The impact of the unilateral EU commitment on the stability of international climate agreements

Th. Bréchet, J. Eyckmans, F. Gérard, Ph. Marbaix,
H. Tulkens and J.P. van Ypersele

Discussion Paper 2008-38

Département des Sciences Économiques
de l'Université catholique de Louvain

UCL

CORE DISCUSSION PAPER
2008/61

The impact of the unilateral EU commitment on the stability of international climate agreements

Thierry BRECHET[1], Johan EYCKMANS[2], François GERARD[3], Philippe MARBAIX[4], Henry TULKENS[5] and Jean-Pascal VAN YPERSELE[6]

November 2008

Abstract

In this paper we analyze the negotiation strategy of the European Union regarding the formation of an international climate agreement for the post-2012 era. We use game theoretical stability concepts to explore incentives for key players in the climate policy game to join future climate agreements. We compare a minus 20 percent unilateral commitment strategy by the EU with a unilateral minus 30 percent emission reduction strategy for all Annex-B countries. Using a numerical integrated assessment climate-economy simulation model, we find that carbon leakage effects are negligible. The EU strategy to reduce emissions by 30% (compared to 1990 levels) by 2020 if other Annex-B countries follow does not induce participation of the USA with a similar 30% reduction commitment. However, the model shows that an appropriate initial allocation of emission allowances may stabilize a larger and more ambitious climate coalition than the Kyoto Protocol in its first commitment period.

Keywords: climate change, coalition theory, integrated assessment model, Kyoto protocol.

JEL Classification: C6, C7, H4, Q5

---

[1] CORE and Chair Lhoist Berghmans in Environmental Economics, Université catholique de Louvain, Belgium. E-mail: Thierry.brechet@uclouvain.be. This author is also member of ECORE, the newly created association between CORE and ECARES.

[2] Center for Economics and Management, European University College Brussels and affiliated researcher Center for Economics Studies, Katholieke Universiteit Leuven, Belgium.

[3] CORE and Chair Lhoist Berghmans in Environmental Economics, Université catholique de Louvain, Belgium.

[4] Institut d'Astronomie et de Géophysique Georges Lemaître, Université catholique de Louvain, Belgium.

[5] CORE, Université catholique de Louvain, Belgium. E-mail: henry.tulkens@uclouvain.be.

[6] Institut d'Astronomie et de Géophysique Georges Lemaître, Université catholique de Louvain, Belgium.

This research was funded by Federal Belgian Science Policy under the contract "Climate, Coalitions and Technology – CLIMNEG III", SD/CP/05A.

This paper presents research results of the Belgian Program on Interuniversity Poles of Attraction initiated by the Belgian State, Prime Minister's Office, Science Policy Programming. The scientific responsibility is assumed by the authors.

1. Introduction and policy questions

In this paper we analyze the proposals regarding greenhouse gas emission reduction for the post-2012 era put forward by the European Council during the Spring 2007 (see Council of the European Union, 2007 and Commission of the European Communities, 2007a). In particular, our purpose it to assess the potential effects of the EU proposal on the incentives for future international cooperation on climate policy after the first commitment period (2008-2012) of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The policy questions we address are the following:

- Will the unilateral 20% emission reduction commitment of the EU cause a "carbon leakage effect" in the countries who have not ratified the Kyoto Protocol (and/or possible subsequent developments). In other words, would they respond to the EU's unilateral commitment by substantially lowering their own emission reductions and therefore annihilating the EU efforts?
- What is the likely effect on non EU countries who did ratify the Kyoto agreement? Will they be inclined to lower or to increase their contribution to a global solution in response to the increase in the EU effort?
- Will the contingent strategy of reducing emissions by 30% by 2020 if other industrialized countries follow, induce current outsiders to join and to step up their emission abatement efforts?
- What is the role of international emissions trading as a transfer mechanism in the EU proposals?

We will not study the question whether the EU proposal is in line with the broader and longer term objective of avoiding dangerous anthropogenic interference with the climate system, as it is referred to in article 2 of the UNFCCC (1992). Nor will we investigate whether the EU proposal is sufficient to meet the European long term global climate objective to keep global mean temperature change below 2°C. Answering these questions requires a different methodology and is not the objective of our paper. These questions are analyzed in detail in, among others, Schellnhuber (2006), Russ *et al.* (2007), Russ *et* *al.* (2005) and Criqui *et al.* (2003). We do not address either the impact the EU proposals will have on the European economy or what policy instruments the EU should adopt to meet its target. The economic costs of the alternative EU emission reduction strategies are documented in the assessment report accompanying the Communication of the European Commission (Commission of the European Communities, 2007b). A comprehensive appraisal of the interactions between the EU climate policy initiatives is analyzed in detail in Stankeviciute and Criqui (2008).

At the 2007 United Nations Climate Change Conference in Bali, attempts to forge a new climate deal for the post-2012 period were cast into a comprehensive negotiation framework, the so-called "Bali roadmap", see Ott, Sterk and Watanabe (2008). This roadmap sketches the path for a negotiating process that should culminate in 2009 in the signing of a new international climate agreement for the post-2012 period[1]. As no consensus on emission targets has been reached yet, emission targets means that the 2007 EU proposal is still the relevant benchmark to consider in the international post-2012 climate policy debate. Therefore, we try in this paper to contribute to the understanding of the international negotiation process by investigating the strategic incentives of different key international players to accept the conditions of the EU proposals.

The objective of our analysis is not normative (*i.e.* what countries ought to do in order to combat future climate change), but rather descriptive (*i.e.* what self-motivated countries are likely to do). Methodologically, we use some game theoretic coalitional stability analysis to explore the strategic incentives of six major players to ratify an international climate agreement: the USA, Japan, the EU, China, the former Soviet Union (FSU) and Rest of the World (ROW). For an introduction on the use of game theory to analyze the formation of international environmental agreements, we refer, among others, to Barrett (2003, 2005), Chander and Tulkens (2006) or Finus (2001, 2003). Given the strong heterogeneity among countries in terms of costs and benefits of greenhouse gas emission reductions, the research questions raised above can only be addressed by simulations with a numerical integrated assessment model. For that purpose we will use the CLIMNEG World Simulation CWS model (see Eyckmans and Tulkens (2003) or Bréchet, Gérard

[1] For more information on the outcome of the Bali conference, see: http://unfccc.int/meetings/cop_13/items/4049.php

and Tulkens (2007) for a description) which is an integrated assessment model adapted for coalitional analysis from the RICE model by Nordhaus and Yang (1996).

We will compare two alternative scenarios reflecting the EU proposal to a reference scenario based on the Kyoto agreement. The reference *Kyoto scenario* assumes that the developed countries that ratified the 1997 Kyoto Protocol continue cooperating after 2012 and determine their emission targets by maximizing their joint discounted welfare and adopt an international emission trading system among agreement members. The first alternative scenario is labeled EU *unilateral commitment scenario* and assumes that the EU commits itself to an emission ceiling of maximally 80% (i.e. 20% reduction) of its 1990 emission level for all periods after 2020. The second alternative scenario is called *Annex-B multilateral commitment scenario* and assumes that all Annex-B countries observe an emission ceiling of 70% (i.e. 30% reduction) compared to 1990. For the last two scenarios, we consider two variants depending on the way the additional commitment makes use, or not, of emissions trading.

