WORKING PAPERS IN ECONOMICS

No. 09/03

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Compliance and Imperfect Intertemporal Carbon Trading*

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July 23, 2003

Abstract

This paper examines three compliance mechanisms of the Kyoto Protocol: (*i*) the *restoration rate*, (*ii*) the *commitment period reserve rule*, and (*iii*) the *suspension mechanism*, all potentially constraining greenhouse gas emissions trading across time and space. The joint effect of these mechanisms on prices and costs is studied in a two-period model under various assumptions about the competitiveness of the permit market and US participation. The analytical results indicate that the restoration rate can make discounted permit prices decrease over time. With the commitment period reserve, marginal costs may not only be lower, but also higher than the permit prices. The suspension rule will under quite general circumstances not affect prices and costs; only shift non-compliance from future sellers to future buyers. The numerical results suggest that with imperfect permit markets and non-participation of the US in the Kyoto Protocol in 2010, none of the three rules becomes binding.

JEL classification: Q25, Q28, Q48
Keywords: compliance, market power, emissions trading, Kyoto Protocol

*We thank Sjur Flåm, Cathrine Hagem, Jostein Aarrestad and Camilla Bretteville for comments on an earlier draft; Frode Meland and Yuri Ermoliev for discussions; and Bing Zhu for running the MERGE model. Odd Godal appreciates financial support from the Research Council of Norway (SAMSTEMT); Stiftelsen Thomas Fearnley, Heddy og Nils Astrup; Professor Wilhelm Keilhau's Minnefond; and Meltzerfondet. The usual disclaimer applies.

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1 Introduction

Addressing emissions of greenhouse gases contributing to global warming, the Kyoto Protocol of 1997 allows signatories (governments) to comply with obligations through emissions trading (Art. 17). Rules for governing such trades were finally established in the Marrakech Accord of 2001. We focus on three of the so-called compliance mechanisms:

• Banking excess permits from one commitment period to the next is allowed, but borrowing is restricted through the *restoration rate*. More specifically, for each ton of CO_2 a party exceeds her quota holdings in one period, she will have deducted 1.3 tons from her endowment of quotas in the consecutive period, thus restricting intertemporal emissions trading;

• The *commitment period reserve* rule states that each party shall maintain a reserve of quotas which should not drop below 90% of the endowment or 100% of the most recently reviewed emissions inventory, whichever is lowest. Hence, this rule potentially restricts permit export;

• The *suspension mechanism* prohibits parties that are non-compliant in one period to sell permits in the next period, until they return to compliance.

These mechanisms define what is allowed (and what is not) in terms of emissions trading across time and space and may therefore affect parties that have the intentions of following the Kyoto rules as assumed here.

Emissions trading has received significant attention even before Montgomery [10] proved that such systems could foster cost-effectiveness. Of particular relevance here is the literature concerning the intertemporal dimension of such systems [14], the effect of market power [6], these two issues in combination [5], and the effect of various rules constraining such trade spatially [4], [17]. An overview of recent numerical studies on the effect of strategic behavior by sellers on the carbon price of the Kyoto Protocol is given in [16].

So far no comprehensive analysis of the compliance mechanisms exists in the literature. [1], [2], [7], [8] as well as [13], limit their attention to the commitment period reserve, while [3] only examines the restoration rate. None of them deals with the suspension rule. Only one paper deals with the analysis of all three compliance rules [12], though separately.

This study fills a gap in the existing literature as we examine the joint effect of the three compliance mechanisms on prices and costs in a dynamic setting with imperfect permit markets. As our analysis shows market power is an important element when investigating the effects of these mechanisms. A dynamic analysis is essential since the compliance rules by design are intertemporal.

In section 2 we therefore characterize a two-period model where a group of Cournot players compete with a competitive fringe in tradeable permits governed by the three compliance rules. The equilibrium conditions are provided. Some general results are presented in section 3, while section 4 offers some simulations. Section 5 concludes.

2 Model

Consider the finite set I of agents (countries) engaged in an intertemporal agreement to control emissions of greenhouse gases. The agreement is assumed to last for $t \in \{1, 2\}$ discrete commitment periods each of finite duration. Agent i is endowed with permits $e_t^i > 0$, chooses emission levels $x_t^i > 0$ and can purchase allowances y_t^i, being positive for a permit buyer and negative for a permit seller. Emission permits are homogeneous (within each period), perfectly divisible, and exchanged in a common market at unit price $p_t > 0$.

The costs of complying with the agreement stem from the (time-separable) costs, $c_t^i(x_t^i)$, associated with keeping emissions down to level x_t^i in period t, and from the purchase of permits, $p_t y_t^i$.[1] Let $c_t^i(x_t^i)$ be non-negative, non-increasing, convex and continuously differentiable. Since there is a limit to how much a country would emit in the absence of emissions regulations, it is clear that $c_t^i(x_t^i) = 0$ for some $x_t^i < \infty$. Let $\widehat{x}_t^i := \min\{x_t^i \,|c_t^i(x_t^i) = 0\}$ be what is commonly known as agent i's baseline or business-as-usual emissions level, and with our assumptions it is clear that $\partial c_t^i(x_t^i) = 0$ for $x_t^i > \widehat{x}_t^i$.[2] We shall assume that $c_t^i(x_t^i)$ is strictly decreasing, strictly convex and two times continuously differentiable for $x_t^i < \widehat{x}_t^i$.

Since choosing emission levels $x_t^i > \widehat{x}_t^i$ subtracts nothing from costs, we assume that all agents prefer $\widehat{x}_t^i$ to $x_t^i > \widehat{x}_t^i$. Potential problems with discontinuities of $\partial c_t^i(x_t^i)$ at $\widehat{x}_t^i$ are discarded. For convenience, we also assume that $|\partial c_t^i(0)|$ is sufficiently large, so that any optimal x_t^i is strictly positive. This seems reasonable, at least in the case when x_t^i are emissions of greenhouse gases and i are countries. To have a well-behaved demand function, we also take it that $|\partial c_t^i(e_t^i)| < \infty$. Time preferences are common across parties and expressed through the discount factor $\delta \in (0, 1]$.

On the behavioral side, each agent $i \in I$ is either a member of the *competitive fringe* across both periods, and then we write $i \in F$, or a *strate-*

[1] Note that $c_t^i(x_t^i)$ is the emission cost function. We will, however, often use the customary wording emission abatement cost function. Moreover, unless otherwise stated, when speaking about marginal costs, we mean the negative marginal costs.

[2] Here and elsewhere, the operator ∂ represents the generalized derivative, occasionally partial.

gist (oligopolist or oligopsonist), in which case we write $i \in S$. Thus I is the disjoint union of F, assumed non-empty, and S. The structure of the game is such that agents $i \in S$ simultaneously choose quantities x_t^i and y_t^i, $t = 1, 2$. The aggregate demand (or supply, if negative), $Y^S := \left(Y_1^S, Y_2^S\right)$ where $Y_t^S := \sum_{i \in S} y_t^i$, $t = 1, 2$, is taken for granted by the fringe who compete perfectly over this quantity, and thus behaves as if

$$\min_{x_t^i, y_t^i} \left\{ \sum_{i \in F} \sum_{t=1,2} \delta^{t-1} c_t^i(x_t^i) \right\} =: c^F \left(Y^S\right) \tag{1}$$

subject to the market clearing constraints

$$\textstyle\sum_{i \in F} y_1^i + Y_1^S \leq 0 \qquad (p_1) \tag{2}$$

and

$$\textstyle\sum_{i \in F} y_2^i + Y_2^S \leq 0 \qquad (\delta p_2). \tag{3}$$

p_1 and δp_2 are the Lagrangian multipliers (shadow prices) associated with (2) and (3) respectively that clear the permit market, thus representing the inverse demand functions.[3] There are of course additional constraints to (1) that appear in (6) - (10).

