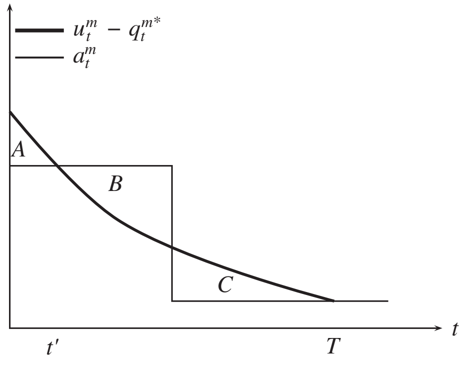

Fig. 3. *Allocation Path Leading to Both Buyer and Seller Power*

when his allocation becomes more generous. Thus, the gains from market manipulation spill over to the fringe's assets. Although using future allocations for current compliance may be ruled out by regulatory design,[20] the large agent can restore the perfectly competitive solution as a subgame-perfect equilibrium by swapping part of his far-term allocations for near-term allocations of competitive agents.[21]

3.2. *Long-run Market Power*

Since long-run market power is directly related to the large agent's long-run flow allocations relative to his emissions, it is possible to make a clear distinction between seller (or buyer) power attributable to the long-run flow allocations and transitory buyer (or seller) power attributable to the stock allocations. Here we discuss only one case in detail as other cases follow a similar analysis.

As illustrated in Figure 4, we introduce long-run seller power with a constant flow allocation to the large agent equal to $a^m > a^{m*}$ for all t. This results in a higher than competitive long-run equilibrium price, i.e., $p^m_{LR} > p^*_{LR}$. 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 initial stock. The equilibrium without transitory market power is characterised by a competitive storage period with a distorted terminal price ($p^m_{LR} > p^*_{LR}$), and with the ending time is such that both the fringe and the large agent are holding stocks to the very end of the storage period (this path is depicted as p^m_0 in Figure 4). The critical stock is defined by this path as the division of the stock that just covers the large agent's own compliance needs while taking into account the trading activity imposed by the long-run equilibrium.[22]

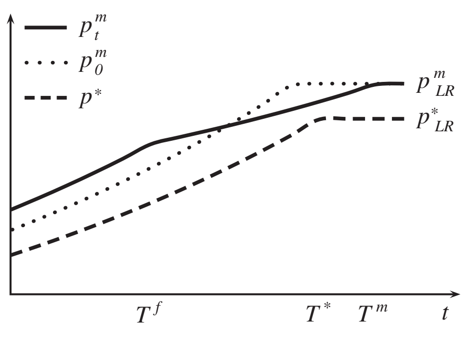

Fig. 4. *Short- and Long-run Seller Power*

[20] In all existing market designs firms are not allowed to 'borrow' permits from far-term allocations to cover near-term emissions (Tietenberg, 2006). Interestingly, the Waxman-Markey bill – US climate change legislation pending approval in the Senate – does allow for some limited amount of borrowing.

[21] 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 sulphur market (Ellerman *et al.*, 2000).

[22] Note that the large agent must start selling to the fringe before the long-run equilibrium is reached. To calculate the large agent's critical stock, let both $c'_m(q^m_t)$ and $p_t = c'_f(q^f_t)$ go up at the interest until reaching their long-term levels ($c'_m(q^m_{LR})$ and p^m_{LR}, respectively, with $c'_m(q^m_{LR}) < p^m_{LR}$) and then use the exhaustion condition to determine the level of these paths.

Even when the storage price path has a competitive shape, the overall stock is depleted faster than what is socially optimal: the long-run seller power allows the large agent to commit to consuming more than the efficient share of the overall stock allocation. When the large agent has a stock holding above the critical level, there will be transitory seller power, leading to an equilibrium price path p_t^m with a familiar shape (see Figure 4). This path reaches price p_{LR}^m at $t = T^m$, which can be smaller or greater than T^* depending on whether the shortening effect from long-run seller power is greater or smaller than the transitory extending effect.[23]

3.3. *Multiple Large Agents*

We now discuss how the equilibrium presented in Section 2 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_t^i, s_t^j, s_t^f), strategic firms simultaneously announce their spot sales/purchases x_t^i and x_t^j. Based on these announcements and the stock vector, fringe firms clear the spot market by setting, on aggregate, $x_t^f = -x_t^i - x_t^j$. 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_t^i, x_t^j).[24]

Neglect any long-run market power and focus exclusively on market power during the depletion of the stocks.[25] Depending on the initial share of the stock and firms' costs, there are three cases to consider:

(*i*) both strategic firms are on the supply side of the market,
(*ii*) both firms are on the demand 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. We will rely on a two-period analysis, which will provide us with all the relevant results for our discussion (one may think of the last two periods before the long-run equilibrium is reached). We have relegated most of the technical analysis to the Appendix.

Consider first case (*i*). There are two periods $t = 1,2$ and initial stock holdings such that $s_1^i, s_1^j > 0$ and $s_1^f = 0$. The discount factor is denoted by δ. We find that spot actions for firm i (and j) are described by conditions

$$c_f'(q_2^f) - x_2^i c_f''(q_2^f) - c_i'(q_2^i) = 0$$

$$c_f'(q_1^f) - x_1^i c_f''(q_1^f) - c_i'(q_1^i) = 0.$$

[23] In contrast, the transitory market power that arises for stock holdings below the critical level would depress the price path.

