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Coalition formation and strategic permit trade under the Kyoto Protocol

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Abstract

This paper discusses coalition formation with side payments in markets for transferable property rights where strategic agents prevail on both sides of the market. Our concern is emissions permit trading under the Kyoto Protocol. While a seller cartel is not profitable, our analysis indicates that coalitions between sellers and buyers pay off. Three stable cartels are found. None involve all agents, yet they all induce overall efficiency. To support a stable coalition, the EU, Japan and Canada may pay together between 0 and 13 billion US dollars per year to Russia. The permit price and society-wide emission reductions are nil.

Keywords: emissions trading, Kyoto Protocol, cartel formation, merger profitability.

JEL codes: C71, C72, Q58.

1 Introduction

As a response to the problem of global warming, the 1997 Kyoto Protocol, now in force, was hammered out to limit emissions of greenhouse gases in the period 2008–2012. Parties to that agreement are the governments of some industrialized countries that have a well-defined endowment of pollution rights. Since Parties may comply via emissions trade (Article 17), a permit market is likely to emerge.

If the number of participants in such a market is large, perfect competition à la Montgomery (1972) may prevail. For the Kyoto Protocol, this assumption appears somewhat optimistic. Moreover, the initial distribution of endowments is skewed compared to corresponding needs. These features create incentives for agents on *both* sides of the market to act strategically. Following Hahn (1984) and Westskog (1996), this calls for Parties to be modeled as price-affecting. More specifically, we posit a scenario where some agents constitute a price-taking (market-clearing) fringe, while others are strategists, taking into account how their own choices affect the price.

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Given such a setting, we ask: *What if some strategically aware Parties form a cartel and coordinate actions against outsiders? Who might find it interesting to participate in such a cartel, and how will prices and abatement costs be affected?*

These issues appear relevant for the Kyoto Protocol (UNFCCC (1997)) since there seem to be no formal hurdles to such syndication. On the contrary, Article 3 states that Parties may cooperate, and compliance is then evaluated against a total, rather than a country-specific, emissions target. The secretariat of the Protocol must be notified of such arrangements upon ratification (Article 4), and this is exactly what the EU did on behalf of its 15 member states, prior to the May 2004 extension (abbreviated as EU15). However, Parties are allowed to exchange permits, and cooperation is therefore not limited by the notification clause, since it is possible to exchange permits and preserve individual compliance for all cooperating Parties. Such joint actions are what we have in mind for the coalitions we will study.

When making predictions about the impact of the Kyoto Protocol in terms of permit prices and abatement costs for the Parties involved, previous studies have either relied on price-taking behavior or limited the discussion of strategic behavior to the seller side of the market. In the latter context, monopolizing supply is profitable and may have a large effect on prices and costs. For a survey of the literature, see Springer (2003). We use predictions about emissions and costs in the year 2010 derived from the MERGE model developed by A. S. Manne and R. G. Richels (see for instance Manne and Richels (1992, 2004)) and disaggregate the data to country levels. Using these data, we show that neglecting strategic behavior on the buyer side rules out an important issue: large buyers can restrict purchases to push permit prices down, just as strategic sellers may restrict sales to induce the opposite effect. This has important consequences for coalition profitability, which depends on the size of the cost savings for those who collude, and the strategic effect from outsiders. More specifically, when sellers form coalitions, our numerical analysis shows that the strategic effect is negative and the internal cost savings are nil. Hence, cooperation between sellers is unprofitable. This is even true with full monopolization on the supply side.[1] With the exception of one case, the same result applies when strategic buyers cooperate, but here cost savings come into effect. Mergers between two agents that show up on different sides of the market, are always profitable since cost savings are then larger and dominate any negative strategic effects.

Going beyond exogenous coalition structures, we also make some tentative suggestions about what may be likely *equilibrium* cartels and the corresponding prices and costs. Our analysis suggests that a coalition between the EU15, Russia, Canada, Japan and either Poland or the Ukraine is stable. We make a ballpark estimate of the possible transfers that may occur between these Parties. While it is possible that Russia may get nothing, we calculate a maximum total transfer level of 13 billion US$ per year, coming from the EU15, Japan and Canada. In total, the EU15 has a maximum payment level (willingness to pay) of 14 billion US$ per year, while the corresponding amounts for Japan and Canada are 6.5 and 0.5 billion US$ per year, respectively. We think that these numbers give a guide to the relative bargaining strengths of the Parties and the actual transfer levels that

[1] Godal et al. (2006) discuss similar issues in a more general framework, focusing on the negative strategic effects of mergers.

could result if efficient coalitions are formed under the Kyoto Protocol. Interestingly, if the EU can persuade their new member countries to let the EU act on their behalf, and this is common knowledge, the EU improves its position at the expense of Japan and Canada. In essence, if the enlarged EU (EU25) can count on the goodwill of its newest members, it is far less dependent upon the formation of the equilibrium coalitions, which leaves much more of the burden of inducing Russia to join on the shoulders of Japan and Canada. Of course, while seeming like a wholesome EU idea, this raises important issues about intra-EU cooperation and transfers to the newest members of the EU.

We organize things as follows. In section 2 we present the game, which for convenience assumes three stages: the coalition formation game, the strategic exchange game, and the pricing of permits (degenerate) game. Section 3 then discusses the parameters of the model and describes the perfectly competitive outcome. The main contribution of the paper is in section 4, where the results of the numerical analysis are presented. We begin there with the benchmark noncooperative case, and then look at exogenous "mergers" in order to understand some of the driving forces in the model. Subsequently we discuss stable coalitions and the distribution of income within these coalitions. An extension concerning the enlargement of the EU and the effect of the so-called commitment period reserve rule, which places limits on sales, appears at the end. Section 5 summarizes and contains some final remarks.

2 The model

Throughout, there is a fixed and finite set I of agents who comprise the signatories of the Kyoto agreement. They set out to keep aggregate emissions of carbon dioxide-equivalent emissions within specific limits. Agent $i \in I$ is endowed with e_i permits to pollute. Besides being transferable, permits are assumed homogeneous, perfectly divisible and nonstorable. Each agent decides to keep the amount $x_i \geq 0$ for themselves, thereby incurring nonnegative, decreasing, convex and continuously differentiable emission costs $c_i(x_i)$.[2] The residual $e_i - x_i$ is exchanged in a common market at unit price $p \geq 0$.

Following the setup for strategic trade of Hahn (1984) and Westskog (1996), we posit a mixed scenario with two types of agents. Some are "small"; they behave as *price-takers* and belong to a nonempty fringe named F. Others are "large"; they are *strategists* (oligopolists or oligopsonists) and belong to a set S. Thus, I is the disjoint union of S and F. Since our focus is on coalitions between large agents, we shall only allow strategists to take part in the *coalition formation game*.

It is convenient to represent the overall game as if there were three stages. *First,* each $i \in S$ decides whether or not they want to join the coalition $C \subseteq S$. *Second*, all $i \in S$ decide simultaneously how many permits they want to keep. Members of a coalition minimize joint costs and compete in a noncooperative fashion against the nonmember strategists, if any. *Third*, price-takers allocate remaining permits via perfect competition, thereby defining the equilibrium market clearing price.