The strategic players are assumed to perfectly foresee how their actions affect prices and acknowledge (from the envelope theorem) that

$$p_1 \left(Y^S\right) = \frac{\partial c^F \left(Y^S\right)}{\partial y_1^{i \in S}} \text{ and } \delta p_2 \left(Y^S\right) = \frac{\partial c^F \left(Y^S\right)}{\partial y_2^{i \in S}}. \tag{4}$$

Thus, p_1, δp_2 will be positive when the constraints (2) and (3) respectively become binding, p_2 being the undiscounted permit price in period two. Now, each and every strategic agent $i \in S$, seeks to minimize the costs including market transactions, that is

$$\min_{x_t^i, y_t^i} \left\{ \sum_{t=1,2} \delta^{t-1} \left(c_t^i(x_t^i) + p_t \left(Y^S\right) y_t^i \right) \right\}. \tag{5}$$

Before we turn to the specific compliance rules, we denote d_t^i as the deposit of permits from period t to period $t + 1$.

In the related literature, terms like banking, borrowing, compliance, non-compliance are closely related. Hence, to remove any possible confusion

[3] When speaking about the fringe, we shall rely on the word *demand* of permits even though they may be net suppliers. Regarding presentation, the attached shadow price on any constraint appears on the right-hand-side of a constraint that is included in the optimization problem.

regarding the terminology used here, we shall rely on the following throughout the paper.

Definition 1. *For any agent $i \in I$ and period $t \in \{1, 2\}$*
(i) $d_t^i \geq 0 \Leftrightarrow$ agent i being ***banking*** *$\Leftrightarrow$ agent i being* ***over-compliant.***
(ii) $d_t^i \leq 0 \Leftrightarrow$ agent i being ***borrowing*** *$\Leftrightarrow$ agent i being* ***non-compliant.***
(iii) $d_t^i = 0 \Leftrightarrow$ agent i being in ***exact compliance.***
When (i) and (ii) are strict inequalities, the term strictly is added. □

2.1 Compliance Constraints

2.1.1 The Restoration Rate

According to the United Nations Framework Convention on Climate Change (UNFCCC) [19], p. 76, parties that are non-compliant in one commitment period will have a "Deduction from the Party's assigned amount [endowment] for the second commitment period of a number of tons equal to 1.3 [denoted f] times the amount in tons of excess emissions". Agents may freely bank emission allowances from one period to the next, without any additional reward or penalty.

The deposit of permits in period t, therefore amounts to the sum of the endowment; the permits bought; less the actual emissions in that period; plus whatever was banked or borrowed from the previous period. Since $d_{t-1}^i \leq f d_{t-1}^i$ if a party was banking in the previous period, whereas $d_{t-1}^i \geq f d_{t-1}^i$ if it was borrowing, it follows that

$$d_t^i = e_t^i + y_t^i - x_t^i + \min[d_{t-1}^i, f d_{t-1}^i]$$

regardless of the sign of d_{t-1}^i.

Parties start with blank sheets, that is $d_0^i = 0$. A party that contends with the terms of the agreement (not cheating) is therefore assumed to clear the books in the last period, $d_2^i \geq 0$. For interpretation (and programming) purposes it is possible and convenient to split this constraint into the following two linear constraints

$$(x_1^i - e_1^i - y_1^i) + (x_2^i - e_2^i - y_2^i) \leq 0 \qquad (\lambda^i) \tag{6}$$

and

$$f\,(x_1^i - e_1^i - y_1^i) + (x_2^i - e_2^i - y_2^i) \leq 0 \qquad (\mu^i) \tag{7}$$

which both should not be violated. We see that the only difference between (6) and (7) is that the first part in the latter constraint is multiplied by f.

If a party is banking, the first part of the constraints (6) and (7) will be negative. And when $f > 1$, it is only (6) that will bind. For a borrowing party however, only (7) will bind. If both constraints bind, the agent is in exact compliance. If $f = 1$, the two constraints coincide, which corresponds to the case of free banking and borrowing.

2.1.2 The Commitment Period Reserve

The commitment period reserve rule limits the amount of permits a party can export, as it must keep a specific number of permits in its national emissions registers. According to [18], p. 54, "Each Party... shall maintain in its national registry a commitment period reserve which should not drop below 90 per cent [denoted k_e] of the Party's assigned amount [endowment], ... or 100 per cent [denoted k_x] of its most recently reviewed inventory, whichever is lowest."

In the climate regime, emission endowments are given for 5-year periods (starting January 1, 2008). Producing an emission inventory is a cumbersome process that takes several years. Reviewing it, can add more time. We take the approach that the emissions of one commitment period (2008-2012) are not reviewed before the start of the next period, (2013-2017). For the first commitment period, denote $\widehat{x}_0^i$ as the latest reviewed emission inventory before the agreement enters into force (taken to be year 2005), that we assume to be exogenously given.

The following example describes our interpretation of this rule. Say endowments for an agent are 100 units in both periods and that actual emissions in year 2005 be 70 units. The commitment period reserve rule in period one then states that this agent must keep the minimum of 90% of 100, or 100% of 70 in its registers. Since that minimum is 70, this agent is only allowed to sell 30 units in period one. Assume she does that, and keeps emissions down to 70 in that period. In period two she must then keep the minimum of 90% of 100 or 100% of 70 (the emissions in period one) in the commitment period reserve, thus she can sell 30 units also in period two. However, she may find it profitable to reduce emissions below 70 in period one (say to 65) and bank these 5 permits to period two. In period two, the constraint is then relaxed by five units since her emissions level in period one is 65, not 70, allowing her to sell 35 units of her endowment in period two, instead of 30. In addition we take it that she is allowed to sell the 5 units banked from period one to period two, since these units are not part of her second period endowment.

Given our approach of "delayed review", the commitment period reserve rule translates into the following general constraint on the exports of permits:

$$e_t^i + \min[d_{t-1}^i, f d_{t-1}^i] - \min\left[k_e e_t^i, k_x x_{t-1}^i\right] \geq -y_t^i.$$

This constraint essentially states that the endowment of permits in period t, plus any deposits from the previous period net what must be kept in reserve must be greater or equal to the volume of permits exported. Since $d_0^i = 0$, this constraint amounts to

$$\min\left[k_e e_1^i, k_x^i \widehat{x}_0^i\right] - y_1^i - e_1^i \leq 0 \qquad (\gamma^i) \tag{8}$$

in period one. Equation (8) simply states that the volume of permits sold ($= -y_1^i$) should be equal or lower than the endowment minus the commitment period reserve. Since $k_e e_1^i, k_x^i \widehat{x}_0^i$ are constants (8) is a linear constraint. The commitment period reserve rule for the second period amounts to

$$\min\left[k_e e_2^i, k_x x_1^i\right] - y_2^i - e_2^i - (e_1^i + y_1^i - x_1^i) \leq 0 \qquad (\sigma^i) \tag{9}$$

if the (selling) party is banking. We see from (9) that the permits sold in period two ($= -y_2^i$) should not exceed the endowment in period two plus whatever she banked from period one, net the commitment period reserve in period two.

