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

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The negotiation strategy of the European Union was analysed with respect to the formation of an international climate agreement for the post-2012 era. Game theory was employed to explore the incentives for key players in the climate policy arena to join future climate agreements. A –20% unilateral commitment strategy by the EU was compared with a multilateral –30% emission reduction strategy for all Annex-B countries. Using a numerical integrated assessment climate–economy simulation model, we found that leakage, in the sense of strategic policy reactions on emissions, was negligible. The EU strategy to reduce emissions by 30% (compared with 1990 levels) by 2020, if other Annex-B countries follow suit, does not induce the participation of the USA with a comparable reduction commitment. However, we argue that the original EU proposal can be reshaped so as to stabilize a larger and more ambitious climate coalition than the Kyoto Protocol in its first commitment period.

Keywords: emissions trading; game theory; integrated assessment; international climate policy

Nous analysons la stratégie de négociation de l'Union européenne concernant l'édification d'un accord international sur le climat pour l'après 2012. La théorie des jeux est utilisée, ainsi qu'un modèle climatico-économique de simulation numérique, pour évaluer les incitations de pays-clés à participer à de tels accords. Trois cas de participations alternatives sont considérés. Tout d'abord, la stratégie unilatérale de l'UE, consistant en une réduction de 20% du niveau de ses émissions d'ici 2020 et par rapport au niveau de 1990, est confrontée à une stratégie multilatérale d'engagements mutuels de tous les pays de l'Annexe B à réduire de 30% dans le même temps leurs émissions. Nous trouvons que dans chacune de ces deux options, les fuites de carbone, possibles réactions stratégiques en termes des émissions des pays extérieurs à ces accords, sont négligeables. Ensuite, nous constatons que, selon le modèle, la stratégie européenne de réduction de 30% de ses émissions d'ici 2020, accompagnée de l'adhésion des autres pays de l'annexe B (hors USA) à la même politique, ne suffirait pas à amener les États-Unis à accepter un accord de réduction comparable. Enfin, nous avançons que la proposition unilatérale de l'UE peut être remodelée de manière à établir une coalition climatique plus large et plus ambitieuse que celle du protocole de Kyoto dans sa première période d'engagement.

Mots clés: échange de quotas d'émissions; évaluation intégrée; politique climatique internationale, théorie des jeux

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1. Introduction and policy questions

This article analyses the proposals regarding greenhouse gas emission reduction for the post-2012 era put forward by the European Council in Spring 2007 (see Commission of the European Communities, 2007a; Council of the European Union, 2007) and endorsed by the European Parliament on 17 December 2008. In particular, our purpose is 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 addressed are:

- Will the unilateral 20% emission reduction commitment of the EU cause a strategic policy reaction in the countries that have not ratified the Kyoto Protocol (and/or possible subsequent developments)? Would these countries respond to the EU's unilateral commitment by increasing their own emissions? Would this therefore nullify the EU's efforts in terms of global warming mitigation?
- What is the likely effect on non-EU countries that 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's 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?

Excluded from the current study is 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 referred to in Art. 2 of the UNFCCC (1992). Nor do 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 article. These questions are analysed in detail by, among others, Schellnhuber et al. (2006), Russ et al. (2005, 2007) and Criqui et al. (2003). We do not address either the impact of EU proposals on the European economy or the policy instruments that 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 analysed in detail by 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 et al., 2008). This roadmap sketches the path for a negotiating process that should culminate in 2009 in the adoption of a new international climate agreement for the post-2012 period.[1] As no consensus on emission targets has yet been reached, 'emission targets' means that the 2007 EU proposal is still the relevant benchmark to consider in the international post-2012 climate policy debate. Therefore, this article contributes to the understanding of the international negotiation process by investigating the strategic incentives of various international key 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 descriptive (i.e. what self-motivated countries are likely to do).

Game theoretic coalitional stability analysis is used 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 the Rest of the World (ROW). For an introduction on the use of game theory to analyse the formation of international environmental agreements, see Barrett (2003, 2005), Chander and Tulkens (2009) and Finus (2001, 2003). Given the strong heterogeneity among countries in terms of the 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. A similar approach has been used by Loulou and Labriet (2003), Carraro and Buchner (2005), Eyckmans and Finus (2006a, 2006b), Yang (2008) and Finus et al. (2009). For this article, the CLIMNEG World Simulation (CWS) model was used (for a description, see Eyckmans and Tulkens, 2003; Bréchet et al., 2007). This is an integrated assessment model based on the RICE model of Nordhaus and Yang (1996) and adapted for coalitional analysis.

We compare two alternative scenarios comparing 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, determine their emission targets by maximizing their joint discounted welfare, and adopt an international emissions trading system. The first alternative scenario is designated the *EU unilateral commitment scenario* and assumes that the EU commits itself to a maximum emission ceiling of 80% (i.e. a 20% reduction) of its 1990 emission level for all periods after 2020. The second alternative scenario is called the *Annex-B multilateral commitment scenario* and assumes that all Annex-B countries observe an emission ceiling of 70% (i.e. a 30% reduction) compared with 1990. For these two scenarios, we consider two variants, depending on the way the additional commitment makes use, or not, of emissions trading.

