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From non-cooperative CO_2 abatement strategies to the optimal world cooperation: Results from the integrated MARKAL model

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From non-cooperative CO_2 abatement strategies to the optimal world cooperation: Results from the integrated MARKAL model[1]

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Résumé

Le travail réalisé propose de modéliser les stratégies de réduction des gaz à effet de serre dans des contextes coopératif et non-coopératif, dans l'objectif d'étudier les conditions de mise en œuvre d'une entente internationale auto-exécutoire sur les changements climatiques. Le modèle utilisé est la version multi-régionale (15 régions) et intégrée du modèle MARKAL-Monde dans lequel les coûts de réduction ainsi que les coûts représentatifs des dommages climatiques sont inclus. La démarche combine la modélisation d'équilibres partiels par MARKAL et les principes de la théorie des jeux coopératifs, et suppose l'existence de transferts interrégionaux pour partager le gain global de la coopération. Les résultats permettent d'illustrer l'écart entre les solutions coopératives et non-coopératives, du point de vue des effets climatiques ainsi que des coûts engendrés, la volonté de coopérer des régions, ainsi que le montant des transferts interrégionaux. La sensibilité des résultats au niveau et à la répartition régionale des dommages, aux coûts de réduction ainsi qu'au niveau d'émission du scénario de référence, est également mise en évidence. Finalement, la stabilité interne de coalitions clairvoyantes sans transfert (c'est-à-dire en situation de non-coopération) est analysée. Le présent projet est innovateur pour son application de principes de la théorie des jeux à un modèle mondial technologique aussi large et détaillé que MARKAL.

Abstract

In order to study the conditions for a world self-enforcing agreement on climate change, we model cooperative and non-cooperative world climate strategies with an integrated version of the world 15-region techno-economic MARKAL model in which abatement costs and climate related damages are both included. Assuming interregional transfers to share the global gain of cooperation, our work adopts the point of view of dynamic partial equilibrium computation coupled with cooperative game-theoretic principles. The results illustrate how the climatic and economic gap between cooperation and non-cooperation, the willingness of regions to cooperate, and the amount of side-payments, depend on the level and distribution of climate damages, the abatement costs, and the emission levels in the reference case. The internal (in)stability of farsighted coalitions without transfers (non-cooperation) is also analyzed. The current project appears to be the first one of the sort using a world, large and detailed technology explicit model such as MARKAL.

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1. INTRODUCTION

Given the nonexcludability and nonrivalry nature of environmental goods, countries' decisions to abate or not the greenhouse gas (GHG) emissions are interdependent and any cost-efficient climate agreement such as the global cooperation may be unprofitable (no guarantee that every country or every coalition of countries will be better off) and unstable (some countries may free-ride in order to enjoy the pollution abatement done by the others, while incurring lower or no abatement costs, Folmer *et al.*, 1998; Sandler, 1997; Toth and Mwandosya, 2001). Moreover, no supranational institution is endowed with the appropriate jurisdiction to enforce international environmental cooperation. Given heterogenous actors' interests, decision analysis may also not easily yield a universally preferred solution, as indicated by the difficulties encountered by the international negotiations on climate change. Hence, the increasing interest in analyzing the conditions for a world self-enforcing agreement on climate change.

The aim of this paper is to characterize climate policy prospects by modeling cooperative and non-cooperative strategies with an integrated version of the techno-economic world MARKAL model, in which climate related damages are added to the abatement costs computed by MARKAL, and the model is used in a cost-benefit mode. The approach, inspired by cooperative game-theoretic principles, follows the normative assumption that appropriate transfers may be calculated so that the cooperation of all regions is less likely to be broken under the conditions we propose. Similar work has been undertaken using either analytical stylized models (for example: Barrett, 1994; Botteon and Carraro, 1998; Carraro and Siniscalco, 1992; Fankhauser and Kverndokk, 1996; Hackl and Pruckner, 2002; Hammitt and Adams, 1996), or computable general-equilibrium models such as RICE/DICE, FUND or IIAM models (Bosello *et al.*, 2001; Ciscar and Soria, 2002; Filar and Gaertner, 1997; Finus *et al.* 2003; Nordhaus and Yang, 1996; Pinto, 1998; Tol, 2001; and works by Chander, 2003; Chander and Tulkens, 1992, 1995, 1997; Eyckmans et al, 2001, 2003). However, the present research appears to be the first one of the sort to use a large, detailed, technology rich model such as MARKAL, that contributes to a higher robustness of the costs computed by the model. The key targets of our works are to evaluate the required effort (in terms of technology decisions, emission reductions and costs) to bridge the gap between non-cooperative and cooperative climate strategies, and to define transfers that would guarantee the stability of the world cooperation. These questions are equivalent to ask what would happen if no international agreement were reached compared to the situation where all countries cooperate, and how the burden of reducing CO_2 might be shared by policy-makers among the different regions to enforce an international climate agreement.

It is our contention that using a technology rich model such as MARKAL adds value to the previous research on the same subject, by providing a second view at the same problem with a different lens. IPCC (2000) and Bataille (2004) underline the inherent differences in the Top-down (TD) and Bottom-up (BU) approaches, and gives many reasons why results obtained via the two types of model may differ. *Ad contrario*, when it is observed that the same conclusions emerge from TD and BU studies, this may well indicate that such results are particularly robust. This is the case for several results presented in this article, such as the dependency of the world gain of cooperation as well as the transfers on the damage factors, and the reduction of the free-riding behaviors when the farsightedness of the regions is considered. The fact that our results generally confirm others obtained by TD models seems to us a very positive result that confers added credibility to both lines of work.

Another strong motivation of our work is that technology rich BU models are fast becoming a requirement (although not an exclusive one) by the policy advisers for the analysis of energy outlooks and climate policies with sufficiently detailed representations of the micro-level actions and measures being evaluated (see, for example, Loulou *et al.*, 2000; Jaccard *et al.*, 2001; Energy Information Administration, 2003; International Energy Agency, 2004). Indeed, the most attractive feature of models like MARKAL is the traceability of a result to the techno-economic assumption(s) responsible for that result. Although tracing results back to technological assumptions is time-consuming, it is our experience that it sheds additional light on the results, increases confidence in the tool, and triggers new thoughts by suggesting sensitivity analyses.

It is therefore our belief that the line of research and analysis started by our and a few other projects has merit, and will expand in the future, when more applications of advanced BU models continue to be made.

The structure of the article is as follows. Section 2 introduces the foundations of our approach by reviewing the cooperative and non-cooperative frameworks in which an international agreement may emerge. Section 3 describes the methodology, including the modelling of energy strategies by MARKAL, and the definition of non-cooperative strategies. Section 4 evaluates the global gain of cooperation (optimal solution) over non-cooperation in terms of climatic and economic results. It also gives an overview of the interest of every region in the world cooperation without transfers. Section 5 computes four allocations of the global gain of cooperation (implying transfers) so that the world cooperation is stable under the proposed conditions. Finally, the stability of small coalitions without transfers is studied is Section 6. Sensitivity analyses are undertaken at each step of the work. Sensitivity analyses are undertaken at each step of the work.

Several results are presented in a condensed manner. In particular, the limited space of this article does not permit a full presentation of the results concerning energy technologies. Additional tables and figures are available from the authors upon request. Some energy and technology decisions obtained with the model under climate policies are also described in Labriet *et al.* (2004).

2. COOPERATION VS NON-COOPERATION

2.1 Some strategic options

The climate decision framework includes several strategic options available to countries.

- *Business-as-usual:* no abatement action is implemented. Countries are considered to be ignorant of the greenhouse effect or of its impacts, or they consider the latter as negligible (Fankhauser and Kverndokk, 1996; Ioannidis *et al.*, 2000); because it affects the level of required emission reductions and the likelihood of coalitions, the base case is a crucial and strategic benchmark for the assessment of climate policies (Toth and Mwandosya, 2001).

- *Global or partial cooperation:* the cooperative solution, as represented by the cost-efficient (socially optimal) solution computed by optimization models, constitutes the first-best solution, and thus the upper or optimistic limit of what is achievable (Sandler, 1997). It is interpreted as a binding agreement between all countries towards world efficiency. However, it does not necessarily constitute an equilibrium since its profitability and stability are not guaranteed, unless the gain from cooperation is redistributed. Another question is then to know whether a partial climate agreement between some countries may emerge as a stable one (Barrett, 1994; Carraro and Siniscalco, 1992).

- *Non-cooperation*[4]: countries pursue their own best payoffs without coordinating with others, but taking into account the other countries' choices. The so-called Nash equilibrium[5] represents the realistic lower end of possible international strategies and it is considered as a threat point: if cooperation cannot be agreed upon, the Nash situation may well result (Folmer *et al.*, 1998; Ioannidis *et al.*, 2000). Being an equilibrium, it refers to a self-enforcing strategy. However, it is usually inefficient since the same overall emissions could be reached at lower cost, and lower global emissions are reached at the optimum.

2.2 Different structures of the energy/environment game

Applied to climate change, the modeling of interdependencies of countries follows two lines of thought. A brief comparison of both approaches[6] helps to understand the different forms of an international agreement, the contrasted possible results, and then, the foundations of our approach.

On the one hand, a series of results based on the *non-cooperative framework* and initiated by Carraro and Siniscalco (1992) and Barrett (1994) support that any self-enforcing agreement will either be signed by very few countries, or, if signed by more countries, will result in small emission reduction compared to the non-cooperative situation (Botteon and Carraro, 1998; Carraro and Siniscalco, 1992, 1998; Hackl and Pruckner, 2003). The stability concept is derived from cartel theory and relies on the definition that no region has the incentive either to free-ride (internal stability) or to broaden a stable coalition (external stability) (D'Aspremont *et al.*, 1983). This branch of work is referred hereafter as the "cartel approach".

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[4] Unilateral action is also possible: a single country, with a marginal cost of abatement lower than its marginal benefits and/or with a high contribution to world emissions, reduces its individual emissions whereas all other countries remain at their base case emission levels (Hackl and Pruckner, 2002; Pinto, 1998).

[5] See definition of game-theoretic terms in Appendix .

[6] Finus and Rundshagen (2002), Finus (2004), Ioannidis *et al.* (2000), Missfeldt (1999) and Tulkens (1998) provide very good reviews of the two approaches.

On the other hand, a series of works based on the *cooperative framework* and initiated by Chander and Tulkens (1992, 1997) asserts the formation of the grand coalition (cooperation of all countries) and analyzes the transfers that ensure its existence. It is called hereafter the "grand coalition approach". The assumption of transfers has a sound justification in welfare economics, since it allows the satisfaction of both efficiency and equity: the countries that abate emissions may differ from the countries that pay for abatement. However, the real-life implementation of transfers is often criticized, and some studies consider that transfers may enhance the profitability of cooperation but remain insufficient to offset the incentices to free-ride (Bosello *et al.*, 2001). The stability used by the cooperative branch is defined in the core-theoretic sense of cooperative games and refers to coalitional rationality (Chander and Tulkens, 1992, 1997): each possible coalition receives at least as much as it can obtain on its own.

Both approaches require the definition of credible *threats* that consist in the reaction of countries when some of them free-ride. The embedded assumption of the cartel approach is that defectors believe that the cooperating coalition will not collapse but will adjust its strategy (renegotiate the agreement) when defectors leave it. The gain from free-riding would then be outweighed by the adjustment of the remaining coalition. Diamantoudi *et al.* (2002) consider that such an assumption encourages deviations and undermines the viability of any agreement. On the contrary, the grand coalition approach assumes that when a country deviates, the whole agreement collapses (coalition unanimity) and each country sticks to its non-cooperative Nash strategy, as defined by the so-called γ-core[64] (Chander and Tulkens, 1992, 1997). Carraro and Siniscalco (1997) and Diamantoudi *et al.* (2002) consider that this pessimistic expectation of defectors represents a hardly credible punishment since it also hurts punishers, and that it encourages global cooperation since stability and profitability conditions then coincide.

Discussing the premises on which the two approaches rest, Tulkens (1998) concludes that the definition of the characteristic function[7] may achieve the convergence of both approaches. In the same direction, Diamantoudi *et al.* (2002) show that some assumptions

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[7] The characteristic function measures the payoff (characteristic value) for every possible combination of players (coalition) of the game. The characteristic value represents the minimum value that a coalition can guarantee for its members. See also definition of game-theoretic terms in Appendix .

related to the countries' behaviours contribute to bring the cartel approach closer to the grand coalition approach: farsighted stable coalitions (i.e. defectors foresee possible further deviations by other countries), are much larger than those supported by non-farsighted coalitions, and coordinated defections (i.e. by group of countries) allow countries to use the collapse of the agreement as a threat to sustain it. Ecchia and Mariotti (1998) and Eyckmans (2001) confirm the result that farsightedness increases the incentives for cooperation. Moreover, Chander (2003) points that the only possibility of coalitions becoming finer and not coarser contributes to the stability of coalitions smaller than the grand coalition. If coalitions can freely merge or break apart and are farsighted, the non-members will not form any non-singleton coalitions; the grand coalition is then justified as the only stable coalition, defined as being in the γ-core.

The approach adopted in the current work follows the cooperative branch of literature. Of course, real agreements may well lie between the pessimistic view (only small coalitions emerge) and the optimistic one (world cooperation emerges). Moreover, the concepts of cooperative agreements have some normative appeal and possess some axiomatic properties, while the non-cooperative branch is concerned with a more positive analysis of coalition formation (Finus and Rundshagen, 2002; Missfeldt, 1999). The choice of a normative angle for the analysis of international climate agreement is consistent with MARKAL's philosophy, which relies on optimal energy decision and is appropriate for prospective analysis (see section 3). Moreover, cooperative cost-sharing solutions may act as focal points in negotiations. However, we also propose (in section 6) a study of the stability of intermediate coalitions without transfers, based on the same model results. These results are closer to the cartel approach.

3. THE INTEGRATED MARKAL MODEL

The cost of carbon mitigation and estimated or perceived damages are crucial parameters of the countries decision. The use of a well-calibrated and reliable model is therefore also crucial for the validity of the calculations. An integrated version of the world multi-region MARKAL model is used.

3.1 Advanced multi-region global MARKAL model

MARKAL is a linear programming model of the production, trading, transformation, distribution and end-uses of various energy forms and some materials that affect CO_2 emissions[8] (Figure 1). Given its high level of technology detail, MARKAL is not only technology explicit; it is technology rich as well. The model has a long and rich history of methodological developments and applications to energy and environmental issues all around the World. The version of the advanced world multi-region MARKAL that is used in this article was developed by the authors; details of the calibration and of the energy and technology decisions under climate policies are described in Labriet *et al.* (2004); the rationale of the model is briefly described below.