There are several issues that should be noted regarding (9). First, this constraint only addresses banking parties. What if the agent was borrowing in the first period? As is clear from the suspension rule discussed below, that question is completely irrelevant since an agent that is borrowing in period one, is not allowed to sell *anything* in period two. Thus we can omit the equivalent constraint to (9) for a borrowing party. Second, it is clear that (9) is a non-linear constraint, where the non-linearity goes in the "wrong" direction and thus may destroy the desired convexity in the domain of the objective function. This may entail problems for existence of equilibrium solutions in general. Nevertheless, we will keep this constraint in the Lagrangian setup as it is. Third, our approach of delayed review seems to be valid if it takes 5 years to produce *and* review an emissions inventory. This is perhaps a little longer than what is the most realistic.[4]

2.1.3 The Suspension Rule

Finally, the negotiators of the UNFCCC agreed that a consequence for non-complying parties would be the "Suspension of the eligibility to make transfers under Article 17 of the Protocol until the party is reinstated in accordance with section X, paragraph 3 or paragraph 4 [i.e. compliance]" [19], p. 76.

[4] According to Knut Alfsen (personal communication) who participated in reviewing an emissions inventory for Canada, this process took about 3 years. What it takes for e.g. Russia, where the background statistics perhaps have a different quality, may be a different issue.

The interpretation of transfer in this context is selling (not buying). Thus, a strictly borrowing party is not allowed to sell anything in the subsequent period. This means that if $d_{t-1}^i < 0$, then $y_t^i \geq 0$, yielding the general constraint $-y_t^i \max[0, -d_{t-1}^i] \leq 0$. In our two-period case this only applies in the second period since $d_0^i = 0$. Hence we get the constraint

$$-y_2^i \max[0, -\left(e_1^i + y_1^i - x_1^i\right)] \leq 0. \tag{10}$$

(10) is a non-linear complementarity constraint, that cannot be handled as it is in a Lagrangian setup, and poses additional trouble with respect to existence of equilibrium. We choose to keep this constraint out of the optimization problem (and hence no multiplier is associated to it) but rather check whether it is violated in an optimal solution. As it turns out, the constraint is not violated under quite general assumptions (discussed below Proposition 6) and in none of our numerical cases.

2.2 Equilibrium

Generally speaking, for the strategists, selling permits in one period, will not only affect the permit price in that period, but also in the other period. Therefore, to ease notation we introduce t' as the duplicate of t and write $\partial p_{t,t'} := \dfrac{\partial p_t\left(Y^S\right)}{\partial y_{t'}^i}$ for $t, t' \in \{1, 2\}$.[5]

The description of our model is now complete and we are ready for

Definition 2. (Cournot-Nash equilibrium) *The choices* $\bar{x}_t^i$, $\bar{y}_t^i$, $i \in S$, $t \in \{1, 2\}$ *constitute a Cournot-Nash equilibrium, if and only if,* $\bar{x}_t^i$, $\bar{y}_t^i$ *minimizes the costs, including transactions, for agent* $i \in S$ *given that the other agents keep the amount* $x_t^j = \bar{x}_t^j$, $y_t^j = \bar{y}_t^j$, $j \neq i$, *for all* $i \in S$. *That is,* $\bar{x}_t^i$, $\bar{y}_t^i$ *must be an optimal solution to the problem (5) subject to (6)-(10) for all* $i \in S$. □

The next questions are evident: *Does an equilibrium exist? If so, is it unique? Does it belong to the interior?* With respect to existence, little can be said. There are at least two reasons for this. Even in the classic one-period model without the compliance rules, there are problems with existence of an equilibrium solution. They originate from the market transactions for the strategic players, since the curvature properties of the term $p_t\left(Y^S\right) y_t^i$, that appear in their objectives, are not easily detected. Recalling that inverse demand is the derivative of the reduced function (1), speaking about curvature properties

[5] For characterization of $\partial p_{t,t'}$ in the case of quadratic abatement costs, employed in the numerical simulations, see Appendix 1.

of the demand function is far from innocuous, and requires looking beyond the curvature properties of the cost functions for the fringe. Moreover, keeping in mind that y_t^i can take on both positive and negative values, making reasonable general assumptions that preserves the convexity of the objective function for the strategists is a challenging task. In addition, the compliance rules themselves (specifically, the commitment period reserve rule and the suspension mechanism) distort the convexity in the domain of the objective function. Hence, the most desirable properties for existence of a Cournot-Nash equilibrium (even in the monopoly/monopsony case) are lacking.

Not surprisingly, we shall therefore simply assume the existence of an interior equilibrium where the first order conditions are satisfied and hold with equality. In that case, an equilibrium should be characterized by [6]

$$\partial c_1^i(x_1^i) + \lambda^i + f\mu^i + \partial \min\left[k_e e_2^i, k_x x_1^i\right]\sigma^i + \sigma^i = 0, \tag{11}$$

$$\partial c_2^i(x_2^i)\delta + \lambda^i + \mu^i = 0, \tag{12}$$

$$p_1 + \left(\partial p_{1,1} y_1^i + \partial p_{2,1} y_2^i \delta\right)\big|_{i\in S} - \lambda^i - f\mu^i - \gamma^i - \sigma^i = 0, \text{ and} \tag{13}$$

$$\delta p_2 + \left(\partial p_{1,2} y_1^i + \partial p_{2,2} y_2^i \delta\right)\big|_{i\in S} - \lambda^i - \mu^i - \sigma^i = 0. \tag{14}$$

However, as shown in Proposition 6 below, it is clear that generally speaking, equilibrium is not unique.

3 Results

Before we start the interpretation of the equilibrium conditions, denote $M_1 \subseteq F$ as the subset of the fringe not constrained by (8) and let $M_2 \subseteq F$ be the subset not constrained by (9) or (10). Throughout our analysis, assume that $M := M_1 \cap M_2$ is non-empty. At a first glance, this may seem restrictive, but a sufficient (not necessary) condition for this to hold is that there exists at least one agent $i \in F$ that is a permit *buyer* in equilibrium in both periods. This seems quite reasonable, and is in fact satisfied in all our numerical simulations. Since permit prices are common for all agents, this construction simplifies the interpretation of the equilibrium conditions. Before studying the effect of the compliance mechanisms, we have

Proposition 1. (On the relationship between marginal costs and permit

[6] Generally speaking if a is a constant, and $f(x)$ is differentiable, then $\partial(\min[a, f(x)]) = \partial(\min[0, f(x) - a] + a) = \begin{cases} \dfrac{f'(x)\min[0, f(x)-a]}{f(x)-a} & \text{when} \quad f(x) \neq a \\ [0, f'(x)] & \text{when} \quad f(x) = a. \end{cases}$

prices I). *Assume agent $i \in I$ is neither constrained by the commitment period reserve rule, nor the suspension mechanism, and that permit prices are strictly increasing in own permit use. Then,*
(i) for $i \in F$, negative marginal costs equals permit prices.
(ii) if $i \in S$ is a permit buyer in both periods, negative marginal costs are higher then equilibrium prices in both periods, and
(iii) if $i \in S$ is a permit seller in both periods, negative marginal costs are lower then equilibrium prices in both periods.