Section 2 of this article describes the methodological framework, 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 modelling framework: integrated assessment and coalition theory

The methodological innovation of our approach is to use both an integrated assessment model and game theory to answer the policy questions raised above. This section describes the main characteristics and assumptions of the model and the way it is used.

Our integrated assessment model, the CLIMNEG World Simulation (CWS) model, closely resembles the original RICE model of Nordhaus and Yang (1996) or variations on it, as described by Eyckmans and Tulkens (2003).[2] We denote by $N = \{i|i = 1,2,\ldots,n\}$ the set of all countries in the world, and we assume that, while choosing climate policy actions, each country's policy makers weigh the benefits (i.e. avoided future climate change damages) against the costs (i.e. the costs of re-orienting their economies towards lower carbon emission levels). When speaking of 'welfare', we mean a 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 is defined as the discounted sum of the stream of consumption levels $Z_{i,t}$.[3] By defining ρ as the discount rate, t as the time period, and Ω as the time horizon, the welfare of a country i is given by:

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

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:

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

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 Eqn (2) as the '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 Eqn (2) shows the uses of Green GDP: goods and services are either 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. In the case of international climate policy coordination, important monetary transfers between countries are perfectly possible through flexibility instruments such as emissions trading, Joint Implementation (JI) and the Clean Development Mechanism (CDM)[4] depending upon the initial allocation of permits, emission reduction efforts and carbon price level. These transfers are not unconditional since they should be backed by emission reductions, and the experience in the European Union with the EU Emissions Trading Scheme (ETS) shows that it is, at least in principle, politically feasible to agree on substantial redistribution of the surplus of climate policy coordination. In our simulation model, this type of financial transfer related to emissions trading is captured by the $X_{i,t}$ variable. Equation (2) is a budget constraint, meaning that in every period, nothing more can be used for consumption, investment and transfers than what is produced.

Production is assumed to be a function of labour and capital. Technical details about the production function and capital accumulation process can be found in Eyckmans and Tulkens (2003). Production causes emissions of greenhouse gases according to the following relationship:

$$E_{i,t} = \sigma_{i,t} . [1 - \mu_{i,t}] . Y_{i,t} \quad (3)$$

The parameter $\sigma_{i,t}$ denotes the emissions–output ratio. This is assumed to decline exogenously over time as a result of technological progress. Emissions can be further reduced at a rate $0 \leq \mu_{i,t} \leq 1$ by means of specific measures, such as replacing a coal-fired power plant by renewable energy sources, investment in fuel-efficient cars, or energy demand management. Typically, the costs of taking action increase with the emission reduction rate at an accelerating rate: $C_{i,t} = C_i(\mu_{i,t})$ with $C'_{i,t} \geq 0$ and $C''_{i,t} \geq 0$. 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). In the CWS model we use cost estimates taken from the RICE model of Nordhaus and Yang (1996).

Emissions of greenhouse gases accumulate in the atmosphere, thereby disturbing the global carbon cycle and ultimately causing climate change. We capture these complex physical processes in the following general relationship:[5]

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

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. The version of CWS used in this article includes the simplified representation of the carbon cycle presented in Nordhaus and Boyer (1999) for the DICE model and also found in later versions (Nordhaus, 2007). Although this version of DICE addresses some of the criticisms levelled at older versions (see Nordhaus, 1991), we are aware that it still has limitations (Joos et al., 1999). In particular the non-linear processes associated with carbon accumulation, and particularly oceanic absorption, are not represented. The climatic part of the CWS model is based on a two-box representation as in the DICE/RICE model (Nordhaus and Boyer, 1999). The parameters of this model have been recalibrated (see Marbaix and Gérard, 2008) so that it closely reproduces the results presented in the IPCC Fourth Assessment Report (IPCC, 2007) for one particular atmosphere–ocean general circulation model: the UK Met Office HadCM3.

Temperature change has a variety of physical impacts including sea level rise, changes in precipitation patterns, and extreme weather events. The economic valuation of the damages caused by these impacts is summarized in an increasing and convex damage function, $D_{i,t} = D_i(\Delta T_t)$. Damage functions are hard to estimate (see, for instance, Tol (1995, 2002a, 2002b), the Stern Review (Stern, 2006) and the IPCC (2007) Working Group II Report, for climate change damage estimates). First, the physical impacts themselves are difficult to estimate, even though several studies have been done, such as for sea-level rise (Marbaix and Nicholls, 2007). Second, monetary valuation of non-market damage, such as biodiversity losses and changes in living amenities, remains challenging, because no market prices are available and because weighting costs and benefits requires normative judgments regarding intergenerational and intragenerational justice. In our simulation model we used damage function parameters from the RICE model of Nordhaus and Yang (1996) but we increased the exponent of the damage functions, as in Eyckmans and Tulkens (2003), to be more in line with recent climate impact studies and damage estimates.