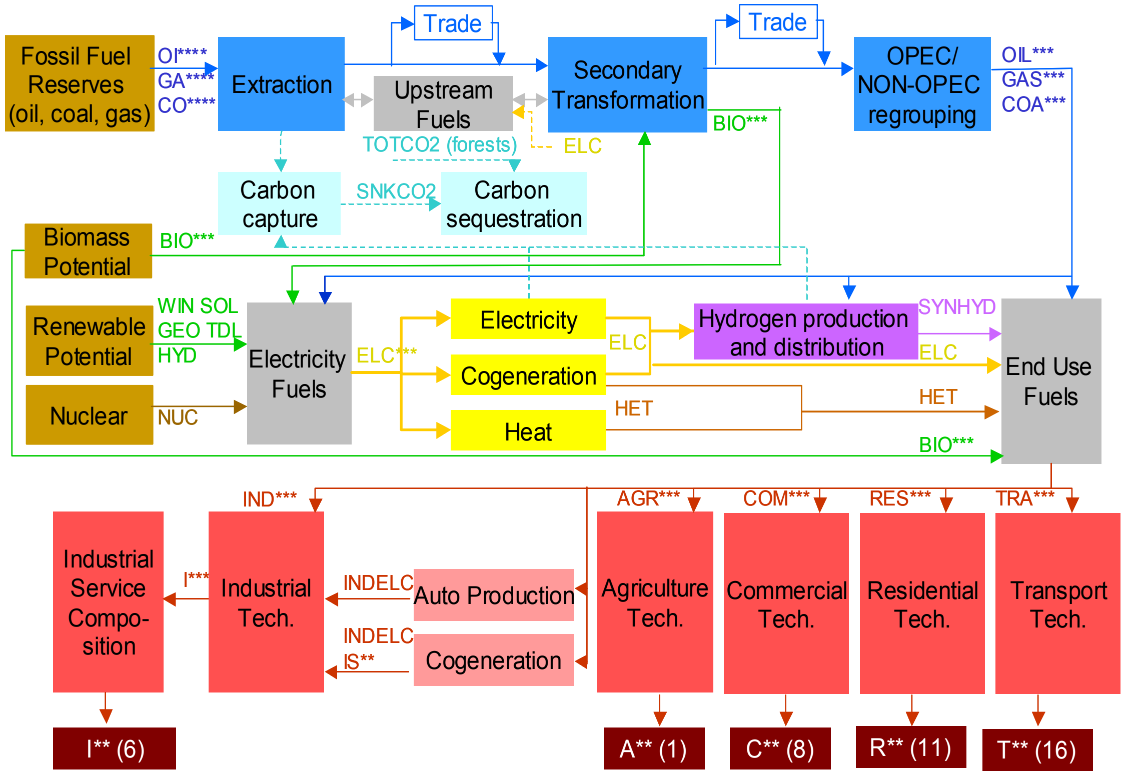

Figure 1. The general Reference Energy System

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[8] In the current version of the model, only CO_2 is analyzed in details. Other greenhouse gases are included through an exogenous radiative forcing (Labriet and Loulou, 2003).

MARKAL computes a global, multi-regional supply-demand inter-temporal partial economic equilibrium on competitive energy markets over 1998-2052 divided into 11 periods of five years each. It maximizes the discounted net total surplus, i.e. the sum of discounted producers' and consumers' surpluses, subject to detailed technological and environmental constraints. The model is driven by the 42 demands for energy services in all end-use sectors (such as space heating, lighting, etc. by residential and commercial buildings, useful energy by each energy intensive industry, and travel demand by each transportation mode). One important characteristic of the model is that energy service demands are provided exogenously only in the reference case. In alternate scenarios, each demand responds endogenously to changes in its own price (prices are also endogenously calculated by the model as marginal values of the commodities). This price reactivity is implemented by a set of user provided own-price elasticities. Accounting for price elasticity of demands captures a major element of feedback effects between the energy system and the economy (Loulou and Kanudia, 2000; Bataille, 2004).

Fifteen regions are identified and modeled based upon political, geographic, and environmental factors (Table 1). The regions are linked via trade variables, for the following commodities: crude oil and oil products, natural gas, coal, electricity, and tradeable emission permits. All agents have perfect information on others and perfect foresight and the markets are assumed competitive, with the notable exception of oil production decisions by OPEC (see below). Equivalently, the MARKAL equilibrium is computed via the dynamic minimization of the discounted total cost. The total cost of the system includes, at each time period: annualized investments in technologies, fixed and variable annual operation and maintenance costs of technologies; cost of energy imports and domestic resource production; the negative of the revenue from energy exports; delivery costs; welfare losses incurred from reduced end-use demands; and taxes and subsidies (if any) associated with energy, technologies, and emissions. While the market just described qualifies as competitive, several additional constraints are added to the model in order to simulate more realistic penetration rates of new technologies, as well as certain national policies (e.g. nuclear policy) and investors' behaviours (e.g. specific hurdle rates by each subsector). With these additional features, the model is a hybrid between purely competitive and behavioural.

Table 1. List of the 15 regions

Code	Region
AFR*	Africa
AUS	Australia-New Zealand
CAN	Canada
CSA*	Central and South America
CHI	China
EEU	Eastern Europe
FSU	Former Soviet Union
IND	India
JPN	Japan
MEX	Mexico
MEA*	Middle-East
ODA*	Other Developing Asia
SKO	South Korea
USA	United States
WEU	Western Europe

*OPEC/Non-OPEC split in upstream and oil trade

Emissions, primary and final energy consumption of the base case of the current version of the model are calibrated to the IPCC's AIM-A1B scenario, which is the most frequently cited one in the literature. This scenario could be qualified as one of continuing economic growth but also of high new technology penetration, so that resulting emissions are relatively low compared to a case where the current energy situation based on fossil fuels is extrapolated into the future (Labriet *et al.*, 2004). Because the level of non-emitting electricity generation is a crucial assumption for projecting future CO_2 policies, and because nuclear and renewable shares of electricity are very optimistic in the A1B scenario, we also build a contrasted alternative base case, called FOS, characterized by lower shares of nuclear and renewable in electricity generation (Labriet *et al.*, 2004).

The market for crude oil is global but not competitive, given the OPEC's cartel power on the international oil market dynamics. The general trend is that climate policies would reduce the global oil demand and thus the revenues of oil-exporting countries (up to 13% & 25% in 2010 under the Kyoto Protocol, respectively with & without emissions trading), but they would have less impact on the real price of oil than has resulted from market fluctuations over the past 30 years (Barker and Srivastava, 2001; Gately, 2004; Hourcade and Shukla, 2001). Of course, OPEC's ability to coordinate output (and thus indirectly pricing) strategy is both critical and uncertain. Given this context, our approach assumes the continuation of OPEC's cartel action over the horizon, and international oil trade is modeled in the following simplified manner: (a) each region is free to import any amount of crude oil and refined products at an exogenously fixed price[9]; (b) exports are then adjusted *ex-post* to balance imports at the world level, so that oil revenues and CO_2 emissions from oil extraction are not distorted. This requires at least two successive runs of the model. The ex-post adjustments are shared between MEA-OPEC, AFR-OPEC and FSU[10], in proportion to their current level of production, i.e. we assume that the regions' share of production will remain unchanged under climate policies. We are aware of the limits of these assumptions, and future work may focus more specifically on other OPEC's strategies.

Economic indicators are reported in US$ of constant 2000 market exchange rate, and the social discount rate for the global economy is 5%.

3.2 The climate damages

3.2.1 Integration of damage costs into MARKAL

The conventional cost-efficiency use of MARKAL consists in setting a global CO_2 target, and solving for a CO_2 constrained equilibrium. The very fact that a global target can be set implies that all regions cooperate. In contrast, the modelling of non-cooperative strategies requires the endogenous computation of the global emissions, since the latter result from the decisions of individual regions minimizing their own costs but taking into consideration the emissions of others. Thus, the modeling of non-cooperative strategies requires the integration of climate damages into MARKAL. Such an integration in turn allows the use of MARKAL for cost-benefit analyses.

We now briefly outline the method used for integrating the damage costs in the World MARKAL model, which is fully described in Labriet and Loulou (2003). In that article, we consider a series of four steps leading from global CO_2 emissions (generated by MARKAL) to the evaluation of damage costs in each region, as follows: a) the calculation of CO_2

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[9] The price trajectory (annual price growth of 0.6% between 2005 and 2050) is similar to that proposed by international literature (see Labriet *et al.*, 2004).

[10] OPEC-CSA and OPEC-ODA have not been modified for simplification purposes, since they represent rather small shares of total oil exports. At the opposite, the adjustment of FSU's exports may be justified by the fact that non-OPEC countries benefit from the cartel action by OPEC (Berg *et al.*, 1998) and therefore, they may be interested in a voluntary contribution to the OPEC effort to limit the fall of oil prices.

concentrations in three reservoirs, b) the calculation of the radiative forcing due to the atmospheric CO_2 concentration, c) the calculation of changes in mean global temperatures in two reservoirs resulting from the change in radiative forcing, and d) the calculation of damage costs in each region using simplified quadratic functions of the change in the mean atmospheric temperature. This approach follows Nordhaus and Boyer (1999). If these intermediate steps were directly integrated in MARKAL, they would result in making the integrated model non-linear and non-convex, and therefore very difficult to use due to its large size. However, in Labriet and Loulou (2003), we conjectured that *each regional damage cost is a function of the global cumulative emissions only*, and we proceeded to empirically test this hypothesis, using a large number of contrasted emission trajectories taken from the literature. It turns out that the conjecture was empirically verified to a high degree of accuracy, and moreover that all relationships between regional damage costs and cumulative global emissions are linear.

The linearity of the damage costs has important consequences for the computation of Nash non-cooperative equilibria. The latter is computed via (1) below, and the derivations below show that (1) is equivalent to (3). Therefore, computing the Non-cooperative equilibrium is reduced to solving a series of 15 independent linear programs (3), one per region *i*.

$$Min_i \left\{ C_i(X_i, E_i) + D_i(\sum_{all\ j} E_j) \right\} \tag{1}$$

which, utilizing the linearity of the damage costs, is identical to :

$$Min_i \left\{ C_i(X_i, E_i) + a_i \times \sum_{all\ j} E_j + b_i \right\} \tag{2}$$

which in turn is identical to

$$\left[a_i \times \sum_{j \neq i} E_j + b_i \right] + Min_i \left\{ C_i(X_i, E_i + a_i \times E_i \right\} \tag{3}$$

where:

$C_i(.)$	total cost of the energy system of region *i*
E_i	cumulative emissions (from 2000 to 2050) of region *i*
E	cumulative global emissions (from 2000 to 2050), $E = \sum E_i$

X_i	all variables influencing the cost of the energy system (investments,operation, etc.)
$D_i(E)$	cumulative climate damage incurred by region *i* (a function of cumulative global emissions). $D_i (E) = a_i,E + b_i$

Note that the term within square brackets in (3) is not under the control of region *i,* since region *i* has no control over emissions from other regions or over the constant term b_i. Thus region *i*'s problem is limited to optimizing the second part of expression (3), which is a decentralized linear program: each country chooses its strategy by considering only the part of its own damage due to its own emissions. In other words, the emissions resulting from the energy decisions taken by other regions have no impact on energy decisions taken by region *i*, and damages paid by each region *i* due to emissions of other countries are added *ex-post.*

As discussed in Labriet and Loulou (2003), the decomposition of (1) into (3) implicitly assumes that the trade between regions is not fundamentally affected by reduction strategies. This is an approximation that we make for ease of computation, but which we could relax in future work, at the expense of additional computational time. In other words, the price of traded commodities is assumed to remain the same in all scenarios, so that the cost of one region's strategy does not depend on other regions' abatement effort. This is the case for oil (fixed price) in the current version of MARKAL. However, results for traded gas show significant price variations in some regions (mostly in 2050) under climate policies. Thus, the Nash equilibria computed in this study should be considered as approximate. The link between climate policies and international trade deserves more attention in future work; for example, relaxing the model constraints on gas extraction and trade would help reduce the observed price variation.

3.2.2 Damage scenarios

Any cost-benefit conclusion obtained by this approach is fully dependent on the damage curves and the climate module. Because damages are subject to high uncertainty, we conduct sensitivity analyses based on both the level of total damages and the regional distribution pattern (Table 2).

- *Reference* damages (REF) are based on the quadratic equations of Nordhaus and Boyer (1999), where damages are higher in developing countries than in industrialized ones except WEU[11].

- *High* damages (HI) are higher in all regions; the exponent of damage equations is increased to three [11].

- *Reverse* damages (REV) are higher in industrialized countries and smaller in developing countries; they are inspired by "Calibration I" from Finus *et al.* (2003), itself based on Fankhauser (1995).

- *High and reverse* damages (HRV) combine the last two changes.

Regions with low damages may be understood as regions with low real damages, or as regions not aware of or paying little attention to climate damages, or finally as regions with a low political willingness to act; in fact, it is sometimes argued that the perceived climate damages of developing countries should be low, as reflected in REV case.

The non-cooperative case is modeled by incorporating the appropriate marginal damage coefficients (a_i in the above formulas) from Table 2 (either regional factors in case of non-cooperative regions, or the sum of the regional factors in case of a group of cooperating countries). Since only the differences of total costs between scenarios (and not the absolute costs) are studied, only a_i (not the constant parameter b_i – see equation 1) is required for the optimization .

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[11] According to the climate model we used (Nordhaus and Boyer, 1999) and assuming that emissions follow the AIM-A1B trajectory until 2100, REF climate damages represent 1.94% of the GDP for a 2.5°C temperature increase, and 1.34% of the GDP for a doubling of CO_2 atmospheric concentration. In HI, the values are respectively 3.82% and 2.24%.

Table 2. Marginal damages (US$$_{2000}$/t$CO_2$) and regional distribution (%)

	Reference (REF)		High (HI)		Reverse (REV)		High & reverse (HRV)	
AFR	4.15	(18.2%)	6.36	(12.9%)	1.13	(5.0%)	2.45	(5.0%)
AUS	0.00	(0.0%)	0.17	(0.3%)	0.22	(1.0%)	0.49	(1.0%)
CAN	0.01	(0.0%)	0.37	(0.7%)	0.22	(1.0%)	0.49	(1.0%)
CHI	0.67	(2.9%)	3.27	(6.6%)	1.36	(6.0%)	2.94	(6.0%)
CSA	1.83	(8.0%)	3.29	(6.7%)	0.91	(4.0%)	1.96	(4.0%)
EEU	0.03	(0.1%)	0.40	(0.8%)	0.22	(1.0%)	0.49	(1.0%)
FSU	-0.03	(-0.1%)	1.88	(3.8%)	1.59	(7.0%)	3.43	(7.0%)
IND	3.65	(16.0%)	6.98	(14.2%)	1.13	(5.0%)	2.45	(5.0%)
JPN	0.31	(1.3%)	1.20	(2.4%)	3.41	(15.0%)	7.36	(15.0%)
MEA	1.33	(5.8%)	2.27	(4.6%)	0.34	(1.5%)	0.73	(1.5%)
MEX	0.65	(2.8%)	1.31	(2.6%)	0.34	(1.5%)	0.73	(1.5%)
ODA	4.14	(18.2%)	7.26	(14.7%)	1.13	(5.0%)	2.45	(5.0%)
SKO	1.06	(4.6%)	1.82	(3.7%)	0.45	(2.0%)	0.98	(2.0%)
USA	0.78	(3.4%)	2.77	(5.6%)	5.00	(22.0%)	10.8	(22.0%)
WEU	4.10	(18.0%)	9.68	(19.7%)	5.23	(23.0%)	11.2	(23.0%)
World	22.75	(100.0%)	49.10	(100.0%)	22.75	(100.0%)	49.10	(100.0%)

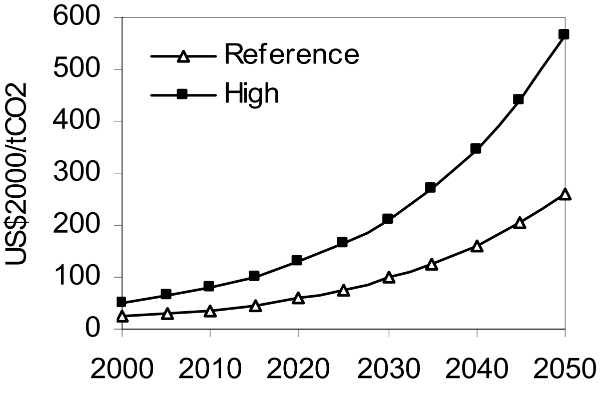

Figure 2. MARKAL carbon tax equivalent to climate damages

Compared to Labriet and Loulou (2003), the current damage factors assume:

- Cumulative damages computed up to 2100, instead of 2050, given the long-term climate effects of CO_2[12]; recall that emissions are computed up to 2050 by the current version of MARKAL;
- Damage discounting of 2%, instead of 5%, in order to value more the long-term climate effects;
- Rapid economic growth rates provided by the "A1 family" scenarios of the IPCC, instead of "A2 family", since MARKAL is calibrated to the IPCC's AIM-A1B scenario (Labriet *et al.*, 2004).