This paper is organized as follows. Section 2 describes the methodological framework and the reference Kyoto scenario is presented in Section 3. Section 4 deals with the EU unilateral commitment scenario and section 5 discusses the Annex-B multilateral commitment scenario. Conclusions and directions for further research are presented in section 6.

2. The modeling framework: integrated assessment and coalition theory

The methodological innovation of our approach is to use both an integrated assessment model and game theoretical arguments to answer the policy questions raised above. The main characteristics and assumptions of the model and the way it is used are described in this section.

Our integrated assessment model, named CWS (CLIMNEG World Simulation model), resembles closely the original RICE model by Nordhaus and Yang (1996) or variations on it as in Eyckmans and Tulkens (2003).[2] We denote by $N = \{1, 2, \ldots, n\}$ the set of all countries in the world and we assume that, while choosing climate policy actions,

[2] See Kelly and Kolstad (1999) or Kolstad and Toman (2005) for an introduction and overview of integrated assessment climate-economy models.

countries' policy makers weigh the benefits (avoided future climate change damages) and costs (costs of re-orientating their economies towards lower carbon emissions level). While speaking about welfare, we will refer to some notion of Green National Product that takes into account both climate change damages and emission reduction costs. More precisely, welfare in a particular country or region will depend on the stream of discounted consumption, $Z_{i,t}$. By denoting ρ the discount rate, *t* the time period and Ω the time horizon, welfare will be given by:

$$(1) \qquad W_{i,t}\left(Z_{i,1}, Z_{i,2}, \ldots, Z_{i,\Omega}\right) = \sum_{t=1}^{\Omega} \frac{Z_{i,t}}{\left[1+\rho\right]^{t-1}}$$

Because climate change has long term impacts the time horizon considered in the model is 300 years. In every region and period, the following resource balance relation holds:

$$(2) \qquad Y_{i,t} - C_{i,t} - D_{i,t} = Z_{i,t} + I_{i,t} + X_{i,t}$$

where $Y_{i,t}$ denotes market value of production, *i.e.* conventional gross domestic product. $C_{i,t}$ and $D_{i,t}$ stand for emission abatement costs and climate change damages, respectively. One may interpret the left hand side of equation (2) as "green GDP" of a country in a particular time period, *i.e.* conventional GDP corrected for the costs of emission reduction and damages incurred from climate change. The right hand side of equation (2) displays the uses of green GDP: either goods and services are consumed ($Z_{i,t}$) or invested ($I_{i,t}$) for generating more capital stock in future periods. The variable $X_{i,t}$ denotes possible transfers (positive or negative) of resources between regions. For instance, in case there is an emissions trading scheme, the financial transfers related to these trade transactions are captured in this variable. Equation (2) is a budget constraint saying that not more can be used for consumption, investment and transfers then what is produced in every period.

Production is assumed a function of labor and capital. Total factor productivity increases exogenously over time and capital accumulation is endogenous in the model. Technical details about the production function and capital accumulation can be found in Eyckmans and Tulkens (2003). Production causes emissions of greenhouse gases according to the following relationship:

$$(3) \qquad E_{i,t} = \sigma_{i,t} \cdot \left[1 - \mu_{i,t}\right] \cdot Y_{i,t}$$

The parameter $\sigma_{i,t}$ denotes the emissions-output ratio. It is assumed to decline exogenously over time as a result of technological progress. Still, emissions can be further reduced at a rate $0 \le \mu_{i,t} \le 1$ by means of specific measures, like replacing a coal fired power plant by renewable energy sources, investment in more fuel efficient cars or energy demand management. The costs of taking action typically are increasing with the emission reduction rate, $C_{i,t} = C_i\left(\mu_{i,t}\right)$. These costs represent annualized investment costs for emission abatement equipment or alternative energy production technologies, output forgone and consumer welfare losses. Emission abatement cost functions are relatively easy to estimate, see for instance Chapter 11 in the IPCC (2007) Working Group III Report for a recent overview on cost estimates. We use in the CWS model cost estimates taken from the RICE model by Nordhaus and Yang (1996).

Emissions of greenhouse gases accumulate in the atmosphere, thereby disturbing the global carbon cycle and causing ultimately climate change. We capture the complex physical processes in the following general relationship:

$$(4) \qquad \Delta T_t = g\left(E_{N,1}, E_{N,2}, \ldots, E_{N,t}\right)$$

Temperature change at time *t* is defined relative to some base year (the pre-industrial era) and depends upon the global carbon emissions history from period *1* to period *t*. Behind this general specification is hidden the complex physical reality of the global carbon cycle and temperature change processes.

Temperature change has a variety of physical impacts, among which sea level rise, changes in precipitation patterns and extreme weather events. The economic valuation of the damages caused by these impacts is summarized in a damage function, $D_{i,t} = D_i\left(\Delta T_t\right)$. Damage functions are hard to estimate, see for instance the Stern Review (2006) or IPCC (2007) Working Group II Report. First, physical impacts are difficult to estimate, even though several studies are available, such as for sea-level rise (Marbaix and Nicholls, 2007). Second, evaluating non-market damage, such as biodiversity losses and changes in living amenities, remains challenging, for no market prices are available for their valuation. Further, weighting costs and benefits requires normative judgments regarding intergenerational justice and intragenerational justice (*i.e.* weighing costs and benefits accruing to different generations over time or to citizens that differ strongly in wealth position within one particular generation). .

In spite of the inherent difficulties with the cost-benefit framework, it remains a useful tool for climate policy analysis because it gives insights in the basic determinants of countries stance on climate change policy issues.

We now turn to the analysis of the EU proposals. We start by describing the three different scenarios: the reference Kyoto scenario, the EU unilateral commitment scenario, and the Annex-B multilateral commitment scenario. These scenarios differ from each other in terms of membership of the international climate agreement and emission reduction commitment. The following table summarizes the main elements of the three scenarios.

Table 1: Coalition membership and commitment in alternative scenarios

scenario number		1	2
scenario name	Reference Kyoto scenario	EU unilateral commitment	Annex-B multilateral commitment
USA	*out*	*out*	-30%
Japan	*in*	*in*	-30%
EU	*in*	-20%	-30%
China	*out*	*out*	*out*
FSU	*in*	*in*	-30%
ROW	*out*	*out*	*out*

Legend:
"*in*": this country/region is member of an international climate agreement and its emission target is calculated in an endogenous way as to maximize discounted group welfare;
"-20%" and "-30%": this country is member of an international climate agreement and commits to a 20% or 30% emission reduction in 2020 and all future periods;
"*out*": this country is not a member of an international climate agreement and determines its emission strategy as to maximize individual welfare

3. Reference situation: the Kyoto coalition

As a reference situation throughout the paper we will consider the Kyoto coalition, that is, the current coalition formed by the developed countries which ratified the Kyoto Protocol and committed themselves to an emission target, *Japan*, *EU* and *Former Soviet Union* in the CWS model. It is assumed that these countries continue cooperating and agree on carbon emissions ceilings that maximize their joint welfare. This reference coalition is one particular Partial Agreement Nash Equilibrium (PANE) in carbon emissions among others.[3] The Kyoto coalition members coordinate their emission strategies as to maximize their joint welfare taking as given the equilibrium emissions of the non-members. Outsiders for their part maximize their individual payoff taking as given the equilibrium emissions strategies of other outsiders and of the Kyoto coalition. The resulting emissions allocation satisfies the following marginal first-order condition for all Kyoto member countries:

$$(5) \qquad \forall i \in S: \qquad \frac{1}{\sigma_{i,t} \cdot Y_{i,t}} \cdot \frac{\partial C_i}{\partial \mu_{i,t}} = \sum_{\tau=t}^{\Omega} \frac{1}{\left[1+\rho\right]^{\tau-t+1}} \cdot \frac{\partial g_\tau}{\partial E_{N,t}} \cdot \sum_{j \in S} \frac{\partial D_j}{\partial \Delta T_\tau}$$

where S represents the coalition. According to expression (5), agreement member i reduces its emission in period t in such a way that the marginal cost of reducing one more ton of carbon (*i.e.* the left hand side of (5)) equals the discounted sum of all future marginal damages due to additional temperature change caused by this additional unit of reduction (right hand side of (5)). At any point in time, Kyoto members internalize all the future negative climate damage externalities of their carbon emissions, to the extent that it affects their fellow coalition members. Climate damages affecting non-members are not taken into account by the members of the coalition.