[2] It is convenient and commonplace in the literature to assume that the cost functions satisfy $c_i' < 0$ and $c_i'' > 0$. However, our parameters do not satisfy these properties. The main reason is that some players, most notably Russia, are endowed with more permits than needed.

Thus, at the last stage, the price-takers face total permit supply

$$Q := \sum_{i \in I} e_i - \sum_{i \in S} x_i,$$

and act as though they solve

$$\min_{\mathbf{x}_F} \left\{ \sum_{i \in F} c_i \left(x_i \right) : \sum_{i \in F} x_i \leq Q \right\}, \tag{1}$$

where $\mathbf{x}_F$ is the allocation $(x_i)_{i \in F}$. The permit price p comes as a Lagrange multiplier (shadow price) associated with the constraint in (1). Observe that among the first-order conditions of problem (1) is

$$-c_i' \left(x_i \right) = p,$$

meaning that marginal *abatement* costs will equal the permit price. This reflects (perfectly) competitive behavior.[3]

Since the permit price p will depend on Q, we write $Q \mapsto P\left(Q\right)$. The members of the coalition C, which at this second stage has already formed, cannot do better than incurring total costs[4]

$$\mathcal{C}_C \left(\cdot, x_{S \setminus C} \right) := \min_{\mathbf{x}_C} \sum_{i \in C} \left\{ c_i \left(x_i \right) + P(e_I - x_{S \setminus C} - x_C) \left(x_i - e_i \right) \right\}, \tag{2}$$

where $\mathbf{x}_C := (x_i)_{i \in C}$. Similarly, every strategist outside the coalition, $i \in S \setminus C$, receives "stand alone" costs

$$\mathcal{C}_i \left(\cdot, x_{S \setminus \{i\}} \right) := \min_{x_i} \left\{ c_i \left(x_i \right) + P(e_I - x_{S \setminus \{i\}} - x_i) \left(x_i - e_i \right) \right\}. \tag{3}$$

There are externalities in this model, since all strategists recognize and account for the fact that p depends on Q.[5]

The specification of the two last stages is now complete, and we turn to the coalition formation game. For games of that sort, many solution concepts are available. What we need is one that allows for the presence of positive and negative externalities; that does not rely on reduced costs that are subadditive across players;[6] and, since we want to quantify things, it should be computationally feasible.

To these ends, we follow d'Aspremont et al. (1983) by allowing the formation of only one coalition. Our focus will be on coalitions between large, price-affecting agents, where

[3] It also reflects the competitive element of a cooperative market game in characteristic function form à la Shapley and Shubik (1969) figuring player set F. That game has a nonempty core governed by shadow prices (see Evstigneev and Flåm (2001)). Adopting this alternative cooperative framework is possible. The case when S is empty, i.e. $F = I$, is included in our numerical analysis and its main characteristics are reported in Table 1 of section 3.

[4] The following notation will be used from here on: if $\mathcal{I}$ is some subset of I, and y_i is some variable, then $y_{\mathcal{I}} := \sum_{i \in \mathcal{I}} y_i$.

[5] Appendix B gives details about the method used to find equilibria of the second-stage game.

[6] That is, superadditive reduced payoffs, which refers to a situation where a coalition can achieve at least as much as its members can achieve individually.

side payments may occur, but only between agents who cooperate.[7] More specifically, our main interest is in a coalition C that satisfies the following properties:

Definition (coalitional stability) *A nonempty coalition C is stable if and only if it satisfies*

$$\begin{array}{llll} \textit{Internal stability:} & \mathcal{C}_C(\cdot) \leq \mathcal{C}_{C\setminus\{i\}}(\cdot) + \mathcal{C}_i(\cdot) & \textit{for all } i \in C, \textit{ and} \\ \textit{External stability:} & \mathcal{C}_{C\cup\{i\}}(\cdot) \geq \mathcal{C}_C(\cdot) + \mathcal{C}_i(\cdot) & \textit{for all } i \in S\setminus C, \textit{ if any.} \ \square \end{array}$$

Internal stability means that the coalition incurs lower costs as a whole, than if a member dropped out, adding the costs this agent would incur alone. A coalition is externally stable if the total costs of the coalition, by including a new member, are larger than the costs of the coalition without this new member, adding the costs this agent would get on its own.

Those readers who are at ease with the overall game being well defined, may immediately jump to section 3.

To determine whether any given coalition structure is stable or not, precisely one equilibrium should exist in the second-stage noncooperative game. From a general point of view, it is well established that games of the second-stage sort have *at least* one equilibrium if strategy sets are nonempty, compact and convex, and the objective functions in (2) and (3) are jointly continuous and convex in the decision variable. All these (sufficient) conditions are satisfied in our set-up, except for one, namely that nonconvexities cannot be ruled out in the objective functions. The problems arise in the market expenses (or revenues), i.e., in the object $P(\cdot, x_i)(x_i - e_i)$. Although, as shown in Appendix B, P is nonincreasing in Q, its curvature properties could, in principle, be anything. Furthermore, since the sign of $x_i - e_i$ is endogenously determined and varies between agents (buyers versus sellers), overall nonconvexities seem like a realistic scenario. Possible remedies to guarantee existence include subscribing to randomized strategies or relaxing the hypothesis of rational expectations (Flåm and Godal (2005)).

With the parameters that will be used below, equilibria exist. However, uniqueness is not always attained. This is not too worrisome since the equilibria differ only in allocation and not in value (payoff or cost).

[7] Even though we adopt the notion of stability used by d'Aspremont et al. (1983), our underlying model of trade differs. First, and as in Veendorp (1993), there are strategic agents on both sides of the market, not merely on the supply side. Second, it is endogenously determined on which side of the market an agent appears. Third, the price curve is endogenous, and it will be constructed from a nonempty fringe. Fourth, this curve is not strictly decreasing, nor continuously differentiable on the relevant domain. Finally, we shall suppose that strategic agents outside the coalition do not join the fringe, but still use whatever market power they have. Another solution concept that is applicable but more computationally demanding, is that of Horn and Persson (2001), which allows for multiple coalitions. A recent comprehensive survey of coalitional games with externalities, the so-called partition function approach as introduced by Thrall and Lucas (1963), is given in Carraro (2003). McMillan (1986) summarizes some facts from the history of international cartels.

3 Parameterization of the model

To quantify the potential importance of cartel formations, emission cost functions were derived from the MERGE model developed by A. S. Manne and R. G. Richels (1992, 2004), and then disaggregated to country levels. Appendix A gives the details.[8] What is worth mentioning here is how we have treated the countries of the EU.

The EU15 have made use of Article 3 in the Protocol to comply together. However, according to Article 4, paragraph 4: "If Parties acting jointly do so in the framework of, and together with, a regional economic integration organization, any alteration in the composition of the organization after adoption of this Protocol shall not affect existing commitments under this Protocol...." It therefore appears most likely that the new EU member countries will not be included in the already existing EU15 agreement. On this basis, we shall first model the EU as a single agent comprising its members prior to the May 2004 extension. How the results change should the enlarged EU come forward as a single agent, is discussed towards the end of the next section.