[24] 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 (2009) for the case in which the market is populated exclusively by large buyers and sellers. See Malueg and Yates (2009) for an application to pollution permit markets.

[25] Related to Gul (1987), one could argue that in the presence of long-run market power the (subgame-perfect) threat of falling into the (long-run) non-cooperative equilibrium may allow strategic buyers to sustain full monopsony/monopoly profits during the stock depletion phase.

One may thus argue that the two strategic sellers behave, at least qualitatively, no differently than a single large seller in that they all equalise marginal revenues to marginal costs in each period. However, there are interesting intertemporal implications. Recall that storage can be seen as an investment allowing each 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). Firms sell less and abate more today in an attempt to capture a larger market share in the future.

In the case of two buyers, case (*ii*), it is clear that the equilibrium outcome is more competitive than in the case where the other firm is part of the fringe, since a firm has less of an incentive to delay purchases and depress prices because of free-riding by its strategic rival.

Let us now turn to case (*iii*) by making $s_1^j = 0$, while maintaining $s_1^i > 0$ and $s_1^f = 0$. 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 countervail j's buying power, i will sell and abate less relative to the case in which j behaves competitively (i.e., j is part of the fringe). Likewise, firm j will countervail i's selling power by buying less and 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 a strategic buyer makes firm i- lower the rate at which it sells its stock over time. In terms of our general model, this reaction will lead to a distortion in the sense that the gap between p_t and δp_{t+1} increases, extending even further the depletion phase. This can be readily seen with our two period model. Rearrange (48) in the Appendix to obtain

$$c_f'(q_1^f) - \delta c_f'(q_2^f) = x_1^i c_f''(q_1^f) - \delta x_2^i c_f''(q_2^f) - \delta x_2^i c_f''(q_2^f)\frac{\partial x_2^j}{\partial s_2^i}.$$

When j is negligible (i.e., $\partial x_2^j/\partial s_2^i \approx 0$), we arrive precisely at the equilibrium condition for the single strategic seller where, as we know from the basic model, $c_f'(q_1^f) = p_1 > \delta p_2 = \delta c_f'(q_2^f)$. As j grows larger, the gap $c_f'(q_1^f) - \delta c_f'(q_2^f)$ increases in equilibrium since we are adding a positive term (recall that $\partial x_2^j/\partial s_2^i < 0$).

3.4. *Alternative Market Structures*

It is natural to focus on spot market transactions when the main objective is to understand the determinants of permit valuations over time. However, in view of the market transactions observed in some permit markets – the US sulphur market in particular (Ellerman *et al.*, 2000) – it is natural to ask whether and how our equilibrium description would change if we were to extend the scope of the market to cover forward transactions. Demand for forward transactions typically arises from the need to hedge risk but it is well known that oligopolistic firms can also choose to enter the forward market for strategic reasons. As first documented by Allaz and Vila (1993), forward contracting of production provides a commitment to a larger market share but, at the same time, it creates a prisoners' dilemma for firms in that they end up competing more intensively.

The pro-competitive effect of Allaz and Vila (1993) cannot be directly applied to the dynamic market considered in this article. Liski and Montero (2006*b*) show that the existence of forward markets increases the scope for collusive outcomes in an oligopolistic setting (i.e., two or more large firms) with a reproducible good and repeated interactions. In an exhaustible-resource market, a different result may follow: the oligopolistic (non-collusive) equilibrium becomes competitive very quickly when forward market interactions are frequent; although asymmetries in stockholdings can help firms to avoid part of the pro-competitive effect coming from contracting (Liski and Montero, 2008). These results are of direct use in a dynamic permit market because of its exhaustible-resource properties but the conclusion depends on further characteristics of the permits market. The long-run market interaction, after the exhaustion of the permit stocks, can in principle continue forever and, in this case, forward trading may help firms to sustain collusion as suggested by the reproducible-good case.

4. Applications

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

4.1. *Sulphur Trading*

The market for sulphur dioxide (SO_2) emissions has been operating since the early 1990s; right after the 1990 CAAA allocated allowances/permits to electric utility units for the next 30 years in designated electronic accounts.[26] We can then make use of agents' actual behaviours, as opposed to hypothetical ones, to check whether the conditions for market manipulation hold. Note that our exercise is by no means a test for market power; for that we would need to estimate marginal abatement cost curves.

The data we use for our exercise, which is publicly available, comprises electric utility units' annual SO_2 emissions and allowance allocations from 1995 – the first year of compliance with SO_2 limits – through 2003. We purposefully exclude 2004 and later years because of the four-fold increase in SO_2 allowance prices during 2004–5 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' behaviour 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.

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

Following our theory, the exercise consists of identifying potential strategic players and checking whether these players are on the supply or demand side of the market and to what extent. The potential strategic players in our analysis, acting either individually or as a cohesive group, are assumed to be the four largest permit-stock holding companies – American Electric Power, Southern Company, FirstEnergy[27] and Allegheny Power – that together account for 42.5% of the permits allocated during Phase I of the Acid Rain Program, i.e., 1995–9, which corresponds to the 'generous-allocation' phase.[28] While s_0^m is readily obtained from the agents' cumulative permit allocations, calculating s_0^{m*} would seem to require a more elaborate procedure based, perhaps, on some abatement cost estimates. However, this is not necessary because we have actual emissions data.