Proof. (i) Since $\gamma^i = \sigma^i = 0$, this is trivial when comparing (11) with (13) and (12) with (14).
(ii) By assumption, $\partial p_{t,t'}$ are strictly positive for all t, t'. Moreover, when i is a permit buyer in both periods $y_1^i, y_2^i > 0$. Thus, adding (11) and (13) yields $p_1 + \partial c_1^i(x_1^i) = \partial p_{1,1} y_1^i + \partial p_{2,1} y_2^i \delta > 0$ in period one, and adding (12) and (14) $\delta p_2 + \partial c_2^i(x_2^i)\delta = \partial p_{1,2} y_1^i + \partial p_{2,2} y_2^i \delta > 0$ in period two.
(iii) Follows directly from (ii) when $y_1^i, y_2^i < 0$. $\square$

Proposition 1 confirms a standard result in imperfect markets: Competitive behavior implies equating marginal costs with price; strategic buyers raise own costs and reduce demand to keep prices down, whereas strategic sellers reduce supply, and thus marginal costs, to keep prices up. But what if a strategic agent is a seller in one period, but a buyer in the other?

Proposition 2. (On the relationship between marginal costs and permit prices II). *When marginal abatement costs are linear for the fringe, then, if for a strategic agent $i \in S$ who is not constrained by (8) - (10) and who is strictly borrowing we have that $y_2^i = -f y_1^i$ in equilibrium, then that agent behaves as being member of the competitive fringe and marginal costs equal permit prices.*

Proof. By comparing (11) with (13) and (12) with (14) for any agent $i \in S$, we have that $p_1 + \partial p_{1,1} y_1^i + \delta \partial p_{2,1} y_2^i = -\partial c_1^i(x_1^i)$ and $\delta p_2 + \partial p_{1,2} y_1^i + \delta \partial p_{2,2} y_2^i = -\partial c_2^i(x_2^i)\delta$. By making use of the assumption $y_2^i = -f y_1^i$ and the price differentials for the linear case in a borrowing equilibrium given in Appendix 1, we get

$$p_1 + \frac{f}{R} y_1^i - \delta \frac{1}{\delta R} f y_1^i = -\partial c_1^i(x_1^i)$$

and

$$\delta p_2 + \frac{1}{R} y_1^i - \delta \frac{1}{f \delta R} f y_1^i = -\partial c_2^i(x_2^i)\delta,$$

where $R > 0$. Clearly, this is nothing else than $p_1 = -\partial c_1^i(x_1^i)$ and $\delta p_2 = -\partial c_2^i(x_2^i)\delta$. $\square$

It is straightforward to show that this result also holds in the case of banking if $y_2^i = -y_1^i$ in equilibrium (simply replace f by 1 and *borrowing* by *banking* in Proposition 2).

From Proposition 2, we see that the agent is trapped. She wants to drive up the price in the period she is a seller, but this hurts in the period she is a buyer and the other way around. Thus efficiency losses stemming from market power are eliminated. This can presumably be implemented by endowing agents in the second period such that $y_2^i = -fy_1^i$ for that agent. However, if agents can reject endowment propositions, it may not be an easy task to accomplish in practice if the agent with market power is a seller in period one.

Finally, if the agent is in exact compliance in equilibrium, it is equivalent to banking or borrowing not being allowed. Hence there would not be a conflict of interest, and the strategic agent would contribute to driving up the price in one period and down in the other.

We now turn to the effect of the compliance rules and start with the restoration rate.

Proposition 3. (On the relationship between prices and the **restoration rate**). *Assume M non-empty and that for an agent $i \in M$ at least one of (6) and (7) are strictly binding. Then, $p_1 \in [\delta p_2, f\delta p_2]$. Moreover, if $i \in M$ is strictly banking, then $p_1 = \delta p_2$, whereas if i is strictly borrowing, then $p_1 = f\delta p_2$. Finally, if $p_1 \in (\delta p_2, f\delta p_2)$, then i is in exact compliance.*

Proof. For $i \in M$ we have by definition, $\gamma^i = \sigma^i = 0$ and that constraint (10) is not binding. When at least one of (6) and (7) is strictly binding $\lambda^i + \mu^i > 0$. By making use of (13) and (14) we get in general that $p_1 = \frac{\lambda^i + f\mu^i}{\lambda^i + \mu^i}\delta p_2$. Since $\frac{\lambda^i + f\mu^i}{\lambda^i + \mu^i} \in [1, f] \Rightarrow p_1 \in [\delta p_2, f\delta p_2]$. In the case of $\lambda^i = 0$, i.e. borrowing, $p_1 = f\delta p_2$; in the case of banking $\mu^i = 0$, thus $p_1 = \delta p_2$. Finally in the case $p_1 \in (\delta p_2, f\delta p_2) \Rightarrow \frac{\lambda^i + f\mu^i}{\lambda^i + \mu^i} \in (1, f)$, thus $\lambda^i, \mu^i > 0$ and the agent is in exact compliance. $\square$

Note that $p_1 = f\delta p_2$ does not imply that agent $i \in M$ is strictly borrowing, it could perfectly well be in exact compliance (similarly in the case of banking). If $f = 1$, Proposition 3 is nothing else than the classic result, that in equilibrium, permit prices rise with the rate of interest.

Moreover, if M contains at least two elements i, j, can, in equilibrium, agent i be banking while j be borrowing? This issue is not only an interesting one in itself, but is relevant for the implications of the suspension rule discussed in connection to Proposition 6.

Proposition 4. (On banking and borrowing with the **restoration rate**). *If M contains at least two elements i, j, then, if $f > 1$, agent i cannot be strictly banking while agent j is strictly borrowing.*

Proof. From Proposition 3 it follows that if agent i is strictly banking, $p_1 = \delta p_2$ and if agent j is strictly borrowing, $p_1 = f \delta p_2$. From this it follows that $f = 1$, a contradiction. □

The intuition for this is clear. If one agent is banking while another is borrowing, which is penalized when $f > 1$, both agents could be strictly better off if the banking agent transferred some period one permits to the borrowing agent, who returned some second period permits to the banking agent. However, in the case when $f = 1$, the motivation for such a mutually beneficial exchange disappears and some could be banking while others were borrowing.

Proposition 5. (On the relationship between marginal costs and permit prices for members of the fringe with the **commitment period reserve** rule) *Assume $k_x > 0$ and consider $i \in F$. Then, if the commitment period reserve rules binds in*
(i) period one only, then $p_1 > -\partial c_1^i(x_1^i)$, and $p_2 = -\partial c_2^i(x_2^i)$,
(ii) period two only, then $p_1 \leq -\partial c_1^i(x_1^i)$, and $p_2 > -\partial c_2^i(x_2^i)$,
(iii) both periods then $p_1 \gtreqless -\partial c_1^i(x_1^i)$ and $p_2 > -\partial c_2^i(x_2^i)$.