Having followed the framework for strategic trade in Hahn (1984) and Westskog (1996), what remains, to have a complete specification of the model, is to classify agents into strategists and price-takers. We are not aware of any guidance on how this choice should be made. What we do is to use a simulation of the perfectly competitive equilibrium to identify agents with a potential dominant position in this market. The results are as follows.[9]

[8] As discussed there, the reader should not put too much emphasis on the results for countries that have small emissions.

[9] Throughout, the following abbreviations are used: M-million, B-billion, t-metric ton, C-carbon, US$-US dollars of 1997, and yr-year. The number $\hat{x}_i$ is the "business-as-usual" emissions level (B-a-u for short), which is what agent $i \in I$ would have emitted in the absence of any restrictions. M-a-c is the marginal cost of reducing emissions, that is, the "marginal abatement cost", while M-s is the "market share".

Table 1. Perfectly competitive permit trading under the Kyoto Protocol.

	Endowment	Kept	B-a-u	M-a-c	Exchanged	M-s
Symbol	e_i	x_i	$\hat{x}_i$	$-c_i'(x_i)$	$x_i - e_i$	α_i
Units	MtC/yr	MtC/yr	MtC/yr	US$/tC	MtC/yr	
Russia	768	555	516	0	−213	−63%
EU15	839	1011	1011	0	172	51%
Japan	258	351	351	0	93	28%
Canada	123	189	189	0	66	20%
Ukraine	228	192	153	0	−36	−11%
Poland	116	83	83	0	−33	−10%
Czech Rep.	51	36	36	0	−15	−4%
Romania	51	38	38	0	−14	−4%
Bulgaria	25	18	18	0	−7	−2%
Hungary	22	16	16	0	−6	−2%
Slovakia	19	14	14	0	−5	−1%
Lithuania	12	9	9	0	−3	−1%
New Zealand	7	10	10	0	3	1%
Estonia	11	8	8	0	−3	−1%
Switzerland	11	14	14	0	2	1%
Latvia	7	5	5	0	−2	−1%
Slovenia	4	3	3	0	−1	0%
Norway	10	11	11	0	1	0%
Iceland	1	1	1	0	0	0%
Total	2563	2563	2485			

Note that aggregate projected emissions without emission reductions (given in column "B-a-u") are smaller than total endowments. Thus, there is a surplus of permits available in total (and the permit price is therefore nil). This may be explained by the economic collapse of the countries of the former Soviet Union (most notably Russia), which are not expecting a full emissions recovery in the projected period (2008–2012). The results compare well with other studies (see, e.g., Springer (2003)), which have projected an aggregate surplus or a very modest shortage of permits without the participation of the US.

Each agent's market share α_i, given in the rightmost column of Table 1, is defined as $(x_i - e_i)/V$ with $V := \frac{1}{2}\sum_{i\in I}|x_i - e_i|$ being the volume of the permit market. Thus, a positive (negative) α_i signifies that the agent comes forward as a buyer (seller) of permits, and market shares add up to 100% for the buyers and –100% for the sellers. The rows in Table 1 have been sorted according to the absolute value of the market shares. Hence, the dominant agent in the market is Russia, which contributes with almost two-thirds of its total permit supply. The second-largest agent is the EU15, purchasing about half of all permits bought, etc. These market shares are not unique, however, since the surplus of permits available can be distributed in a continuum of ways. The span in market shares that supports equilibrium is nevertheless not substantial.[10]

Table 1 indicates that strategic permit trading indeed appears to be a relevant feature due to the presence of large agents. But who should be modeled as strategists? Russia and the EU15 only? Japan? A line must be drawn somewhere, and when doing so, there appears to be a trade-off between assuming relatively large agents to be price-takers, and to have a fringe that is very small.

We shall assume, quite arbitrarily, that countries that make up at least 10% of total sales or purchases in the perfectly competitive equilibrium depicted above, will act strategically. Even though the above equilibrium is not unique, these Parties also have the largest excess or lack of permits relative to an average level, making them the Parties with the highest stakes in the market.[11] There are then six strategists: Russia, Ukraine, Poland, the EU15, Japan and Canada. The other countries constitute the fringe in our model. With this split, we have what appears to be three strategists on each side of the market. Even though, in principle, there could be situations where one of these agents, in some equilibrium, came forward on the "other" side of the market, this never happens in our simulations. Thus, the strategic agents can safely be categorized as sellers (Russia, Ukraine and Poland) and buyers (EU15, Japan and Canada).[12] The fringe will be a net seller of quotas in our setting.

4 Numerical analysis

The numerical analysis was carried out by fixing the membership of a first-stage coalition and then solving the second-stage game. How the model was solved numerically is discussed in Appendix B.

In this section, we start off with the benchmark case with an empty coalition. Subsequently, we will discuss several exogenous coalition structures, foremost to gain an understanding of the key driving forces and to compare with the literature on Cournot mergers. The endogenously determined stable coalitions appear towards the end, followed by notes on the commitment period reserve rule and the enlarged EU. In the interest of parsimony, the fringe countries are presented as a single player.

4.1 The benchmark case

With an empty coalition, the characteristics of the noncooperative equilibrium of the model are given in Table 2.

[10] In calculating the market shares, we have assumed that Russia and the Ukraine are keeping all excess quotas. Thus, their market shares are at comparatively low levels, while other sellers are at their "peak" market shares. This also explains the difference between kept levels in the second column and the B-a-u levels.

[11] Their B-a-u levels minus their endowments are furthest from the average of this measure across all parties.

[12] Choosing a cutoff that leaves a minimum of three strategic agents on both sides of the market also has advantages in relation to discussing coalition profitability, since we can then discuss two-party coalitions that do not lead to a full concentration (on one side of the market).

Table 2. Imperfect competition without coalitions under the Kyoto Protocol.

	Used	M-a-c	Exchange	Costs
Symbol	x_i	$-c_i'(x_i)$	$x_i - e_i$	C_i
Unit	MtC/yr	US$/tC	MtC/yr	BUS$/yr
Russia	761	0	−7	−0.4
Ukraine	221	0	−7	−0.4
Poland	109	0	−7	−0.4
EU15	867	267	28	20.7
Japan	290	298	32	10.8
Canada	140	181	17	5.4
Fringe	175	53	−56	−2.8
Total	2563		0	32.9

When comparing with the perfectly competitive outcome, the figures in Table 2 show that supply of permits into the market is restricted by the strategic sellers, and the permit price jumps from 0 to 53 US$/tC (the marginal abatement cost of the fringe). Total costs (a negative measure of welfare) increase by nearly 33 BUS$/yr, indicating that oligopolistic behavior has the power to significantly reduce overall welfare. Another reason total costs soar (which incidentally also prevents an even higher price) is that the strategic buyers restrict purchases relative to the competitive scenario.