Table 2 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.[29] 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,[30] 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.

Taking a linear extrapolation of aggregate emissions from their 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 2000–3,[31] the numbers in the

[27] 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.

[28] 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 US 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 of TVA shows a deficit of permits while Union Electric shows a mild surplus.

[29] 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.

[30] 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 US EPA allowance tracking system. We will come back to the issue of imperfect observability in the concluding Section.

[31] 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.

Table 2

Evolution of Largest Holding Companies' Compliance Paths in the Sulphur Market

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

last row of Table 2 show that the compliance paths followed by the potential strategic players, taken either individually or collectively, do not support, according to our theory, a concern for significant market manipulation.[32] As established by Propositions 1 and 2 and the discussion that followed, market power is much more of a problem when (potential) strategic players are on the supply side of the market, which does not happen in the sulphur market: all four large firms are net buyers for the 1995–2012 period.

There is a second piece of evidence, based on trading activity, that reinforces our finding that market power is less of a problem in the sulphur market. According to our theory, a large agent exercising buyer-power will never sell permits in the market. However, the EPA allowance tracking system shows significant sales by our four large net-buyers. For example, by the end of year 2000, American Electric Power had sold about 1.1 million of current-vintage allowances and Southern Company about 1.5 million.[33] These are significant amounts if we compare them to firms' annual allocations.

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 subsection 3.2, is not feasible without having data on actual long-run behaviour. 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 SO_2 emissions.

4.2. *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 stabilise carbon emissions and, hence, carbon concentrations in the atmosphere. At this point all we know is that regardless of the regulatory mechanism adopted, there will be a long transition period of a few decades between now and the time of stabilisation. And 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 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 stabilise emissions in the long-run. Second, there will be large players, i.e., countries or groups of countries with the ability to manipulate market prices if it is in their best interest to do so.[34]

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

[33] Personal communication with Denny Ellerman on March 2009. It is worth mentioning that obtaining estimates of trading activity at the firm level from the EPA allowance tracking system requires an enormous amount of computational effort. Such data has not been produced by EPA.

[34] We are certainly not the first to argue that large countries such as Russia and the US can affect prices. See, for example, Bernard *et al.* (2003), and Hagem and Westskog (1998).

Even when a country 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 global prices can set a subsidy on cleaner but more expensive technologies (e.g., some of the renewable energies), thereby reducing the country's aggregate demand for permits. On the other hand, a country that wants to exercise upward pressure on prices can levy a tariff on permit exports, thereby depressing the country's aggregate supply of permits. It would be hard to argue against such a measure if the resulting revenues are aimed at financing R&D on cleaner technologies.[35]

There is another reason to believe that countries/regions – not individual facilities – are the relevant players for understanding the exercise of market power in a global market for carbon permits. As argued by Jaffe and Stavins (2009), it is very unlikely to see, at least in the medium-term, a truly international carbon market with a unique market price but rather multiple permit markets in different countries/regions. These markets will be (imperfectly) linked to each other so that some exchange of permits will be allowed across markets. Countries, not individual facilities, will decide through different domestic policies how much 'linkage' to have with the rest of the world. Hence, the interesting question is under what circumstances a large country would find in its best interest to implement domestic policies or market designs (i.e., introduction of safety valves, subsidies, standards etc.) that would work as if the country were exercising market power in a truly international market. Or alternatively put, if we observe the implementation of domestic policies that prevent a perfect linkage among the different permit markets to what extent we can claim that these policies are driven by a genuine interest in altering international prices or rather they are the result of internal domestic forces (politics) unrelated to market power.

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 primarily illustrative. In this simple exercise we ask to what extent the proportions used in the Kyoto Protocol to allocate permits among the Annex I (i.e., more developed) countries make the exercise of market power more or less likely in a global carbon market that goes 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 (CO2-e), the first three columns of Table 3 show 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).

[35] 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.

Table 3

Emissions and Allocations in a Global Carbon Market Beyond Kyoto

	Kyoto period: 2010			Transition period: 2010–2050		
	Baseline emissions Gg CO2-e	Kyoto allocations Gg CO2-e	Kyoto share	Baseline emissions Gg CO2-e	Efficient path Gg CO2-e	Efficient share
FSU	3.61	4.37	24%	219.45	131.59	18%
USA	7.68	5.71	32%	457.58	285.09	40%
EUR	5.11	4.00	22%	292.55	160.38	22%
Rest of Annex I	4.07	3.89	22%	232.37	143.48	20%
Total Annex I	20.47	17.96	100%	1201.95	720.55	100%
Total World	40.07			2527.77	1712.05	

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

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 2010 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 is above its perfectly competitive emissions path. Babiker *et al.* (2008) report the perfectly competitive emission paths that would stabilise world GHG emissions by 2050.[36] The following columns of Table 2 present cumulative baseline GHG emissions and cumulative emissions along the competitive path for the period 2010–50 and for the different countries/regions.[37] 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 cost-effective institutions – the numbers in Table 3 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%). This risk of market manipulation would greatly diminish if the FSU allocation would come closer to 18%. Note that the Kyoto shares of some other parties are surprisingly close to their efficient shares.