3.3 Definition of the non-cooperative scenario

The computation of non-cooperative scenarios and of transfers to guarantee the formation of the grand coalition requires the definition of both the behaviour of regions that are not members of the cooperative coalition (equivalent to the definition of the threat in case of defection), and the information structure of the energy/environment decisions taken by the regions.

3.3.1 Behaviour of outsiders

We adopt the γ-characteristic function proposed by Chander and Tulkens (1997): when a sub-coalition *S* forms, outsiders do not take particular coalitional actions against *S* (e.g. more emissions such as leakage) or favouring *S* (e.g. less emissions if they form another coalition) but remain as singletons, adopt their individual Nash strategies and enjoy the cleaner environment induced by *S*'s actions. This defines a partial Nash equilibrium with respect to *S*. This grants *S* a certain degree of pessimism, since *S* would be better off if the regions outside would form one or more non-singleton coalitions and then reduce more their emissions (Chander and Tulkens, 1997). This is also equivalent to saying that if a region or

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[12] Longer-term computation is not necessary given the discounting effect. For example, cumulative damages up to 2200 add 10% to cumulative damages up to 2100.

group of regions deviates, the remaining players split up into singletons and play their Nash strategy (see section 2.2). The possibility of highest emissions (α-characteristic function) is not appropriate since it is self-punishing in the context of global pollution (Chander and Tulkens, 1997; Zaccour, 2003).

3.3.2 Open-loop information structure

The open-loop information structure that we use corresponds to negotiations that take place once: a binding agreement is signed in the first period and remains valid until the end of the horizon; no change can be made in response to new information along the time path. This assumption is consistent with the perfect information and foresight characteristics of MARKAL. Thus, the problem is dynamic as regards MARKAL energy decisions, but it is static from the point of view of gains and transfers.

Such an information structure may appear unrealistic, since the renegotiation of climate agreements is not allowed and the distribution over time of the gain of cooperation is ignored. At the opposite, the feedback structure, under which the regions may adapt their policy along the time path, implies that the solution will be reached from any point on the time path (time consistency). Nevertheless, the interest in open-loop equilibrium is based on the easier way to calculate it (Fudenberg and Tirole, 1991; Yang, 2003). Moreover, the open-loop structure might be viewed as more acceptable when considering the long-term nature of some energy decisions. Typically, the stock of the pollutant (concentration of CO_2) is lower in the open-loop Nash equilibrium than in the feedback solution. The intuition is that under a feedback structure, countries have an incentive to increase emissions as this will be partly offset by the others; but all countries think the same; hence the higher emissions (Folmer *et al.*, 1998; de Zeeuw and Van der Ploeg, 1991). Moreover, Germain and Van Ypersele (1999) show that the transfers given or received by regions are higher but have the same magnitude in the open-loop than in the feedback climate policies. This confirms that although less realistic and more optimistic in terms of abatement, the open-loop solution gives an acceptable approximation of the feedback solution and remains appropriate to describe what would happen if any international agreement were reached.

4. THE GAP BETWEEN COOPERATION AND NON-COOPERATION

This step of the analysis has two objectives: first, evaluate the gain of cooperation over non-cooperation in terms of climatic and economic results; second, give an overview of the interest of the 15 regions in global cooperation without transfers. The gain of cooperation is defined as the difference between the total discounted cost of the global cooperation, i.e. the socially optimal solution, and the sum of the total discounted costs of each region under the individual Nash equilibrium. Cooperation and non-cooperation must be considered as solutions where the regions are committed and stick to their respective strategies; in other words, free-ride and stability issues are not covered here but in section 5.

The general tendency is that the Nash equilibrium is closer to the base case than to the global cooperation (Table 3). The detailed description of results focuses on the A1B-REF case. Results for the other cases are provided in section 4.3.

4.1 Climatic and economic results (A1B-REF)[13]

Focussing on the A1B-REF case compared to the A1B base case, the reduction of cumulative emissions under the non-cooperative strategy represents only 21% of the reduction induced by the cooperation of all regions (Table 3). This indicates that climate change reflects to a large extent a collective problem, as confirmed for example by Eyckmans and Tulkens (2003)[14]. As regards the temperature increase in 2050[15], it is 1.55°C under the non-cooperative scenario (CO_2 concentration of 497 ppm) and 1.33°C under cooperation (433 ppm), against 1.60°C in the base case (514 ppm). The relatively small differences in climate results between cooperation and the base case may be explained by the relatively short-term calculations compared to the long-term climate dynamics. The discounted gain of cooperation over non-cooperation amounts to 11400 $G\$_{2000}$, which is equal to a modest 3.5% of the total world discounted cost of cooperation. Other studies show different results (e.g. Eyckmans and Finus, 2003; Eyckmans and Tulkens, 2003) but different model nature and assumptions on the regional abatement costs and climate damages are

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[13] See other results in appendix B, Table B.1 to Table B.3.

[14] Hammitt and Adams (1996) and Hackl and Pruckner (2002) conclude the opposite, but both explain that the specifications of their model (e.g. the form of the cost and benefit curves) may be responsible for this result.

[15] Climatic results are based on the reduced-form climate module proposed by Nordhaus and Boyer (1999).

certainly leading to these differences. Moreover, results from top-down models are expressed in consumption units while our results are in cost units.

Table 3. Gain and climatic results (no transfer)[16]

	A1B- REF	A1B-HI	A1B-REV	A1B-HRV	A1B-REF No sink
Gain of cooperation over non-cooperation (G$\$_{2000}$ DPV)					
World	11395.0	27780.5	12104.1	30821.9	9007.2
Net emissions in 2050 (GtC)					
BAU	17.0	17.0	17.0	17.0	17.0
NASH	15.0	13.0	14.8	13.4	15.5
COOP	7.3	5.9	7.3	5.9	9.6
CO_2 concentration in 2050 (ppm)					
BAU	514.4	514.4	514.4	514.4	514.4
NASH	497.1	481.9	499.3	486.9	500.2
COOP	432.5	414.7	432.5	432.5	451.1
Temperature increase in 2050 (°C)					
BAU	1.60	1.60	1.60	1.60	1.60
NASH	1.55	1.50	1.56	1.52	1.56
COOP	1.33	1.25	1.33	1.25	1.39

Table 4. Regional strategic choices (no transfer)[17]

	A1B-REF	A1B-HI	A1B-REV	A1B-HRV	A1B-REF No sink
AFR	COOP	COOP	COOP	COOP	COOP
AUS	NASH	COOP	COOP	COOP	NASH
CAN	NASH	COOP	COOP	COOP	NASH
CHI	NASH	COOP	COOP	COOP	NASH
CSA	COOP	COOP	COOP	COOP	COOP
EEU	NASH	NASH	NASH	COOP	NASH
FSU	BAU	COOP	COOP	COOP	BAU
IND	COOP	COOP	COOP	COOP	COOP
JPN	COOP	COOP	COOP	COOP	COOP
MEA	NASH	NASH	NASH	NASH	COOP
MEX	COOP	COOP	NASH	NASH	COOP
ODA	COOP	COOP	COOP	COOP	COOP
SKO	COOP	COOP	COOP	COOP	COOP
USA	NASH	NASH	COOP	COOP	NASH
WEU	COOP	COOP	COOP	COOP	COOP

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[16] See other results in appendix B, Table B.1 and Table B.2. The results for FOS case are included in Table B.4 to Table B.6.

[17] See the numerical results in appendix B, Table B.3. The results for FOS case are included in Table B.7 and Table B.8.

4.2 The regional interests in cooperation (A1B-REF)

The analysis of the preferred strategies shows that the regions with low and intermediate marginal damages (less than 1.0 $/tCO_2$) are generally not interested in cooperation, because the benefits of cooperation are too small compared to the abatement costs incurred. This is the case for AUS, CAN, CHI, EEU and USA (Table 4). At the opposite, regions with higher marginal damages prefer cooperation; they are either developing countries (AFR, CSA, IND, ODA) or WEU. In other words, the incentive for developing regions and Western Europe to participate in an agreement is motivated, among others, by the high damages they would suffer from climate change. As regards MEA, the level of oil exports explains its preferred strategy, as discussed below. Finally, FSU prefers the situation where the CO_2 emissions are the highest, i.e. the base case, because of its negative marginal damage factor!

4.3 Sensitivity analyses

Several sensitivity analyses are conducted on the availability of carbon sequestration, on the damage factors and on the nature of the base case. We briefly comment each variant.

A1B-REF No sink: This variant assumes that no CO_2 sequestration is allowed. Based on the current world MARKAL model, CO_2 sequestration helps reduce carbon price by more than two in 2050 (Labriet *et al.*, 2004). This variant shows that the gain of cooperation is reduced by 21% compared to the REF case (Table 3). Moreover, although the resulting preferred strategies by all regions except MEA are not affected (Table 4), the incentive for cooperation, measured as the regional gain, is higher in all regions when CO_2 sequestration is allowed (not shown here). MEA's interest for cooperation is explained by FSU's oil imports under the global cooperation: if allowed, FSU prefers extracting its own resources and sequestrating CO_2 at low cost; if CO_2 sequestration is not possible, FSU imports oil from MEA. MEA's preferred strategy is then dependant on the level of the revenues induced by oil exports. However, the losses of MEA under cooperation are small (0.1% of the costs of cooperation), so that the strategic choice of MEA of not cooperating should not be considered as a strong choice.

A1B-HI variant: Higher estimated climate damages increase not only the world gain of cooperation, more than doubled compared to A1B-REF (Table 3) but also the incentive for cooperation of several regions (Table 4): AUS, CAN, CHI and FSU become interested in cooperation (note that FSU marginal damages are not negative anymore). USA and EEU remain better off under the non-cooperative scenario, but their respective losses under cooperation are considerably reduced compared to REF case (by more than 80% - not shown here). MEA remains also better off under non-cooperation because of the level of its oil exports. Ciscar and Soria (2002), Fankhauser and Kverndokk (1996) and Finus *et al.* (2003) also emphasize the effect of the level of damages on cooperation.

A1B-REV variant: This case illustrates how the regional distribution of damages may affect the preferred regional strategies. While the total gain of cooperation increases (+6%) but remains close to the REF case (Table 3), AUS, CAN, CHI, FSU, USA become interested in cooperation because of the higher local damages (Table 4). Despite the decrease in local damages, AFR, CSA, IND, ODA and SKO remain interested in cooperation, while MEX is the only region that is better off under the non-cooperative scenario (Table 4). EEU and MEA remain better off under the non-cooperative case, the latter because of the losses of exports revenues, and the former because the local climate damages remain too low. The high dependency of results on regional damages is supported by several studies, such as Fankhauser and Kverndokk (1996) or Finus *et al.* (2003).

A1B-HRV variant: The case with high and reverse damages confirms all the above results. More particularly, it demonstrates that EEU may change its preferred strategy if its estimated marginal local damages reach a level between 0.40 (better off under Nash in the A1B-HI case) and 0.49 US$/t$CO_2$ (better off under cooperation in the A1B-HRV case).

FOS base case[18]: Finally, the same analysis was made with the alternative FOS base case. Among the results (not shown here), we want to emphasize the following ones: first, the world gain of cooperation increases up to 17,800 G$\$_{2000}$, which represents 5.5% of the total cost of cooperation. Despite this higher gain, it must be recognized that a pessimistic base case such as FOS could make the agreement more difficult because larger emission

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[18] See detailed results in appendix B, Table B.4 to Table B.8.

reductions have to be agreed upon[19] (Finus, 2004; Tol, 2001, Toth and Mwandosya, 2001). Second, given slightly higher oil exports in MEA, the latter prefers cooperation to non-cooperation in all cases except REV and HRV cases. Finally, under the HI case, all regions appear to prefer cooperation. However, this doesn't mean that the world cooperation is self-enforcing: some regions may be better off by choosing their Nash strategy and letting the other ones cooperating. Recall that both the cooperative and the non-cooperative scenarios must be understood as solutions where the regions are *committed to stick* to their respective strategies, and that defecting behaviours, at the heart of the stability issue, were not taken into consideration in this section.

4.4 Comparison of emissions with Kyoto targets and with the 550 ppm stabilization

The comparison of emission results with the Kyoto targets and the emissions corresponding to the stabilization of CO_2 concentration at 550 ppm[20] may provide an estimate of the self-enforcing property of these targets. The comparison focuses on the A1B-REF and A1B-REV cases (Table 5).

First, it must be noted that the Kyoto targets of FSU and EEU are higher than their respective 2010 emissions in the base case; the difference is the so-called "hot air", estimated to a total of 136 MtC in 2010 in our model (64 MtC in EEU and 72 MtC in FSU) compared to a range from 100 to 500 MtC provided by most economic modeling studies (Paltsev, 2000).

It appears that only a small share of the Kyoto targets is in the regions' self-interest, as represented by the small Nash reductions w.r.t. BAU in 2010. However, the Kyoto Protocol is consistent with or less demanding than the optimal cooperative scenario for all concerned regions except USA and CAN, where the Kyoto target is more demanding. Analysis with the alternative FOS base case would not make a difference since FOS diverges from A1B later than 2010.

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[19] Finus (2004) emphasizes this result as a paradox: the higher the benefit-cost ratio from abatement, the higher are free-rider incentives, since the environmental target will then be higher, but the larger is also the gain from cooperation.

[20] The emission path corresponding to the stabilization of atmospheric CO_2 concentration at 550 ppm is based on the AIM-A1B scenario provided by IPCC (Nakicenovic and Swart, 2000).

Table 5. Emissions w.r.t. BAU and shares of reduction (550-stabiliz, A1B-REF, A1B-REV)

	Emissions (%) w.r.t. BAU in 2010				Emissions (%) w.r.t. BAU in 2050				Share (%) of emission reduction in 2050			
	Kyoto Protocol	COOP A1B-REF	NASH A1B-REF	NASH A1B-REV	Stabiliz A1B-550	COOP A1B-REF	NASH A1B-REF	NASH A1B-REV	Stabiliz A1B-550	COOP A1B-REF	NASH A1B-REF	NASH A1B-REV
AFR	-	-32	-18	-2	-30	-48	-21	-8	4	4	8	3
AUS	-17	-38	0	0	-55	-72	0	-1	1	1	0	0
CAN	-40	-33	-3	-3	-59	-70	-9	-11	2	2	1	1
CHI	-	-40	0	0	-40	-63	-6	-13	17	17	7	16
CSA	-	-30	-9	-4	-25	-46	-10	-7	7	8	8	5
EEU	30	-17	-1	-1	-58	-75	0	-1	7	6	0	0
FSU	9	-19	0	0	-32	-48	4	-13	4	4	-2	5
IND	-	-31	-11	-1	-21	-41	-14	-5	3	3	6	2
JPN	0	-23	-1	-7	-45	-57	-1	-32	2	2	0	5
MEA	-	-24	-7	0	-41	-59	-20	-3	19	17	28	3
MEX	-	-15	0	0	-27	-46	-6	-1	3	4	2	0
ODA	-	-19	-8	0	-28	-49	-18	-3	7	8	14	3
SKO	-	-20	-1	0	-48	-63	-3	-1	4	4	1	0
USA	-32	-19	-1	-5	-36	-63	-4	-35	11	12	3	30
WEU	-26	-25	-8	-10	-44	-67	-37	-42	9	9	24	26
WORLD	-	-25%	-4%	-3%	-36%	-57%	-12%	-13%	100%	100%	100%	100%

Remark: COOP scenario is the same for A1B-REF and A1B-REF since the total world damages are taken into account in this case, whatever the regional distribution is.

In terms of world emission reduction, the stabilization scenario in 2050 (-36%) is less demanding than the global cooperation (-57%) and much more demanding than the Nash solution (-12%). The regional Nash reductions (self-enforcing) appear to represent more than 50% of the stabilization targets in several regions, such as AFR, IND, ODA and WEU.

The comparison of the regional distributions of abatement[21] helps understand the regional interests for cooperation: regions that bear a much larger share of the world reduction under stabilization or cooperation than under non-cooperation, such as CHI, USA, would be reluctant to ratify any world agreement. This result is confirmed by the results of Table 4.