Note that this condition implies that marginal emission abatement costs are equalized among all Kyoto Protocol members, which implies that their overall emission reduction target is achieved in a cost efficient way. Cost efficiency prevails when market based environmental policy instruments are used, as it is the case with the flexible mechanisms of the Kyoto Protocol.

---

[3] For a precise definition of this game theoretic solution concept, see Chander and Tulkens (1995, 1997). See Eyckmans and Finus (2006a, 2006b) for an analysis with the CWS model of all possible PANEs.

The countries outside the Kyoto coalition take into account their own individual climate change damages, neglecting negative climate change externalities to other countries:

$$(6) \qquad \forall i \in N \setminus S: \qquad \frac{1}{\sigma_{i,t} \cdot Y_{i,t}} \cdot \frac{\partial C_i}{\partial \mu_{i,t}} = \sum_{\tau=t}^{\Omega} \frac{1}{[1+\rho]^{\tau-t+1}} \cdot \frac{\partial g_\tau}{\partial E_{N,t}} \cdot \frac{\partial D_i}{\partial \Delta T_\tau}$$

Starting from this reference situation, which reflects the current state of international climate agreements, we can explore the implications of the unilateral EU strategy. We present now two scenarios designed for that purpose and reflecting the Council's proposal.

4. The EU unilateral commitment scenario

4.1 Description

In this first scenario it is assumed that, starting from the Kyoto coalition, an additional constraint is imposed which requires that EU's carbon emissions cannot exceed 80% of their 1990 emissions level for all time periods beyond 2020.[4] Two cases will be considered in our scenario, depending on whether emissions trading is allowed or not.

Without *emissions trading* the following additional constraint is added to the Kyoto coalition optimization problem for the EU:

$$(7) \qquad \forall t \geq 2020: \qquad E_{EU,t} \leq [1-0.20] \cdot E_{EU,1990}$$

It results that, in that coalitional equilibrium, the distribution of the reduction effort among the Kyoto coalition is no longer cost-efficient. Marginal abatement costs are equalized among all unconstrained coalition members but are now higher within the EU.[5] Since this difference in marginal abatement costs is hard to reconcile with the assumption that the Kyoto coalition fully makes use of market based environmental policy instrument, such as emissions trading, we therefore consider a second variant including full emissions trading.

[4] As the time step of the CWS model is 10 years, the transition path cannot be displayed.

[5] Marginal abatement costs will be higher only if the unilateral commitment entails stronger reductions than in the reference unconstrained Kyoto coalition equilibrium. In other words, only if constraint (7) is binding, marginal abatement costs between agreement signatories will be different.

In the variant *with emissions trading* a constraint is introduced in the whole Kyoto group emissions instead of individual emissions constraints for the EU only, as in (7). The new emissions constraint in replacing (7) in the optimization problem for the Kyoto coalition now writes,

$$(8) \qquad \forall t \geq 2020: \qquad \sum_{j \in S} E_{j,t} \leq \sum_{j \in S} \hat{E}_{j,t}$$

For the 'constrained coalition member', the EU, we set $\hat{E}_{EU,t} = [1-0.20] \cdot E_{EU,1990}$, i.e. 20% below 1990 emission levels. For all other coalition members, we set $\hat{E}_{j,t}$ equal to their emission level in the reference Kyoto coalition scenario.

The difference between the variants *with* and *without emissions trading* lies in the flexibility regarding where, and thus at what cost, emission reductions are actually taking place. In the scenario without emissions trading (equation (7)), the constrained countries have to perform all additional reduction effort domestically. In the scenario with emissions trading (equation (8)), any additional reduction commitment by one agreement member leads to higher demand and higher equilibrium prices for permits in the permit market. In that case, the additional reduction commitment can be shared over the different coalition members in a cost efficient way.

Regarding the initial allocation of permits in future commitment periods, we assume that all unconstrained agreement members get exactly their emissions of the reference Kyoto allocation. Constrained members' initial allocations (the European Union) are in line with their individual reduction commitment. Hence, initial permit holdings coincide with $\hat{E}_{i,t}$ as defined above and financial transfers related to permit trade transactions are captured by the transfer variable $X_{i,t}$ in every country's budget balance equation (1):

$$(9) \qquad X_{i,t} = p_t \cdot \left[\hat{E}_{i,t} - E_{i,t} \right]$$

The equilibrium price p_t of emissions permits in period t corresponds to the shadow price of the joint emissions constraint (8).

4.2 The key issue of "carbon leakages"

From our computations it turns out that the EU unilateral commitment of limiting by the year 2020 its emissions to 80% of its 1990 emission level represents a more stringent emission policy than what the EU would be committed to under the *reference Kyoto* scenario. This will constitute a crucial point in our analysis. Actually, the additional emission reduction by the EU gives something like a 'climate bonus' to other countries since they will be confronted with lower climate change damages, which increases, everything else equal, their welfare. We will call this effect the *climate externality effect* of the EU's unilateral commitment. In the environmental economics literature, considerable concern has been raised about the fact that this positive externality gives other countries an incentive to lower their own contribution to solving the global climate change problem, see for instance Hoel (1992). This is called *carbon leakage*[6] and results from free riding reactions under the assumed selfish behavior of non-participating countries.

Though theoretically undisputable, the relevant policy question is whether this carbon leakage effect would be so strong that the EU's additional emission reduction effort is partially (or even completely) compensated by an increase in emissions by other countries. Because of the further decrease of EU emissions in comparison with the unconstrained scenario, world emissions and carbon concentrations are reduced, and the temperature rise is smaller, *ceteris paribus*. Therefore, climate damages borne by all regions are reduced, leading to a decrease in damages in all countries. Consequently, some more resources are available to be spent in consumption (variable $Z_{i,t}$ in (2)), investment in physical capital (variable $I_{i,t}$ in (2)) and on emission mitigation measures (variable $C_{i,t}$ in (2)). The objective of each country being to maximize its net welfare over time, it chooses its optimal strategy under the following trade-offs:

- to increase its green consumption, (which does not yield further emissions);

[6] Carbon leakage is a more general term that is used for other spillover effects in international climate policy as well like for instance, delocalization of carbon intensive industries to non-participating countries. In this paper, the term carbon leakage only refers to strategic climate policy reactions by governments.

- to invest in physical capital infrastructure so as to increase production in the forthcoming periods, (and consume more later on, leading to higher emissions during the periods when production is increased);
- to abate more emissions now to curb the temperature increase and avoid future damages.