5. Concluding Remarks

We develop a model of a market for storable pollution permits in which a large polluting agent (or a few polluting agents) and a fringe of small agents gradually consume a stock of permits until they reach a long-run emissions limit. We characterise the properties of the subgame-perfect equilibrium for different permit allocations and found the conditions under which market power is greatly mitigated. The latter occurs when the large agent's intertemporal permits endowment is below his efficient allocation (i.e., the allocation profile that would cover his total emissions along the

[36] 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.

[37] 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).

perfectly competitive path). In this case, the large agent has difficulties in credibly committing to restrict his purchases below the perfectly competitive level. 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 sulphur 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). This is in sharp contrast with predictions from static models where such redistribution of permits could result in an increase of market power by moving, for example, from no market power to monopsony power. Closely related to the latter, the third implication is that our results make a stronger case for auctioning off permits instead of allocating them for free (as considered throughout the article). 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 of the large agent's incentives to buy additional permits in the after market.

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 sulphur market,[38] it is still interesting to ask what would happen to our equilibrium solution if we let stock-holdings be somewhat private information (or alternatively, assume that large stockholders can use third parties, e.g., brokers, to hide their identities). Lewis and Schmalensee (1982) have already identified this incomplete information problem for a conventional non-renewable 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 his Salant equilibrium output. We see the exact same problems affecting our equilibrium solution. Unfortunately, Lewis and Schmalensee (1982) 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 putting together the strategic elements found in this article with those of the literature of investment under uncertainty (e.g., Dixit and Pindyck, 1994).

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

Finally, one can view our sulphur application as one of the few attempts at empirically studying market power in pollution permit trading,[39] but it is important to emphasise that we do not provide a formal test of market power (a test comparing prices and marginal abatement costs) in part because we do not have reliable estimates of marginal cost curves. Our exercise simply showed that the initial allocations of permits to the large firms made these firms net buyers in the market, ruling out any exercise of market power according to our theory. We nevertheless think it is an interesting area for future research, estimating marginal cost curves from publicly available data such as prices and emissions and then comparing those cost figures to actual prices. Notice that finding evidence of market power (i.e., departure from marginal cost pricing) under such a test would open up an entirely new set of theoretical questions as to what could explain the presence of market power beyond that attributed to the initial allocation of permits.

Appendix

A.1. *Proof of Proposition 1*

We introduce the game in discrete time with a period length Δ that can be made arbitrarily small. We look for equilibrium strategies that depend on the current state of the market, i.e., Markovian equilibrium strategies. At the beginning of each period $t = 0, 1, 2, \ldots$ all agents observe the stock holdings of both the large polluter, s_t^m, and the fringe, s_t^f. Having observed stocks s_t^m and s_t^f and the large agent's sales x_t^m, fringe members form rational expectations about future supplies by the large agent and make their abatement decision q_t^f as to clear the market, i.e., $x_t^f = -x_t^m$, at a price $p_t \geq 0$. The fringe abatement strategy depends on the observable triple (x_t^m, s_t^m, s_t^f), so we will write $q_t^f = q^f(x_t^m, s_t^m, s_t^f)$. Note that we assume that the fringe does not observe q_t^m before abatement at t, so decisions on abatement are simultaneous (but this is not essential for the results).

At each t and given stocks (s_t^m, s_t^f), the large agent chooses x_t^m and decides on q_t^m knowing that the fringe can correctly replicate the large agent's problem in the subgame starting at next period. Let $V^m(s_t^m, s_t^f)$ denote the large agent's payoff given (s_t^m, s_t^f). Note that $\delta = e^{-r\Delta}$ would be the discount factor associated with the discount rate $r > 0$ and period length $\Delta > 0$. Then, the equilibrium strategy for the large agent $\{x^m(s_t^m, s_t^f), q^m(s_t^m, s_t^f)\}$ solves

$$V^m(s_t^m, s_t^f) = \max_{\{x_t^m, q_t^m\}} \{[p_t x_t^m - c_m(q_t^m)]\Delta + e^{-r\Delta} V^m(s_{t+\Delta}^m, s_{t+\Delta}^f)\} \tag{15}$$

where

$$s_{t+\Delta}^m = s_t^m + (a^m - u^m + q_t^m - x_t^m)\Delta \tag{16}$$

$$s_{t+\Delta}^f = s_t^f + (a^f - u^f + q_t^f - x_t^f)\Delta \tag{17}$$

$$x_t^f = -x_t^m \tag{18}$$

$$q_t^f = q^f(x_t^m, s_t^m, s_t^f), \tag{19}$$

$$p_t = c_f'(q_t^f). \tag{20}$$

[39] Kolstad and Wolak (2008) is another attempt.

and $q^f(x_t^m, s_t^m, s_t^f)$ is the fringe's equilibrium strategy.