We now turn to the analysis of the EU proposals, and 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 number of signatories of the international climate agreement and the size of their emission reduction commitment. Table 1 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

'In': this country/region is a member of an international climate agreement and its emission target is calculated in an endogenous way so as to maximize discounted group welfare.
–20%' and –30%': this country is a member of an international climate agreement and commits to a 20% or 30% emission reduction in 2020 and all subsequent periods.
'Out': this country is not a member of an international climate agreement and determines its emission strategy so as to maximize individual welfare.

3. Reference situation: the Kyoto coalition

The reference scenario throughout this article is the Kyoto coalition, formed by those developed countries which ratified the Kyoto Protocol and committed themselves to an emission target (*Japan*, the *EU* and the *former Soviet Union* in the CWS model). It is assumed that these countries continue cooperating and agree on future carbon emission ceilings that maximize their joint welfare. This reference coalition may be seen as a partial agreement Nash equilibrium (PANE) in carbon emissions.[6] In the PANE concept, Kyoto coalition members are assumed to coordinate their emission strategies as to maximize their joint welfare, taking as given the equilibrium emissions of non-members. Outsiders, for their part, are assumed to maximize their individual payoff, taking as given the equilibrium emission strategies of other outsiders and of the Kyoto coalition. As shown by Chander and Tulkens (1995, 1997) and Eyckmans and Tulkens (2003), every coalition member in a PANE reduces its emissions at a particular point in time in such a way that the marginal cost of reducing one more ton of carbon emissions equals the discounted sum of all corresponding future marginal damages avoided by all coalition members. 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. However, climate damages affecting non-members are not taken into account by the members of the coalition. Note that this optimality 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-effective way. Cost-effectiveness prevails when market-based environmental policy instruments are used, as it is the case with the flexible mechanisms of the Kyoto Protocol.

The countries outside the Kyoto coalition take into account only their own individual climate change damages when maximizing their individual welfare, thus ignoring negative climate change externalities to other countries. The PANE for the Kyoto coalition is the simultaneous solution to the optimization problems of coalition members and outsiders. The resulting emission reduction levels are thus determined endogenously in the model via joint welfare maximization.

Starting from this reference situation, we can explore the implications of the unilateral EU strategy. We present 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 the EU's carbon emissions cannot exceed 80% of their 1990 emission levels for all time periods beyond 2020.[7] Two cases are 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:

$$\forall t \geq 2020: \quad E_{EU,t} \leq [1-0.20].E_{EU,1990} \tag{5}$$

with the result 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.[8] 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 instruments, such as emissions trading, we therefore consider a second variant including full emissions trading.

In the variant *with emissions trading* a constraint is introduced on the emissions of the whole Kyoto group instead of individual emissions constraints for the EU only, as in (5). The new emissions constraint replacing (5) in the optimization problem for the Kyoto coalition can now be written as

$$\forall t \geq 2020: \quad \sum_{j \in S} E_{j,t} \leq \sum_{j \in S} \hat{E}_{j,t} \tag{6}$$

For the 'constrained coalition member', the EU, we set its initial permit allocation equal to 20% below 1990 emission levels: $\hat{E}_{EU,t} = [1 - 0.20] \cdot E_{EU,1990}$. For all other coalition members, we set $\hat{E}_{j,t}$ equal to their emission levels 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 (Eqn (5)), the constrained country has to perform all additional reduction effort domestically. In the scenario with emissions trading (Eqn (6)), any additional reduction commitment by one agreement member leads to higher demand and higher equilibrium prices for permits in the permit market. In other words, introducing a market for emissions trading allows for cost-effectiveness, but it also introduces a pecuniary externality among the countries involved in that market via the equilibrium price of emission permits. In that case, any additional reduction commitment by one country is shared over the different coalition members in a cost-effective way, but it also increases the permit price, and that supplementary cost is shared by all coalition members.

Financial transfers resulting from permit trade transactions are captured by the transfer variable $X_{i,t}$ which is entered in each country's budget balance equation (2):

$$X_{i,t} = p_t \cdot \left[\hat{E}_{i,t} - E_{i,t} \right] \tag{7}$$

The equilibrium price p_t of emission permits in period t corresponds to the shadow price of the joint emissions constraint (Eqn (6)).

4.2. The key issue of 'strategic policy reaction'

From our computations it can be seen 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 constitutes 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 experience lower climate change damages, which increases their welfare. We 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 externality gives other countries an excuse to change their own contribution to solving the global climate change problem (see, for instance, Hoel, 1992). In a setting where countries do not cooperate, this constitutes a *strategic policy reaction* resulting from free-riding incentives under the assumed selfish behaviour of non-cooperating countries.