In the following analysis, it is important to keep in mind that abatement efforts, and thus temperature increases, are endogenous in the CWS model in the sense where they result from the cost-benefit analyses undertaken in each country. Furthermore, the outcome of these cost-benefit analyses is coalition-dependent. Full numerical results of the simulations are reported in Table 2 in the appendix. We will focus here on the interpretation of these results.

4.3 Slight carbon leakages, but welfare gains for outsiders

A first observation is that the 20% unilateral reduction commitment implies a real cut in EU's emissions. EU should reduce its emissions by an additional 24% in 2020 compared to what would have done in an unconstrained Kyoto scenario (see appendix, table 2). Outsiders (*i.e.* countries having no commitment) react only marginally to the EU's unilateral action. They increase their own emissions by about 0.13%, with some differences among countries: the USA +0.18%, China +0.34% and Rest of the World +0.03%. Carbon leakage elasticity is therefore extremely small. This constitutes a very positive signal from an environmental standpoint: an additional cut by one percent by the EU triggers an increase of only 0.005% by the outsiders, which can be seen as negligeable. Hence, carbon leakage to non-ratifying countries should therefore be little a concern. The reason for this moderate reaction is most likely the fact that future marginal climate change damages (hence marginal benefits of emission reductions) are rather insensitive to changes in current regional emissions due to the strong inertia in the carbon cycle and climate system. The fact that the CWS model considers a very long time span (which is adequate concerning global warming) may explain that result.

In spite of their small reaction in terms of carbon emission increases, outsiders of the Kyoto coalition do gain in terms of welfare: USA gains about 0.31%, China 0.62% and ROW 1.02% in the constrained compared to the unconstrained Kyoto scenario. This observation is important because it shows that EU strategy generates small, though not negligible, free riding incentives in other countries. Countries that do not participate in the Kyoto Protocol are better off if protocol members increase the efforts to limit their emissions and slow down global climate change. The same holds true for the other Kyoto ratifying countries. Japan and Former Soviet Union react similarly as the non-ratifying countries: they increase slightly their emissions in response to the EU's proposal in the absence of emissions trading (Japan +0.23% and FSU +0.53%). The reason is that they enjoy the same positive climate externality bonus as non-members. In spite of their reaction, the overall emissions of the Kyoto group go down because the additional commitment of the EU outweighs the other members' emission increases, which is the objective pursued by the EU.

4.4 The key role of emissions trading

The picture for agreement members looks different if a system of emissions trading among the Kyoto countries is assumed. In that case, other ratifying countries also decrease their actual emissions strongly after an additional commitment by the EU: Japan minus 9.32% and Former Soviet Union even minus 21.82%. The reason for the marked difference is that under emissions trading, it is profitable for the EU to buy some emissions permits in the market instead of meeting their minus 20% reduction commitment by means of internal emissions reduction projects only. As a result, the additional EU demand for permits pushes the equilibrium market price up and induces other market participants to produce more emission reduction. Through the permit price, the different signatories' reduction efforts are positively linked. This type of linkage is not present in the absence of emissions trading.

Both with and without emissions trading, the Kyoto coalition experiences a loss in welfare. This is obvious because the constrained Kyoto outcome is also a feasible solution to the unconstrained Kyoto welfare maximization problem. Adding an additional constraint on the effort allocation cannot but lead to a decrease in the optimal welfare of the group. The loss is more pronounced without emissions trading (-0.72%) than with emissions trading (-0.37%). Without trading, the allocation of efforts is not cost efficient for the Kyoto coalition. Trading allows for more flexibility in the abatement burden allocation and results in a cost efficient allocation of reduction efforts over all Kyoto members. Compared to the incomplete trading solution, the full trade equilibrium allows cutting total compliance costs by half.

4.5 On the stability of the Kyoto coalition

The overall welfare loss of the unilateral commitment for the Kyoto group implies that there is a smaller surplus compared to free riding payoffs, *i.e.* the welfare levels that current members can achieve if they would leave the coalition. The Kyoto coalition with 20% emission reduction for the EU would not be stable in a game theoretical sense. Making such commitment is a political choice that is not "rational" in the game theory framework: the sum of the payoffs within the coalition is not large enough to compensate for the welfare loss in the EU. The unconstrained Kyoto coalition (our reference Kyoto situation) was able to produce more welfare than the sum of the payoffs of their members under complete absence of cooperation[7] (*i.e.* the so-called Nash equilibrium). Given this surplus, there are numerous ways to redistribute the gains of cooperation (for instance through an appropriate initial assignment of emission permits under an emission trading scheme) such that every individual member is better off joining than not joining. This can be seen in Table 4 in appendix. Without cooperation (Nash equilibrium), the Kyoto group {*Japan, EU, FSU*} achieves a payoff of 1421.59 trillion $US\$_{2000}$, which is slightly less than in the reference scenario (1422.28 trillion). However, due to the unilateral commitment by the EU (scenario 1), the overall surplus for the Kyoto coalition drops to 1416.99, which is well below 1421.59 under the Nash scenario. In spite of that, the members of the coalition apart from EU (i.e. Japan and FSU) are still better off than in the reference situation. The stability of the coalition is thus maintained as long as he EU is willing to incur the loss to achieve its mitigation policy.

[7] Implicitly we assume here that if a member would defect from the Kyoto coalition, the agreement would completely collapse and we would revert to the complete absence of cooperation. Practically speaking, this is consistent with the ratification thresholds in the Kyoto Protocol. Theoretically speaking, this assumption corresponds to the notion of the core in cooperative game theory, see Chander and Tulkens (1995, 1997). However, it should be noted that there are other free riding notions in which it is assumed that after defection by one member, the remaining coalition members continue cooperating (see Barrett 2005). The later interpretation of free riding leads to even higher free riding incentives and would reinforce our arguments on (in)stability of the Kyoto coalitions.

Global temperature increase by 2100 amounts to +3.5°C without EU's unilateral commitment, versus +3.4°C with 20% additional commitment. Overall, the impact of the sustained minus 20% objective on temperature levels is limited because of the relatively small share of Kyoto countries in global emissions, and because of the relatively weak emissions target of 80% of 1990 emissions levels. We are well aware that it is very likely that for future periods beyond 2020 more ambitious targets and unilateral commitments might be implemented.

Global welfare increases by 0.33% (without emissions trading) or 0.42% (with emissions trading) compared to the reference Kyoto scenario. The welfare increase is due to the fact that the unconstrained Kyoto scenario is globally strongly inefficient given our damage parameters and discount rate. Global carbon emissions are too high compared to the global optimal level that maximizes world welfare. Thus, the EU's unilateral commitment is a move into the direction of the global optimum.

5. The Annex-B multilateral commitment scenario

5.1 Description

We now turn to the second part of the EU proposal: the conditional reduction by 30% if other developed countries are willing to assume similar reduction objectives. This may be interpreted as further abatements efforts within Annex-B countries. This strategy of the EU resembles what is called a *tit-for-tat* strategy, see Axelrod (1984), in repeated non-cooperative games[8]. Tit-for-tat strategies essentially mean that every player copies the strategy played by its opponent in the previous period. So, I cooperate if I observe that you cooperated in the previous period. But I will deviate if I observe that you deviated in the previous period. This type of strategies is a special case of the more general class of *trigger strategies* that all share the characteristic that they contain some kind of credible punishment threat if the opponent deviates. It is well known that this type of future punishment possibility can be sufficient to sustain in an infinitely repeated game a cooperative solution as a Nash equilibrium. This is the so-called "folk theorem"; see among others, Montet and Serra (2003) for an introduction.