Of course, different conclusions emerge from the alternative regional share of damages (A1B-REV) especially for USA and CHI, which contribute much more to the world reduction, and MEA and ODA, which contribute much less.

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[21] Of course, the regional distribution of abatement under cooperation is also suggestive of both the marginal abatement costs and the potential for abatement implicit in the model specification.

5. ALLOCATION OF THE GLOBAL GAIN

Adopting the point of view of the cooperative framework, we now turn to analyze whether transfers can be defined to ensure the stability of the grand coalition.

5.1 Transfers and allocation methods

Transfers between regions result from the sharing of the global (world) surplus of cooperation over non-cooperation, where the latter is modelled by the individual Nash solution and the former by the social optimum (see section 3.3). Several allocation rules[22] are proposed by cooperative game theory and are characterized by specific axiomatic properties reflecting different principles of justice. We first define an *allocation* as the portion of the global gain of cooperation that is attributed to a player (region) to reduce its cost in the cooperation. A *transfer* is the resulting amount to pay or receive by a region; it is the difference between every regional cost under cooperation before and after allocation of the global gain. The sum of allocations is equal to the total gain from cooperation; the sum of transfers is null.

- *The core* is the set of all allocations (payoffs) that are not dominated for any sub-coalitions: every sub-coalition (including singletons) receives at least as much as it can obtain on its own. Thus, allocations satisfy both individual and coalitional rationality, so that the core defines a certain form of stability (Eyckmans and Tulkens, 2003). The core may be empty or include an infinity of allocations.

- *The Shapley value* (Shapley, 1953) attributes to each player a payoff that reflects its average contribution to every possible sub-coalition. It has the desirable properties of, among others, efficiency (also called group rationality: the total gain is allocated) and symmetry (regions with similar power receive similar payoff). Mainly because of the latter property, it is interpreted as a normative allocation rule close to both the measure of strategic power of players, and the proportionality or merit principle that regions receive in proportion to what they put in. The Shapley Value is always unique.

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[22] See more details in Appendix A.

- *The nucleolus* (Schmeidler, 1969) is a centrally located element of the core (if the latter exists) defined by an egalitarian arbitration among coalitions. It yields an allocation such that the excesses of the coalitions are the lexicographical minimum. The excess is defined as the difference between the payoff a coalition can obtain on its own and the payoff received by the proposed allocation: the larger the excess of a particular allocation, the less a coalition is satisfied with this allocation. In that sense, the nucleolus may be related to the Rawlsian philosophy that worse-off regions (those with the highest excesses) should be first satisfied. Hence, the nucleolus increases stability in the sense that it minimises the highest dissatisfaction among all coalitions, and the coalitions with the highest dissatisfaction levels are likely to have incentives to defect (Van Steenberghe, 2003). The nucleolus always exists, is unique and lies within the core provided the core is non-empty.

- *The Germain-Toint-Tulkens transfer rule* (Germain *et al.*, 1999) consists of both a payment by each region that represents its gain of cooperation over non-cooperation, and a payment to each region that divides the world gain of cooperation in proportion to each regions' preference for environmental quality, as represented by the marginal climate damages. According to this rule, regions that benefit more from emission reductions pay more, i.e. they bear a larger share of the burden, and regions with high environmental preferences or high regional damages receive more. Germain *et al.* (1999) show that if damages are linear in temperature, the rule results in strategic stability in the sense of the γ-core.

- *The equalization of total abatement cost per GDP* refers to the horizontal equity principle of comparable burdens: all regions should be affected "similarly". For example, the study by Bosello *et al.* (2001) suggests that the equalization of abatement costs per GDP and per capita would be more fruitful in inducing large stable coalitions than social equity rules. Total abatement cost is defined as the difference between the cost incurred under cooperation and the cost incurred in the individual Nash strategy, including both energy and damage costs.

5.2 Number of players and scenarios

The total discounted gain of a coalition *S* is defined as the difference between the total discounted costs of *S* under the partial agreement Nash equilibrium w.r.t. *S* (see section 3.3.1) and the sum of the total discounted costs of the members of *S* under the individual Nash equilibrium. The calculation of transfers requires the computation of the gain for every possible coalition structure of the game, i.e. each partition of the set into subsets. The number of coalition structures is 15 for 4 players, 52 for 5 players, 203 for 6 players, and grows very rapidly for larger numbers of players. The assumption that the regions that are out of a cooperative coalition play individually (see section 3.3.1) reduces the number of coalition structures to the number of possible sub-coalitions, namely: 15, 31 and 63 coalitions for 4, 5 and 6 different regions respectively (2^n-1 coalitions for n regions).

The computation of each coalition's gain requires one run of World MARKAL[23]. Therefore, we chose to limit the number of players to four, by regrouping the original 15 regions into 4 "super-regions". USA was kept as a specific region, given its negotiating power, its withdrawal from the current Kyoto Protocol and its large economy and CO_2 emissions. WEU was also kept as a specific region, given its negotiating power and its commitment to act as a bubble. Developing countries, formed by AFR, CSA, CHI, IND, MEX, MEA and ODA, and the rest of OECD and countries with an economy in transition, formed by AUS, CAN, JPN, SKO, EEU and FSU, are the other two regions, noted DC and OCD+. Clearly, DC represents a heavy region in terms of both the high political importance of its participation in climate policies (illustrated by the US withdrawal from the Kyoto Protocol), its cumulative emissions in the base case and its cumulative reduction in the global cooperative case, reflecting the potential for cheap abatement options (Table 6). Moreover, while the regional share of climate damages is very unequal under the reference case REF, regional damages are more evenly shared under the reverse case REV (Table 6). The same remark applies to the emission reductions of regions w.r.t. their BAU situation. However, in both REF and REV cases, DC's reduction remains higher than the world average reduction (Table 6). It is also important to remember that every player now represents a cooperating coalition of countries (except player 1 which is the USA alone). Two consequences follow: first, non-cooperation

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[23] Equivalent to around 617000 rows, 1.5 hours, Cplex 7.5 (interior point), PC Pentium 4, 1.8 GHz, 523 Mo.

with 4 regions is “more” than with 15 regions[24]; for example, the temperature increase reaches 1.43°C with four non-cooperating players and 1.55°C with 15 non-cooperative players in 2050; also, the non-cooperative reduction of cumulative emissions is equal to 66% of the cooperative reduction with 4 players, versus 21% with 15 players (see section 4); second, because DC and OCD+ consist of a large number of different countries, it is rather difficult to outline a uniform strategy that would be optimal for all these countries. We are fully aware of the importance of the choice of four regions on the results; other definitions of the regions may be tested in further work, or better, a higher number of regions may be modeled if the computational constraint can be lifted.

As regards the scenarios, combining different assumptions on a large number of parameters may result in a too-complicated case-by-case analysis, and was somewhat simplified as follows: we kept the contrasted assumptions for damages (REF, REV), given their crucial role in the allocation of the gain, and for base case (A1B, FOS), given their effect on energy/emission decisions.

Table 6. Characteristics of the 4 regions[25]

	Share (%) of cum emi	Marginal dam (US$$_{2000}$/tCO$_2$) and regional share (%)		Cum emissions (%) w.r.t. A1B-BAU			Share (%) w.r.t. World cum emission reduction		
	BAU	-	-	COOP	NASH	NASH	COOP	NASH	NASH
	A1B-BAU	REF damages	REV damages	A1B-REF	A1B-REF	A1B-REV	A1B-REF	A1B-REF	A1B-REV
USA	14.5%	0.78 (3.4%)	5.00 (22.0%)	-33.8%	-1.7%	-14.1%	11.9%	1.0%	8.7%
WEU	10.0%	4.10 (18.0%)	5.23 (23.0%)	-40.0%	-17.1%	-20.2%	9.7%	6.6%	8.6%
DC	57.8%	16.45 (72.3%)	6.37 (28.0%)	-43.6%	-39.7%	-26.5%	61.3%	88.7%	65.0%
OCD+	17.7%	1.40 (6.1%)	6.14 (27.0%)	-39.6%	-5.5%	-23.7%	17.1%	3.7%	17.8%
World	100.0%	22.75 (100%)	22.75 (100%)	-41.1%	-25.9%	-23.6%	100.0%	100.0%	100.0%

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[24] See the numerical results in appendix B, Table B.11.

[25] See the results related to FOS in appendix B, Table B.10.

5.3 Results on allocations and transfers

Temperature increase and emission reach[26], in 2050, 1.43°C, 1.46°C, 10.3 GtC and 10.7 GtC under A1B-NASH-REF and A1B-NASH-REV scenarios respectively. The same results under base case and cooperative scenarios are 1.60°C, 1.33°C, 17 GtC, and 7.3 GtC respectively. Temperature increase and emission reach 1.49°C, 1.50°C, 12.8 GtC and 11.9 GtC under FOS-NASH-REF and FOS-NASH-REV scenarios against 1.69°C, 1.33°C, 23.7 GtC and 7.8 GtC under FOS-BAU and FOS-COOP scenarios.

We now focus on transfers and allocations. Figure 3 and Table 7 show the allocation of the world gain of cooperation and the amounts of transfers between the four regions, for the four allocation rules: Nucleolus (NU), Shapley Value (SV), Germain-Toint-Tulkens' solution (GTT) and equalization of total abatement cost per GDP (TAC).

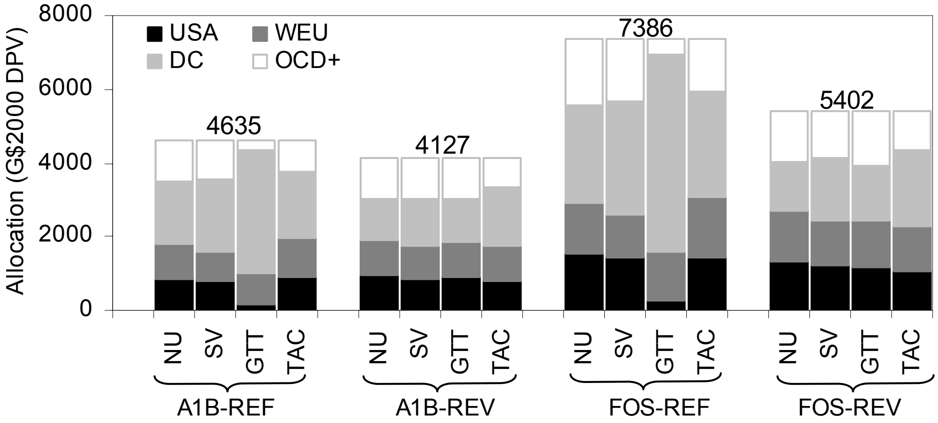

Figure 3. Allocation of the gain of cooperation over non-cooperation[27]

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[26] See the numerical results in appendix B, Figure B. 1 and Figure B. 2.

[27] See the numerical results in appendix B,Table B.12 to Table B.16.

Table 7. Transfers between regions (G$$_{2000}$ DPV and % of total transfers)

Scenario	Rule	USA		WEU		DC		OCD+		Transfers
A1B-REF	NU	1493	(48%)	-28	(-1%)	-3077	(-99%)	1612	(52%)	3106
	SV	1405	(47%)	-119	(-4%)	-2837	(-96%)	1552	(52%)	2957
	GTT	792	(52%)	-116	(-8%)	-1414	(-92%)	739	(48%)	1532
	TAC	1520	(51%)	99	(3%)	-2968	(-10%)	1348	(45%)	2968
A1B-REV	NU	-424	(-26%)	-769	(-48%)	1591	(100%)	-397	(-24%)	1591
	SV	-522	(-29%)	-846	(-47%)	1785	(100%)	-416	(-23%)	1786
	GTT	-488	(-29%)	-754	(-46%)	1636	(100%)	-393	(-24%)	1637
	TAC	-605	(-29%)	-767	(-37%)	2083	(100%)	-710	(-34%)	2083
FOS-REF	NU	2378	(50%)	-101	(-2%)	-4629	(-98%)	2353	(50%)	4732
	SV	2231	(50%)	-266	(-6%)	-4210	(-94%)	2245	(50%)	4477
	GTT	1075	(52%)	-112	(-5%)	-1926	(-94%)	962	(47%)	2038
	TAC	2236	(51%)	232	(5%)	-4401	(-99%)	1932	(44%)	4401
FOS-REV	NU	-355	(-19%)	-843	(-45%)	1837	(100%)	-638	(-35%)	1838
	SV	-482	(-22%)	-974	(-45%)	2162	(100%)	-705	(-33%)	2162
	GTT	-518	(-26%)	-951	(-47%)	1999	(100%)	-530	(-26%)	2000
	TAC	-670	(-26%)	-967	(-37%)	2584	(100%)	-945	(-36%)	2584

Remark: Negative values mean that the region is a donor. Recall also that a transfer is the difference between the regional costs under cooperation before and after allocation of the global gain. For example: under A1B-REF, the gain of cooperation over non-cooperation of DC is 4767 G$ (not shown here); however, the NU rule allocates 1690 G$ to DC (Figure 3). It means that DC is ready to "loose", in other words, transfer 3077 G$ to other players (Table 7) in order to guarantee the cooperation of all regions.

As a first result, the total gain of cooperation over non-cooperation (Figure 3) decreases under the REV case, and it is higher under the more emitting FOS base case. This latter observation, already observed with 15 regions, confirms that an optimistic base case may underestimate the potential benefits of cooperation (but also the difficulties in reaching an agreement - see section 4.3). The former observation is explained by the fact that the increase in the cost incurred by USA, WEU and OCD+ under NASH-REV compared to NASH-REF does not fully cover the decrease in the cost incurred in DC under NASH-REV, so that the total cost of non-cooperation under REV is smaller than under REF. This is equivalent to saying that a more evenly distributed mitigation, resulting from more evenly distributed damages, costs less.

As a second result, we verified that the four allocations are in the γ-core of the game. In other words, they all guarantee that every (sub-)coalition enjoys at least as much as it can obtain on its own. In fact, the core of this game allows for a relatively large flexibility in the selection of allocations. Consequently, the choice of the allocation will depend on the properties of the allocations that the decision-makers would favour in the light of international negotiations. Moreover, the possible variation of payoffs (not shown here) is higher under REF than under REV cases; in other words, the more asymmetric the regions, the higher are free-ride incentives but also the flexibility in sharing the cost of cooperation.

As a third result, the different rules obviously lead to different allocations and transfers, as shown also by Eyckmans and Tulkens (2003), Eyckmans and Finus (2003), Filar and Gaertner (1997), Van Steenberghe (2003), or also by Vaillancourt (2003) using a multicriterion analysis which combines several conflicting and more socially oriented visions of equity. Several remarks follow.

- First, the GTT rule favours regions with high climate damages, so that DC receives a higher share of the gain under REF cases, while USA and OCD+ receive a much smaller share (Figure 3). Under REV cases, allocations are more evenly distributed among regions since damages are also more evenly distributed (Figure 3).

- Second, the comparison of SV and NU solutions shows that only DC prefers the allocation provided by SV (Figure 3). This result reflects the merit property of the SV (see section 5.1), according to which regions receive in proportion to their contribution to the world gain of cooperation. Because of its low abatement costs, DC's contribution to the world reduction under cooperation, and then to the world gain of cooperation, is high. The other three regions prefer the allocation provided by NU, which favours regions with large abatement costs and/or low benefits from climate policies, since such regions are likely to be less satisfied with world climate strategies (see section 5.1).