Though theoretically indisputable, the relevant policy question is whether this strategic policy reaction would be so strong that the EU's additional emission reduction effort would be partly (or even completely) wiped out by an increase in emissions by other countries. World emissions and carbon concentrations are reduced, and the temperature rise is smaller, *ceteris paribus*, because of the further decrease of EU emissions in comparison with the unconstrained scenario. Therefore, climate damages borne by all regions are reduced, leading to a decrease in damages in all countries. Consequently, more resources are available to be spent in consumption (variable $Z_{i,t}$ in Eqn (2)), investment in physical capital (variable $I_{i,t}$ in Eqn (2)) and on emission mitigation measures (variable $C_{i,t}$ in Eqn (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);
- 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 bear in mind that future abatement efforts, and thus temperature increases, are endogenously determined in the CWS model in the sense that 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 the Appendix: Table A1 (EU unilateral commitment, scenario 1) and Table A2 (Annex-B multilateral commitment, scenario 2). We focus here on the interpretation of these results, starting with the EU unilateral commitment scenario.

4.3. Slight strategic policy reactions, but welfare gains for outsiders

A first observation is that the 20% unilateral reduction commitment implies a real cut in the EU's emissions. The EU should reduce its emissions by an additional 24% in 2020 compared with what it would have done in an unconstrained Kyoto scenario (see Table A1). 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 between countries: the USA +0.18%, China +0.34% and Rest of the World +0.03%. Strategic policy reactions therefore seem quite small. This constitutes a very positive signal from an environmental point of view: an additional cut of 1% by the EU triggers an increase of only 0.005% by the outsiders, which can be considered negligible. Hence, carbon leakage due to strategic policy reactions, i.e. emission increases, in non-ratifying countries should therefore be of little concern. The reason for this moderate reaction is most probably 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 horizon (which is appropriate in the context of 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 efforts to limit their emissions and to slow down global climate change. The same holds true for the other Kyoto-ratifying countries. Japan and the former Soviet Union react in a similar way to the non-ratifying countries: they increase their emissions slightly 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 –9.32% and the FSU as much as –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 –20% reduction commitment by means of internal emission 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 reductions. Through the permit price, the different signatories' reduction efforts are 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-effective for the Kyoto coalition. Trading allows for more flexibility in the abatement burden allocation and results in a cost-effective allocation of reduction efforts over all Kyoto members. Compared with the incomplete trading solution, the full trade equilibrium allows total compliance costs to be cut 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 with free-riding payoffs, i.e. the welfare levels that current members could achieve if they were to leave the coalition. In fact, 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.[9]

This is illustrated in Appendix Table A3. The overall surplus for the Kyoto coalition drops to 1,417 trillion US$$_{2000}$ in the case of a –20% unilateral commitment by the EU (scenario 1). This is well below 1,422 trillion US$$_{2000}$ under the Nash scenario (i.e. under complete absence of cooperation) and the reference Kyoto scenario (i.e. unconstrained Kyoto coalition). In spite of that, the individual members of the coalition apart from the EU (i.e. Japan and the FSU) are still better off than in the reference situation according to Table A2. The stability of the coalition is thus maintained as long as the EU is willing to incur the loss to achieve its mitigation policy.

By 2100, global temperature increase compared with pre-industrial times amounts to +3.5°C without the EU's unilateral commitment, versus +3.4°C with 20% additional commitment. Overall, the impact of the sustained –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 emission target of 80% of 1990 emission 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 with 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 with the global optimal level that maximizes world welfare. Thus, the EU's unilateral commitment is a move in 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 abatement efforts within Annex-B countries. This EU strategy resembles what is called a *tit-for-tat* strategy in repeated games, see Axelrod (1984).[10] Tit-for-tat strategies essentially mean that, while initially cooperating, every player copies the strategy played by its opponent in the previous period. So I continue cooperating 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 strategy is a special case of the more general class of *trigger strategies* in that all have the characteristic of containing some kind of credible punishment threat if the opponent deviates. For a tit-for-tat strategy to work well, it is of crucial importance that the punishment part of the strategy be sufficiently harsh to deter non-cooperative behaviour. Termed 'folk theorem', this theory establishes that this type of future punishment possibility can be sufficient to sustain a cooperative solution as a Nash equilibrium in an infinitely repeated game (for an introduction, see, among others, Montet and Serra, 2003).

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) with 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 emission levels.[11] As before, we distinguish between solutions *with* and *without emissions trading* (see Table A2 for the detailed results).

5.2. EU trigger strategy alone is not sufficient

According to calculations with the CWS model, the surplus of the expanded coalition is always lower in the multilateral –30% scenario than in the EU unilateral –20% scenario. Hence, including the USA and observing the 70% of 1990 emissions ceiling does not constitute a strict welfare improvement for the expanded group of countries. Some participants are bound to lose from expanding the coalition with the USA and meeting a –30% target. Allowing for emissions trading or not does not fundamentally alter this conclusion because the expanded coalition cannot generate enough surplus to guarantee the free-riding claims of all of its members.