[8] Strictly speaking, environmental games with stock pollutants do not belong to the class of repeated games since the accumulation of the stock pollutant changes the fundamentals of each stage game. However, due to the strong inertia in the stock accumulation process in the CWS model, the comparison with repeated games is justified.

The EUs conditional strategy to reduce greenhouse gas emissions by 30% by 2020 if the other developed countries follow can be interpreted as a kind of tit-for-tat strategy. Only if the EU observes that the other industrialized countries are willing to assume similar reduction efforts, the EU reduces its emissions by 30%. In the other case, EU reverts to its original proposal of minus 20% unilateral reduction. For a tit-for-tat strategy[9] to work well, it is of crucial importance that the punishment part of the strategy be sufficiently harsh to deter non-cooperative behavior by the other industrialized countries.

In order to test whether the 30% proposal can generate incentives for current non-members of the Kyoto Protocol to join, we compare the EU's unilateral commitment scenario (scenario 2) to a new scenario, called *Annex-B multilateral commitment*, in which the USA joins the club and all members of the expanded agreement observe an emission ceiling of 70% of their 1990 emissions level.[10] Like before we distinguish between a solution *with* and *without emissions trading*. See Table 3 in appendix for the detailed results.

5.2 EU trigger strategy may work

Computations with the CWS model reveal that the surplus of the expanded coalition is always higher in the multilateral -30% scenario than in the EU alone -20% scenario. Hence, including the USA and observing the 70% of 1990 emissions ceiling would constitute a clear welfare improvement for the expanded group of countries. Interestingly, allowing for emissions trading or not does not fundamentally alter the conclusion. The natural question is therefore: would it be possible to give an incentive for the USA to join the coalition?

In Table 4 we summarize the relevant welfare data for USA and the Kyoto coalition for all scenarios considered. We observe from Table 4 that USA would be worse off joining the club compared to the EU unilateral commitment scenario, their welfare level would

[9] Admittedly, there are some interpretation difficulties. First, the climate change problem is strictly speaking not a repeated game. In every subsequent period, the game is slightly different because of the accumulative nature of greenhouse gas emissions. But in the short run, we believe the situation can be approximated as a repeated game. Also the fact that the EU's proposal remains vague on its longer run strategy complicates the interpretation of its proposal as a tit-for-tat strategy.

[10] This is a simplification of the EU negotiation position, as the Council refers to "comparable" reductions: these might not be numerically exactly the same, but our scenario lies in the appropriate range, specifically as we consider a possible redistribution of initial allocations within the coalition.

decrease by 19.13 trillion US$$_{2000}$ (1410.72 versus 1391.59). Hence, the USA have little incentive to join the Kyoto coalition despite the EU commitment. However, this conclusion about the individual payoff of one member of the coalition is to be interpreted with great care because it depends strongly on the initial allocation of permits and, hence, of possible revenues or expenses of permit sales and acquisitions. The relevant question is whether the expanded group can be stabilized with some appropriate transfers (*i.e.* appropriate initial allocations of permits).

This question can be answered by having a careful look at Table 4 again. For the USA to be willing to join the Annex-B multilateral commitment with trade scenario (scenario 2, with trade), they need at least a pay-off of 1410.72 trillion US$$_{2000}$. This leaves 2845.36 – 1410.72 = 1434.64 for the original Kyoto members. This is more than what these original Kyoto members can achieve under the "Kyoto coalition + EU minus 20 with trade" scenario (1416.99, according to Table 4) and even more than under the plain "Kyoto scenario" (1422.28, according to Table 4). Hence, it is possible to design a transfer scheme (for example, an initial allocation of permits) such that the USA can be persuaded to join the Kyoto group which observes a 30% reduction target. In other words, there is sufficient payoff in the expanded coalition to pay for the USA free riding claim and also to preserve a sufficient surplus to make all original Kyoto members better-off compared to both of our scenarios. However, this would require a substantial additional amount of permits to be given to the USA compared to the -30% uniform allocation that was assumed in scenario 2.

6. Conclusion

In this paper we compare two different scenarios referring to the European Council international climate initiative of February 2007. We first consider a reference situation based on the current Kyoto Protocol coalition in which only the countries committed to a quantified target under the Kyoto protocol are assumed to continue cooperating in the future. In order to predict future emission strategies by this Kyoto coalition and other non-members we adopt the Partial Agreement Nash Equilibrium (PANE) concept of Chander and Tulkens (1995, 1997). This concept implies that agreement signatories coordinate their emission strategies by maximizing their joint welfare and take as given the emissions by non-members. Outsiders to the agreement are assumed to maximize individual welfare taking emissions of all other countries as given.

This reference situation is confronted with a scenario in which the EU commits unilaterally to an emission reduction of 20% compared to 1990 (scenario 1) and a scenario in which all Annex-B countries multilaterally commit to a minus 30% compared to 1990 strategy (scenario 2). For these two scenarios we distinguish between two polar cases, an inflexible (no emissions trading among countries of the coalition) and a flexible (emissions trading is allowed) burden sharing case.

The main findings are as follows:

1. In all scenarios, the model reveals that carbon leakages caused by free riding behavior of outsider countries in reaction to unilateral or multilateral emission reduction are not a concern. The reaction of the outsiders is quite limited (the elasticity of their emissions *w.r.t.* a change in the EUs emissions is smaller than 0.01 in absolute value). The reason for the weak carbon leakage effect is that marginal damages from climate change prove to be relatively insensitive to changes in regional emissions' reduction effort.

1. Under the first scenario, the main strategic effect occurs *within* the coalition. When emissions trading is allowed, a unilateral additional commitment by one member drives up the market price of permits considerably, which therefore induces the fellow coalition members to reduce their emissions in order to sell tradable emission permits. Through the permit price set up in marker equilibrium, reduction efforts by the coalition members are interconnected. Thus, under an emissions trading system, unilateral commitment of EU to reduce its emissions by 20% leads to a decrease 2.5% of accumulated global emissions between 2000 and 2100 and to an increase in global welfare by 0.4%.

2. Without emissions trading, in the same scenario, the effect on global emissions and welfare is a little smaller. The main reason for this is that without emissions trading, the overall emission target is produced in a cost inefficient way. This cost inefficient production of abatement induces a slightly less ambitious overall emission commitment for the Kyoto coalition as a whole.

3. Concerning the conditional strategy to reduce emissions by 30% if other industrialized countries follow (the scenario 2), from the model the implicit threat to revert to 20% unilateral emission reduction is too weak to induce countries like the USA to join the climate agreement and to accept a 30% reduction commitment without emissions trading. In welfare terms, USA is better off free-riding on the 20% Kyoto coalition than joining the Kyoto group under a joint minus 30% target without trading. When trading is allowed, the results are markedly different as it becomes possible to redistribute coalitional surplus through permit trading and alternative initial allocations of permits. We showed that it is in principle possible to design a transfer scheme (and therefore an initial allocation of permits) such that the USA can be persuaded to join the Kyoto group which observes a 30% reduction target. There is sufficient payoff in the expanded coalition to pay for the USA free riding claim and still to retain sufficient surplus to make all original Kyoto members better off compared to the EU unilateral commitment scenario with trade (scenario 2) and even the reference Kyoto scenario.