- The NU allocation under REV deserves a specific remark: DC and OCD+ receive the same gain under A1B and the total gain is equally shared among the four regions under FOS (Figure 3). In fact, the order of excess minimization of every sub-coalition indicates the level of dissatisfaction and then the free-ride incentive faced by every sub-coalition. Under A1B-REF, the sub-coalition formed by {USA, DC, OCD+} and its complementary coalition[28] equivalent to the singleton {WEU} are the first to be satisfied. The second

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[28] By definition, when the payoff allocated to a sub-coalition formed by 3 regions is defined, the payoff allocated to the 4th region is fixed and equal to the remaining gain.

ones are the sub-coalition formed by {WEU, DC, OCD+} and its complement {USA}; indeed, {USA, DC, OCD+} and {WEU, DC, OCD+} have high benefits under non-cooperation and will gain little from the world cooperation. The third coalitions to be satisfied are both {DC} and {OCD+}, which means that no intermediate coalitions have an incentive to form[29] and none of these two regions is dissatisfied with cooperation as far as the cooperation of USA and WEU is guaranteed, so that the remaining part of the world gain is equally shared. Under FOS-REF, no intermediate coalition has the power to impact the allocation of the world gain[81], so that the world gain is divided equally between the four regions. In other words, more evenly distributed damages and higher emission reductions tend to favour more equal distribution of the world cooperation gain.

- Given their definition (section 5.1), abatement costs represent the negative of the regional gains of cooperation. Therefore, the TAC allocation guarantees the equalization of the regional gains per GDP to the world gains per GDP, which reach 0.32%, 0.28%, 0.50% and 0.37% under A1B-REF, A1B-REV, FOS-REF and FOS-REV respectively (not shown here). The TAC allocation favours WEU and DC, reflecting the high GDP of these regions, while OCD+ receives the smallest part of the world gain compared to the other rules.

- The analysis of transfers (Table 7) shows that a donor can become a receiver in another context. For example, under REF scenarios, WEU becomes a receiver under TAC, while it contributes to payment in the other solutions. More globally, under the REF scenarios, DC and, to a lesser extent, WEU, pay for USA and OCD+ accepting to cooperate. At the opposite, under the REV scenarios, USA, WEU and OCD+ pay for DC accepting to cooperate. In other words, transfers are very sensitive to the level of regional climate damages. Moreover, the total amount of transfers depends also on the allocation's rule: the highest amount of total transfer occurs with the nucleolus, the smallest amount occurs under GTT allocation. The choice of the allocation rule then raises the question of whether the implementation of transfers would be easier when the absolute level of

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[29] The sub-coalitions that have an impact on the allocation of the world gain (in the nucleolus sense) are the ones that guarantee to themselves under non-cooperation a payoff equal to more than the half of the world gain. Under FOS-REF, no sub-coalition can guarantee itself such a payoff, so that the world gain is equally shared between regions.

transfers is lower. Moreover, we observe (not shown here) that the transfers given by donors represent a smaller fraction of their benefits before transfers (although this fraction reaches up to 65% under A1B-REF) than the transfers received by receivers in proportion to their costs before transfers. Germain and van Ypersele (1999) also observe this result with time-dependent transfers.

- Although the mitigation efforts do not aim at reducing the world inequities, it is interesting to note that under REV scenarios, the transfers flow from richer to poorer regions and may contribute to reduce inequities (Table 7). We also note that TAC transfers are the most favourable to DC.

- Finally, the comparison of results between our approach and a multicriterion analysis (Vaillancourt, 2003) confirms that scenarios based on REV damages could be considered as scenarios satisfying some equity preoccupations[30]. Indeed, transfers obtained under REV scenarios are more favourable to developing countries than transfers obtained by the Vaillancourt's cases, which were the most favorable to developing countries (more emission rights allocated to developing countries). In other words, approaches based on a single economic criterion, such as ours, may also be appropriate for integrating the social equity criterion in the burden-sharing.

As a fourth result, the cost incurred by a sub-coalition decreases under a multi-coalition structure when outsiders form another sub-coalition instead of playing as singletons[31]. This expected result is explained by smaller damages resulting from smaller world emissions when outsiders form another coalition and reduce more their own emissions compared to their individual Nash strategy. However, the decrease of the cost incurred by a coalition under a multi-coalition structure remains small (between 0 and 1.7%, depending on coalitions and scenarios). Finus and Rundshagen (2002) point that it may be the case that more could be achieved if separate agreements were designed for different group of countries. However, in cases studied by Bosello *et al.* (2001), the possibility of multiple coalitions is of no help for increasing coalitions'stability. This issue deserves more attention in future work.

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[30] See the numerical results in appendix B, Table B.17.
[31] See the numerical results in appendix B, Table B.18 and Table B.19.

Finally, results are of course very sensitive to the regional disaggregation of the world. As pointed in section 5.2, every region represents a group of cooperating countries, so that a higher level of cooperation is implicitly assumed with a more limited number of regions. Moreover, several allocation rules are sensitive to the regional disaggregation: both the nucleolus (as noted by Van Steenberghe, 2003) and the Shapley Value, consider the absolute gain from cooperation, without paying attention to the size of the coalitions enjoying this surplus, while the other solutions are based on proportional sharing (related to damages or GDP). Another definition of the nucleolus considers the per capita excess, and of course, any other variant could also be used.

We voluntarily did not try to explain the differences or similarities between our numerical results and those provided by other studies (for example, Hackl and Pruckner, 2002; Fankhauser and Kverndokk, 1996; Pinto, 1998) since the numerical results are highly dependent on the mitigation costs and climate benefits specified in each model, as noted by most authors. However, the general trends of our results are in agreement with those observed in similar approaches such as Eyckmans and Tulkens (2003), Eyckmans and Finus (2003), Finus *et al.* (2003) and Van Steenberghe (2003).

6. FARSIGHTED STABILITY

We complete the analysis by a study of the (in)stability of intermediate coalitions without transfers. The assumptions of the γ-core are no longer made..

Under a myopic analysis without transfers, where players consider only the immediate consequences of their own defection and not the possible subsequent defections by other players, the grand coalition is not internally stable in the sense of the cartel approach (see section 2.2): every region except DC is better off if it leaves the agreement and assumes the others still cooperate (not shown here). DC is a special case: because of high marginal damages, it is better off remaining in the grand coalition so that all regions take into account its damages and reduce their respective emissions. At the opposite, each of the other regions has an incentive to leave the coalition and then not to pay for the high damages of DC.

The farsighted analysis is more representative of a region' decision to deviate as it takes into account the full possible subsequent deviations by all remaining regions, and it may be rich in learnings about intermediate coalitions that are internally stable without transfers. We make the assumption that coalitions will not merge again after deviating, and that multiple coalitions are not allowed[32]. The deviation by each region is analyzed by checking the regional costs[33] (energy costs + damages) resulting from *each possible subsequent deviation*. The results show that introducing farsightedness may restrict the number of credible free-riding strategies, a result also found by Eyckmans (2001).

For example, let us analyze the deviation by USA from the grand coalition in the A1B-REF case (Table 8). If USA deviates from the grand coalition, it would be better off whatever the other regions decide, since its cost under cooperation is the highest one USA may pay. So, USA will defect. Will WEU, DC and OCD+ still cooperate? OCD+ is better off if it leaves the remaining coalition, whatever WEU and DC do, since its cost under {WEU,DC,OCD+} is higher than under {WEU,DC} and under non-cooperation. Then, OCD+ will defect if USA defects. Finally, WEU also has an incentive to leave the remaining coalition since its cost under {WEU,DC} is higher than under non-cooperation. In other words, the grand coalition is unstable under A1B-REF: at least USA has an incentive to leave the grand coalition, eventually resulting in the individual Nash solution. The similar analysis of all other possible defections from the grand coalition (not shown here) shows that no intermediate coalition is internally stable. In this case, farsightedness does not increase the stability of any coalition.

Table 8. Deviation of USA from the grand coalition[34]

		A1B-REF			
		Cost (G$_{2000}$ DPV)			
Coalition	Defectors	USA	WEU	DC	OCD+
{All}	None	59342	53657	147902	52353
{WEU,DC,OCD+}	USA	58525	54121	149620	52526
{DC,OCD+}	USA,WEU	58610	53995	150628	52388
{WEU,OCD+}	USA,DC	58659	54328	151326	51830
{WEU,DC}	USA,OCD+	58668	54705	151740	51825
{None}	All	58711	54610	152669	51900

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[32] These assumptions aim only at simplifying the analysis.

[33] Regional costs are the ones computed for every possible coalition structure (see section 5.2).

[34] See the results for the other deviations in appendix B, Table B.20.

Table 9. Deviations from the Kyoto coalition

		A1B-REF				
		Cost (G$$_{2000}$ DPV)				Emi (GtC)
Coalition	Defectors	USA	WEU	DC	OCD+	World
{USA,WEU,OCD+}	DC	58772	54094	150308	51782	467
{WEU,OCD+}	DC,USA	58659	54328	151326	51830	484
{USA,WEU}	DC,OCD+	58799	54425	151769	51852	493
{USA,OCD+}	DC,WEU	58712	54479	152121	51866	498
{none}	All	58711	54610	152669	51900	507

Let us now assume that DC is out of the agreement, so that the remaining cooperative coalition is representative of the Kyoto Protocol[35] (Table 9). Does any region have an incentive to leave the remaining coalition? If USA deviates, it is better off whatever WEU and OCD+ decide: (58772 G$ if it cooperates with WEU and OCD+, 58659 G$ if it leaves the coalition but WEU and OCD+ still cooperate, and 58711 G$ if WEU or OCD+ defects). But, neither WEU nor OCD+ have an incentive to break apart and play the individual Nash strategies, since their respective costs would then increase: the cost of WEU is 54610 G$ in the Nash solution, compared to 54328 G$ if WEU still cooperates with OCD+; the cost of OCD+ is 51900 G$ in the Nash solution, compared to 51830 G$ if OCD+ still cooperates with WEU. Consequently, the coalition formed by WEU and OCD+, while USA and DC are singletons, is internally stable. Similar analyses of the defections by WEU and OCD+ from the Kyoto coalition demonstrate that such defections would be irrational for WEU and OCD+. It should however be noted that the forming of the stable subcoalition {WEU,OCD+} results in rather small world emission reduction (one fourth of the reduction of global cooperation), which is in agreement with other studies of non-cooperative strategies (Botteon and Carraro, 1998; Carraro and Siniscalco, 1998; Hackl and Pruckner, 2002; Tol, 2001).

Sensitivity analysis conducted with A1B-REV (not shown here)[36] demonstrates that the intermediate coalition formed by USA and WEU is internally stable without transfers. Emission reduction is also small (one tenth of the reduction of global cooperation). Sensitivity

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[35] Given our data, this decision is irrational for DC, since its cost then increases whatever the other regions decide.

[36] See the results in appendix B, Table B.21.

analyses conducted with the FOS base case[37] show no different conclusion than with A1B. It would be interesting to evaluate the required level of damages making the grand coalition internally stable. The intuition is to increase damages in regions with high abatement costs; indeed, these regions are likely to defect if their local damages are small compared to the world damages they have to pay for in the global cooperation.

7. CONCLUSION

The modeling of cooperative and non-cooperative climate strategies with an integrated version of the multi-regional world MARKAL model allows the study of conditions for a world self-enforcing agreement on climate change with side-payments. The key elements of our approach are: the modeling of the technology and emission abatement decisions (with MARKAL), the carbon cycle (based on existing climate models) and the regional damages (based on the literature). Despite the uncertainties with respect to the parameters, the results offer some insights on the economic incentives for CO_2 abatement and different possibilities for sharing the burden of reducing CO_2 among the different regions. This project appears to be the first one of the sort using a large and technology rich model such as MARKAL and the fact that our results generally confirm others obtained by top-down models is a positive result that confers added credibility to both lines of work.

As regards the required effort to bridge the gap between non-cooperative and cooperative climate strategies, the study suggests that non-cooperation, as modeled by a Nash equilibrium, is closer to the base case than to the cooperative solution in terms of climatic, energy and emission results. The world cooperation surplus increases with the level of emissions in the base case and with the level of asymmetries of climate damages among regions. Therefore, the energy structure of the base case is crucial to both the energy and technology decisions required to mitigate climate change, as well as to the side-payments emerging from a self-enforcing international agreement. The results show, among other things, the crucial role of CO_2 capture and sequestration; the robustness of combined cycle gas turbine, as it provides a transition to more advanced fossil and zero-carbon technologies; the possible increase of the future primary consumption of coal when associated with the

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[37] See the results in appendix B, Table B.22 and Table B.23.

capture of flue gas CO_2 at power plants; the substitution of oil by biofuels in transportation, to the extent allowed by a sustainable supply of biomass; and finally the price-induced reduction of elastic demands, especially under high emission reduction strategies.

As regards the analysis of transfers, the four proposed rules, inspired by cooperative game-theoretic principles, lead to contrasted allocations and transfers that guarantee the stability of the world cooperation. This offers flexibility in the choice of the preferred sharing of the burden, which will depend on the properties of the allocations that the decision-makers would prefer in the light of international negotiations. In fact, the more asymmetric the regions (when damage costs are unevenly distributed among regions), the higher the free-ride incentives but also the flexibility in sharing the cost of cooperation (contrasted allocations of the gain). The results are particularly sensitive to the climate damages as well as to the level of the required abatement itself. It is interesting to note that the analysis of a farsighted framework, closer to the cartel approach, shows that intermediate coalitions might be stable without transfers. Thus, for practical reasons, decision-makers may prefer second-best solutions such as intermediate coalitions without transfers, to first-best solutions such as the social optimum with transfers.

Further work could take into account several of the caveats of the current work. *As regards climate modeling*, a more complex climate model could be used with the same approach, although the simplified climate model proposed by Nordhaus and Boyer (1999) is recognized as already capturing much of the information on temperature change (Drouet *et al.*, 2004; Germain *et al.*, 2002). A longer time horizon, made possible with the advanced TIMES modeling framework (ETSAP, 2005) would also be desirable, raising the question of the validity of the relationship between cumulative damages and cumulative emissions. *As regards MARKAL modeling*, other greenhouse gases are being introduced, given their potential to reduce abatement costs in the short-term (Hyman *et al.*, 2003). Different assumptions for social discounting rates (values, path, geographic variation) might also reflect different valuation of distant benefits of climate mitigation. Other OPEC's behaviour (competitive oil markets; other future price assumptions; etc.) and the effects of climate policies on international trade would also deserve more attention, given their impact on the modeling of non-cooperative scenarios. *As regards the modeling of non-cooperative and partially cooperative scenarios*, removing the computational constraint would help model a larger, more realistic number of regions, which would be an important added value to the proposed methodology, since both the overall gain of cooperation and the allocations are sensitive to the level of regional disaggregation. Moreover, different characteristics of the game might be explored; for example, a feedback structure would allow the computation of the time path of transfers and the study of renegotiation of climate coalitions; the approach proposed by Yang (2003) and expressing the closed-loop solution as a series of open-loop equilibria deserve more attention; a multi-coalition structure would also help understand whether separate agreements could contribute to identify stable intermediate coalitions. Finally, given the uncertainties associated to several of the crucial parameters of the study (e.g. level and distribution of damages, climate parameters), the feasibility of going beyond the deterministic structure of the game should be explored, via the stochastic version of the TIMES model.

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APPENDIX A

GAME-THEORETIC DEFINITIONS[38]

***Profitability and stability**:* The likelihood of a coalition S is defined by S's profitability and stability.

- A coalition S is *profitable* when the gain received by each country belonging to S is higher than the gain it would receive outside the coalition. Profitability is necessary for a coalition (or an agreement) to come into force, but not sufficient, given free-ride incentives.

- A coalition S is *stable* when it is immune to deviations. Stable coalitions are synonym for self-enforcing agreements: no country wants to change its course of action, given the action of the other countries. The formal definition of stability varies, as discussed in section 2.2.

***Pareto-solution**:* An allocation or assignment of resources is Pareto optimal when it is not possible to improve the well-being of one individual without harming at least one other. Then, the total marginal damage over all countries equals each country's marginal cost.

Nash equilibrium: Assuming that all other players stick to their respective *Nash* strategy, no country can improve its payoff by playing another strategy than its Nash strategy.

***Characteristic function**:* The characteristic function of a cooperative game specifies the worth of each coalition, i.e. the gain that a coalition can guarantee to its members, whatever the actors outside do. It relies on the definition of countries' behaviour if some of them defect (see section 3.3.1).