Appendix Table A3 summarizes the relevant welfare data for the USA and the Kyoto coalition for all scenarios considered. It can be observed in Table A3 that the USA would be worse off joining the club compared with the EU unilateral commitment scenario. The USA's welfare level would decrease by US$41 trillion (year 2000 value) (1,411 in scenario 1 versus 1,370 in scenario 2). Hence, the USA has little incentive to join the Kyoto coalition. Transfers, organized by an appropriately defined permit allocation, cannot solve the problem, since the expanded coalition generates only 2,804 trillion US$$_{2000}$. If they were to guarantee the USA their free-riding payoff, the remaining coalition members would be left with a surplus of 2,804 – 1,411 = 1,393, which is less than 1,417, their welfare under the EU unilateral commitment scenario 2 and definitely below their welfare level in the Kyoto reference scenario. Therefore, this coalition can only be stable if at least one of the countries is willing to incur a loss (in addition to the one already accepted by the EU in the unilateral –20% case).

However, this conclusion must be interpreted with great care because it depends strongly on, first, the overall abatement target of the expanded coalition (–30% compared with 1990 emission levels); second, on the assumed costs and damage functions; and third, on the assumed possibility of the USA to free-ride on the Kyoto coalition's efforts in the EU unilateral commitment scenario. In the remainder of this section, we test the robustness of our conclusions by changing these assumptions. The natural question then is: would it be possible to reshape the EU proposal so as to (1) give an incentive to the USA to join the coalition and (2) to stabilize the expanded coalition in a game theoretic sense?

5.3. An alternative EU trigger strategy might work

As suggested by Finus and Maus (2008), a possible way to stabilize internally instable coalitions is to lower their overall emission reduction target compared with the target that would result from unrestricted coalitional welfare optimization. Table A3 therefore reports simulations for less ambitious coalitional emission ceilings: plus (instead of minus) 25% compared with 1990 ('sensitivity 1') and stabilization compared with 1990 ('sensitivity 2'). First, consider the +25% scenario. In this scenario, the joint surplus of the expanded coalition amounts to 2,828 trillion $US\$_{2000}$, which is exactly the same amount as the welfare of the USA and Kyoto (USA + Japan + EU) coalition under scenario 2, the unilateral EU commitment scenario. Hence, it takes an extreme watering-down of the overall emission ceiling for the expanded coalition in order to make the members of the expanded coalition jointly as well off as in the EU unilateral scenario. In other words, there is a high price to be paid in terms of the feasible joint emission reduction target in order to stabilize the expanded coalition in a game theoretic sense. Still, this emission ceiling represents a significant reduction compared to 'business-as-usual' emissions, since it implies more global emission reductions than the unilateral EU –20% strategy. However, it is nowhere near enough to meet long-term climate change stabilization targets, and it is therefore politically indefensible in international climate policy negotiations.

Implicitly, in the scenario 2 and the first sensitivity analysis, it is assumed that the EU and the other Kyoto members – Japan and the FSU – will continue cooperating if the USA does not join the expanded coalition. This corresponds to the notion of internal and external stability in game theoretical analysis of international environmental agreements.[11] Alternatively, we may assume that the EU and the other Kyoto members would not stick to the EU unilateral commitment scenario but would revert to a non-cooperative Nash strategy instead, i.e. the scenario labelled the 'Nash equilibrium' in Table A3. In that case, less emission reduction is produced by the Kyoto coalition, leading to stronger climate change damages. As a result, the USA's welfare would fall back to 1,406 trillion $US\$_{2000}$ (see Table A3, Nash equilibrium scenario). Using this value for the USA as its free-riding welfare level, we can again compute the critical emission ceiling for the expanded coalition that would produce enough joint surplus to compensate all members' free-riding claims. It turns out that a *stabilization of emissions at the 1990 level* is the critical joint effort level that can be sustained by the expanded coalition (see Table A3, sensitivity 2).

The bottom line of this sensitivity analysis is that using the very demanding game theoretic stability notion of internal and external stability, the EU proposal for observing an emission ceiling of 70% of 1990 emission levels cannot be implemented by means of a self-enforcing international climate agreement. Even if the USA was given a sufficient compensation (in the form of a generous initial allocation of emission permits in the tradable permit scheme) to make it better off compared with the EU minus 20 unilateral commitment scenario, other coalition members would be worse off, and that undermines the internal stability of the expanded coalition.

However, the expanded coalition can be stabilized provided that it aims at a less ambitious emission reduction target. The critical overall emission ceiling that stabilizes the expanded coalition strongly depends on the outside option that is available for the USA. If the EU and its fellow Kyoto subscribers were to continue cooperating when the USA refuses to join, they would give a strong free-riding welfare bonus to the USA. If, instead, they were to revert to a non-cooperative strategy (either Nash equilibrium or reference Kyoto scenario), the Kyoto coalition members would produce much stronger leverage to convince the USA to adopt more restrictive emission ceilings. Moreover, this threat of non-cooperation on behalf of the original Kyoto members is perfectly credible, since it corresponds to an individual (Nash equilibrium) and/or group rational (Kyoto reference scenario) emission strategy. In game theoretic sense, this attitude is in line with the alternative stability concept called 'gamma core', as developed in Chander and Tulkens (1995, 1997).