4. All scenarios that we studied indicate that the unilateral commitment proposed by the EU may induce current non-members to the Kyoto Protocol to join in the future, conditional upon a substantial redistribution of the gains of cooperation. This redistribution of the cooperative surplus is an essential element to achieve effective and stable international climate policy in the long run. In a system of emissions trading, it should be implemented by means of an initial allocation of permits that explicitly takes into account free riding claims by coalition members. Transfer schemes like those of Chander and Tulkens (1995, 1997) and Eyckmans and Finus (2003) offer explicit formulae to determine an initial permit allocation which is incentive compatible in this sense.

References

Axelrod, R. (1984), *The Evolution of Cooperation* (Basic Books, New York).
Barrett, S. (2003), *Environment and statecraft: the strategy of environmental treaty-making* (Oxford. University Press, Oxford), 427 pp.

Barrett, S. (2005), The theory of international environmental agreements, in: K.-G. Mäler and J.R. Vincent (eds), *Handbook of Environmental Economics Volume 3*, (Elsevier, Amsterdam-New York), chapter 28, 1457–1516.

Bréchet, T., F. Gérard and H. Tulkens (2007). Climate coalitions: a theoretical and computational appraisal. UCL-CORE Discussion Paper 2007/3 (Université catholique de Louvain, Belgium).

Chander, P. and Tulkens, H. (1995). A Core-Theoretic Solution for the Design of Cooperative Agreements on Transfrontier Pollution. *International Tax and Public Finance* **2**: 279–293.

Chander, P. and Tulkens, H. (1997). The core of an economy with multilateral environmental externalities. *International Journal of Game Theory* **26** (3): 379–401.

Chander, P., H. Tulkens, J.-P. van Ypersele and S. Willems. The Kyoto protocol: an economic and game-theoretic interpretation. In B. Kriström, P. Dasgupta, and K-G. Löfgren (eds.). Economic Theory for the Environment. Essays in Honour of Karl-Göran Mäler. Cheltenham, Edward Elgar, 98-117, 2002.

Criqui, P., A. Kitous, M. Berk, M. den Elzen, B. Eickhout, P. Lucas, D. van Vuuren, N. Kouvaritakis and D. Van Regemorter (2003), Greenhouse gas reduction pathways in the unfccc process up to 2025 (Technical Report for EU Commission DG Environment).

Council of the European Union (2007), Brussels European Council 8/9 March 2007. Presidency conclusions. Council document 7224/07 (EU Council, Brussels).

Commission of the European Communities (2007a), Limiting Global Climate Change to 2 degrees Celsius - The way ahead for 2020 and beyond. COM/2007/0002 (EU Commission, Brussels).

Commission of the European Communities (2007b), Limiting Global Climate Change to 2 degrees Celsius - The way ahead for 2020 and beyond. Impact Assessment. Commission staff working document accompanying document COM/2007/0002 (EU Commission, Brussels).

Eyckmans, J. and Tulkens, H. (2003). Simulating Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem. *Resource and Energy Economics* **25**: 299–327.

Eyckmans, J. and M. Finus (2004). An Almost Ideal Sharing Scheme for Coalition Games with Externalities, Energy, Transport and Environment Working Paper 2004-14 (Katholieke Universiteit Leuven, Centrum voor Economische Studiën, Belgium).

Eyckmans, J. and Finus, M. (2006a), Coalition formation in a global warming game: how the design of protocols affects the success of environmental treaty-making, *Natural Resource Modeling* **19**(3), 323–358.

Eyckmans, J. and Finus, M. (2006b), New Roads to International Environmental Agreements: The Case of Global Warming, *Environmental Economics and Policy Studies* **7**(4), 391–414.

Finus, M. (2001), *Game Theory and International Environmental Cooperation* (Edward Elgar, Cheltenham, UK).

Finus, M. (2003), Stability and Design of International Environmental Agreements: The Case of Transboundary Pollution. In: Folmer, H. and T. Tietenberg (eds), *International Yearbook of Environmental and Resource Economics*, 2003/4, (Edward Elgar, Cheltenham, UK), chapter 3, 82–158.

Hoel, M. (1992). International environment conventions: the case of uniform reductions of emissions. *Environmental and Resource Economics* **2** (2): 141–159.

Joos, F., G. Muller-Furstenberger, and G. Stephan (1999). Correcting the carbon cycle representation: How important is it for the economics of climate change? *Environmental Modeling and Assessment*, **4**:133–140.

Kelly, D. and C.D. Kolstad (1999), Integrated Assessment Models for Climate Change Control, in: H. Folmer and T. Tietenberg (eds), *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues* (Edward Elgar, Cheltenham, UK), chapter 4, 171–197.

Kolstad, C.D. and M. Toman (2005), The Economics of Climate Policy, in: K.-G. Mäler and J.R. Vincent (eds), *Handbook of Environmental Economics Volume 3*, (Elsevier, Amsterdam-New York), chapter 30, 1561–1618.

Marbaix, P. and F. Gérard (2008). A new climate and carbon cycle representation for the CWS model, mimeo (Université catholique de Louvain, Belgium).

Marbaix, P. and R. J. Nicholls. Accurately determining the risks of rising sea level. EOS Transactions, AGU 88 (43), 441-442.

Nordhaus, W.D. (1991). To slow or not to slow: The economics of the greenhouse effect. *The Economic Journal*, **101**(407), 920–937.

Nordhaus, W.D. and Z. Yang (1996). A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies, *American Economic Review* **86**(4), 741–765.

Nordhaus, W.D. and J. Boyer (1999). *Roll the DICE Again: Economic Models of Global Warming*, Chapter 2. The structure and derivation of RICE-99 (MIT Press, Boston Mass).

Nordhaus, W.D. (2007). The challenge of global warming: economic models and environmental policy. Technical report (Yale University, USA).

Montet, D. and D. Serra (2003), *Game Theory and Economics* (Palgrave – Macmillan, Basingstoke UK and New York), pp. 487.

Ott, H.E., W. Sterk and R. Watanabe (2008), The Bali roadmap: new horizons for global climate policy, *Climate Policy* **8**, 91–95.

Russ, P., T. Wiesenthal, D. Van Regemorter and J.C. Císcar (2007), Global climate policy scenarios for 2030 and beyond – analysis of greenhouse gas emissions reduction pathway scenarios with the POLES and GEM-E3 models (European Commission – Joint Research Center JRC – Institute for Prospective Technological Studies IPTS, Sevilla).

Russ, P., J.C. Císcar and L. Szabó (2005), Analysis of Post-2012 Climate Policy Scenarios with Limited Participation (European Commission – Joint Research Center JRC – Institute for Prospective Technological Studies IPTS, Sevilla)

Schellnhuber, H.J., W. Cramer, N. Nakicenovic, T. Wigley, G Yohe, editors (2006), Avoiding Dangerous Climate Change, Cambridge University Press, pp. 406.

Stankeviciute, L. and P. Criqui (2008), Energy and climate policies to 2020: the impacts of the European «20/20/20» approach, working paper (LEPII, Grenoble).

Stern, N. (2006), *The Economics of Climate Change, the Stern Review* (Cambridge University Press, Cambridge UK), pp. 712.

Tulkens, H. and P. Chander (2006), Cooperation, Stability and Self-Enforcement in International Environmental Agreements: A Conceptual Discussion, Working Paper 2006.36, (Fondazione Eni Enrico Mattei, Milan).