On the up-side, this type of behavior also yields some emission reductions that we did not have under perfect competition. Any benefits in terms of a better climate are not accounted for in our measure of welfare.

4.2 Exogenous coalitions

We start by discussing coalitions where "similar" Parties are involved.

4.2.1 Mergers between sellers

In the literature on strategic permit supply under the Kyoto Protocol, countries of the former Soviet Union are often treated as a single agent, Russia and the Ukraine being the two most important members (see, for example, Manne and Richels (2004) and the overview by Springer (2003)). Table 3 sheds some light on the profitability of such coordinated strategic supply, given the presence of strategic buyers.[13]

[13] Tables 3 to 5 should be read in the following manner. The first row assigns to each column a reference number for later use. Columns with identical reference numbers represent the same simulations. In the row below, the equilibrium price is given. All other figures are total costs, including revenues/expenses from permit trade. Each column shows the distribution of costs given a particular coalition. An $*$ indicates membership of the coalition or cartel, and total costs for those members are given in the second row. The first column gives the reference coalition structure. The last row then shows the cost increment for the members of the cartel as compared to their aggregate costs in the reference column. Hence, a positive number in the last row indicates that the cartel is unprofitable compared to the reference figures.

Table 3. Cartels with strategic sellers. The permit price is given in US$/tC. All other figures are total costs measured in BUS$/yr.

	#1	#2	#3	#4	#5
Price	53	64	64	64	79
Cartel		−0.5	−0.5	−0.5	−0.8
Russia	−0.4	*	*	−0.5	*
Ukraine	−0.4	*	−0.5	*	*
Poland	−0.4	−0.5	*	*	*
EU15	20.7	21.2	21.2	21.2	21.9
Japan	10.8	11.3	11.3	11.3	12.1
Canada	5.4	5.7	5.7	5.7	6.1
Fringe	−2.8	−3.4	−3.4	−3.4	−4.3
Total	32.9	34.2	34.2	34.2	35.7
Cost incr. cartel		0.2	0.2	0.2	0.3

We see that for two-country seller cartels (#2, #3 and #4), the members lose about 200 MUS$/yr as compared to the no-cartel case, while the "outside" strategic seller wins some 100 MUS$/yr. The strategic buyers all lose. The figures are identical no matter which two countries form a cartel. This is because, in all cases, the sellers have zero marginal costs in equilibrium, and consequently it does not matter which countries cooperate even though their size and surplus of quotas differ.

These results are clearly reminiscent of the traditional merger results (Salant et al. (1983)) and follow the usual intuition that the outside strategic agent on the same side of the market as those that merge, has fewer competitors after a merger. In a Cournot setting, this leads to an expansion of that agent's output at the expense of the merging firms' market shares.[14] While our results may not seem very surprising in light of this, it is notable that they still prevail with strategic agents on both sides of the market.

The results from the merger literature also suggest that, while a merger between any two sellers may not be beneficial, a merger involving all three agents, should be so. Our results (case #5) do not follow the classic model here, since it turns out that such a merger is not profitable (the concentration is still not sufficient). It may seem strange that the sellers do not win from such a "monopolization". The reason for this is that, while they restrict sales to push up prices, the buyers' equilibrium response is to restrict purchases further.[15] It follows that the buyers will also lose from such a cartel. The price-takers in this particular example win on average, because of the abundance of quotas among these

[14]It is worth noting that the Salant et al. results may be reversed under Bertrand competition. However, we would argue that modeling a framework like this as a Bertrand game would be less realistic due to the fact that restricting capacity (which is something at least the well-endowed countries can credibly do without threat of being driven out of the market) is exactly the way to resurrect the Cournot model from a Bertrand setting (see Kreps and Scheinkman (1983)).

[15]It may be argued that since the fringe is a supplier of permits, the coalition does not involve all sellers. However, this is *not* the reason for the above result, which is further discussed in Godal et al. (2006). The results from the next section illustrate this. There, it is shown that a buyer "monopsony" is also unprofitable. This holds even though there are sizable cost savings in that case.

agents.

In conclusion, then, one may argue that the above results cast some doubts on lumping Russia, the Ukraine and other sellers together as if they were to form a cartel. The reason monopolization is profitable in studies that do this, is because the demand side is assumed to be price-taking.[16]

4.2.2 Mergers between buyers

With coalitions on the demand side, the same qualitative results prevail as was the case for sellers. This is clear from Table 4.

Table 4. Cartels with strategic buyers. Units as in Table 3.

	#1	#6	#7	#8	#9
Price	53	17	28	26	0
Cartel		35.3	27.5	17.9	39.1
Russia	−0.4	0.0	−0.1	−0.1	0.0
Ukraine	−0.4	0.0	−0.1	−0.1	0.0
Poland	−0.4	0.0	−0.1	−0.1	0.0
EU15	20.7	*	*	19.2	*
Japan	10.8	*	9.4	*	*
Canada	5.4	4.2	*	*	*
Fringe	−2.8	−0.8	−1.5	−1.3	0.0
Total	32.9	38.6	35.2	35.5	39.1
Cost incr. cartel		3.9	1.5	1.7	2.3

Observe that the price is zero in what may be dubbed a "monopsony" (case #9 where all three strategic buyers form a cartel). This may seem surprising since the cartel incurs substantial costs. However, it cannot reap the full benefits of a price of zero, since that would increase prices. Thus, the cartel simply empties the fringe of excess quotas at a price of zero, taking care not to increase purchases above this level, which would induce a positive price on all purchased quotas. The sellers are obviously adversely affected by such a low price.[17] Comparing with the results under a three-seller cartel, the fact that the price-takers lose is straightforward: they won in that case because they are relatively well endowed as a whole, and they lose (as a whole) now for exactly the same reason.

A lesson to be learned from case #9, is that, while the competitive equilibrium is efficient (with a price equal to zero), observing such a price in no way signals an efficient

[16] Assuming only the three sellers to be strategists, coalitions between Russia and the Ukraine, Russia and Poland and between all three strategists, all turn out to be beneficial. A coalition between Poland and the Ukraine is not. In all two-party cases, however, the outside strategist earns more than the merging parties, which means that the merger paradox (Salant et al. (1983)) prevails under these circumstances.

[17] *Ceteris paribus*, the sellers would be equally well off by dumping their excess quotas on the market, but if the buyers were to purchase these quotas, it would be better for the sellers to restrict output, increasing the price above zero. Thus, there is no Nash equilibrium where the strategic sellers dump excess quotas on the market at a price of zero.

(competitive) permit allocation.[18] The permit allocation is so inefficient that aggregate costs may be some 39 BUS$/yr above the costs in the competitive equilibrium. "Fortunately" though, this turns out to be an unstable coalition.

4.2.3 Merger between a buyer and a seller

So far we have shown that cartels formed between the large agents on either side of the market seem to be an unlikely occurrence since they simply do not pay off. The next step is then to check for cartels between agents that tend to come forward on different sides of the market.

Looking at two-country situations only, the nine possible cartel combinations produce outcomes as given in Table 5.

Table 5. Cartels with a strategic seller and a strategic buyer. Units as in Table 3.