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[38] Among the numerous comprehensive books on game theory, we may retain Fudenberg and Tirole (1991), as a mathematical-oriented book, and Shubik (1985), as an application-related book.

***Core**:* The core of a game is the set of all allocations x_i such that:

$$\Sigma_{i=1,\,n}\, x_i = v(N) \text{ and } \Sigma_{i\in S}\, x_i \geq v(S) \qquad (A1)$$

with v the characteristic function of the cooperative game
x_i the imputation of i
n number of players in the game
N the grand coalition
S any sub-coalition

Characteristic function: The characteristic function of the cooperative game is defined as:

$$v(S) = C_{PANE}(S) - \Sigma_{i\in S}\, C_{NASH}(i) \qquad (A2)$$

with		
	$C_{PANE}(S)$	the total discounted costs of S under Partial Agreement Nash Equilibrium where regions of S cooperate and regions out of S play their individual Nash strategy
	$C_{NASH}(i)$	the cost borne by region i of S under its individual Nash strategy

Shapley value: The Shapley value is calculated as:

$$\phi_i = \sum_{S\subseteq N\setminus\{i\}} \frac{(n-s)!\,(s-1)!}{n!} \times \left[v(S \cup \{i\}) - v(S) \right] \qquad (A3)$$

with s number of players in the coalition S

Nucleolus: The nucleolus is the set of all allocations x_i such that the excesses of the coalitions are the lexicographical minimum. Its first concern is with the highest excess, which is minimized; then, the second highest excess is made as low as possible, and so on. The nucleolus is computed by solving iteratively the set of equations (A4). The value obtained after each iteration replaces *e* in equations with no surplus and with non-zero dual price (a zero dual price would mean that the equation is not active).

$$\text{min } e \text{ submitted to } e \geq v(S) - \Sigma_{i\in S}\, x_i\,, \quad e(x,S) = v(S) - \Sigma_{i\in S}\, x_i \qquad (A4)$$

with e(x,S) the excess related to the imputation x for a coalition S

If e < 0, $v(S) < \Sigma_{i\in S}\, x_i$ => S receives more than its potential v(S), |e| represents a gain
=> S is satisfied, but the higher e (e negative), the less S is satisfied
If e > 0, $v(S) > \Sigma_{i\in S}\, x_i$ => S receives less than its potential v(S), e represents a loss
=> S is not satisfied, and the higher e, the more S is dissatisfied

Germain-Toint-Tulkens transfers: The GTT transfers[39] are calculated as:

$$T_i = \left[C_i^{COOP} - C_i^{NASH} \right] - \frac{d_i}{\sum\limits_{j=1,n} d_j} \times \left[\sum_{j=1,n} C_j^{COOP} - \sum_{j=1,n} C_j^{NASH} \right] \qquad (A5)$$

with	T_i	the transfer received by region i (if $T_i < 0$, T_i is paid by i)
	C_i^{COOP}	the cost borne by i under the world cooperation
	C_i^{NASH}	the cost borne by i under the individual Nash strategy
	d_i	the marginal damages of i

Equalization of abatement cost per GDP[40]: It refers to the following calculation:

$$\frac{C_1^{COOP} - C_1^{NASH} - T_1}{GDP_1} = \dots = \frac{C_i^{COOP} - C_i^{NASH} - T_i}{GDP_i} = \frac{\sum\limits_{k=1,n} (C_k^{COOP} - C_k^{NASH})}{\sum\limits_{k=1,n} GDP_k} \qquad (A6)$$

with	T_i	the transfer received by region i (if $T_i < 0$, T_i is paid by i)
	GDP_i	the gross domestic product of region i

(A6) means that: $T_i = C_i^{COOP} - C_i^{NASH} - \theta \times GDP_i$, $\theta = \frac{\sum\limits_{k=1,n} (C_k^{COOP} - C_k^{NASH})}{\sum\limits_{k=1,n} GDP_k}$ (A7)

with	θ	the world abatement cost per GDP, also equal to the world gain of cooperation

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[39] In open-loop structure, transfers, costs, GDP do represent the lump-sum discounted values for 2000-2050.

[40] Idem

APPENDIX B

DETAILED RESULTS OBTAINED FOR COOPERATIVE AND NON-COOPERATIVE SCENARIOS

This appendix includes all the numerical results that are discussed but not presented in a detailed manner in chapter V.

Table B.1 to Table B.9 refer to the section 4.

- Table B.1 to Table B.3 complete the results for A1B scenarios;
- Table B.4 to Table B.8 include the detailed results for FOS scenarios;
- Table B.9 computes the free-rider incentive index (Finus *et al.*, 2003).

Table B.10, Table B.11, Figure B. 1 and Figure B. 2 refer to the beginning of section 5.

- Table B.10 characterize the four regions under FOS scenario (section 5.2.);
- Table B.11 compare the results obtained with 15 players and the ones obtained with 4 players (section 5.2.);
- Figure B. 1 and Figure B. 2 illustrate the climatic and emissions results under A1B and FOS scenarios (section 5.3.).

Table B.12 to Table B.19 detail the results associated to allocations and transfers presented in section 5.3.

- Table B.12 and Table B.13 detail the regional costs for the different coalitional structures of the game; these costs are used to compute the allocations and transfers;
- Table B.14. provide the numerical values of the allocations of the gain;
- Table B.15 compares the allocations to the maximal payoff a region may receive, and Table B.16 compares the different allocations to the limits of the core;
- Table B.17 computes the transfers obtained by Vaillancourt (2003).
- Table B.18 and Table B.19 analyze the impacts of the uni-coalition and the multi-coalition structure on the costs.

Table B.20 to Table B.23 analyze the internal stability of farsighted coalitions without transfer and refer to section 6.

Table B.1. Cumulative emissions and emission reduction under A1B scenarios (GtC)

	A1B- REF	A1B-HI	A1B-REV	A1B-HRV	A1B-REF No sink
BAU	684.3	684.3	684.3	684.3	684.3
NOCO	625.5	573.8	633.6	590.3	636.2
COOP	402.8	338.8	402.8	338.8	466.7
Reduction NASH w.r.t. reduction COOP	21%	32%	18%	27%	22%

Table B.2. Economic results under A1B-REF

Total cost (G$_{2000}$ DPV)	
BAU	339525.0
NASH	334925.1
COOP	323530.1
Gain of cooperation (% of COOP costs)	3.5%
Cost of the energy system – from MARKAL (G$_{2000}$ DPV)	
BAU	272214.1
NASH	272515.3
COOP	279697.7
Cumulative damages (G$_{2000}$ DPV) and share of Total cost (%)	
BAU	67310.9 (19.8%)
NASH	62409.7 (18.6%)
COOP	43832.3 (13.5%)
Abatement cost (G$_{2000}$ DPV and % from COOP Total cost)	
COOP (cost COOP - cost NASH)	7182.3 (2.2%)
Reduction of damages (G$_{2000}$ DPV and % from COOP Total cost)	
COOP (dam NASH - dam COOP)	18577.3 (5.7%)

Table B.3. Variations of regional total costs under A1B scenarios (G$$_{2000}$ DPV)

	A1B-REF			A1B-HI			A1B-REV		
	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO
AFR	-3929	-904	-3025	-3929	-2544	-4746	-817	-124	-693
AUS	11	-12	23	-136	-96	-40	-216	-67	-150
CAN	29	-50	80	-436	-193	-243	-187	-86	-101
CHI	189	-146	336	-2448	-1245	-1203	-520	-240	-281
CSA	-1313	-378	-934	-3010	-1329	-1681	-356	-190	-166
EEU	142	-28	170	-172	-199	27	-54	-70	16
FSU	925	161	764	-747	-556	-191	-750	-173	-577
IND	-3614	-846	-2767	-8296	-2856	-5440	-1011	-225	-786
JPN	-173	-68	-105	-1243	-486	-757	-3373	-622	-2751
MEA	-58	-89	31	-644	-680	35	966	-28	994
MEX	-359	-161	-198	-883	-562	-322	-40	-60	20
ODA	-3654	-838	-2816	-7745	-2808	-4937	-550	-188	-362
SKO	-880	-222	-658	-1920	-725	-1195	-253	-80	-172
USA	199	-170	369	-991	-1037	46	-4152	-816	-3336
WEU	-3513	-849	-2664	-10845	-3712	-7133	-4680	-921	-3759
Total	-15995	-4600	-11395	-46806	-19026	-27781	-15995	-3891	-12104

	A1B-HRV			A1B-REF No sink		
	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO
AFR	-2343	-797	-1545	-3074	-759	-2316
AUS	-542	-207	-336	-5	-12	7
CAN	-586	-210	-376	10	-50	59
CHI	-2026	-965	-1061	-19	-121	102
CSA	-1319	-648	-670	-972	-323	-649
EEU	-280	-202	-78	49	-27	76
FSU	-2711	-949	-1761	928	162	767
IND	-2564	-892	-1672	-2786	-709	-2077
JPN	-9045	-2499	-6546	-115	-55	-60
MEA	1303	-162	1465	-375	-27	-348
MEX	-149	-269	120	-341	-136	-206
ODA	-1651	-805	-846	-2744	-687	-2057
SKO	-858	-330	-528	-731	-181	-551
USA	-11156	-3420	-7736	159	-129	288
WEU	-12880	-3629	-9251	-2763	-719	-2043
Total	-46806	-15984	-30822	-12780	-3773	-9007

Remark: Negative values represent a gain / Positive values represent a loss

Table B.4. Gain and climatic results under FOS base case (no transfer)

	FOS-REF	FOS-HI	FOS-REV	FOS-HRV	FOS-REF No sink
Gain of cooperation over non-cooperation (G$\$_{2000}$ DPV)					
World	17808.8	38397.6	18007.4	42205.4	13587.6
Net emissions in 2050 (GtC)					
BAU	23.7	23.7	23.7	23.7	23.7
NOCO	20.7	16.3	20.1	17.7	21.3
COOP	7.8	6.2	7.8	6.2	12.0
CO_2 concentration in 2050 (ppm)					
BAU	551.9	551.9	551.9	551.9	551.9
NOCO	530.6	505.3	530.4	511.3	534.1
COOP	435.6	416.7	435.6	416.7	462.2
Temperature increase in 2050 (°C)					
BAU	1.69	1.69	1.69	1.69	1.69
NOCO	1.63	1.56	1.64	1.58	1.64
COOP	1.33	1.25	1.33	1.25	1.42

Table B.5. Emissions and emission reduction under FOS scenarios (GtC)

	FOS-REF	FOS-HI	FOS-REV	FOS-HRV	FOS-REF No sink
BAU	808.6	808.6	808.6	808.6	808.6
NOCO	737.1	650.7	736.3	671.5	749.4
COOP	413.5	345.2	413.5	345.2	505.0
Reduction NASH w.r.t. reduction COOP	18%	34%	18%	30%	20%

Table B.6. Economic results under FOS-REF

Total cost ($G\$_{2000}$ DPV)	
BAU	345996.8
NASH	340389.5
COOP	322580.7
Gain of cooperation (% of COOP costs)	5.5%
Cost of the energy system – from MARKAL ($G\$_{2000}$ DPV)	
BAU	268313.1
NASH	268672.9
COOP	277860.8
Cumulative damages ($G\$_{2000}$ DPV) and share of Total cost (%)	
BAU	77683.7 (22.4%)
NASH	71716.5 (21.0%)
COOP	44719.8 (13.8%)
Abatement cost ($G\$_{2000}$ DPV and % from COOP Total cost)	
COOP (cost COOP - cost NASH)	9187.9 (2.8%)
Reduction of damages ($G\$_{2000}$ DPV and % from COOP Total cost)	
COOP (dam NASH - dam COOP)	26996.7 (8.4%)

Table B.7. Regional strategic choices under FOS base case (no transfer)

	FOS-REF	FOS-HI	FOS-REV	FOS-HRV	FOS-REF No sink
AFR	COOP	COOP	COOP	COOP	COOP
AUS	NASH	COOP	COOP	COOP	NASH
CAN	NASH	COOP	COOP	COOP	NASH
CHI	NASH	COOP	COOP	COOP	COOP
CSA	COOP	COOP	COOP	COOP	COOP
EEU	NASH	COOP	COOP	COOP	NASH
FSU	BAU	COOP	COOP	COOP	BAU
IND	COOP	COOP	COOP	COOP	COOP
JPN	COOP	COOP	COOP	COOP	COOP
MEA	COOP	COOP	NASH	NASH	COOP
MEX	COOP	COOP	COOP	NASH	COOP
ODA	COOP	COOP	COOP	COOP	COOP
SKO	COOP	COOP	COOP	COOP	COOP
USA	NASH	COOP	COOP	COOP	NASH
WEU	COOP	COOP	COOP	COOP	COOP

Table B.8. Variations of regional total costs under FOS scenarios ($G\$_{2000}$ DPV)

	FOS-REF			FOS-HI			FOS-REV		
	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO
AFR	-5385	-1100	-4285	-5385	-3656	-6021	-1016	-182	-835
AUS	-3	-11	8	-225	-109	-116	-322	-76	-246
CAN	74	-61	135	-393	-269	-124	-230	-115	-115
CHI	54	-177	231	-3640	-1685	-1955	-942	-342	-601
CSA	-1806	-485	-1322	-4155	-1854	-2301	-463	-138	-325
EEU	153	-32	184	-289	-275	-15	-122	-94	-28
FSU	1149	225	923	-1320	-804	-516	-1204	-187	-1016
IND	-5098	-1087	-4010	-11273	-4103	-7170	-1444	-330	-1114
JPN	-265	-82	-184	-1702	-695	-1007	-4759	-893	-3865
MEA	-313	-66	-247	-1258	-991	-268	1125	-89	1214
MEX	-563	-225	-338	-1373	-832	-541	-115	-58	-57
ODA	-5256	-1002	-4254	-10799	-4008	-6791	-899	-304	-595
SKO	-1308	-273	-1035	-2691	-1045	-1646	-428	-118	-309
USA	212	-178	389	-1815	-1461	-354	-5898	-1159	-4739
WEU	-5060	-1054	-4006	-14846	-5272	-9574	-6699	-1324	-5375
Total	-23416	-5607	-17809	-65455	-27057	-38398	-23416	-5409	-18007

	FOS-HRV			FOS-REF No sink		
	COOP-BAU	NOCO-BAU	COOP-NOCO	COOP-BAU	NOCO-BAU	COOP-NOCO
AFR	-3042	-1120	-1922	-4088	-933	-3155
AUS	-770	-307	-462	45	-12	57
CAN	-594	-246	-348	62	-61	123
CHI	-3074	-1331	-1744	-160	-148	-12
CSA	-1886	-874	-1012	-1221	-409	-812
EEU	-434	-287	-147	12	-30	42
FSU	-3954	-1495	-2459	1284	252	1031
IND	-3584	-1356	-2229	-3970	-928	-3041
JPN	-12166	-3653	-8513	-178	-68	-111
MEA	1354	-222	1575	-601	-6	-594
MEX	-388	-402	14	-593	-196	-397
ODA	-2625	-1228	-1397	-3855	-835	-3019
SKO	-1266	-487	-780	-1057	-225	-832
USA	-15449	-4952	-10498	37	-144	181
WEU	-17575	-5291	-12284	-3969	-921	-3048
Total	-65455	-23249	-42205	-18252	-4664	-13588

Remark: Negative values represent a gain / Positive values represent a loss

Table B.9. Free-ride index

Annual emission reduction percentage in region i under cooperation
divided by the regional benefits received from abatement (Finus *et al.*, 2003)

	A1B					FOS				
	A1B-REF	A1B-HI	A1B-REV	A1B-HRV	A1B-REF no sink	FOS-REF	FOS-HI	FOS-REV	FOS-HRV	FOS-REF no sink
AFR	0.2	0.1	0.6	0.4	0.1	0.3	0.2	0.5	0.3	0.2
AUS	34.0	1.6	1.1	0.6	32.3	37.0	1.8	0.5	4.0	34.9
CAN	16.5	0.9	1.3	0.7	12.5	21.5	1.2	0.8	2.8	17.1
CHI	5.5	1.3	2.7	1.4	4.5	7.5	1.7	1.7	3.3	6.0
CSA	1.0	0.7	2.0	1.1	0.8	1.3	0.9	1.2	1.2	0.9
EEU	20.9	2.2	3.5	1.8	17.0	31.0	3.1	2.4	6.8	24.8
FSU	na	0.8	0.8	0.5	na	na	1.2	0.5	3.0	na
IND	0.2	0.2	0.8	0.5	0.2	0.4	0.2	0.6	0.3	0.3
JPN	1.3	0.4	0.1	0.1	1.0	2.3	0.7	0.1	1.2	1.9
MEA	2.3	1.6	9.2	5.1	1.8	2.8	1.9	5.1	2.6	2.0
MEX	1.2	0.8	2.4	1.4	0.8	2.5	1.4	2.2	2.0	1.8
ODA	0.4	0.3	1.4	0.8	0.3	0.5	0.3	0.8	0.5	0.4
SKO	0.6	0.4	1.4	0.7	0.4	0.6	0.4	0.6	0.5	0.4
USA	3.1	1.2	0.5	0.3	2.5	4.9	1.7	0.4	3.0	3.9
WEU	0.5	0.3	0.4	0.2	0.4	0.7	0.3	0.2	0.5	0.5

Remarks

- The free-rider incentive index aims at capturing the general incentive to participate in cooperation. A high free-rider index represents a low interest in cooperation: a high numerator means that the region has to contribute a lot to joint abatement, so that its incentive to cooperate is low; a low denominator means that the region doesn't benefit much from the cooperation, so that its incentive to cooperate is low. This index is only a crude measure of the cooperation incentive since its calculation doesn't integrate all the possible coalition structures (Eyckmans and Finus, 2003; Finus *et al.*, 2003);

- "na" corresponds to regions that positive climate damages;

- This table confirm the results presented in section 5.4.: the dependency of the regional interest in cooperation on the estimated or perceived damages; the decrease of the free-ride incentive when sinks are available; the increase of the free-ride incentive under FOS scenarios, i.e. when emissions in the base case are higher, so that larger emission reductions are necessary and abatement becomes more costly.