Proof. Adding (11) and (13) yields

$$\partial c_1^i(x_1^i) + p_1 + \partial \min \left[k_e e_2^i, k_x x_1^i\right] \sigma^i - \gamma^i = 0 \tag{15}$$

whereas adding (12) and (14) yields

$$\partial c_2^i(x_2^i)\delta + \delta p_2 - \sigma^i = 0. \tag{16}$$

(i) When only (8) binds $\gamma^i > 0$, whereas $\sigma^i = 0$. The result now follows when inserting this into respectively (15) and (16).
(ii) Similarly, insert $\gamma^i = 0$, $\sigma^i > 0$ in (15) and (16) respectively. From this, it is clear that $p_2 > -\partial c_2^i(x_2^i)$. Moreover, if $k_e e_2^i > k_x x_1^i \Rightarrow \partial \min\left[k_e e_2^i, k_x x_1^i\right] = k_x$. Hence, (15) amounts to $-\partial c_1^i(x_1^i) - p_1 = k_x \sigma^i > 0$. However, if $k_e e_2^i \leq k_x x_1^i \Rightarrow \partial \min\left[k_e e_2^i, k_x x_1^i\right] = 0$, and hence $-\partial c_1^i(x_1^i) - p_1 = 0$.
(iii) When $\gamma^i > 0$, $\sigma^i > 0$, we have from (16) that $\partial c_2^i(x_2^i)\delta + \delta p_2 = \sigma^i > 0$.

Furthermore, from (15) it is clear that $\partial c_1^i(x_1^i) + p_1 = \gamma^i - k_x\sigma^i$, when $k_e e_2^i > k_x x_1^i$. Hence, $\partial c_1^i(x_1^i) + p_1 \gtreqless 0$ whenever $\gamma^i \gtreqless k_x\sigma^i$. However, if $k_e e_2^i \leq k_x x_1^i$, then, again $\partial \min[k_e e_2^i, k_x x_1^i] = 0$, and $\partial c_1^i(x_1^i) + p_1 = \gamma^i > 0$.

Proposition 5 yields some trivial and some surprising results. On the intuitive side, the period the rule is binding leads to lower marginal costs than the permit price in that period. The agent wants to sell more permits, but is not allowed to do so. Less obvious is that the commitment period reserve rule in the second period may induce a higher marginal cost than permit price in period *one*, since reducing emissions beyond where these are equal may provide the agent with a less stringent constraint in the second period. The arguments have the same structure in the case when the agent is a strategist, but then the agent must also account for changes in the permit price by own actions.

To be able to draw some inferences about the effect of the suspension mechanism, we ask the following question: Can we determine a unique distribution of permits across all agents in each period?

Proposition 6. (On the uniqueness of equilibrium in the permit market). *Take a borrowing equilibrium, i.e.* $p_1 = f\delta p_2$ *and a permit allocation* $\tilde{y}_1^i, \tilde{y}_1^j, \tilde{y}_2^i$ *and* $\tilde{y}_2^j, i, j \in M$ *that belongs to equilibrium. Assume that* $\tilde{d}_1^j < 0$ *and that the left hand side of (8) - (10) are strictly negative for* $i, j \in M$*, thus not binding. Then there exists a* $\Delta > 0$ *leading to a different permit allocation* $\dot{y}_1^i \leftarrow \tilde{y}_1^i - \Delta$, $\dot{y}_1^j \leftarrow \tilde{y}_1^j + \Delta$, $\dot{y}_2^i \leftarrow \tilde{y}_2^i + f\Delta$ *and* $\dot{y}_2^j \leftarrow \tilde{y}_2^j - f\Delta$ *that also belongs to equilibrium.*

Proof. Keep equilibrium emission levels fixed. For any borrowing agent we know that (7) is binding, thus $f(\tilde{x}_1^i - e_1^i - \tilde{y}_1^i) + (\tilde{x}_2^i - e_2^i - \tilde{y}_2^i) = 0$ (equivalently for j). Choose any $\Delta > 0$ and update the permit allocation according to the proposition, thus satisfying, $f(\tilde{x}_1^i - e_1^i - (\tilde{y}_1^i + \Delta)) + (\tilde{x}_2^i - e_2^i - (\tilde{y}_2^i - f\Delta)) = 0$, $f(\tilde{x}_1^j - e_1^j - (\tilde{y}_1^j - \Delta)) + (\tilde{x}_2^j - e_2^j - (\tilde{y}_2^j + f\Delta)) = 0$ and $\tilde{y}_t^i + \tilde{y}_t^j = \dot{y}_t^i + \dot{y}_t^j$, $t = 1, 2$. If the new distribution of permits leads to the violation of any of the constraints (8) - (10) for i, j, simply reallocate permits by using a smaller Δ until that is no longer the case. The assumption that (8) - (10) are strictly negative takes care of the existence of a strictly positive Δ. $\square$

Before drawing some conclusions from Proposition 6, let

$$y^i := \begin{cases} fy_1^i + y_2^i & \text{when } p_1 = f\delta p_2 \\ y_1^i + y_2^i & \text{otherwise.} \end{cases}$$

In Proposition 6 we showed that the distribution of permits in equilibrium is not necessarily unique. The same argument follows for the banking case (simply replace f with 1 in Proposition 6). However, y^i seems to be unique. Only in the case when agents are in exact compliance ($\mu^i, \lambda^i > 0$), we are able to determine a unique distribution of permits across all agents and both periods.

A more important implication of Proposition 6 is:

Remark 1. (On the **suspension** rule) *With the assumptions of Proposition 6, then, in a borrowing equilibrium, we can determine the total volume of non-compliance, but not by how much each country will borrow (similarly in a banking equilibrium). It follows that the suspension mechanism does not affect the total volume of non-compliance in a period, nor prices and costs, it only shifts the individual amounts of non-compliance from the next period sellers to the next period buyers.* □

To clarify the implication of the suspension rule, consider a hypothetical two-agent case of Russia and the EU. Take a borrowing equilibrium, $f = 1.3$, and let permit prices be $p_1 = 130$, thus $\delta p_2 = 100$. We fix optimal emissions levels throughout the example, hence abatement costs are constant. Assume we have calculated an equilibrium where Russia is selling some permits to the EU in period two, but both parties were non-compliant by five units in period one. In this case, Russia is violating the suspension rule. To surpass that problem, Russia can buy five units of period one permits from the EU. This will add $5 \times 130 = 650$ units to her costs. Russia is now in exact compliance in period one, but the EU has increased her volume of non-compliance to 10 units. The aggregate volume of non-compliance is constant. Since all emissions levels are fixed, Russia is over-compliant in period two by $5 \times 1.3 = 6.5$ units. So, let Russia now in addition offer 6.5 units of permits in period two to the EU at the discounted price 100. Would the EU accept this offer? She has no reason to reject it, since she increased non-compliance in period one by five units, and therefore needs 6.5 additional period two units to cover up for this. Thus, after this permit swap, both parties are equally well off, Russia does not violate the suspension rule, and the aggregate volume of non-compliance in period one remains the same.

For this to be true, it is necessary that the EU is allowed to transfer a sufficient amount of permits to Russia in period one, which can only happen if such transfer does not make her violate the commitment period reserve (8). Similarly, Russia must be allowed to sell 6.5 units in period two to the EU, without violating the commitment period reserve rule in period two (9).