5.4. Sensitivity analysis

In common with all numerical simulation exercises, our results depend heavily on the parameters of the CWS model. A full sensitivity analysis cannot be reported here due to space constraints. However, we do report on one particular sensitivity analysis regarding the damage function parameters for the different regions. In particular, we suggest that if damages are more important to the USA relative to other Kyoto members, the USA will be inclined to accept more stringent coalitional effort levels. The reduced level of climate change saves them more damage costs, leading to higher welfare levels in cooperative scenarios. Appendix Table A4 replicates Table A3 but with alternative damage function parameters. In particular, we have increased the exponent of the damage function of the USA to a value of 3.5 and decreased it to 2.5 for all other regions. As can be seen from Table A4, our conjecture is confirmed. More stringent coalition emission ceilings can be sustained in a stable coalition including the USA. For the unilateral commitment case, the critical emission ceiling acceptable to the USA is about 1990 emission levels plus 20%. For the case where Kyoto members do not commit to unilateral action but revert to their Nash strategies, the critical ceiling is 1990 emission levels minus 15%. Hence, damage function estimates matter a great deal for the precise number, though the fundamental rationale remains similar.

5.5. Main results at a glance

1. In all scenarios, the model reveals that carbon leakages due to strategic policy reactions (an increase in the free-riding incentive of outsiders in reaction to unilateral or multilateral emission reductions is not a concern). The reaction of the outsiders is quite limited (the elasticity of their emissions with respect to a change in the EU's emissions is smaller than 0.01 in absolute values). The reason for the negligible strategic policy reaction is that marginal damages from climate change prove to be relatively insensitive to changes in regional emission reduction efforts.
2. 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 more. Through the permit price set up in market equilibrium, reduction efforts by the coalition members are interconnected. Thus, under an emissions trading system, a unilateral commitment of the EU to reduce its emissions by 20% leads to a decrease of 2.5% of accumulated global emissions between 2000 and 2100 and to an increase in global welfare by 0.4%. 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, inducing a less ambitious overall emission reduction commitment for the Kyoto coalition as a whole.
3. Concerning the conditional strategy to reduce emissions by 30% if other industrialized countries follow (scenario 2), the model indicates that the implicit threat to revert to a 20% unilateral emission reduction is too weak to induce countries such as the USA to join the climate agreement and to accept a 30% reduction commitment. In welfare terms, the USA is better off free-riding on the 20% Kyoto coalition than joining the Kyoto group under a joint –30% target. There is insufficient surplus of cooperation in the expanded coalition to pay for the USA's free-riding claim and still retain sufficient surplus to make all the original Kyoto members better off compared with the EU unilateral commitment scenario.
4. However, we showed that it is 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. Stabilizing, in a game theoretic sense, such an expanded coalition requires reducing the coalition's emission

reduction ambition. If the EU commits to its unilateral –20% reduction target, even if the USA does not join, the critical target emission ceiling for stabilizing the expanded coalition amounts to the 1990 emission level plus 15%. Although this would yield globally more reduction than the EU unilateral –20%, this emission ceiling is obviously not defensible in international negotiations, since it falls short of attaining any reasonable climate change stabilization target.
5. The results could be improved if the original Kyoto members did not commit to a strong unilateral emission reduction strategy in the absence of cooperation by the USA. If they were to revert instead to a non-cooperative strategy, they could increase the cost to the USA of not joining, as long as the USA did not commit to comparable effort levels. The overall emission level would be higher, leading to higher damages and hence lower welfare levels for the USA and all other countries. This prospect is less attractive for the USA than free-riding on a strong unilateral commitment by the Kyoto members, but, for that very reason, it might force them to join a fully cooperative agreement.
6. Our numerical results are sensitive to assumptions regarding damage function parameters. When the damage function was made steeper (with respect to temperature change) for the USA and smoother for the other countries, it proved possible to sustain a 1990 emission level plus 20% (in the case of unilateral commitment of Kyoto members) and a 1990 emission level minus 15% emission ceiling for the expanded coalition including the USA. Hence, the higher valuation of damages by the USA makes it possible to sustain more stringent emission ceilings in a stable coalition compared with our reference simulation run, especially in the situation where the original Kyoto members do not commit to strong unilateral reduction in the absence of the USA.

6. Conclusions

This article compared, at global level, two alternative scenarios implied by the European Council's international climate initiative of February 2007. First, a reference situation was considered, 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, the partial agreement Nash equilibrium (PANE) concept of Chander and Tulkens (1995, 1997) was adopted. 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 the 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 with 1990 (scenario 1) and a scenario in which all Annex-B countries multilaterally commit to a –30% compared with 1990 strategy (scenario 2). For these two scenarios we distinguish between two polar cases, an inflexible (no emissions trading between countries of the coalition) and a flexible (emissions trading is allowed) burden-sharing case.