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Table B.10. Characteristics of the 4 regions under FOS scenarios

	Share (%) of cum emi	Marginal dam ($\text{US\$}_{2000}/\text{tCO}_2$) and regional share (%)		Cum emissions (%) w.r.t. A1B-BAU			Share (%) w.r.t. World cum emission reduction		
	BAU	-	-	COOP	NASH	NASH	COOP	NASH	NASH
	FOS-BAU	REF damages	REV damages	FOS-REF	FOS-REF	FOS-REV	FOS-REF	FOS-REF	FOS-REV
USA	14.7%	0.78 (3.4%)	5.00 (22.0%)	-44.2%	-1.1%	-23.4%	13.3%	0.5%	11.2%
WEU	9.7%	4.10 (18.0%)	5.23 (23.0%)	-46.8%	-21.3%	-26.1%	9.3%	6.7%	8.2%
DC	58.0%	16.45 (72.3%)	6.37 (28.0%)	-50.9%	-47.2%	-33.7%	60.4%	89.4%	63.8%
OCD+	17.7%	1.40 (6.1%)	6.14 (27.0%)	-47.2%	-5.8%	-29.1%	17.1%	3.4%	16.8%
World	100.0%	22.75 (100%)	22.75 (100%)	-48.9%	-30.6%	-30.7%	100.0%	100.0%	100.0%

Table B.11. Comparison of results with 15 and 4 players

A1B	Temperature increase in 2050 (°C)	Atmospheric concentration in 2050 (ppm)	Emissions in 2050 (GtC/yr)	Cum emi 2000-1050 (GtC)	Reduction of cum emi from BAU (GtC)
BAU	1.60	514.4	17.0	700.5	0.0
NASH-REF 15 players	1.55	497.1	15.0	645.7	54.8
NASH-REF 4 players	1.43	459.5	10.3	526.4	174.1
COOP	1.33	432.5	7.3	438.1	262.3

FOS	Temperature increase in 2050 (°C)	Atmospheric concentration in 2050 (ppm)	Emissions in 2050 (GtC/yr)	Cum emi 2000-1050 (GtC)	Reduction of cum emi from BAU (GtC)
BAU	1.69	551.7	23.7	811.4	0.0
NASH-REF 15 players	1.63	530.6	20.7	745.4	66.0
NASH-REF 4 players	1.49	478.3	12.7	585.1	226.3
COOP	1.33	435.6	7.8	447.7	363.8

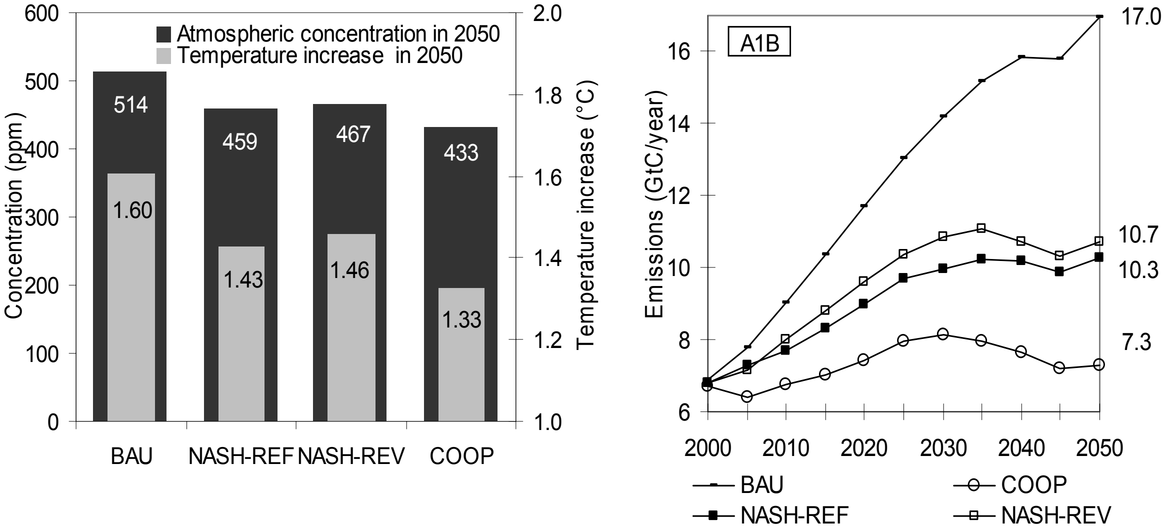

Figure B. 1. Climatic results in 2050 and emission paths with 4 players under A1B scenarios

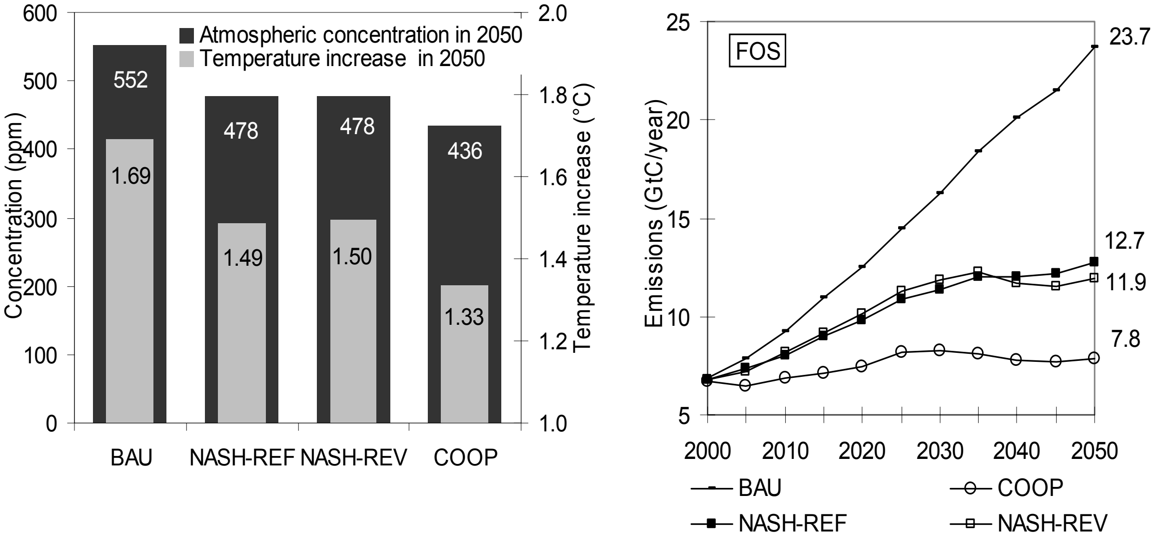

Figure B. 2. Climatic results in 2050 and emission paths with 4 players under FOS scenarios

Table B.12. Total regional costs under A1B scenario (G$$_{2000}$ DPV)

	A1B-REF						
	Structure*	USA	WEU	DC	OCD+	World	Coalition
	BAU	59143	57172	160808	52365	329489	-
COOP	1111	59342	53657	147902	52353	313255	313255
3 regions	1110	59415	54249	150010	51816	315490	263674
	1101	58772	54094	150308	51782	314956	164648
	1011	59220	53536	148983	52291	314029	260493
	0111	58525	54121	149620	52526	314792	256267
2 regions**	1100	58799	54425	151769	51852	316845	113224
	1010	59255	54162	151075	51831	316322	210330
	1001	58712	54479	152121	51866	317178	110578
	0011	58610	53995	150628	52388	315621	203016
	0101	58659	54328	151326	51830	316142	106158
	0110	58668	54705	151740	51825	316938	206446
NASH	0000	58711	54610	152669	51900	317890	-

	A1B-REV						
	Structure*	USA	WEU	DC	OCD+	World	Coalition
	BAU	69725	60010	135502	64251	329487	-
COOP	1111	65572	55328	133004	59350	313253	313253
3 regions	1110	66037	55891	132737	59081	313746	254665
	1101	66716	56609	131749	60339	315413	183664
	1011	65914	55423	132748	59427	313513	258090
	0111	65462	55837	132867	59525	313691	248229
2 regions**	1100	66913	56897	132249	60318	316376	123810
	1010	66499	56309	132588	59796	315192	199087
	1001	66912	56732	132178	60423	316245	127335
	0011	66158	56204	132633	59952	314946	192585
	0101	66678	56890	132192	60544	316305	117434
	0110	66278	56496	132562	59981	315316	189058
NASH	0000	66969	57031	132523	60858	317381	-

* The structure of the game must be read as follows: The four numbers represent the four regions in the order USA, WEU, DC, OCD+. 1 means that the corresponding region does cooperate and belongs to the coalition, 0 means that the corresponding region remains a singleton.
E.g.: 1100 means that USA and WEU cooperate, DC and OCD+ remain as singletons.

** When 2 regions form a coalition, the remaining two regions play individually and do not form any coalition.

Table B.13. Total regional costs under FOS scenario (G$\$_{2000}$ DPV)

	FOS-REF						
	Structure*	USA	WEU	DC	OCD+	World	Coalition
	BAU	59204	58781	165356	52429	335770	-
COOP	1111	59415	53719	146992	52177	312304	312304
3 regions	1110	59537	54591	150198	51408	315734	264326
	1101	58692	54335	150248	51467	314742	164494
	1011	59317	53598	148408	52100	313423	259824
	0111	58324	54474	149897	52454	315150	256826
2 regions**	1100	58802	54764	152517	51522	317605	113566
	1010	59414	54419	151511	51413	316757	210925
	1001	58588	54984	153521	51566	318660	110154
	0011	58432	54352	151150	52307	316241	203457
	0101	58500	54804	152290	51569	317163	106373
	0110	58503	55326	153053	51653	318534	208378
NASH	0000	58596	55163	154260	51671	319690	-

	FOS-REV						
	Structure*	USA	WEU	DC	OCD+	World	Coalition
	BAU	71708	62135	135452	66538	335834	-
COOP	1111	65810	55434	131700	59424	312368	312368
3 regions	1110	66425	56198	131448	59476	313546	254070
	1101	67131	57070	130214	60976	315392	185177
	1011	66252	55531	131429	59925	313137	257606
	0111	65673	56088	131607	60018	313386	247713
2 regions**	1100	67370	57472	130928	61000	316771	124842
	1010	66967	56722	131213	60375	315277	198180
	1001	67320	57164	130767	61192	316443	128512
	0011	66475	56536	131224	60653	314889	191877
	0101	67110	57411	130749	61318	316588	118729
	0110	66686	56978	131249	60470	315382	188227
NASH	0000	67516	57628	131213	61349	317706	-

* See above how the structure of the game must be read.

** When 2 regions form a coalition, the remaining two regions play individually and do not form any coalition.

Table B.14. Allocation of the gain of cooperation over non-cooperation (G$_{2000}$ DPV)

	Rule	USA	WEU	DC	OCD+	World gain
A1B-REF	NU	862	924	1690	1160	4635
	SV	774	833	1930	1099	4635
	GTT	161	836	3353	286	4635
	TAC	889	1052	1799	895	4635
A1B-REV	NU	972	934	1111	1111	4127
	SV	874	857	1305	1091	4127
	GTT	908	949	1156	1114	4127
	TAC	792	936	1602	797	4127
FOS-REF	NU	1559	1342	2639	1847	7386
	SV	1412	1177	3058	1739	7386
	GTT	256	1332	5342	456	7386
	TAC	1417	1676	2867	1427	7386
FOS-REV	NU	1351	1351	1351	1351	5402
	SV	1224	1219	1675	1283	5402
	GTT	1188	1243	1513	1459	5402
	TAC	1036	1226	2097	1043	5402

Table B.15. Comparison of the allocation of the gain of cooperation and the maximal payoff a region may receive

		USA	WEU	DC	OCD+
A1B-REF	*Max payoff * (G$_{2000}$ DPV)*	*1723*	*1848*	*4063*	*2319*
	NU	50%	50%	42%	50%
	SV	45%	45%	48%	47%
	GTT	9%	45%	83%	12%
	TAC	52%	57%	44%	39%
A1B-REV	*Max payoff * (G$_{2000}$ DPV)*	*1945*	*1868*	*2933*	*2270*
	NU	50%	50%	38%	49%
	SV	45%	46%	44%	48%
	GTT	47%	51%	39%	49%
	TAC	41%	50%	55%	35%
FOS-REF	*Max payoff * (G$_{2000}$ DPV)*	*3118*	*2684*	*6450*	*3694*
	NU	50%	50%	41%	50%
	SV	45%	44%	47%	47%
	GTT	8%	50%	83%	12%
	TAC	45%	62%	44%	39%
FOS-REV	*Max payoff * (G$_{2000}$ DPV)*	*3018*	*3022*	*4114*	*3180*
	NU	45%	45%	33%	42%
	SV	41%	40%	41%	40%
	GTT	39%	41%	37%	46%
	TAC	34%	41%	51%	33%

* The maximal payoff of region i is obtained by maximizing X_i whithin the CORE constraints

Table B.16. The definition of the CORE and the excess received by each sub-coalition ($G\$_{2000}$ DPV)

	A1B-REF					A1B-FOS				
	CORE*	NU	SV	GTT	TAC	CORE*	NU	SV	GTT	TAC
X1+X2+X3	2316	1160	1220	2033	1424	1858	1159	1178	1155	1473
X1+X2+X4	572	2373	2133	710	2264	1194	1822	1628	1777	1331
X1+X3+X4	2787	924	1016	1013	797	2259	934	1011	919	931
X2+X3+X4	2912	862	950	1563	834	2183	972	1071	1037	1153
X1+X2	97	1689	1510	900	1844	191	1716	1541	1667	1537
X1+X3	1050	1502	1654	2463	1638	405	1678	1774	1659	1989
X1+X4	33	1988	1840	414	1751	491	1592	1474	1531	1097
X3+X4	1554	1296	1475	2086	1141	795	1426	1601	1475	1604
X2+X4	352	1732	1580	770	1595	455	1590	1494	1609	1279
X2+X3	834	1780	1929	3355	2017	496	1548	1666	1609	2043
X1	0	862	774	161	889	0	972	874	908	792
X2	0	924	833	836	1052	0	934	857	949	936
X3	0	1690	1930	3353	1799	0	1111	1305	1156	1602
X4	0	1160	1099	286	895	0	1111	1091	1114	797

	A1B-REF					A1B-FOS				
	CORE*	NU	SV	GTT	TAC	CORE*	NU	SV	GTT	TAC
X1+X2+X3	3693	1847	1955	3237	2267	2222	1830	1897	1722	2137
X1+X2+X4	936	3811	3392	1108	3583	1289	2763	2438	2601	2017
X1+X3+X4	4703	1342	1506	1352	1008	2380	1672	1803	1780	1797
X2+X3+X4	4269	1559	1706	2862	1701	2385	1667	1793	1829	1982
X1+X2	193	2708	2396	1395	2900	302	2399	2142	2129	1960
X1+X3	1931	2267	2539	3667	2353	484	2217	2416	2217	2649
X1+X4	113	3293	3038	600	2731	326	2375	2182	2321	1754
X3+X4	2475	2011	2322	3324	1819	593	2109	2366	2379	2548
X2+X4	461	2728	2455	1327	2641	220	2481	2282	2481	2049
X2+X3	1045	2936	3191	5629	3498	549	2152	2346	2206	2774
X1	0	1559	1412	256	1417	0	1351	1224	1188	1036
X2	0	1342	1177	1332	1676	0	1351	1219	1243	1226
X3	0	2639	3058	5342	2867	0	1351	1675	1513	2097
X4	0	1847	1739	456	1427	0	1351	1283	1459	1043

* This column represents the minimal coalitional payoffs that an allocation must satisfied in order to belong to the core. E.g.: Under A1B-REF, the core is the set of allocations (X_1, X_2, X_3, X_4) such that:

$$\begin{cases} X_1+X_2+X_3 \geq 2316 \\ X_1+X_2+X_4 \geq 572 \\ X_1+X_3+X_4 \geq 2787 \\ \text{etc.} \end{cases}$$

The other columns represent the excess as defined by the differences between the coalitional payoffs obtained under each allocation rule, and the core's minimal coalitional payoffs as included in the CORE column.