Interior first-order conditions for q_t^m and x_t^m are, respectively,

$$[-c_m'(q_t^m) + e^{-r\Delta} V_{s_t^m}^m]\Delta = 0 \tag{21}$$

$$[p_t + \frac{\partial p_t}{\partial q_t^f}\frac{\partial q_t^f}{\partial x_t^m} x_t^m - e^{-r\Delta} V_{s_t^m}^m + e^{-r\Delta} V_{s_t^f}^m \times (1 + \frac{\partial q_t^f}{\partial x_t^m})]\Delta = 0. \tag{22}$$

The equilibrium described in the text can be constructed from these conditions as follows. If $s_t^m = s_t > 0$ and $s_t^f = 0$, the large agent becomes a monopolist, so the equilibrium conditions reduce to

$$-c_m'(q_t^m) + e^{-r\Delta} V_{s_t^m}^m = 0 \tag{23}$$

$$c_f'(u^f - a^f - x_t^m) - c_f''(u^f - a^f - x_t^m)x_t^m - e^{-r\Delta} V_{s_t^m}^m = 0. \tag{24}$$

By (23), $V_{s^m}^m$ equals the marginal cost of using a permit for own abatement. Cost minimisation over time implies, then, that $V_{s^m}^m$ grows at the rate of interest and, thus, as $\Delta \to 0$

$$dc_m'(q_t^m)/dt = rc_m'(q_t^m), \tag{25}$$

as long as $s^m > 0$, where $V_{s^m}^m = c_m'(u^m - a^m)$. Using (24), we obtain

$$MR_t = c_m'(q_t^m), \tag{26}$$

where $MR_t = c_f'(u^f - a^f - x_t^m) - c_f''(u^f - a^f - x_t^m)x_t^m$ is the marginal revenue, given that the fringe is not holding stocks (i.e., $s_t^f = 0$). Thus, both marginal revenue and marginal cost grow at the rate of interest over time until the large agent exhausts his stock,

$$dMR_t/dt = rMR_t. \tag{27}$$

In continuous time, the equilibrium conditions can be expressed as in the text. Note that $MR_t = p_t(1 + 1/\varepsilon_t)$, where $\varepsilon_t = -dx^m/dp \times p/x^m = [dc_f'(q^f)/dq^f \times x^m/p]^{-1}$ is the demand elasticity (defined to be positive). Since ε_t increases over time, it follows that

$$\frac{dMR_t/dt}{MR_t} = r > \frac{dp_t/dt}{p_t}.$$

From this we can conclude that competitive agents do not save permits for future use along the monopolist's first best solution.

We can now proceed to the main case, where the fringe has some stock $s_0^f > 0$ but still less than the efficient share (i.e., $s_0^f < s_0^{f*}$ and $s_0^{m*} > s_0^m$). We proceed immediately to the continuous-time limit, assume that the large agent can commit to a path $(x_t^m, q_t^m)_{t \geq 0}$ at $t=0$, and then argue that this path is subgame perfect. After announcing $(x_t^m, q_t^m)_{t \geq 0}$, the large agent understands that fringe's arbitrage requires $dp_t/dt = rp_t$ as long as $s_t^f > 0$. Integrating gives

$$p_t = p_0 e^{rt} \text{ for } t \leq T^f.$$

The large agent's objective can then be written as

$$\max p_0 \int_0^{T^f} x_t^m dt - \int_0^{T^m} c_m(q_t^m)e^{-rt}dt = p_0 X^m - \int_0^{T^m} c_m(q_t^m)e^{-rt}dt$$

where X^m is the total amount sold by the large agent during $[0, T^f]$. We can thus express the optimal sales condition as

$$\frac{\partial p_0}{\partial X^m} X^m + p_0 = \mathrm{e}^{-rT^f} MR_{T^f} \tag{28}$$

where the right-hand side 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 (28) says that the large agent receives the same discounted marginal revenue from all $t \leq T^m$. In particular, condition (28) holds if the agent implements the total sale X^m by choosing $(x_t^m)_{T^f > t \geq 0}$, so that (27) is satisfied. The equilibrium conditions are then (25)–(27) 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 the first-order conditions.

A.2. *Proof of Proposition 2*

When $s_0^m < s_0^{m*}$, the large firm is a buyer of permits during some part of the equilibrium path. In continuous time, we can express the buyer's equilibrium payoff as

$$V^m(s_t^m, s_t^f) = \int_t^T [p_t x_t^m - c_m(q_t^m)] \mathrm{e}^{-r(\tau - t)} \mathrm{d}\tau + \mathrm{e}^{-r(T-t)} V^m(0,0)$$

where T is the exhaustion time and $V^m(0,0)$ is equal to the long-run compliance cost, i.e., $-c_m(u^{m*} - a^{m*})/r$.

When time is discrete but the period length Δ is small, we can express the buyer's payoff as

$$V^m(s_t^m, s_t^f) = [p_t x_t^m - c_m(q_t^m)]\Delta + \mathrm{e}^{-r\Delta} V^m(s_{t+\Delta}^m, s_{t+\Delta}^f).$$

We derive the equilibrium conditions for the case $s_t^m = 0$ and $s_t^f > 0$, i.e., the large agent has no stock of his own but is buying from the fringe to comply. As explained in the text, this must be the case in the final part of the equilibrium path. Now, the large agent's choice is effectively only x_t^m since $q_t^m = u^m - a^m + x_t^m$ when $s_t^m = 0$. The interior first-order condition is then

$$\left[p_t + \frac{\partial p_t}{\partial q_t^f} \frac{\partial q_t^f}{\partial x_t^m} x_t^m - c_m'(q_t^m) + \mathrm{e}^{-r\Delta} V_{s_t^f}^m \times \left(1 + \frac{\partial q_t^f}{\partial x_t^m}\right) \right] \Delta = 0.$$

As $\Delta \to 0$, this reduces to

$$p_t - c_m'(q_t^m) + V_{s_t^f}^m = 0. \tag{29}$$

When the fringe is holding stocks and $\Delta \to 0$, today's prices depend only on tomorrow's expected prices which, in turn, depend on how much stock is left for tomorrow. The effect of x_t^m on stocks and thus on prices is captured in the term $V_{s^f}^m$ and, hence, x_t^m has no independent price effect today, i.e., $\partial q_t^f / \partial x_t^m = 0$.