4 Simulation results

To make numerical inferences about the model, we used marginal abatement cost functions supplied by the International Institute of Applied Systems Analysis, (IIASA) generated from the MERGE model [9], (see also www.stanford.edu/group/MERGE/). MERGE was calibrated to the B2 emissions scenario made for the Intergovernmental Panel on Climate Change [11]. The original parties of the Kyoto Protocol are aggregated into five parties, EEFSU (Eastern Europe and Former Soviet Union), OECDE (OECD Europe), CANZ (Canada, Australia and New Zealand), Japan and the US.

The applied version of MERGE only accounted for energy related CO_2-emissions. Values are reported in constant US dollars of 1997. Marginal abatement cost functions were generated by imposing various levels of carbon taxes on the model. OLS regression on these data indicated a good linear fit such that $\partial c_t^i(x_t^i) = a_t^i + b_t^i x_t^i$ with $a_t^i < 0$, and $b_t^i > 0$, $t = 1, 2$ whenever $x_t^i \leq -a_t^i / b_t^i = \widehat{x}_t^i$ and $\partial c_t^i(x_t^i) = 0$ for $x_t^i > \widehat{x}_t^i$. The parametrization of the cost functions are given in Appendix 2.

The emission endowments for the first commitment period, e_1^i, are defined in the Kyoto Protocol as a percentage change, q^i, with emissions in 1990 as base-year, x_b^i. Hence, the endowment in the first commitment period are given by, $e_1^i = (1 + q^i)\, x_b^i$. Emissions endowments for the second commitment period have not yet been negotiated. Lacking strong reasons to choose anything else, we assume that they are identical to the Kyoto targets (measured in terms of metric tons), that is, $e_2^i = e_1^i$ for all $i \in I$. Endowments and baseline emissions are presented in Table 1.[7]

[7] A word about abbreviations fits here: $ is US dollars; C, carbon; t, tons; M, million; B, billion and yr, year.

Table 1. The committed change in emissions compared to 1990-levels, the 1990 emission levels, the permit endowments and the estimated baseline emissions in years 2005, 2010 and 2015.

	Kyoto targets	Emissions 1990	Endow-ments	Baseline Emissions		
				2005	2010	2015
Variable	q^i	x_b^i	e_1^i, e_2^i	$\widehat{x}_0^i$	$\widehat{x}_1^i$	$\widehat{x}_2^i$
Units	%	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr
US	-7.0	1345	1251	1681	1820	1914
OECDE	-7.9	934	860	998	1039	1072
Japan	-6.0	274	258	324	350	352
CANZ	-0.7	217	215	284	313	319
EEFSU	-1.7	1337	1314	876	899	946
Total	-5.1	4107	3898	4163	4420	4604

In the Kyoto Protocol, the following parameterization has been agreed upon: $f = 1.3$, $k_e = 100\%$, and $k_x = 90\%$. The annual interest rate r, is set at 5% since this is consistent with MERGE. As each commitment period in the Kyoto Protocol is of 5-year duration, the discount factor, δ, is then given by $\delta = 1/(1+r)^5 = 0.784$.

The model was programmed in GAMS, using the MCP solver (see e.g. [15]). Costs, C^i, that appear in the tables, are the average annual discounted costs across the 2×5 year commitment periods (even for parties only participating in one period) and include market transactions. We first investigate the benchmark model without restrictions on spatial or temporal trade, and then study the effects of each rule separately, before bringing everything together. All cases are examined under two market structures, the fully competitive and the monopoly case. Moreover, since the US announcement of not ratifying the Protocol is likely to have a significant impact on the outcome of the agreement, we do all scenarios with and without US participation in the first commitment period.

4.1 The benchmark case

4.1.1 With the US

Without any restrictions on emissions trading (i.e. $f = 1$, and constraints (8)-(10) are removed) then, with the US participating in both periods, the results are as in Table 2.[8]

[8] In all proceeding Tables, the discounted permit prices in period one and two are located in the coordinates Total/∂c_1^i and Total/$\delta \partial c_2^i$ respectively.

Table 2. Emissions trading with free compliance, with the US.

	Competitive Trading				Monopolistic Trading			
	Permits Bought	Marginal Costs		Total Costs	Permits Bought	Marginal Costs		Total Costs
Period	1+2	1	2	1+2	1+2	1	2	1+2
Variable	y^i	∂c_1^i	$\delta \partial c_2^i$	C^i	y^i	∂c_1^i	$\delta \partial c_2^i$	C^i
Units	MtC/yr	\$/tC	\$/tC	B\$/yr	MtC/yr	\$/tC	\$/tC	B\$/yr
US	628	120	120	56	538	138	138	61
OECDE	186	120	120	17	155	138	138	19
Japan	119	120	120	9	109	138	138	10
CANZ	68	120	120	8	48	138	138	9
EEFSU	-1000	120	120	-54	-850	37	37	-58
Total	0	120	120	37	0	138	138	41

With competitive trading, discounted marginal costs are equal across parties and periods, which requires the borrowing of 83 MtC/yr of period two permits in aggregate. However, since $f = 1$, some maybe banking while others are borrowing. Quite naturally, when the EEFSU exercises market power, permit prices are higher since she holds back on sales. The total amount borrowed is approximately the same as in the competitive case.

4.1.2 Without the US

When the US does not participate in the first commitment period, the results are as in Table 3.

Table 3. Emissions trading with free compliance, without the US.

	Competitive Trading				Monopolistic Trading			
	Permits Bought	Marginal Costs		Total Costs	Permits Bought	Marginal Costs		Total Costs
Period	1+2	1	2	1+2	1+2	1	2	1+2
Variable	y^i	∂c_1^i	$\delta \partial c_2^i$	C^i	y^i	∂c_1^i	$\delta \partial c_2^i$	C^i
Units	MtC/yr	\$/tC	\$/tC	B\$/yr	MtC/yr	\$/tC	\$/tC	B\$/yr
US	411	0	78	21	312	0	109	27
OECDE	257	78	78	13	205	109	109	16
Japan	142	78	78	6	125	109	109	8
CANZ	114	78	78	6	80	109	109	8
EEFSU	-925	78	78	-33	-721	0	0	-39
Total	0	78	78	13	0	109	109	20

Without the US, a large buyer has left the market in period one. As a result, considerable banking (191 MtC/yr in the competitive case and 179 MtC/yr in the monopolistic one) occurs and permit prices drop under both market configurations.

4.2 The Restoration Rate

Turning to the effects of the compliance rules, we first consider the effect of the restoration rate (setting $f = 1.3$). With the US included in the first period, parties have incentives to be non-compliant, i.e. borrowing in period one. The results are presented in Table 4.

Table 4. Emissions trading with the restoration rate, with the US.