UNFCCC (1992), United Nations Framework Convention on Climate Change, protocol text, see: http://unfccc.int/resource/docs/convkp/conveng.pdf

Appendix: the carbon cycle in CWS

The version of CWS used in this paper includes the simplified representation of the carbon cycle presented in Nordhaus and Boyer (1999) for the DICE model, also found in its latest versions (Nordhaus, 2007). It is important to note that this version of DICE addressed part of the critics that applied to older versions, based on Nordhaus (1991). We use this formulation mainly because it is simple and computationally efficient. However, we are aware that it has limitations (Joos et al., 1999), in particular the non-linear processes associated with carbon accumulation, and particularly oceanic absorption, are not represented. A detailed investigation of this issue in the CWS framework is provided in Marbaix and Gérard (2008).

The climate part of the CWS model is equivalent to the DICE/RICE model (Nordhaus and Boyer 1999), namely it include two boxes representing fast and slow temperature change, the latter being associated with the bulk of the oceans. However, the parameters have been changed so that the results are close to results presented in the IPCC 4th assessment report (IPCC, 2007) for one of the atmosphere- ocean general circulation models, the UK Met Office HadCM3. The aim of this calibration is to obtain global average temperature changes that follow an up to date climate model quite closely. While the uncertainty associated with climate can be explored by calibrating CWS to other complex climate models (Marbaix and Gérard, 2008), here we selected a model that is widely recognized in the climate modeling community and provides results “close to the middle of the range”, possibly a bit above that, particularly in the first decades. CWS provides higher temperature changes than the 1999 version of DICE, and it is also somewhat above results from the 2007 version of DICE although this one also has an higher sensitivity to greenhouse gases compared to older versions. In summary, this is far from the highest climate sensitivity that could be possible, but it is certainly provides plausible estimations of climate change that are not in the lower part of the range of values currently obtained by complex models.

Table 2: EU unilateral commitment (scenario 1)

		Reference Kyoto scenario	Kyoto plus EU minus 20			
			no trading		trading	
temperature change 2100		3.455	3.404	-1.47	3.404	-1.48
carbon concentration 2100		1523.607	1501.344	-1.46	1501.211	-1.47
carbon price 2020		54.98	n.a.	n.a.	112.78	105.12
accumulated emissions 2000-2100	Kyoto	226.615	179.347	-20.86	179.035	-21.00
	Non-Kyoto	1576.286	1578.229	0.12	1578.256	0.12
	World	1802.902	1757.575	-2.51	1757.291	-2.53
regional emissions 2020	USA	1.882	1.886	0.18	1.886	0.18
	Japan*	0.324	0.325	0.23	0.294	-9.32
	EU*	0.932	<u>0.705</u>	-24.39	0.848	-9.06
	China	1.721	1.727	0.34	1.727	0.34
	FSU*	0.517	0.520	0.53	0.404	-21.82
	ROW	5.047	5.048	0.03	5.049	0.03
	Kyoto	1.773	1.549	-12.63	1.546	-12.82
	Non-Kyoto	8.65	8.661	0.13	8.662	0.13
	World	10.424	10.211	-2.04	10.207	-2.08
regional discounted welfare	USA	1406.37	1410.70	0.31	1410.72	0.31
	Japan*	294.43	295.11	0.23	295.98	0.53
	EU*	1033.18	1021.93	-1.09	1024.34	-0.86
	China	1426.79	1435.65	0.62	1435.69	0.62
	FSU*	94.67	95.03	0.38	96.67	2.11
	ROW	1613.48	1630.01	1.02	1630.09	1.03
	Kyoto	1422.28	1412.08	-0.72	1416.99	-0.37
	Non-Kyoto	4446.64	4476.36	0.67	4476.51	0.67
	World	5868.93	5888.43	0.33	5893.49	0.42
				(%)		(%)

Legend
Countries denoted by * are members of the international climate agreement, underlined numbers refer to the fact that the emission constraint in binding in 2020 and % refers to percentage change compared to the reference Kyoto coalition (first column).
Temperature change is measured in degrees Celsius compared to pre-industrial era.
Carbon emissions and *concentrations* are reported in gigatons of carbon.
The *carbon price* is measured in $ (of year 2000) per ton of carbon, and all welfare figures refer to the discounted sum of payoffs between 2000 and 2300 and is measured in trillion US$ (10^{12} US$) of the year 2000).

Table 3: Annex-B multilateral commitment scenario (scenario 2)

		Reference Kyoto scenario + USA	Annex-B minus 30			
			no trading		trading	
temperature change 2100		3.390	3.133	-9.33	3.178	-8.02
carbon concentration 2100		1496.041	1384.318	-9.14	1401.707	-8.00
carbon price 2020		111.154	*n.a.*	*n.a.*	221.58	302.99
accumulated emissions 2000-2100	Kyoto	453.364	266.279	-48.05	304.178	-40.65
	Non-Kyoto	1292.101	1246.273	-3.42	1245.009	-3.52
	World	1745.465	1512.552	-16.10	1549.187	-14.07
regional emissions 2020	USA*	1.686	<u>0.938</u>	-50.17	1.387	-26.32
	Japan*	0.295	<u>0.213</u>	-34.19	0.253	-21.98
	EU*	0.850	<u>0.617</u>	-33.84	0.733	-21.37
	China	1.728	1.782	3.54	1.776	3.21
	FSU*	0.407	0.430	-16.77	0.251	-51.47
	ROW	5.049	5.066	0.38	5.065	0.36
	Kyoto	3.238	2.198	-39.87	2.624	-28.22
	Non-Kyoto	6.777	6.848	1.18	6.841	1.08
	World	10.015	9.046	-13.21	9.465	-9.20
regional discounted welfare	USA*	1407.06	1389.11	-1.23	1391.59	-1.05
	Japan*	294.78	298.30	1.31	298.13	1.25
	EU*	1034.74	1043.46	0.99	1042.61	0.91
	China	1436.73	1514.42	6.14	1510.64	5.88
	FSU*	94.30	97.45	2.93	113.04	19.40
	ROW	1631.63	1763.74	9.31	1757.92	8.95
	Kyoto	2830.88	2828.32	-0.01	2845.36	0.59
	Non-Kyoto	3068.36	3278.16	7.82	3268.56	7.51
	World	5899.24	6106.48	4.05	6113.92	4.17
				(%)		(%)

Legend

Countries denoted by * are members of the international climate agreement, underlined numbers refer to the fact that the emission constraint in binding in 2020 and % refers to percentage change compared to the reference Kyoto coalition (first column in Table 2).

Temperature change is measured in degrees Celsius compared to pre-industrial era.

Carbon emissions and *concentrations* are reported in gigatons of carbon.

The *carbon price* is measured in \$ (of year 2000) per ton of carbon, and all welfare figures refer to the discounted sum of payoffs between 2000 and 2300 and is measured in trillion US\$ (10^{12} US\$) of the year 2000).

Table 4: Coalitional welfare comparison

	scenarios			
	Nash equilibrium	Reference Kyoto	1 EU unilateral commitment	2 Annex-B multilateral commitment
Kyoto {*Japan, EU, FSU*}	1421.59	1422.28	1416.99	1453.77
USA	1405.53	1406.37	1410.72	1391.59
Kyoto + USA {*USA, Japan, EU, FSU*}	2826.12	2828.65	2827.71	2845.36

Legend
Nash equilibrium refers to complete absence of cooperation under which every country maximizes its individual welfare taking as given similar behavior by all other countries. Emissions strategies would neglect environmental externality effects are governed by expression (5) for all countries/regions and time periods.
Figures refer to welfare measured as the discounted sum of payoffs between 2000 and 2300 in trillion US\$ (10^{12} US\$) of the year 2000.