To find an expression for $V_{s_t^f}^m$, totally differentiate V^m to get

$$\mathrm{d}s_t^f V_{s_t^f}^m = \mathrm{d}V^m = \tag{30}$$

$$\int_t^T \left(p_\tau + \frac{\partial p_\tau}{\partial q_\tau^f} \frac{\partial q_\tau^f}{\partial x_\tau^m} x_\tau^m \right) \mathrm{d}x_\tau^m \mathrm{e}^{-r(\tau - t)} \mathrm{d}\tau + \tag{31}$$

$$\int_t^T c_m'(q_\tau^m) \mathrm{d}q_\tau^m \mathrm{e}^{-r(\tau - t)} \mathrm{d}\tau + \tag{32}$$

$$\mathrm{e}^{-r(T-t)} [p_t x_t^m - c_m(q_t^m) - rV^m(0,0)] \mathrm{d}T + \tag{33}$$

$$\int_t^T x_\tau^m \mathrm{d}p_\tau \mathrm{e}^{-r(\tau-t)} \mathrm{d}\tau. \tag{34}$$

Lines (31) and (32) are zero because we are evaluating these changes along the equilibrium path: marginal perturbation of the equilibrium choice variable must yield a zero improvement in value (recall that x_t^m is effectively the only choice variable). Line (33) is also zero because the long-run is reached at T, and $x_T^m = 0$ and $c_m(q_T^m) = -rV^m(0,0) = c_m(u^{m*} - a^{m*})$. The last term on line (34) is the marginal change in the purchase cost due to a price change. We can then write

$$\int_t^T x_\tau^m p_\tau \mathrm{e}^{-r(\tau-t)} \mathrm{d}\tau = \mathrm{e}^{-r(T-t)} \bar{p} \int_t^T x_\tau^m \mathrm{d}\tau = \mathrm{e}^{-r(T-t)} \bar{p} X_t. \tag{35}$$

The first equality follows from the fact that prices grow at the rate of interest (fringe firms are holding permits until T). The second equality uses X_t as a shorthand for total purchases along the equilibrium path at t. Since $\bar{p}$ is fixed (the long-run price), the price effect comes only from the postponement of the choke price and, thus, the expression for $\mathrm{d}s_t^f V^m$ simplifies to

$$\mathrm{d}s_t^f V_{s_t^f}^m = -r\mathrm{e}^{-r(T-t)} \bar{p} X_t \, \mathrm{d}T = -rp_t X_t \, \mathrm{d}\tau,$$

where $\mathrm{d}T = \mathrm{d}\tau$ because the marginal increase in T equals the period length. Furthermore, since $\mathrm{d}t = \mathrm{d}\tau$ and $\mathrm{d}s_t^f = (a^f - u^f + q_t^f - x_t^f)\mathrm{d}t$, we can write

$$V_{s_t^f}^m = \frac{rp_t X_t}{u_t^f - a_t^f - q_t^f + x_t^f}.$$

Using this expression, rewrite now the first-order condition (29), as

$$c_m'(q_t^m) - p_t = \frac{rp_t X_t}{u_t^f - a_t^f - q_t^f + x_t^f} > 0 \tag{36}$$

for all $t < T$ where $X_t > 0$. This is the condition presented in the text.

If we fix T, X_t can be solved from

$$X_t = -\int_t^T x_\tau^f \mathrm{d}\tau = s_t^f - (a^f - u^f)(T-t) - \int_t^T q_\tau^f \mathrm{d}\tau, \tag{37}$$

where q_τ^f is given by the condition

$$c_f'(q_\tau^f) = p_\tau = \bar{p}\,\mathrm{e}^{-r(T-\tau)}. \tag{38}$$

Also,

$$-x_t^f = x_t^m = a^m - u^m + q_t^m. \tag{39}$$

Using (36)–(39), we can solve q_t^m as a function of s_t^f and T, i.e., $q_t^m = q^m(s_t^f, T)$. Then, we can use this in the fringe's budget constraint

$$\mathrm{d}s_t^f/\mathrm{d}t = a^f - u^f + q_t^f - u^m + a^m + q^m(s_t^f, T). \tag{40}$$

Equation (40) can now be (numerically) solved with the boundary condition $s_T^f = 0$. This will determine the path $(s_\tau^f)_{T \geq \tau \geq t}$ and the terminal time T.