	#1	#10	#11	#12	#13	#14	#15	#16	#17	#18
Price	53	13	8	29	37	17	29	50	38	45
Cartel		0.0	0.0	−0.1	6.0	0.4	−0.1	12.9	4.2	1.4
Russia	−0.4	∗	∗	∗	−0.2	0.0	−0.1	−0.3	−0.2	−0.3
Ukraine	−0.4	0.0	0.0	−0.1	∗	∗	∗	−0.3	−0.2	−0.3
Poland	−0.4	0.0	0.0	−0.1	−0.2	0.0	−0.1	∗	∗	∗
EU15	20.7	∗	18.2	19.4	∗	18.7	19.4	∗	19.9	20.2
Japan	10.8	8.5	∗	9.5	9.9	∗	9.5	10.6	∗	10.3
Canada	5.4	4.1	4.0	∗	4.9	4.2	∗	5.3	4.9	∗
Fringe	−2.8	−0.6	−0.4	−1.5	−1.9	−0.8	−1.5	−2.7	−2.0	−2.4
Total	32.9	12.0	21.7	27.0	18.5	22.4	27.0	25.4	26.6	29.1
Cost incr. cartel		−20.3	−10.4	−5.1	−14.3	−10.0	−5.1	−7.4	−6.2	−3.6

Not surprisingly, all cartels are now profitable. The nonmember strategists either win, or lose much less than they gain from the cartel formation, and the total effect on welfare is positive, i.e., total costs go down. Most gains are available for Russia and the EU15, where total costs for the two decrease by 20 BUS$/yr. Together, a seller and a buyer can avoid the common tragedy of holding back on supply and demand (to induce a price increase and decrease, respectively). Outside strategists never win as much as the coalition partners.

4.3 Stable coalitions

Having explored the driving forces in the model, we now turn to the stable coalitions. These are given in Table 6.[19]

[18] This is qualitatively the same as Veendorp (1987, p. 525) finds in a (symmetric) model with strategic buyers and sellers.

[19] One way to find the stable coalitions is to add sequentially the nonmember agents that could contribute with the largest cost savings to the already existing coalition. Starting off with EU and Russia (cf., Tables 3–5), one would, following this procedure, continue with Japan and then Canada. When

Table 6. Stable coalitions. Units as in Table 3.

	#19	#20	#21
Price	0	0	0
Cartel	0.00	0.00	0.00
Russia	*	*	*
Ukraine	*	0.00	*
Poland	0.00	*	*
EU15	*	*	*
Japan	*	*	*
Canada	*	*	*
Fringe	0.00	0.00	0.00
Total	0.00	0.00	0.00

In all three stable coalition structures, the permit price is nil, and there are no emission reductions.[20] Since no other combination of countries has been found to give these results, we also argue that these are the only stable coalitions. From a welfare point of view, the overall outcome with a stable coalition does not differ from the perfectly competitive equilibrium, even though not all agents are taking part in the coalition. These results are dependent upon the fact that the price-takers are net suppliers. If the price-takers were buyers, strategists could try to monopolize on this "exogenous" demand. However, with the fringe having enough permits to satisfy their B-a-u levels, the best a coalition could do is to achieve zero net costs. The grand coalition has enough permits to do this entirely on its own. The coalition without Poland needs 4 MtC/yr from the fringe to achieve zero costs, while the coalition without the Ukraine needs 46 MtC/yr (the excess permits of the fringe amount to 49 MtC/yr).

Some points about the stable structures found above deserve mentioning. First of all, reasonable alternative assumptions about who are strategists do not change the basic result that any equilibrium coalition would have zero costs and cannot exploit the fringe; letting one or more of the sellers (the most relevant one being Poland) be a price-taker only increases the excess supply of the fringe. Letting, for instance, Canada be a price-taker changes matters, but it seems unwarranted to exclude Canada without at least also excluding Poland. In that case, the price-takers are still net suppliers. Adding some of the price-takers as strategists reduces the excess permits of the fringe, but moving down Table 1 it is easy to see that the fringe would, at the maximum, buy a marginal amount. We would have to include another six strategists before the fringe even stops being a net supplier, and even then the fringe only lacks approximately 1 MtC/yr to induce zero costs.

Second, we do not believe that the use of other reasonable coalition stability con-

subsequently adding either Poland or the Ukraine, or both, the coalition becomes both internally and externally stable.

[20] As discussed in Appendix B, there are multiple equilibria in all these cases. This is a result of differences in the distribution of excess quotas, which do not affect reduced costs.

cepts will change what constitutes the stable coalitions here. Since, as argued above, exploitation of the fringe is practically impossible and the minimum cost option for all strategists is available, we find it reasonable that a stable coalition should imply zero costs across the board. The framework of Horn and Persson (2001), for instance, allows for multiple coalitions. In the grand coalition, all players are what Horn and Persson dub "decisive". In accordance with their solution concept, it suffices to compare total costs in the grand coalition to all other coalition structures. However, since the grand coalition by construction minimizes joint costs, it will have at least as low costs as every other coalition structure. Thus it is an equilibrium. In the two other stable coalition structures that we found, the outside Parties (the Ukraine or Poland) may not be decisive. However, even though transfers *between* coalitions may not be allowed, the fact that the Ukraine or Poland may not be decisive can only strengthen the conclusion: neither the Ukraine nor Poland can possibly do worse than obtaining net costs of zero. Thus, if they are not decisive, there is never a potential *loss* that is not accounted for by the decisive owners. Since the stable coalitions minimize aggregate costs, there is no possibility that any other coalition (or, indeed, set of coalitions) can be strictly better for the decisive owners. Thus, all three stable coalition structures are equilibria under the Horn–Persson framework.

Based on the above discussion and results, any stable coalition will involve zero costs for all involved Parties as a whole. However, side payments may come into play to secure participation of vital players. To quantify the importance of such considerations, we shall discuss what each agent is willing to pay to join the coalition, as well as what all other coalition partners are willing to pay for each agent's membership. The figures are given in the left and right subcolumns, respectively, in Table 7.

Table 7. Total costs of exit from a stable coalition by each country. Units as in Table 3 and "n.a." means not applicable.

Equilibrium structure as in	#19		#20		#21	
Symbol	$\mathcal{C}_i$	$\mathcal{C}_{C\setminus\{i\}}$	$\mathcal{C}_i$	$\mathcal{C}_{C\setminus\{i\}}$	$\mathcal{C}_i$	$\mathcal{C}_{C\setminus\{i\}}$
Russia	0	19	0	29	0	13
Ukraine	0	0.3	n.a.	n.a.	0	0
Poland	n.a.	n.a.	0	0.3	0	0
EU15	14	0	14	0	14	0
Japan	4.7	0	4.7	0	4.7	0
Canada	0.5	0	0.5	0	0.5	0

Table 7 indicates that, no matter which stable coalition is considered, the EU15 loses about 14 BUS$/yr by standing alone. The figures for Japan and Canada are considerably lower. If any of these buyers leaves, costs for the remaining Parties are zero. If Russia were to drop out of the coalition, it would always earn nothing, but the cost increment for the coalition partners depends very much on which stable structure has formed. If, looking at the one where Poland is not a member (#19), the remaining agents incur 19 BUS$/yr in costs. Given the stable coalition without the Ukraine, the corresponding figure is 29, while for the grand coalition it is 13 BUS$/yr.