Table B.17. Transfers obtained by a multicriterion approach (Vaillancourt, 2003)

	EFFICIENT SOLUTION	RULE NORTH*	RULE SOUTH*	RULE AFR-AML*
Abatement costs** (G$\$_{2000}$ DPV)				
AFR	767	2692	113	-4460
AUS	70	441	201	323
CAN	111	134	-186	91
CHI	1518	4437	-529	1704
CSA	919	2937	2261	1524
EEU	103	349	-62	-32
FSU	464	595	669	-3676
IND	521	2708	653	1497
JPN	72	-351	-554	372
MEA	746	4365	4051	4212
MEX	395	1643	1393	1484
ODA	520	3278	1188	1582
SKO	68	626	498	613
USA	1316	-12785	-858	1264
WEU	452	-3026	-795	1544
WORLD	*8043*	*8043*	*8043*	*8042*
USA	1316	-12785	-858	1264
WEU	452	-3026	-795	1544
DC	5386	22060	9130	7543
OCD+	889	1794	566	-2309
Transfers*** = ABATEMCOST$_{EFF}$ - ABATEMCOST$_{RULE}$ G$\$_{2000}$ DPV)				
USA		14101	2174	52
WEU		3478	1247	-1092
DC		-16674	-3744	-2157
OCD+		-905	323	3198
WORLD		*0*	*0*	*0*

* The North rule favours the emission needs of industrialzed countries, the AFR-AML rule well as the South rule favour the emission needs of developing countries, but the latter lies between North and SoutB.

** Abatement costs include only the costs of the energy system (computed by MARKAL). Residual climate damages are not included in the study.
Negative values of the abatement costs mean that the region sells permits; in other words, it receives emission rights higher than the efficient reduction.

*** Positive values mean that the region receives transfers by selling permits

Reference:

Vaillancourt, K. (2003). Équité et scénarios mondiaux de réduction des émissions de gaz à effet de serre: Une approche multicritère dynamique combinée au modèle énergétique MARKAL . Thèse de doctorat, Université du Québec à Montréal (UQAM), Département des sciences de l'environnement, Montreal (Canada), p.306.

Table B.18. Comparison of regional and coalitional costs** under uni-coalition and multi-coalition structures (G$\$_{2000}$ DPV)

	A1B-REF						
Structure*	USA	WEU	DC	OCD+	World	$C_{COALITION\_1}$	$C_{COALITION\_2}$
1122 w.r.t. 1100	-105	-619	-1992	464	-2252	-724	-1528
1212 w.r.t. 1010	-47	-286	-1307	-93	-1733	-1354	-379
1221 w.r.t. 1001	-50	95	-867	-1	-792	-51	-741
2211 w.r.t. 0011	84	-189	-851	-72	-1028	-922	-105
2121 w.r.t. 0101	549	-453	-1558	-92	-1553	-545	-1008
2112 w.r.t. 0110	-6	-132	-486	40	-553	-617	65

	A1B-REV						
Structure*	USA	WEU	DC	OCD+	World	$C_{COALITION\_1}$	$C_{COALITION\_2}$
1122 w.r.t. 1100	-807	-811	115	-629	-2132	-1618	-514
1212 w.r.t. 1010	-267	-114	-333	-60	-773	-600	-173
1221 w.r.t. 1001	-708	-538	63	-705	-1888	-1414	-474
2211 w.r.t. 0011	-52	-118	-270	-263	-703	-533	-170
2121 w.r.t. 0101	-447	-695	63	-808	-1886	-1503	-384
2112 w.r.t. 0110	-74	-302	-321	-263	-959	-623	-337

	FOS-REF						
Structure*	USA	WEU	DC	OCD+	World	$C_{COALITION\_1}$	$C_{COALITION\_2}$
1122 w.r.t. 1100	-169	-817	-3107	646	-3448	-986	-2462
1212 w.r.t. 1010	-103	-361	-1905	-81	-2450	-2008	-442
1221 w.r.t. 1001	-97	161	-1133	0	-1043	-97	-946
2211 w.r.t. 0011	201	-405	-1740	-139	-2083	-1879	-204
2121 w.r.t. 0101	810	-746	-2683	-236	-2856	-983	-1873
2112 w.r.t. 0110	-11	-180	-665	-87	-918	-845	-73

	FOS-REV						
Structure*	USA	WEU	DC	OCD+	World	$C_{COALITION\_1}$	$C_{COALITION\_2}$
1122 w.r.t. 1100	-1003	-1119	-70	-727	-2919	-2122	-797
1212 w.r.t. 1010	-428	-235	-497	-61	-1221	-925	-296
1221 w.r.t. 1001	-813	-679	-9	-897	-2399	-1710	-689
2211 w.r.t. 0011	-109	-183	-365	-380	-1037	-746	-291
2121 w.r.t. 0101	-570	-924	-33	-1005	-2532	-1929	-604
2112 w.r.t. 0110	-178	-493	-492	-175	-1338	-985	-354

* The structure of the game must be read as follows: 0 means that the corresponding region remains a singleton, 1 means that the corresponding region does cooperate and belongs to the coalition, 2 means that the corresponding region does form another non-singleton coalition. E.g.: 1122 means that USA and WEU form a sub-coalition, and DC and OCD+ form another subcoalition.

** Negative values mean that the corresponding player is better off. In fact, cooperating players 1 are always better-off if ousiders for a coalition; but outsiders are not always better off when they form a second sub-coalition (e.g. in the A1B-REF scenario, OCD+ is better off under 1100 than under 1122).

Table B.19. Variation of coalitional costs* under uni-coalition and multi-coalition structures ($G\$_{2000}$ DPV)

	A1B-REF	A1B-REV	FOS-REF	FOS-REV
USA-WEU	-0.6%	-1.3%	-0.9%	-1.7%
USA-DC	-0.6%	-0.3%	-1.0%	-0.5%
USA-OCD+	0.0%	-1.1%	-0.1%	-1.3%
DC-OCD+	-0.5%	-0.3%	-0.9%	-0.4%
WEU-OCD+	-0.5%	-1.3%	-0.9%	-1.6%
WEU-DC	-0.3%	-0.3%	-0.4%	-0.5%

* The variation of coalitional costs is defined as the difference between the costs of every 2 player-coalition when outsiders form another coalition, and the costs of the same 2 player-coalition when outsiders play as singletons. Negative variations mean that the coalition is better off when outsiders form a coalition.

Table B.20. Stability analysis of coalitions without transfers under A1B-REF

		Total cost (G$_{2000}$ DPV)				Cum emi (GtC)
		USA	WEU	DC	OCD+	World
DC defects (the remaining coalition is the Kyoto coalition)						
COOP	1111	59342	53657	147902	52353	403
3 players (Kyoto)	1101	58772	54094	150308	51782	467
2 players	1100	58799	54425	151769	51852	493
2 players	1001	58712	54479	152121	51866	498
2 players	0101	58659	54328	151326	51830	484
NASH	0000	58711	54610	152669	51900	507
USA defects						
COOP	1111	59342	53657	147902	52353	403
3 players	0111	58525	54121	149620	52526	437
2 players	0011	58610	53995	150628	52388	465
2 players	0101	58659	54328	151326	51830	484
2 players	0110	58668	54705	151740	51825	482
NASH	0000	58711	54610	152669	51900	507
OCD+ defects						
COOP	1111	59342	53657	147902	52353	403
3 players	1110	59415	54249	150010	51816	449
2 players	1100	58799	54425	151769	51852	493
2 players	1010	59255	54162	151075	51831	477
2 players	0110	58668	54705	151740	51825	482
NASH	0000	58711	54610	152669	51900	507
WEU defects						
COOP	1111	59342	53657	147902	52353	403
3 players	1011	59220	53536	148983	52291	434
2 players	1010	59255	54162	151075	51831	477
2 players	1001	58712	54479	152121	51866	498
2 players	0011	58610	53995	150628	52388	465
NASH	0000	58711	54610	152669	51900	507

Remarks:

- Column 2 must be read as follows. The four numbers represent the four regions in the order USA, WEU, DC, OCD+. 1 means that the corresponding region does cooperate and belongs to the coalition, 0 means that the corresponding region remains a singleton. E.g.: 1100 means that USA and WEU cooperate, DC and OCD+ remain as singletons.
- No intermediate coalition is internally stable when the starting coalition is the grand coalition.
- If the starting coalition in the Kyoto coalition (see DC defects), then the coalition 0101, i.e. {WEU,OCD+} is internally stable.

Table B.21. Stability analysis of coalitions without transfers under A1B-REV

		Total cost (G$_{2000}$ DPV)				Cum emi (GtC)
		USA	WEU	DC	OCD+	World
DC defects (the remaining coalition is the Kyoto coalition)						
COOP	1111	65572	55328	133003	59351	403
3 players (Kyoto)	1101	66716	56610	131749	60340	484
2 players	1100	66913	56897	132248	60318	510
2 players	1001	66912	56733	132177	60424	507
2 players	0101	66678	56891	132192	60545	508
NASH	0000	66969	57032	132522	60859	523
USA defects						
COOP	1111	65572	55328	133003	59351	403
3 players	0111	65462	55838	132866	59526	440
2 players	0011	66158	56204	132633	59952	478
2 players	0101	66678	56891	132192	60545	508
2 players	0110	66278	56497	132561	59981	486
NASH	0000	66969	57032	132522	60859	523
OCD+ defects						
COOP	1111	65572	55328	133003	59351	403
3 players	1110	66037	55892	132737	59081	446
2 players	1100	66913	56897	132248	60318	510
2 players	1010	66499	56309	132588	59797	484
2 players	0110	66278	56497	132561	59981	486
NASH	0000	66969	57032	132522	60859	523
WEU defects						
COOP	1111	65572	55328	133003	59351	403
3 players	1011	65914	55424	132748	59428	436
2 players	1010	66499	56309	132588	59797	484
2 players	1001	66912	56733	132177	60424	507
2 players	0011	66158	56204	132633	59952	478
NASH	0000	66969	57032	132522	60859	523

Remarks:

- See above how column 2 must be read.
- DC has an incentive to deviate from the grand coalition since it is then better off whatever the other players decide.
- The coalitions 1100 i.e. {USA,WEU} is internally stable.

Table B.22. Stability analysis of coalitions without transfers under FOS-REF

		Total cost (G$_{2000}$ DPV)				Cum emi (GtC)
		USA	WEU	DC	OCD+	World
DC defects (the remaining coalition is the Kyoto coalition)						
COOP	1111	59415	53719	146992	52177	413
3 players (Kyoto)	1101	58692	54335	150248	51467	492
2 players	1100	58802	54764	152517	51522	533
2 players	1001	58588	54984	153521	51566	549
2 players	0101	58500	54804	152290	51569	527
NASH	0000	58596	55163	154260	51671	561
USA defects						
COOP	1111	59415	53719	146992	52177	413
3 players	0111	58324	54474	149897	52454	468
2 players	0011	58432	54352	151150	52307	502
2 players	0101	58500	54804	152290	51569	527
2 players	0110	58503	55326	153053	51653	530
NASH	0000	58596	55163	154260	51671	561
OCD+ defects						
COOP	1111	59415	53719	146992	52177	413
3 players	1110	59537	54591	150198	51408	478
2 players	1100	58802	54764	152517	51522	533
2 players	1010	59414	54419	151511	51413	512
2 players	0110	58503	55326	153053	51653	530
NASH	0000	58596	55163	154260	51671	561
WEU defects						
COOP	1111	59415	53719	146992	52177	413
3 players	1011	59317	53598	148408	52100	452
2 players	1010	59414	54419	151511	51413	512
2 players	1001	58588	54984	153521	51566	549
2 players	0011	58432	54352	151150	52307	502
NASH	0000	58596	55163	154260	51671	561

Remarks:

- See above how column 2 must be read.
- No intermediate coalition is internally stable when the starting coalition is the grand coalition.
- If the starting coalition in the Kyoto coalition (see DC defects), then the coalition 0101, i.e. {WEU,OCD+} is internally stable.

Table B.23. Stability analysis of coalitions without transfers under FOS-REV

		Total cost (G$_{2000}$ DPV)				Cum emi (GtC)
		USA	WEU	DC	OCD+	World
DC defects (the remaining coalition is the Kyoto coalition)						
COOP	1111	65810	55434	131700	59360	413
3 players (Kyoto)	1101	67131	57070	130279	61004	510
2 players	1100	67370	57472	130993	61027	544
2 players	1001	67320	57164	130832	61219	537
2 players	0101	67110	57411	130814	61346	539
NASH	0000	67516	57628	131213	61349	561
USA defects						
COOP	1111	65810	55434	131700	59360	413
3 players	0111	65673	56088	131671	60046	458
2 players	0011	66475	56536	131289	60681	503
2 players	0101	67110	57411	130814	61346	539
2 players	0110	66686	56978	131314	60497	515
NASH	0000	67516	57628	131213	61349	561
OCD+ defects						
COOP	1111	65810	55434	131700	59360	413
3 players	1110	66425	56198	131512	59503	466
2 players	1100	67370	57472	130993	61027	544
2 players	1010	66967	56722	131278	60402	513
2 players	0110	66686	56978	131314	60497	515
NASH	0000	67516	57628	131213	61349	561
WEU defects						
COOP	1111	65810	55434	131700	59360	413
3 players	1011	66252	55531	131494	59953	452
2 players	1010	66967	56722	131278	60402	513
2 players	1001	67320	57164	130832	61219	537
2 players	0011	66475	56536	131289	60681	503
NASH	0000	67516	57628	131213	61349	561

Remarks:

- See above how column 2 must be read.
- DC has an incentive to deviate from the grand coalition since it is then better off whatever the other players decide.
- The coalitions 1100 i.e. {USA,WEU} is internally stable.

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