	Competitive Trading				Monopolistic Trading			
	Permits Bought	Marginal Costs		Total Costs	Permits Bought	Marginal Costs		Total Costs
Period	1+2	1	2	1+2	1+2	1	2	1+2
Variable	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i
Units	MtC/yr	\$/tC	\$/tC	B\$/yr	MtC/yr	\$/tC	\$/tC	B\$/yr
US	628	141	109	58	535	163	125	63
OECDE	188	141	109	18	158	163	125	20
Japan	119	141	109	10	108	163	125	11
CANZ	66	141	109	8	45	163	125	9
EEFSU	-1000	141	109	-56	-847	41	32	-61
Total	0	141	109	38	0	163	125	42

As compared to a situation with free borrowing, the presence of the restoration rate reduces the aggregate volume borrowed from 83MtC/yr to 6MtC/yr. The additional social cost of this constraint amount to about 1 B\$/yr. In accordance with Proposition 3, the discounted permit price in period two is lower than in period one, more specifically $p_1 = 141$ \$/tC and $\delta p_2 = 109$ \$/tC. When permit prices fall, parties would like to borrow, but since borrowing is penalized by a factor of 1.3, that will be exactly the extra price for borrowing. In the non-competitive case, there is still some borrowing and permit prices rise to $p_1 = 163$ \$/tC and $\delta p_2 = 125$ \$/tC, but the direction of the results is the same. In the case of US non-participation in period one, parties would be banking and the restoration rate has no effect (confer Table 3).

4.3 The Commitment Period Reserve

We now introduce the commitment period reserve rule given in (8) - (9) that limits the export of permits. We first assume free banking and borrowing to get a clear picture of the effect of this instrument in isolation. Intuition indicates that EEFSU is the only seller in each period, thus the only potential candidate to be restricted by this rule. In period one, the rule implies that the EEFSU should keep the minimum of 90% of her endowment in period one (= 90%(1314) = 1183 MtC/yr) or 100% of her latest reviewed emissions inventory (that we take to stem from the year 2005) thus being 100%(876) = 876 MtC/yr (confer Table 1). Thus the term $\min[k_e e_1^i, k_x^i \widehat{x}_0^i]$ in (8) can simply be replaced by $k_x^i \widehat{x}_0^i$. It is, however, important to keep in mind that the EEFSU is allowed to have lower emissions than 876 MtC/yr in period one, if the extra emission permits not used are banked to the next period.

In period two, the EEFSU must keep the minimum of 90% of the endowment in period two (assumed equal to the period one endowment) or 100% of the emissions level in period one in the commitment period reserve. This amounts to the minimum of 1183 MtC/yr or 100%(x_1^i), for i = EEFSU. Since the baseline emissions for the EEFSU in period one are 899 MtC/yr, the term $\min[k_e e_2^i, k_x x_1^i]$ in (9), can simply be replaced with $k_x x_1^i$ when programming. Hence (9) becomes a linear constraint.

4.3.1 With the US

The implications of this rule in the case when the US participates in both periods are presented in Table 5.

Table 5. Emissions trading with the commitment period reserve, with the US.

	Competitive Trading				Monopolistic Trading			
	Permits Bought	Marginal Costs		Total Costs	Permits Bought	Marginal Costs		Total Costs
Period	1+2	1	2	1+2	1+2	1	2	1+2
Variable	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i
Units	MtC/yr	$/tC	$/tC	B$/yr	MtC/yr	$/tC	$/tC	B$/yr
US	626	121	121	56	538	138	138	61
OECDE	185	121	121	17	155	138	138	19
Japan	119	121	121	9	109	138	138	10
CANZ	67	121	121	8	48	138	138	9
EEFSU	-996	130	111	-54	-850	37	37	-58
Total	0	121	121	37	0	138	138	41

The results in the competitive case indicate that this constraint becomes binding for the EEFSU in the second period. More specifically the EEFSU will bank permits and constraint (9) binds. The corresponding period one constraint (8) does not bind. In the second commitment period, the difference between the permit price $\delta p_2 = 120.7$ $/tC and the marginal emission reduction cost for the EEFSU, $\delta\partial c_2^i(x_2^i) = 111.5$ $/tC equals the shadow price of (9), σ^i.

The marginal value of reducing one unit in period *one* has therefore two components. One, it allows for either selling one more permit in period one, or for banking one extra permit to the second period which both has a discounted value of 120.7 $/tC. Two, it relaxes the constraint on the export of permits in the second period with one unit, which has a value of $120.7 - 111.5 = 9.2$ $/tC, exactly the value of σ^i. Therefore it is optimal for the EEFSU to have a higher marginal abatement cost in period one ($120.7+9.2 = 130.1$ $/tC) than the other parties that abate to the level where (negative) marginal abatement costs equals permit price.

In total, permits amounting to 75 MtC/yr are borrowed from the second period.[9] With monopolistic emissions trading, the EEFSU holds back on permit exports sufficiently for the compliance period reserve to no longer bind.

[9] Keep in mind that since $f = 1$ here, some agents may be banking while others are borrowing, thus not contradicting Proposition 4.

4.3.2 Without the US

With the commitment period reserve rule, but without the US participation in the first commitment period, this rule does not bind for any party neither in the competitive nor in the non-competitive case. Hence, the commitment period reserve only binds in a competitive market when the US participates in both periods.

4.4 The suspension rule

To study the effect of the suspension rule in isolation, the model was run with free banking and borrowing, first including the US in both periods. In this case, we found an equilibrium where the EEFSU is in non-compliance in period one and selling permits in period two, thus violating the suspension rule. All other agents are buying permits in period two, thus following the rule. Controlling for the suspension mechanism, we forced the EEFSU to be compliant in period one (i.e. by adding the constraint $x_1^i - e_1^i - y_1^i \leq 0$). In the new equilibrium, the EEFSU is in exact compliance in period one, but the shadow price associated with the added constraint is zero. Marginal costs, permit prices, and total costs are identical for all parties. The suspension rule therefore does not change the value of the objective function for each agent in equilibrium, but only restricts the possible set of equilibria. Without US participation in the first period, all parties bank, and obviously, the suspension rule does not bind.

4.5 All compliance rules in combination

4.5.1 With the US

When we include all compliance rules (the restoration rate, commitment period reserve and the suspension rule), and we assume that the US joins in the first period, then, the results are as given in Table 6.

Table 6. All compliance rules, with the US.

	Competitive Trading				Monopolistic Trading			
	Permits Bought	Marginal Costs		Total Costs	Permits Bought	Marginal Costs		Total Costs
Period	1+2	1	2	1+2	1+2	1	2	1+2
Variable	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i	y^i	∂c_1^i	$\delta\partial c_2^i$	C^i
Units	MtC/yr	\$/tC	\$/tC	B\$/yr	MtC/yr	\$/tC	\$/tC	B\$/yr
US	698	146	112	59	615	163	126	63
OECDE	210	146	112	18	183	163	126	20
Japan	135	146	112	10	126	163	126	11
CANZ	71	146	112	8	52	163	126	9
EEFSU	-1114	119	106	-57	-975	36	33	-61
Total	0	146	112	39	0	163	126	42

The results indicate that in the competitive case there is borrowing of 5 MtC/yr in aggregate. The discounted permit price is 1.3 times higher in period one than in period two (p_1 = 146.0 \$/tC and δp_2 = 112.3 \$/tC). The EEFSU is constrained by the commitment period reserve rule in both periods.

In period two, EEFSU abates to the level where marginal abatement costs are 105.6 \$/tC. The difference between δp_2 and the discounted marginal abatement cost in period two exactly equals the value of the shadow price of the commitment period reserve constraint in period two (9). This is taken account for in period one, since constraint (9) actually depends on the abatement level in period one.