So which coalition appears most likely to be formed, and how much should Russia be expected to earn? It is clear that side payments of zero support any stable coalition, and this can therefore be seen as a minimum possible transfer level. Furthermore, it appears that Russia should not be able to demand more than 13 BUS$/yr, since it would be cheaper for the buyers to pay a nonmember (either the Ukraine or Poland) to join. Thus, we believe more strongly in the formation of the grand coalition than the other coalitions, at least when it comes to determining realistic levels of the side payments that may befall Russia. The result is a payment of some amount between 0 and 13 BUS$/yr (in total) from the EU15, Japan and Canada to Russia.

It is worth noting that the payments by the buyers in a stable coalition are considerably smaller than in the benchmark case of no coalitions (where annual costs were roughly 21, 11 and 5 BUS$, see Table 2). Russia has the potential to earn a great deal more, while the Ukraine and Poland earn less. This is because of their lack of importance since they are not both needed for costs to vanish.

4.4 Extension 1: The commitment period reserve rule

Until now, we have ignored the fact that the Parties of the Protocol have agreed on the so-called commitment period reserve rule, which limits the amount of permits a Party can sell. Clearly such constraints may affect our results. The rule, which was written into the Marrakesh Accords and finally adopted in Montreal in 2005, states (UNFCCC (2001) p. 99) that: "Each Party ... shall maintain in its national registry a commitment period reserve which should not drop below 90 per cent of the Party's assigned amount, ... or 100 per cent of its most recently reviewed inventory, whichever is lowest." The term "assigned amount" corresponds to what we have called endowment. Concerning the term "recently", we follow the approach in Godal and Klaassen (2006) and suppose that this amounts to the emissions in the year 2005, denoted by $\bar{x}_i$. This chosen lag is due to the fact that producing an emissions inventory (and having it reviewed) takes several years. Given these interpretations, the commitment period reserve rule can then be included in the model by conditioning problems (1), (2) and (3) on the constraint

$$x_i \geq \min\left[0.9e_i, \bar{x}_i\right] \tag{4}$$

for each $i \in F$, $i \in C$ and $i \in S \setminus C$, respectively. This constraint says that the number of permits an agent holds cannot be lower than what must be kept in the reserve.

We did not include this rule in all the simulations, since we wanted to have a clean picture of the key driving forces. However, for our stable coalitions given in Table 6, the rule does not become binding for any Parties and therefore has no effect.

4.5 Extension 2: The enlarged EU as a single agent

So far, we have treated Poland and other more recent members of the EU as outsiders to the EU, since they are not part of the EU agreement to comply jointly with the Protocol.

Suppose instead that the enlarged EU comes forward as a single strategic agent.[21] How would such an arrangement affect coalition formation? Notice that this change does not only alter the player set in the noncooperative game, but also the price function, since many small new EU members were previously supposed to be price-takers. However, the EU is still a buyer of permits in all scenarios, and the fringe is still a net seller.

With these changes, the following results are obtained.

1. In the benchmark case (five-strategist noncooperative oligopoly), the EU25 has to pay significantly less (8 BUS$/yr) because of the inclusion of permit-abundant countries. Canada and Japan are much worse off, incurring total costs of 7 and 15 BUS$. These countries lose more because the price is higher (88 US$/tC), which is due to a more concentrated seller side and efficient sharing between the EU25 countries, leaving fewer permits for sale on the open market. Russia and the Ukraine are slightly better off than in the benchmark case with six strategists.

2. Concerning profitable mergers, a two-party coalition between Russia and the Ukraine is still not beneficial (recall Poland is now part of the EU25, so this is a seller's monopoly). The same does not hold if any two of the buyers form a coalition: if the EU25 and Japan were to cooperate, they force prices down and obtain an efficient distribution of permits between themselves. The latter effect is very important, which can be seen from the fact that Canada, benefiting from the price reduction, does not win nearly as much as the coalition (0.8 vs. 2.6 BUS$/yr). In contrast, a coalition between Canada and the EU25 or Japan is only marginally beneficial, and the outsider (Japan or the EU25, respectively) wins considerably more than the coalition. In these two latter cases, the "merger paradox" thus prevails. A coalition between all buyers is also beneficial. All other two-party coalitions (between a seller and a buyer) reduce aggregate costs of the coalition partners, with Russia and Japan forming the most beneficial one at a net annual cost reduction of 15 BUS$.

3. As it turns out, and as would be expected from the previous analysis, there are two internally and externally stable coalitions: the coalition formed by all strategists, and the coalition formed by all strategists except the Ukraine. In all cases, the total costs society-wide are zero, and the commitment period reserve rule, constraint (4), does not bind any Party.

4. Focusing on the grand coalition, for reasons discussed before, if Russia leaves this coalition, the coalition stands to lose a little less than 13 BUS$/yr. If the EU25 leaves, it loses 6.5 BUS$/yr. If Japan exits, the coalition partners win a little (because they are sellers and the price increases above zero), but Japan loses severely. The net annual cost increase of all the coalition partners is nearly 14 BUS$/yr. If Canada exits, the loss is some 5 BUS$/yr. The Ukraine earns nothing outside the coalition, and the rest of the strategists have access to enough quotas without the Ukraine.

[21] That is, it includes the EU15 plus Poland, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Slovakia and Slovenia. The abbreviation EU25 is used, even though the two remaining new countries, Malta and Cyprus, are not included in the model.

Under the assumption that all EU25 countries behave as a single strategic player under the Protocol, we have thus found that the EU stands to pay a maximum of 6.5 BUS$/yr, which is considerably less than when it came forward as the EU15. Russia is not much affected by such an enlargement of the EU15, but Japan and Canada clearly are: they stand to pay (to Russia) a maximum of 14 and 5 BUS$/yr, respectively. Interpreting these maximum payments as an (inverse) indication of the countries' bargaining power, it seems clear that Canada and Japan should try to prevent such EU coordination. Their success depends on the interpretation of Article 4 (it is the EU15 that has signed the agreement to be treated as a single party under the Protocol) and/or the willingness and ability of the EU25 countries to trade at marginal costs among themselves. The latter could involve some substantial fixed transfers from the old to the new EU countries, most notably Poland. Thus, the inclusion of the new EU countries as a single partner under the Kyoto Protocol could potentially come forward as a controversial issue not only between the large Kyoto partners, but also *within* the EU.

5 Some final remarks

This paper studied cartel formation in the permit market under the Kyoto Protocol. Our main findings can be summarized as follows.

1. Gains from cooperation are much larger when sellers and buyers join up (such as Russia and the EU) than if Parties on the same side of the market cooperate (like Russia and the Ukraine). The latter is typically unprofitable, and, somewhat surprisingly, this even holds when all large sellers cooperate.