A.3. *Multiple Large Firms*

Consider case (*i*) as described in the text. We proceed by backward induction. At $t = 2$ and for any given stock vector (s_2^i, s_2^j), firm $i = i,j$ solves

$$\max_{x_2^i} p_2(x_2^i, x_2^j)x_2^i - c_i(q_2^i)$$

where $q_2^i = u^i - a^i - s_2^i + x_2^i$, $p_2(x_2^i, x_2^j) = c_f'(q_2^f)$, and $q_2^f = u^f - a^f - x_2^i - x_2^j$. Using the best response

$$c_f'(q_2^f) - x_2^i c_f''(q_2^f) - c_i'(q_2^i) = 0 \tag{41}$$

for both i and j, we obtain the subgame-perfect quantity $x_2^i(s_2^i, s_2^j)$ and profit

$$\pi_2^i(s_2^i, s_2^j) = p_2\left[x_2^i(s_2^i, s_2^j), x_2^j(s_2^i, s_2^j)\right]x_2^i(s_2^i, s_2^j) - c_i\left[q_2^i = x_2^i(s_2^i, s_2^j) - s_2^i + u^i\right]. \tag{42}$$

At $t = 1$ firm i must decide on two independent variables, x_1^i and q_1^i; hence, it solves

$$\max_{x_1^i, q_1^i} p_1(x_1^i, x_1^j)x_1^i - c_i(q_1^i) + \delta\pi_2^i(s_2^i, s_2^j)$$

where $p_1(x_1^i, x_1^j) = c_f'(q_1^f)$, $q_1^f = u^f - x_1^i - x_1^j$, $\pi_2^i(s_2^i, s_2^j)$ is given by (42) and

$$s_2^i = s_1^i - u^i + q_1^i - x_1^i. \tag{43}$$

The first-order conditions for x_1^i and q_1^i are, respectively

$$c_f'(q_1^f) - x_1^i c_f''(q_1^f) + \delta\frac{\partial\pi_2^i}{\partial s_2^i}\frac{\partial s_2^i}{\partial x_1^i} = 0 \tag{44}$$

$$-c_i'(q_1^i) + \delta\frac{\partial\pi_2^i}{\partial s_2^i}\frac{\partial s_2^i}{\partial q_1^i} = 0. \tag{45}$$

Since $\partial s_2^i/\partial q_1^i = -\partial s_2^i/\partial x_1^i = 1$, we obtain that in equilibrium

$$c_f'(q_1^f) - x_1^i c_f''(q_1^f) - c_i'(q_1^i) = 0. \tag{46}$$

From looking at (41), (46) and (13), one may argue that the two strategic sellers behave very much like the single-large seller in that they all equalise marginal revenues to marginal costs in each period. There are important intertemporal differences, however.

From the envelope theorem, we know that

$$\frac{\partial\pi_2^i(s_2^i, s_2^j)}{\partial s_2^i} = x_2^i\frac{\partial p_2}{\partial x_2^j}\frac{\partial x_2^j(s_2^i, s_2^j)}{\partial s_2^i} - c_i'(q_2^i)\frac{\partial q_2^i(x_2^i, s_2^i)}{\partial s_2^i}. \tag{47}$$

Since $\partial q_2^i/\partial s_2^i = -1$ and $\partial p_2/\partial x_2^j = -c_f''(q_2^f)$, replacing (47) into (44) and (45), using (46) and rearranging we obtain

$$c_f'(q_1^f) - x_1^i c_f''(q_1^f) + \delta x_2^i c_f''(q_2^f)\frac{\partial x_2^j}{\partial s_2^i} = \delta[c_f'(q_2^f) - x_2^i c_f''(q_2^f)] \tag{48}$$

$$c_i'(q_1^i) + \delta x_2^i c_f''(q_2^f)\frac{\partial x_2^j}{\partial s_2^i} = \delta c_i'(q_2^i). \tag{49}$$

Clearly the equilibrium conditions above differ from those corresponding to the large seller, i.e., (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 (47) 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 $\delta x_2^i c_f'' \partial x_2^j(s_2^i, s_2^j)/\partial s_2^i = -\delta x_2^i(\partial p_2/\partial x_2^j)[\partial x_2^j(s_2^i, s_2^j)/\partial s_2^i]$, which is negative since a larger second-period stock necessarily produces a contraction in j's second-period sales.[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 (48), abating an extra unit today carries the additional benefit of increasing the stock available for tomorrow ($\partial s_2^i/\partial q_1^i > 0$; see (43)), which induces j to sell less tomorrow ($\partial x_2^j/\partial s_2^i < 0$), which in turn, puts upward pressure on p_2 ($\partial p_2/\partial x_2^j < 0$). The same logic explains why the strategic interaction in (49) makes i sell a bit less. Because of this strategic interaction marginal costs and marginal revenues will go up at a rate strictly lower than the interest rate in equilibrium.[41] Overall, however, the two sellers will behave more competitively relative to a cartel compromising the two firms.

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References

Allaz, B. and Vila, J.-L. (1993). 'Cournot competition, forward markets and efficiency', *Journal of Economic Theory*, vol. 59, pp. 1–16.

Babiker, M., Gurgel, A., Paltsev S. and Reilly, J. (2008). 'A forward looking version of the MIT emissions prediction and policy analysis (EPPA) model' , MIT-Joint Program Report No. 161.

Bernard A., Paltsev, S., Reilly, J., Vielle, M. and Viguier, L. (2003). 'Russia's role in the Kyoto Protocol' , MIT-Joint Program Report No. 98.