All of the examined scenarios indicate that a substantial redistribution of the gains of cooperation is an essential element to achieve effective and stable international climate policy in the long run. In a system of emissions trading, this should be implemented by means of an initial allocation of permits that explicitly takes into account free-riding claims by coalition members. Transfer schemes such as those of Chander and Tulkens (1995, 1997) and Eyckmans and Finus (2004) offer explicit formulae to determine an initial permit allocation that is incentive-compatible in this sense.

More important than the numerical results of the simulation model runs is the fundamental rationale illustrated by the model. First, in order to convince other countries to join the global effort to fight climate change, negotiators have to take into account these countries' 'outside options', i.e. the welfare levels they can enjoy when they do not join and instead free-ride on the remaining coalition's emission reduction efforts. For some countries, this implies that they should receive important transfers before they are willing to join cooperative climate policy agreements. In some cases, it might even be necessary to revise downwards the ambition of the expanded coalition. Second, the free-riding or outside option can be made less attractive if the coalition does not commit to substantial unilateral actions. If commitments are cancelled in the absence of cooperation, the free-rider's welfare is lower because of higher climate change damages. Game theoretical analysis shows that substantial unilateral commitments by a group of countries can make it more attractive for free-riders to remain outsiders, even though there may be other motivations for such commitments.

Finally, several caveats and possibilities for extending the analysis need to be mentioned. First, the numerical results depend on the precise parameters of the CWS model. Changing these parameters will change the welfare levels, but the fundamental rationale, i.e. the strategic incentives for the players, will remain the same. The steepness of the marginal climate change damage function for the USA is a very important parameter in the analysis. The steeper their marginal damage function, the sooner the USA would be willing to join coalitional emission reduction efforts, because the prospect of high climate change damages puts them off. Second, only a uniform emission ceiling was considered (i.e. emissions in the future should not exceed a particular value). This is only one of many possible specifications of emission ceilings in the future. Allowing for others (for instance, emission ceilings decreasing monotonically through time) would be an interesting extension. Finally, this article focused on the position of the USA, but similar arguments could be made for other countries such as China, India or Brazil that, up until now, have not adopted quantified greenhouse gas emission reduction targets. Considering a wider set of possible extensions of the current group of Annex-B members of the Kyoto Protocol definitely enlarges the scope for implementing emission reduction targets consistent with global climate change stabilization scenarios, as called for by Art. 2 of the 1992 United Nations Framework Convention on Climate Change.

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Notes

1. For more information on the outcome of the Bali conference, see http://unfccc.int/meetings/cop_13/items/4049.php.
2. See Kelly and Kolstad (1999) and Kolstad and Toman (2005) for an introduction and overview of integrated assessment climate–economy models.
3. Implicitly, we are using the so-called transferable utility (TU) framework, which is adopted in the bulk of the economic literature on international environmental agreements; see Barrett (2005) or Finus (2001) for an overview. In our case, the use of this assumption is justified, since we assume that welfare can be redistributed (by means of an appropriately designed emission permit trading scheme) in an unrestricted way.
4. See http://www.unfccc.org for precise definitions of the different flexibility instruments of the 1997 Kyoto Protocol.
5. Subscript N denotes the sum of a variable over all the countries in the world.
6. 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.

7. As the time step of the CWS model is 10 years, the transition path cannot be displayed.
8. Marginal abatement costs will be higher only if the unilateral commitment entails more stringent reductions than in the reference unconstrained Kyoto coalition equilibrium. In other words, marginal abatement costs between agreement signatories will be different only if constraint (5) is binding.
9. We implicitly assume here that if a member defected 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 latter interpretation of free-riding leads to even higher free-riding incentives and would reinforce our arguments on the (in)stability of the Kyoto coalitions.
10. Strictly speaking, environmental games with stock pollutants do not belong to the class of repeated games because the accumulation of the stock pollutant modifies the state variables of the dynamic system of each stage of the game. Moreover, due to the fact that the EU's proposal remains vague on its longer-run strategy, the game itself is not properly defined. However, in view of the strong inertia in the stock accumulation process in the CWS model, the gist of our referring to a tit-for-tat strategy lies in suggesting an equilibrium interpretation to the scenario being discussed here.
11. 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.

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Appendix

TABLE A1 EU unilateral commitment (scenario 1)