2. A stable coalition can be formed by as few as five Parties, viz., Russia, the EU15, Japan, Canada and either the Ukraine or Poland.

3. To uphold this cartel, no side payments need to be made, but it could involve a transfer to Russia of up to 13 BUS$/yr, which is paid by the EU15, Japan and Canada.

4. A stable cartel induces the overall Pareto-efficient outcome with a vanishing permit price and no emission reductions.

A few of many limitations to this study are worth noting. First, our parameters do not include noncarbon greenhouse gases, the Clean Development Mechanism (the possibility to reduce emissions in countries without binding commitments) or forestation. However, it is worth noting that studies encompassing these items, generally find that prices and costs are lowered by these options (Springer, 2003). Since we find that the prices and costs in our equilibrium coalitions are zero, we feel that these additional considerations may not be of paramount importance to our results. The unprofitability of seller (and other) coalitions rests on differences in costs more than on absolute costs, and appear, as such, more immune towards omitted items that simply bring costs down.

Another shortcoming is the lack of bargaining costs. However, since incentives to cooperate are in the range of a hundred million to several billion US$ per year, we believe that omitting such costs in our model should not prove detrimental. A potentially more important weakness, is the fact that our model is static and does not allow for the possibility that permits can be saved for later periods. Permit banking is legal under the Kyoto Protocol, and may seem a likely scenario since the price we calculate in equilibrium is nil. That, of course, does not imply that permits have no value in equilibrium, since they generate transfers that could be substantial. The effect on permit prices with banking, but without coalition formation, is discussed in Godal and Klaassen (2006) and could, in principle, be added to an extended model. On a more general note, it also appears that other solution concepts for the second-stage noncooperative permit market could be envisaged. To this end, the material in Gabszewicz (2002) may turn out to be useful.

Finally, reflecting on the Kyoto Protocol setting, there is no apparent legal hurdle for governments to form coalitions. On the contrary, such arrangements are even encouraged. There is however no immediately identifiable body that has the power to enforce such agreements should that be necessary. The possible implications of any breaches of agreements, could also be an interesting topic for further study.

APPENDIX A

The functional forms and parameters of the cost functions applied in the simulations were derived from simulation data provided by the International Institute of Applied Systems Analysis, Laxenburg, Austria, in 2001. These data were extracted from the MERGE model (see Manne and Richels (1992) for a general description of MERGE, and www.stanford.edu/group/MERGE/ for more recent information). In essence, MERGE (A **M**odel for **E**valuating the **R**egional and **G**lobal **E**ffects of Greenhouse Gas Reduction Policies), is an intertemporal computable general equilibrium model with a more detailed representation of the energy sector (the prime source of greenhouse gas emissions) than the remainder of the economy. Only the energy-related CO_2 emissions were accounted for in the applied version of MERGE, which was calibrated to the so-called B2 emissions scenario made for the Intergovernmental Panel on Climate Change (Nakicenovic and Swart (2000)).

By imposing various levels of a global carbon tax in MERGE for the year 2010 and computing the resulting emissions, marginal emission cost functions were derived by simple OLS regression. The marginal emission costs were well approximated by linear functions for taxes in the range 0 to 250 US$/tC.

Since some agents have an excess of permits, costs must also be specified when keeping more permits than needed. Therefore, cost functions are piecewise quadratic linear and given by:

$$c_i(x_i) = \begin{cases} \frac{1}{2b_i}(b_i x_i - a_i)^2 & \text{when } x_i \leq a_i/b_i \\ 0 & \text{when } x_i > a_i/b_i, \end{cases} \tag{5}$$

for all $i \in I$, where a_i, $b_i > 0$. It is clear from (5) that costs are once continuously differentiable, but not twice; nor strictly decreasing or strictly convex everywhere.

The level of aggregation of countries in MERGE is completely unsatisfactory for the purpose of this study. For the Parties that have ratified the Kyoto agreement, MERGE uses the aggregation: 1) Eastern Europe and Former Soviet Union, 2) OECD Europe, 3) Canada, New Zealand and Australia (which has not ratified) and 4) Japan. By making use of the emissions in 1990 given on a country basis by the United Nations Framework Convention on Climate Change (http:\\unfccc.int), country-specific marginal cost functions were constructed on the basis of requiring that the emissions of a MERGE region would equal the sum of the emissions of the countries in that region, given any common marginal cost.

One should note that this procedure for splitting MERGE aggregates will neglect any heterogeneity beyond size emissions-wise. In other words, the disaggregation is done in such a way that for any permit price (carbon tax), the price elasticity of demand (emissions) is equal for all countries being part of a specific group, and of course also equal to what was found using MERGE for that particular group. To achieve this, the marginal cost functions have the same intercepts but different slopes. Heterogeneities that are left out may be important, in particular for countries with small emissions. The reader should therefore not put too much emphasis on the results for those countries.

The endowments of permits under the Kyoto Protocol are defined as a percentage change of the emissions in the year 1990 for each party. To compute the endowments, the 1990 emissions level given by MERGE (so as to obtain the same emissions coverage as for the cost functions) were combined with the required reduction percentages given in the Kyoto agreement. These MERGE aggregate endowments where then disaggregated according to the national 1990 emission levels. The parameters of the cost functions and the computed endowments are given in Table A1.

Table A1. The parameters used in the numerical analysis. "Proj. rev. em." is an abbreviation for "projected reviewed emissions", which are used to determine commitment period reserves.

	Cost function parameters		Endowment	Proj. rev. em.
Units	Marg. costs measured in US$/tC		MtC/yr	MtC/yr
Symbol	a_i	b_i	e_i	$\bar{x}_i$
Canada	693	3.7	123	172
New Zealand	693	67.2	7	9
Bulgaria	1410	77.0	25	18
Czech Rep.	1410	39.1	51	35
Estonia	1410	171.0	11	8
Hungary	1410	90.4	22	15
Latvia	1410	261.0	7	5
Lithuania	1410	164.0	12	8
Poland	1410	17.0	116	81
Romania	1410	37.5	51	37
Russia	1410	2.7	768	503
Slovakia	1410	104.0	19	13
Slovenia	1410	465.0	4	3
Ukraine	1410	9.2	228	149
Japan	1730	4.9	258	324
Iceland	1880	2880.0	1	1
Norway	1880	176.0	10	10
Switzerland	1880	139.0	11	13
EU15	1880	1.9	839	974

APPENDIX B

This appendix explains how the model was solved numerically. For each given coalition structure, C, an equilibrium to the second-stage game was searched for. The nonnegativity constraints on $x_i, i \in I$, played no role in the simulations. Therefore, the Kuhn–Tucker conditions to problems (1)-(3) amount to

$$\left.\begin{array}{lll} c_i'(x_i) + p = 0 & \text{for each} & i \in F, \\ c_i'(x_i) + p + p' \sum_{i \in C}(x_i - e_i) = 0 & \text{for each} & i \in C, \\ c_i'(x_i) + p + p'(x_i - e_i) = 0 & \text{for each} & i \in S \diagdown C, \\ \sum_i x_i \leq \sum_{i \in I} e_i,\ p \geq 0 & \text{and} & \\ (\sum_i x_i \leq \sum_{i \in I} e_i)p = 0. & & \end{array}\right\} \tag{6}$$

