Coalition formation in Integrated Assessment Models

Exploration of international climate agreements in FAIR and MERGE

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Report R-09/03

15 February 2009

This report was commissioned by: Milieu en Natuur Planbureau

It was internally reviewed by Onno Kuik

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Abstract

Most economic analyses of international climate policies are based on the assumption of a single global decision maker, who acts as a “benevolent dictator”. In reality, such a global decision maker does not exist, and international climate policy will have to be formulated on the basis of voluntary cooperation in the form of an International Climate Agreement (ICA). Recent developments on non-cooperative game theory, especially in the field of coalition formation, can provide insight in the incentives of regions to collaborate in an ICA. Before a full integration of the methodology of coalition formation and stability can be achieved, a number of obstacles have to be overcome. This report discusses these obstacles and formulates which steps can be taken to improve the analysis of international climate policy.

Specifically, this report explores options to integrate the STACO (STAbility of COalitions) model (www.enr.wur.nl/UK/staco/) with the FAIR (Framework to Assess International Regimes for differentiation of commitments) model and the MERGE (Model for Estimating the Regional and Global Effects of greenhouse gas reductions) model in order to provide an assessment of stability of International Climate Agreements based on existing estimates and projections of climate impacts. The report identifies policy relevant questions that call for further research.

1. Introduction

1.1 Background

Most economic analyses of international climate policy are based on the assumption of a single global decision maker, who acts as a “benevolent dictator”. The current generation Integrated Assessment Models (IAMs) virtually all assume that countries or regions[1] have either no interest in cooperation at all (usually labelled the “non-cooperative solution”) or that all regions want to collaborate (the “cooperative solution”), and some models do not even consider these two extremes. In reality, such a global decision maker does however not exist, and international climate policy will have to be formulated on the basis of voluntary cooperation in the form of an International Climate Agreement (ICA), as for example the Kyoto Protocol. While negotiations on a new climate agreement are ongoing, it is unlikely that the result will be either full global cooperation or no agreement at all. This makes the concept of a “partial agreement” highly relevant from a policy perspective.

Recent developments on non-cooperative game theory, especially in the field of coalition formation, can provide insight in the incentives of regions to collaborate in a partial agreement. Most of these game-theoretic models use the concept of a “partial agreement Nash equilibrium” (Chander and Tulkens 1992). This concept assumes a binding contract can be formulated, but that such a contract will only be signed (and ratified) when this is in the interest on the region. For identical players, Barrett (1994) showed that only small coalitions can be stable if the potential gains from cooperation are large. To understand this result notice that as the gains from cooperation increase, the incentives for regions to deviate (or “free-ride”) also increase. More recent studies highlight the role of the design of the agreement on stability, for example the role of restricted membership and the role of financial transfers to compensate regions for their mitigation efforts. The conclusion from these studies is that well-designed contracts can stimulate cooperation and increase the stability of partial coalitions, but that global cooperation is likely to be unattainable because of the huge free-rider incentives.

Before a full integration of the methodology of coalition formation and stability can be achieved, a number of obstacles have to be overcome. This report discusses these obstacles and formulates which steps can be taken to improve the analysis of international climate policy. By confronting the restrictions of the current generation of game-theoretic models with the restrictions of the current generation IAMs, a tentative research agenda will be formulated. After all, it seems evident that an improved insight into the incentives of regions to participate in international agreements is essential.

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[1] As most models aggregate countries in regions, we will use the term regions from now on, even though a region can in principle consist of one country.

1.2 Scope and setup of the report

The project aims to provide an exploration of the current state of the art in research on the economic incentives of regions to engage in international climate policies, with special attention to the formation and stability of international climate agreements using Integrated Assessment Models. The first part of the report focuses of the most recent insights from the game-theoretic literature, and provides an overview of the implications for international climate policy making. International climate policies are shaped in an ongoing negotiation process. Coalition theory has been employed to explore conditions to reach a stable International Climate Agreement (ICA) and to identify barriers to effective cooperation. This work is partly purely theoretical and partly applied to investigate in 'small' empirically calibrated models the impacts of certain design features, such as transfers and restricted membership, on the stability of coalitions. This part will rely to a large extent on the insights of the ongoing research programme of Wageningen University, the STACO model.

The second part of the report uses these insights and explores the limitations of the current IAMs. Decision making assumptions in the most important models will be discussed. It also provides the necessary embedding of the two main models that are investigated in this report, FAIR and MERGE. The FAIR model, with its simple and flexible structure, offers an excellent setting for investigating different assumptions with respect to the costs and benefits of climate policies. This can be used to assess the incentives of regions to collaborate and thus explore the stability of climate coalitions. The MERGE model is one of the leading models for the analysis of optimal climate policy, and contains elaborate information on the costs and benefits of climate policy for different regions. By introducing coalition formation in this model, a rich image can be projected on the possibilities and pitfalls of integrating game-theoretic methodology in complex IAMs.