Recent titles

CORE Discussion Papers

2008/23. Marco MARINUCCI. Optimal ownership in joint ventures with contributions of asymmetric partners.
2008/24. Raouf BOUCEKKINE, Natali HRITONENKO and Yuri YATSENKO. Optimal firm behavior under environmental constraints.
2008/25. Ana MAULEON, Vincent VANNETELBOSCH and Cecilia VERGARI. Market integration in network industries.
2008/26. Leonidas C. KOUTSOUGERAS and Nicholas ZIROS. Decentralization of the core through Nash equilibrium.
2008/27. Jean J. GABSZEWICZ, Didier LAUSSEL and Ornella TAROLA. To acquire, or to compete? An entry dilemma.
2008/28. Jean-Sébastien TRANCREZ, Philippe CHEVALIER and Pierre SEMAL. Probability masses fitting in the analysis of manufacturing flow lines.
2008/29. Marie-Louise LEROUX. Endogenous differential mortality, non monitored effort and optimal non linear taxation.
2008/30. Santanu S. DEY and Laurence A. WOLSEY. Two row mixed integer cuts via lifting.
2008/31. Helmuth CREMER, Philippe DE DONDER, Dario MALDONADO and Pierre PESTIEAU. Taxing sin goods and subsidizing health care.
2008/32. Jean J. GABSZEWICZ, Didier LAUSSEL and Nathalie SONNAC. The TV news scheduling game when the newscaster's face matters.
2008/33. Didier LAUSSEL and Joana RESENDE. Does the absence of competition *in* the market foster competition *for* the market? A dynamic approach to aftermarkets.
2008/34. Vincent D. BLONDEL and Yurii NESTEROV. Polynomial-time computation of the joint spectral radius for some sets of nonnegative matrices.
2008/35. David DE LA CROIX and Clara DELAVALLADE. Democracy, rule of law, corruption incentives and growth.
2008/36. Jean J. GABSZEWICZ and Joana RESENDE. Uncertain quality, product variety and price competition. 2008/37. Gregor ZOETTL. On investment decisions in liberalized electricity markets: the impact of price caps at the spot market.
2008/38. Helmuth CREMER, Philippe DE DONDER, Dario MALDONADO and Pierre PESTIEAU. Habit formation and labor supply.
2008/39. Marie-Louise LEROUX and Grégory PONTHIERE. Optimal tax policy and expected longevity: a mean and variance approach.
2008/40. Kristian BEHRENS and Pierre M. PICARD. Transportation, freight rates, and economic geography.
2008/41. Gregor ZOETTL. Investment decisions in liberalized electricity markets: A framework of peak load pricing with strategic firms.
2008/42. Raouf BOUCEKKINE, Rodolphe DESBORDES and Hélène LATZER. How do epidemics induce behavioral changes?
2008/43. David DE LA CROIX and Marie VANDER DONCKT. Would empowering women initiate the demographic transition in least-developed countries?
2008/44. Geoffrey CARUSO, Dominique PEETERS, Jean CAVAILHES and Mark ROUNSEVELL. Space-time patterns of urban sprawl, a 1D cellular automata and microeconomic approach.
2008/45. Taoufik BOUEZMARNI, Jeroen V.K. ROMBOUTS and Abderrahim TAAMOUTI. Asymptotic properties of the Bernstein density copula for dependent data.
2008/46. Joe THARAKAN and Jean-Philippe TROPEANO. On the impact of labor market matching on regional disparities.
2008/47. Shin-Huei WANG and Cheng HSIAO. An easy test for two stationary long processes being uncorrelated via AR approximations.
2008/48. David DE LA CROIX. Adult longevity and economic take-off: from Malthus to Ben-Porath.
2008/49. David DE LA CROIX and Gregory PONTHIERE. On the Golden Rule of capital accumulation under endogenous longevity.

Recent titles

CORE Discussion Papers - continued

2008/50. Jean J. GABSZEWICZ and Skerdilajda ZANAJ. Successive oligopolies and decreasing returns.
2008/51. Marie-Louise LEROUX, Pierre PESTIEAU and Grégory PONTHIERE. Optimal linear taxation under endogenous longevity.
2008/52. Yuri YATSENKO, Raouf BOUCEKKINE and Natali HRITONENKO. Estimating the dynamics of R&D-based growth models.
2008/53. Roland Iwan LUTTENS and Marie-Anne VALFORT. Voting for redistribution under desert-sensitive altruism.
2008/54. Sergei PEKARSKI. Budget deficits and inflation feedback.
2008/55. Raouf BOUCEKKINE, Jacek B. KRAWCZYK and Thomas VALLEE. Towards an understanding of tradeoffs between regional wealth, tightness of a common environmental constraint and the sharing rules.
2008/56. Santanu S. DEY. A note on the split rank of intersection cuts.
2008/57. Yu. NESTEROV. Primal-dual interior-point methods with asymmetric barriers.
2008/58. Marie-Louise LEROUX, Pierre PESTIEAU and Gregory PONTHIERE. Should we subsidize longevity?
2008/59. J. Roderick McCRORIE. The role of Skorokhod space in the development of the econometric analysis of time series.
2008/60. Yu. NESTEROV. Barrier subgradient method.
2008/61. Thierry BRECHET, Johan EYCKMANS, François GERARD, Philippe MARBAIX, Henry TULKENS and Jean-Pascal VAN YPERSELE. The impact of the unilateral EU commitment on the stability of international climate agreements.

Books

Y. POCHET and L. WOLSEY (eds.) (2006), *Production planning by mixed integer programming.* New York, Springer-Verlag.
P. PESTIEAU (ed.) (2006), *The welfare state in the European Union: economic and social perspectives.* Oxford, Oxford University Press.
H. TULKENS (ed.) (2006), *Public goods, environmental externalities and fiscal competition.* New York, Springer-Verlag.
V. GINSBURGH and D. THROSBY (eds.) (2006), *Handbook of the economics of art and culture.* Amsterdam, Elsevier.
J. GABSZEWICZ (ed.) (2006), La différenciation des produits. Paris, La découverte.
L. BAUWENS, W. POHLMEIER and D. VEREDAS (eds.) (2008), *High frequency financial econometrics: recent developments*. Heidelberg, Physica-Verlag.
P. VAN HENTENRYCKE and L. WOLSEY (eds.) (2007), *Integration of AI and OR techniques in constraint programming for combinatorial optimization problems*. Berlin, Springer.

CORE Lecture Series

C. GOURIÉROUX and A. MONFORT (1995), Simulation Based Econometric Methods.
A. RUBINSTEIN (1996), Lectures on Modeling Bounded Rationality.
J. RENEGAR (1999), A Mathematical View of Interior-Point Methods in Convex Optimization.
B.D. BERNHEIM and M.D. WHINSTON (1999), Anticompetitive Exclusion and Foreclosure Through Vertical Agreements.
D. BIENSTOCK (2001), Potential function methods for approximately solving linear programming problems: theory and practice.
R. AMIR (2002), Supermodularity and complementarity in economics.
R. WEISMANTEL (2006), Lectures on mixed nonlinear programming.

Département des Sciences Économiques
de l'Université catholique de Louvain
Institut de Recherches Économiques et Sociales

Place Montesquieu, 3
1348 Louvain-la-Neuve, Belgique

ISSN 1379-244X D/2008/3082/038