In period one, the shadow price of constraint (8) equals 33.7 \$/tC. The interpretation is as follows. Had that constraint been relaxed by one unit, EEFSU could have received $146.0 - 119.1 = 26.9$ \$/tC from reducing one ton of emissions and would have been able to sell one additional permit in period one. Consequently, the constraint in period two, (9), would have been relaxed marginally since it depends on the emissions level in period one, and the EEFSU would have been allowed to also sell one other permit in period two, which has a value of $112.3 - 105.6 = 6.8$ \$/tC. Thus, the shadow price of (8) amounts to the sum of these two: $26.9 + 6.8 = 33.7$ \$/tC. However, since the EEFSU is not allowed to sell more permits in period one, the opportunity costs of abating one more unit in period one does not equal the permit price in that period, but equals rather the value of banking one unit ($= \delta p_2$) plus the value of relaxing constraint (9) by one unit. This is why the marginal abatement cost in period one for the EEFSU = 112.3 + 6.8 = 119.1 \$/tC.

It is interesting to observe that the EEFSU actually is banking in equilibrium, while the others are borrowing even though $f \neq 1$. This does, however, not contradict Proposition 4 since the EEFSU in this case is constrained by (9) thus not attaining membership of M. The EEFSU wants to sell more permits in period one, in exchange of permits in period two, since the discounted permit price is higher in period one. Other agents are willing to buy such permits, decreasing the amount borrowed. However, since the EEFSU is constrained by (8), she cannot sell more period one permits. The fact that the EEFSU undertakes emissions abatement in period one at a marginal cost of 119 \$/tC even though she can only sell these at the discounted value of 112 \$/tC in period two, is to be able to get a more relaxed commitment period reserve rule in period two. Hence, it is the commitment period reserve rule that makes it attractive for the EEFSU to strictly bank while the others are borrowing, not the suspension rule.

In the case when the EEFSU monopolizes permit supply, the total volume of permits borrowed by all parties now amounts to 7 MtC/yr. The discounted permit price is 1.3 times higher in period one than in period two ($p_1 = 163.2$ \$/tC and $\delta p_2 = 125.5$ \$/tC). The EEFSU is constrained by the commitment period reserve rule only in period one. In contrast to the perfectly competitive case, the EEFSU does not bank, but borrows. However, by adding the same constraint as described in section 4.3 to control for the suspension rule, the EEFSU is in exact compliance in period one without changing the important characteristics of equilibrium.

Note that the aggregate abatement costs of the agreement across all agents and periods are 42 B\$/yr, less than what it costs for the US alone. This is of course because most of the costs incurred by the US are not associated with any emissions abatement, but represents only a financial transfer to the EEFSU (through the permit market). In fact, the US would be better off financing the emissions abatement efforts of all parties, rather than going along with the endowments of the Kyoto Protocol and emissions trading.

4.5.2 Without the US

When the US only enters in the second commitment period, considerable banking occurs and the commitment period reserve rule is not binding for any party in any period. Hence, none of the three compliance mechanisms analyzed in this paper would bind, and the results are identical to the benchmark case given in Table 3.

5 Concluding remarks

The aim of this paper was to assess analytically and numerically the implications of the three compliance mechanisms included in the Kyoto Protocol on permit trading in a setting where some agents may have market power. Our analytical findings suggest the following:

1. With free banking, but borrowing constrained by the restoration rate, the development of the permit price from one period to the next is likely to be somewhere in the range of increasing with the rate of interest and falling at the discounted restoration rate.

2. The commitment period reserve may make (negative) marginal costs lower than the permit price, or higher. This is because the (reviewed) emissions in one period have implications for the level of this constraint in the next period.

3. The suspension mechanism is neither likely to become binding, nor likely to affect the total volume of non-compliance, as it may only shift the borrowing of permits from future sellers to future buyers, at zero costs.

From our numerical analysis, we conclude that:

1. The restoration rate and the commitment period reserve rule may be binding only when the US takes part in the first period.

2. The restoration rate limits the incentives to borrow permits from future periods, and contributes to reduce, but not eliminate such borrowing.

3. The commitment period reserve rule is more likely to become binding when permit trade is competitive than when trade is manipulated by a large seller. This is so because a strategic seller holds back on permit export to keep prices up.

4. The suspension rule is not binding in any of the cases examined, regardless of market structure and US participation.

This study has limitations. First, we have neglected issues of carbon sinks, non-CO_2 greenhouse gases and the Clean Development Mechanism. Moreover, only the perfectly competitive and the monopoly configuration of the model were considered, neglecting possible market power on the demand side. In addition, issues of transaction costs and uncertainty were ignored and the analysis was limited to two periods. Finally, we only considered countries that were not cheating, thus in effect being non-compliant in the last period. Some of the compliance mechanisms are clearly designed with purposes not considered here.

Nevertheless, given our broad set of assumptions, the paper yields insight on the impacts of the compliance mechanisms agreed in the Kyoto Protocol when the setting is a dynamic imperfect market for emission quota.

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Appendix 1: Differentiated inverse demand

The differentiated inverse demand functions, $\partial p_{t,t'}$ in the case when marginal costs are linear, the set M is non-empty and permit prices are strictly positive, are found by making use of (2)-(7) and (11)-(14).

To summarize, in the case of strict borrowing or strict banking the price differentials $\partial p_{t,t'}$ for all $t, t' = 1, 2$ are given by

$$\partial p_{1,1} = \frac{Q}{R}, \partial p_{1,2} = \frac{1}{R}, \partial p_{2,1} = \frac{1}{\delta R}, \partial p_{2,2} = \frac{1}{Q\delta R} \tag{17}$$

where

$$Q := \left\{ \begin{array}{l} f \text{ when } \lambda^i = 0, f \neq 1 \\ 1 \text{ otherwise} \end{array} \right| \text{ for any arbitrary } i \in M$$

and

$$R := \sum_{i \in M_1} \frac{Q}{b_1^i} + \sum_{i \in M_2} \frac{1}{Q\delta b_2^i}.$$

In the case of exact compliance (i.e. $\lambda^i, \mu^i > 0$ for any arbitrary $i \in M$), they are given by

$$\partial p_{1,1} = \frac{1}{\sum_{i \in M_1} \frac{1}{b_1^i}}, \partial p_{1,2} = \partial p_{2,1} = 0, \partial p_{2,2} = \frac{1}{\sum_{i \in M_2} \frac{1}{b_2^i}} \tag{18}$$

We see from (17) that the 2×2 matrix $\partial p_{t,t'}$ $t, t' = 1, 2$ is singular when there is strictly banking or borrowing. This seems to confirm the lack of a unique permit pattern across agents and periods. In the case when all agents are in exact compliance, (18), the matrix, is not singular, and a unique permit pattern is established.

Appendix 2: Parameterization of marginal costs

The values of the marginal cost function parameters, a_t^i and b_t^i, are presented in Table 7.

Table 7. Marginal cost function parameters.

Party	Year 2010		Year 2015	
	a_1^i	b_1^i	a_2^i	b_2^i
US	-1003	0.551	-760	0.397
OECDE	-1883	1.813	-1185	1.105
Japan	-1727	4.933	-1258	3.574
CANZ	-693	2.216	-611	1.914
EEFSU	-1410	1.569	-1034	1.093

Units are such that marginal costs, $a_t^i + b_t^i x_t^i$, are measured in terms of \$/tC.