Introducing partial collaboration in these IAMs does not only provide a more detailed answer to existing policy questions, but can also shed light on a new set of policy questions, especially those related to the formation and stability of climate coalitions. This report will also deal with the possibilities to assess the ways in which incentives of regions to be part of an ambitious international climate policy are affected by related issues. One can think of local air pollution or energy security, which provide local benefits to mitigation, and adaptation, which provides a local alternative to mitigation. These related issues do not only affect the optimal level of mitigation as assessed by the current generation IAMS, they may also crucially influence the incentives of regions to collaborate. And finding ways to stabilise a larger coalition may imply substantial improvements in terms of the global ambition level for mitigation.

Section 2 of the report surveys the main streams of the literature in coalition theory as far as they are considered relevant also for applied modelling. Section 3 then describes a quickscan of the most relevant applied models, and thus puts the models discussed in the later chapters in perspective. Next, Chapter 4 deals with the prospects for coalition formation in FAIR and MERGE. Section 5 concludes.

2. Economics of International Environmental Agreements

This section provides an overview of different model variants to study International Environmental Agreements (IEAs). We first explain basic concepts and a base type model (2.1). We go on to explain some general results from the base model (2.2) and discuss several extensions and there impacts on participation and success (2.3). Finally we discuss refinements of solution concepts (2.4).

2.1 Basic concepts

In game theory the issue of coalition stability has for long remained exclusively a topic of cooperative game theory. Cooperative game theory assumes that players can make binding agreements. Full compliance with an agreement is always assumed, hence monitoring and enforcement are not considered. The focus of cooperative game theory is the stability of the grand coalition, the coalition of all players. The most prominent solution concept is the *core*. An outcome (a vector specifying the payoffs of all players) is in the core if no coalition can improve their payoff upon what they receive according to that outcome (i.e. what they receive in the grand coalition).

By contrast non-cooperative game theory does not assume the possibility of binding agreements. Usually monitoring and enforcement are important issues and the most prominent solution concept is *Nash equilibrium*. In a Nash equilibrium each player adopts a strategy that is a best response to what other players are doing. Generally, there is nothing that guarantees that full cooperation is a Nash equilibrium, i.e. the Nash equilibrium will usually not be Pareto-efficient. Traditionally non-cooperative game theory has paid little attention to the issue of coalition formation.

Given cooperative game theory's focus on the grand coalition and non-cooperative game theory's neglect of coalition formation, a new class of games emerged in the early 1990s specifically designed to study partial coalitions. A prominent area of application of these games are IEAs; see e.g. Hoel (1992), Cararro and Siniscalco (1993), Barrett (1994). These games, which we call IEA-games in what follows, are hybrids of cooperative and non-cooperative games. Players who are members of a coalition can make binding agreements. However, the participation decision is modelled as a non-cooperative game and, hence, the analysis is not confined to the grand coalition but also considers partial coalitions. An IEA is usually a partial agreement comprising a subset of the set of players. The grand coalition and no coalition are just specific cases in this more general set-up. Usually only a single coalition is considered and these games are referred to as cartel games. The signatories of an agreement, the *coalition*, play a non-cooperative game against non-signatories. More precisely, an IEA-game is a two-stage game where in the first stage players sign an IEA; in the second stage the coalition of players who signed act jointly and play an abatement game against all other players who act independently. The Nash equilibrium of the second stage game is called a Partial Agreement Nash Equilibrium (PANE) (Chander and Tulkens 1997). The PANE payoffs provide a γ-characteristic function that assigns a payoff for each possible coalition and the respective singleton players. The γ-characteristic function amended with a sharing rule of the coalition payoff among members serves as a base for the study of incentives of individual players to join or not to join the IEA. This determines the equilibria of the first stage. The equilibria are called *stable coalitions*. The stability feature – that no player wants to change her strategy, given what other players are doing – can be decomposed into external stability and internal stability. More formally, consider a set N of individual countries $i \in N$. Payoffs that accrue depend on the coalition formed $K \subseteq N$. Payoffs are determined from costs and benefits of equilibrium abatement of GHGs in an abatement game. Note that GHG abatement is a public good. It is well known for public goods games that the grand coalition $K = N$ is efficient, while any partial agreement with $K \subset N$ is not (e.g. Dasgupta 1982). In a public goods game a singleton coalition $K = \{i\}$ will not be effective and give the same payoffs as $K = \varnothing$. We will refer to both cases as 'all-singletons'. To be more precise about payoffs, the abatement game invokes a partition function $V(K)$ that determines payoffs V_K for the coalition and for each singleton player $V_j(K)$, $j \notin K$. Before we can introduce the notion of stability in a more formal way, we need to define individual payoffs for coalition members. We assume that some sharing rule r applies that distributes the coalition payoff $V_K(K)$ among members. Thus we arrive at a per-member partition function, also called a valuation function. For convenience we denote it by $V({}^rK)$; individual payoffs under coalition K when sharing rule r applies are denoted by $V_i({}^rK)$. Of course, for every sharing rule r we have $V_K(K) = \sum_{i \in K} V_i({}^rK)$. We adopt the shorthand notation K_{-i} for $K \setminus \{i\}$ with $i \in K$ and K_{+j} for $K \cup \{j\}$ with $j \notin K$. Define the coalition surplus $S_K \equiv V_K(K) - \sum_{i \in K} V_i(K_{-i})$.