		Reference Kyoto scenario	Kyoto plus EU minus 20			
			No trading		Trading	
Temperature change 2100		3.46	3.40	–1.5%	3.40	–1.5%
Carbon concentration 2100		1,524	1,501	–1.5%	1,501	–1.5%
Carbon price 2020		54.98	n.a.	n.a.	113	105.1%
Accumulated emissions 2000–2100	Kyoto	227	179	–20.9%	179	–21.0%
	Non-Kyoto	1,576	1,578	0.1%	1,578	0.1%
	World	1,803	1,758	–2.5%	1,757	–2.5%
Regional emissions 2020	USA	1.88	1.89	0.2%	1.89	0.2%
	Japan*	0.32	0.33	0.2%	0.29	–9.3%
	EU*	0.93	0.71	–24.4%	0.85	–9.1%
	China	1.72	1.73	0.3%	1.73	0.3%
	FSU*	0.52	0.52	0.5%	0.40	–21.8%
	ROW	5.05	5.05	0.0%	5.05	0.0%
	Kyoto	1.77	1.55	–12.6%	1.55	–12.8%
	Non-Kyoto	8.65	8.66	0.1%	8.66	0.1%
	World	10.42	10.21	–2.0%	10.21	–2.1%
Regional discounted welfare	USA	1,406	1,411	0.3%	1,411	0.3%
	Japan*	294	295	0.2%	296	0.5%
	EU*	1,033	1,022	–1.1%	1,024	–0.9%
	China	1,427	1,436	0.6%	1,436	0.6%
	FSU*	95	95	0.4%	97	2.1%
	ROW	1,613	1,630	1.0%	1,630	1.0%
	Kyoto	1,422	1,412	–0.7%	1,417	–0.4%
	Non-Kyoto	4,447	4,476	0.7%	4,477	0.7%
	World	5,869	5,888	0.3%	5,893	0.4%

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

TABLE A2 Annex-B multilateral commitment scenario (scenario 2)

		Reference Kyoto scenario + USA	Annex-B minus 30			
			No trading		Trading	
Temperature change 2100		3.39	3.18	–8.1%	3.22	–6.8%
Carbon concentration 2100		1,496	1,407	–7.7%	1,425	–6.5%
Carbon price 2020		111.15	n.a.	n.a.	221.58	303.0%
Accumulated emissions	Kyoto	453	25	–48.3%	304.01	–40.67%
2000–2100	Non-Kyoto	1,292	1,298	0.6%	1,297	0.5%
	World	1,745	1,563	–13.3%	1,601	–11.2%
Regional emissions 2020	USA*	1.69	<u>0.94</u>	–50.2%	1.39	–26.3%
	Japan*	0.30	<u>0.21</u>	–34.2%	0.25	–22.0%
	EU*	0.85	<u>0.62</u>	–33.8%	0.73	–21.4%
	China	1.73	1.75	1.9%	1.75	1.6%
	FSU*	0.41	0.42	–18.8%	0.25	–51.5%
	ROW	5.05	5.06	0.2%	5.05	0.2%
	Kyoto	3.24	2.19	–40.2%	2.62	–28.2%
	Non-Kyoto	6.78	6.81	0.6%	6.80	0.5%
	World	10.02	9.00	–13.7%	9.43	–9.6%
Regional discounted welfare	USA*	1,407	1,368	–2.8%	1,370	–2.6%
	Japan*	295	295	0.2%	295	0.1%
	EU*	1,035	1,029	–0.4%	1,028	–0.5%
	China	1,437	1,467	2.9%	1,463	2.6%
	FSU*	94	95	0.8%	111	17.4%
	ROW	1,632	1,687	4.6%	1,681	4.2%
	Kyoto	2,831	2,787	–1.5%	2,804	–0.9%
	Non-Kyoto	3,068	3,155	3.8%	3,144	3.4%
	World	5,899	5,942	1.2%	5,948	1.3%

Countries denoted by * are members of the international climate agreement, underlined numbers refer to the fact that the emissions constraint is binding in 2020 and % refers to percentage change compared with the reference Kyoto coalition (first column in Table A1). See footnote to Table A1 for definitions and units.

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TABLE A3 Coalitional welfare comparison (reference run)

	Scenarios					
	Nash equilibrium	Reference Kyoto	1 EU unilateral commitment	2 Annex-B multilateral commitment −30%	Sensitivity 1 Annex-B multilateral commitment +25%	Sensitivity 2 Annex-B multilateral commitment 0%
Kyoto	1,422	1,422	1,417	1,434	1,438	1,438
USA	1,405	1,406	1,411	1,370	1,390	1,384
Kyoto + USA	2,826	2,829	2,828	2,804	2,828	2,822

'Kyoto' refers to the countries that ratified the 1997 Kyoto Protocol, i.e. Japan, EU, FSU.
'Nash equilibrium' refers to complete absence of cooperation under which every country maximizes its individual welfare, taking as given similar behaviour by all other countries. Emission strategies neglect environmental externality effects to other countries in that scenario.
Figures refer to welfare measured as the discounted sum of consumption between 2000 and 2300 in trillion US$ (10^{12} US$) (year 2000 value).

TABLE A4 Coalitional welfare comparison (alternative damage function parameters)

	Scenarios					
	Nash equilibrium	Reference Kyoto	1 EU unilateral commitment	2 Annex-B multilateral commitment −30%	Sensitivity 1 Annex-B multilateral commitment +20%	Sensitivity 2 Annex-B multilateral commitment −15%
Kyoto	1,446	1,446	1,442	1,451	1,459	1,456
USA	1,351	1,359	1,362	1,331	1,344	1,336
Kyoto + USA	2,805	2,805	2,804	2,782	2,803	2,792

See footnotes to Table A3. The exponent of the climate change damage functions has been raised to 3.5 for the USA and lowered to 2.5 for all other regions in the model.

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