As hinted at in section 2, these necessary conditions may not be sufficient since nonconvexities cannot be ruled out. However, this is not the only problem, as it turns out that the objective functions in (2)-(3) are not continuously differentiable. This is because the slope of the price function, derived in Flåm and Godal (2005), is given by

$$p' := -\frac{\partial P}{\partial Q} = \frac{\partial P}{\partial x_i} = \begin{cases} \left[\sum_{i \in F} \left[c_i''(x_i)\right]^{-1}\right]^{-1} & \text{when} \quad Q < \sum_{i \in F} \hat{x}_i \Leftrightarrow p > 0 \\ 0 & \text{when} \quad Q > \sum_{i \in F} \hat{x}_i \Leftrightarrow p = 0, \end{cases} \tag{7}$$

where the finite number

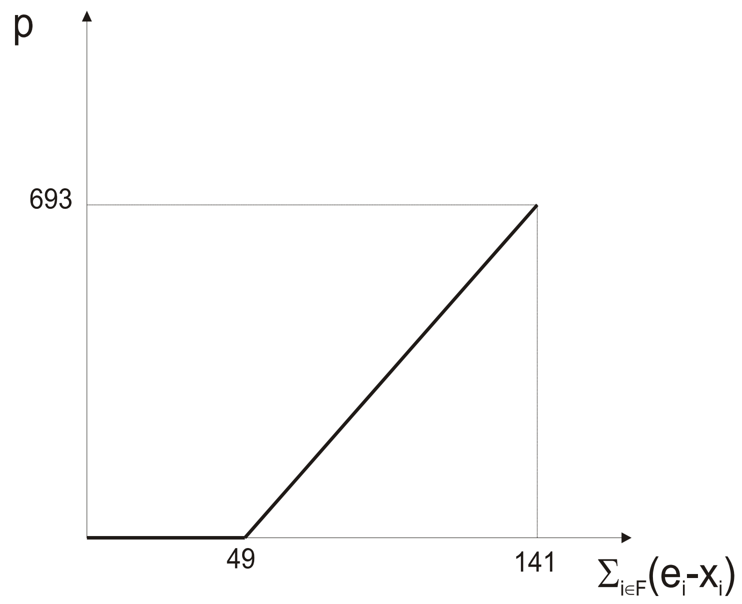
$$\hat{x}_i := \min\{x_i : c_i(x_i) = 0\} \tag{8}$$

is what is called the "business-as-usual" emission level (see also Table 1). However with our data, P is not differentiable at $Q = \hat{Q} := \sum_{i \in F} \hat{x}_i$, which, in fact is a typical supply of permits in equilibrium. Thus, our second-stage game does not satisfy the differentiability assumption of the Kuhn–Tucker Theorem.[22]

To explain how we dealt with these problems, consider first our main case when the EU comes forward as EU15. The inverse permit supply function for the fringe (as an aggregate) then becomes as depicted in Figure B1.

[22] Although nonsmooth problems may be regularized by using techniques as given in Clarke et al. (1998), the additional insight that we can obtain by going through such an exercise would still be rather limited since smoothness does not help to rule out nonconvexities. Hence, a first-order equilibrium would still not automatically be a Nash equilibrium.

Figure B1. Inverse permit supply when the EU15 comes forward as a single agent. The price is US$/tC, the quantity is MtC/yr.



At $p = 693$ the supply curve kinks again, but $p > 693$ plays no role in our analysis since all agents have lower marginal abatement costs in autarchy than 458 US$/tC. The number 49 on the horizontal axis in Figure B1 depicts the excess quotas of the fringe at $p = 0$, and thus, for demand lower than (or equal to) 49 MtC/yr, the price is zero.

Given this supply function by the fringe, we have proceeded as follows.

1. We suppose that in equilibrium $p' = 7.58$ (the slope of the supply function for $p > 0$), and we use GAMS to search for a candidate Nash equilibrium. Whenever GAMS returns $p > 0$, it is argued in step 2 below that the solution is indeed a Nash equilibrium. This happened in simulations #1-#8 and #10-#18. Whenever it produces $p = 0$ we proceed to step 3. This happened in simulations #9 and #19-#21.

2. If, hypothetically, the $p > 0$ segment describes the entire relevant supply function, the problem yields a single Nash equilibrium (Flåm and Godal (2005), Theorem 2). The potential problem lies in the fact that the supply curve is nonlinear, not strictly decreasing, and has a kink. Now, a seller will clearly not benefit from supplying enough quotas to induce a price $p = 0$. A buyer can possibly improve the situation by reducing demand sufficiently to induce a price of zero. However, at any proposed equilibrium where $p > 0$, a buyer has positive marginal costs. Decreasing purchases to induce a price of zero increases marginal costs, and it is thus never beneficial to move total demand below 49 MtC. However, one can get arbitrarily close to this

point along the $p > 0$ segment, such that any deviation to 49 MtC total demand should not be beneficial. Hence, the candidate from step 1 is a (the only) Nash equilibrium.

3. When returning $p = 0$, the calculations also show strategic sellers to be inactive, because of the (faulty) assumption that $p' > 0$. Total demand by the strategists is also, in all cases, lower than the 49 MtC of the excess quotas that the fringe possesses. The fact that total demand of 49 MtC is not returned is again due to the assumption $p' > 0$, making buyers restrict purchases (the opposite result would be merely a coincidence). As long as buyers have positive marginal costs, no such situation can be part of an equilibrium. The only candidate for an equilibrium will entail the buyers to purchase all available quotas at $p = 0$. For $p = 0$ and $p' = 0$, sellers could also sell more quotas, but if the buyers empty whatever excess quotas there are onto the market, a strategic seller would reap a first-order benefit from reducing sales slightly beyond such a level (inducing $p > 0$). Thus, such a situation can never be part of an equilibrium. When $p = 0$ is returned, two possible types of *mutually exclusive* equilibria then exist, and they have the following characteristics.

   (a) At least one strategic buyer has positive marginal costs, buyers share the excess quotas of the fringe and sellers are inactive.[23] These are characteristics of the equilibrium presented in simulation #9.

   (b) All buyers have zero marginal costs, and the fringe is either emptied while sellers are inactive, or nonemptied. In the latter case, sales by the sellers cannot be restricted to push prices above zero (or else it would not be an equilibrium). This happens in simulations #19–#21. In all these cases the fringe has enough quotas to make buyers reach zero marginal costs. Thus, multiple equilibria exist because whether the strategic sellers or the fringe provide the quotas does not matter. Costs are however the same in all cases.

The same type of argument applies for the simulations concerning the enlarged EU, but the supply function is different since some fringe countries are then assumed to be part of the strategic player EU. However, the fringe is still a net supplier of permits.

[23] The sharing rule between buyers must also be such that the buyers do not have marginal costs so high that increasing purchases and inducing a positive price is beneficial.

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