Stability is defined as follows:

DEFINITION 1 A coalition K is stable under sharing rule r if it is

a) Internally stable, i.e.

$$V_i({}^rK) \geq V_i(K_{-i}) \text{ for all } i \in K,$$

and

b) Externally stable, i.e.

$$V_j(K) \geq V_j({}^rK_{+j}) \text{ for all } j \in N \setminus K.$$[2]

Alternative solution concepts relevant for coalition games are briefly discussed in section 2.4 below.

2.2 The ICA base model

The work on International Climate Agreements (ICAs) is part of a larger body of literature on International Environmental Agreements (IEAs). The broader literature on IEAs offers many relevant insights. Two features are, however specific to the climate problem:

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[2] The tie-breaking rule is here that a player would join the coalition if she is indifferent between joining and staying out. Hence, by this definition, the empty set $\varnothing$ is not externally stable, and a trivial coalition is internally stable.

a) That greenhouse gases are a stock pollutant and

b) That greenhouse gas abatement is a global public good.

The valuation function $V({}^{r}K)$ which is decisive for the stability of ICAs is usually generated by a transboundary pollution game (e.g. Barrett 1994, Chander and Tulkens 1997). In general, the strategic situation in transboundary pollution game is determined by upstream/downstream position of countries captured in a transport matrix (Mäler 1989, Folmer and v. Mouche 2000). In the case of greenhouse gases, a uniformly mixing pollutant, all elements of the transport matrix are 1 and countries are symmetric with respect to the upstream/downstream aspect. Consequently, a transport matrix does not show up explicitly in the formal model and the game is a pure public goods game.

Two types of base models can be found in the literature: (i) the first considers private benefits from pollutive production and (public) damages from emissions; (ii) the second considers benefits and costs of abatement. Diamantoudi and Sartzetakis (2006) have shown that type (i) models can be translated to type (ii) models. Hence, we restrict the following exposition to models of type (ii) where abatement is the choice variable. More specifically, following specifications adopted for the STACO model, consider all regions $i \in N$ adopt their abatement strategies simultaneously. The abatement strategy space of a region is defined as $q_{it} \in [0, \bar{e}_{it}]$, where $\bar{e}_{it}$ denotes regional emission levels in the business-as-usual (BAU) scenario with no abatement. Consider a planning horizon of T years. Each region obtains benefits b_{it} which depend on *global* emission reductions and bears costs c_{it} which depend on the emission reduction *by the region itself.* b_{it} is a concave benefit function of past and current global abatement in period *t*, and c_{it} is a convex abatement cost function of regional current abatement. Benefit and abatement cost functions are specified in detail below The payoff for each region π_i is defined as follows:

$$\pi_i(\mathbf{q}) = \sum_{t=1}^{\infty} \left\{ (1+\rho)^{-t} \cdot (b_{it}(q_1,...,q_t) - c_{it}(q_{it})) \right\} \tag{2.1}$$

where the model horizon accounting for future benefits is infinity, ρ is the discount rate, $\mathbf{q}$ is an abatement matrix of dimension $N \times T$.[3] The right hand side of equation 2.1 is the net present value of the stream of payoffs. Following Bloch (1997), we assume that signatories and singletons play a Nash equilibrium with regard to their abatement strategies, which is also called a partial agreement Nash equilibrium between the coalition and the remaining singletons (Chander and Tulkens, 1995 and 1997). Once a coalition is formed, regions play an abatement game. We assume that regions which join a coalition $K \subseteq N$ set their abatement level by maximising the sum of the payoffs of the signatories taking the abatement levels of non-signatories as given. Non-signatories $i \notin K$ choose their abatement level by maximising their own payoffs taking the other regions' abatement levels as given. This abatement game has a unique interior solution under the STACO specification of benefit and cost functions (see below). When coalition K is formed, the optimal solution of the abatement game is denoted by $\mathbf{q}_i^*(K)$. Hence,

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[3] We adopt the common notation where subscripts are dropped to denote aggregation over that index.