Bulow, J. (1982). 'Durable-goods monopolists', *Journal of Political Economy*, vol. 90, pp. 314–32.

Coase, R. (1972). 'Durability and monopoly', *Journal of Law and Economics*, vol. 15, pp. 143–49.

Dixit, A. and Pindyck, R. (1994). *Investment under Uncertainty*, Princeton, NJ: Princeton University Press.

Ellerman, A.D., Joskow, P., Schmalensee, R., Montero, J.-P. and Bailey, E.M. (2000). *Markets for Clean Air: The US Acid Rain Program*, Cambridge: Cambridge University Press.

Ellerman, A.D. and Montero, J.-P. (2007). 'The efficiency and robustness of allowance banking in the US Acid Rain Program', *Energy Journal*, vol. 28, pp. 47–71.

Gul, F. (1987). 'Noncooperative collusion in durable goods oligopoly', *RAND Journal of Economics*, vol. 18, pp. 248–54.

Hagem, C. and Westskog, H. (1998). 'The design of a dynamic tradable quota system under market imperfections', *Journal of Environmental Economics and Management*, vol. 36, pp. 89–107.

Hahn, R. (1984). 'Market power and transferable property rights', *Quarterly Journal of Economics*, vol. 99, pp. 753–65.

Hendricks K. and McAfee, R.P. (2009). 'A theory of bilateral oligopoly', *Economic Inquiry*, forthcoming.

[40] An expression for $\partial x_2^j(s_2^i, s_2^j)/\partial s_2^i$ can be obtained from total differentiating expression (46) with respect to s_2^i for both i and j and then simultaneously solving for $\partial x_2^j(s_2^i, s_2^j)/\partial s_2^i$ and $\partial x_2^i(s_2^i, s_2^j)/\partial s_2^i$. If, for example, $c_f'''(q_t^f) = 0$, then

$$\frac{\partial x_2^j(s_2^i, s_2^j)}{\partial s_2^i} = \frac{-c_i'' c_f''}{3\left(c_f''\right)^2 + 2c_f''\left(c_i'' + c_j''\right) + c_i'' c_j''} < 0.$$

[41] It 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) no longer holds 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.

Hörner, J. and Kamien, M. (2004). 'Coase and Hetlling: a meeting of the minds', *Journal of Political Economy*, vol. 112, pp. 718–23.

Hotelling, H. (1931). 'The economics of exhaustible resources', *Journal of Political Economy*, vol. 39, pp. 137–75.

Jaffe, J. and Stavins, R. (2009). 'Linkage of tradeable permit systems in international climate policy architecture', mimeo, Harvard University.

Joskow, P., Schmalensee, R. and Bailey, E.M. (1998). 'The market for sulfur dioxide emissions', *American Economic Review*, vol. 88, pp. 669–85.

Karp, L. and Newbery, D. (1993). 'Intertemporal consistency issues in depletable resources', in (A.V. Kneese and J.L. Sweeney, eds), *Handbook of Natural Resource and Energy Economics*, vol. 3, pp. 881–931, Amsterdam: North Holland.

Kolstad, J. and Wolak, F. (2008). 'Using environmental emissions permit prices to raise electricity prices: evidence from the California electricity market', mimeo, Harvard University.

Lewis, T. and Schmalensee, R. (1982). 'Cartel deception in nonrenewable resource markets', *Bell Journal of Economics*, vol. 13, pp. 263–71.

Liski, M. and Montero, J.-P. (2006*a*) On pollution permit banking and market power', *Journal of Regulatory Economics*, vol. 28, pp. 283–302.

Liski, M. and Montero, J.-P. (2006*b*) Forward trading and collusion in oligopoly', *Journal of Economic Theory*, vol. 131, pp. 212–30.

Liski, M. and Montero, J.-P. (2008). 'Forward trading in exhaustible-resource oligopoly', MIT-CEEPR Working Paper No. 2008-006.

Liski, M. and Montero, J.-P. (2009). 'On Coase and Hotelling', MIT-CEEPR Working Paper No. 2009-003.

Malueg, D. and Yates, A. (2009). 'Bilateral oligopoly, private information, and pollution permit markets', *Environmental and Resource Economics*, vol. 43, pp. 553–72.

Maskin, E. and Newbery, D. (1990). 'Disadvantageous oil tariffs and dynamic consistency', *American Economic Review*, vol. 80, pp. 143–56.

Montero, J.-P. (1999). 'Voluntary compliance with market-based environmental policy: evidence from the US Acid Rain Program', *Journal of Political Economy*, vol. 107, pp. 998–1033.

Morris, J., Paltsev, S. and Reilly, J. (2008). 'Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: results from the EPPA model', MIT-Joint Program Report No. 164.

Newbery, D.M. (1981). 'Oil prices, cartels and the problem of dynamic inconsistency', Economic Journal, vol. 91, pp. 617–46.

Rubin, J.D. (1996). 'A model of intertemporal emission trading, banking, and borrowing', *Journal of Environmental Economics and Management*, vol. 31, pp. 269–86.

Salant, S.W. (1976). 'Exhaustible resources and industrial structure: a Nash-Cournot approach to the world oil market', *Journal of Political Economy*, vol. 84, p. 1079–93.

Tietenberg, T. (2006). *Emissions Trading: Principles and Practice*, Washington, DC: Resources for the Future.