the uniqueness of the solution enables us to rewrite payoffs which are functions of the abatement paths as payoffs which are functions of the coalition structure. Moreover, transfer schemes are applied among the signatories. A financial transfer $F_i(K)$ is implemented among the signatories, such that $\sum_{i \in K} F_i = 0$. Therefore, we obtain a valuation function $V_i(K)$ which assigns the payoff to every region $i \in N$ given the coalition K. The payoffs of non-signatories and the payoffs of signatories are defined as follows:

$$V_i(K) \equiv \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (b_{it}(\mathbf{q}^*) - c_{it}(\mathbf{q}_i^*)) \right\} \qquad \text{for } i \notin K, \tag{2.2}$$

$$V_i(K) \equiv \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (b_{it}(\mathbf{q}^*) - c_{it}(\mathbf{q}_i^*)) \right\} + F_i(K) \qquad \text{for } i \in K, \tag{2.3}$$

where $V_i(\varnothing) = V_i(\{j\})$ for all $i, j \in N$, and $\mathbf{q}^*$ denotes the equilibrium abatement.

This base model considers the stability of a single IEA with a stock pollutant. Barrett (1994) has analysed the case with no transfers and symmetric countries for a set of different benefits and cost functions. Barrett's findings can be summarised in the following table:

Table 2.1 Size of IEAs for different payoff specifications with symmetric players.

Payoff type	Benefits	Abatement costs	Number of signatories
Linear-quadratic [a)]	linear	quadratic	3
Linear logarithmic	linear	logarithmic	2
Linear-cubic[b)]	linear	cubic	2
Quadratic-linear [c)]	quadratic	linear	1
Quadratic-quadratic	quadratic	quadratic	Few when gains of cooperation are large; Many when gains of cooperation are small

Notes: a) There is no leakage in this type of payoff function; b) STACO specification, not considered by Barrett (1994) c) There is full leakage in this type of payoff function.

A general conclusion from these findings is that one cannot expect successful stable IEAs for global problems when there are many equal players. The free-rider incentives are particularly strong if there is leakage, i.e. additional abatement by a group of signatories is (partially or fully) offset by addional emissions of of non-signatories.

2.3 Options to stabilise more ambitious coalitions

More recent work on the stability of ICAs has explored different options to stabilise larger and more successful coalitions. It is apparent from this work (e.g. Botteon and Carraro 1997, Weikard *et al*. 2006, Carraro *et al*. 2006) that exploiting the asymmetries between countries is a key issue. In particular, differences in abatement costs between countries open the possibility of carbon trade. Abatement can take place where it is cheapest while abating countries receive compensation for costs. Thus, international transfers (or side-payments) are generated that can enhance the stability of a coalition. We will address the issue of transfers first. But in addition other issues have been studied which have led to refinements and amendments of the base model sketched above.

In the remainder of this section we provide an overview of issues with some selected results. We address the following:

- Transfers
- Access rules
- Technological change and technology cooperation
- Uncertainty and learning
- Renegotiations

The section closes with a table providing numerical results from STACO. These give an indication of the effects of institutional designs (such as transfers and renegotiations) and developments (such as technological change and learning) on coalition stability

2.3.1 Transfers and side-payments

In the literature on the formation and stability of international environmental agreements (IEAs) it has been emphasised that transfers will strengthen incentives to join. Two main insights have been established. First, if countries are identical, transfers will not be effective (Carraro and Siniscalco 1993). If countries differ in costs and benefits of pollution abatement, transfers can be used to buy the cooperation of countries with low marginal costs of abatement. Hence, agreements between countries with large marginal abatement benefits and countries with low marginal abatement costs will be particularly successful (Barrett 2001, Weikard *et al*. 2006a). Second, it is evident from a number of studies that incentives to join an IEA will be very sensitive to the design of the transfer rule (e.g. Botteon and Carraro 1997, Tol 2001, Carraro *et al*. 2006, Altamirano-Cabrera and Finus 2006, Weikard *et al*. 2006a). Carraro *et al*. (2006) provide a comparison of different transfer schemes with respect to participation incentives, global welfare and abatement.

Here we provide a comparison of different transfer schemes based on the STACO model Our analysis employs the two-stage cartel game introduced in section 2.1. The first stage is an announcement game where players (regions) choose to sign or not to sign an IEA. The signatories and the remaining singletons then play a non-cooperative abatement game where the signatories maximise joint welfare at the second stage. This establishes a ‘partial agreement Nash equilibrium’ (Chander and Tulkens 1995). A stable agreement is a Nash equilibrium of the announcement game where payoffs are derived from the (unique) second stage equilibrium and a transfer scheme.

Following Rose *et al*. (1998) *allocation*-based and *outcome*-based transfer schemes can be distinguished. The former implement transfers by distributing emission permits, the latter distribute gains from cooperation. Looking at allocation-based rules where coalition members receive tradable emission permits, Altamirano-Cabrera and Finus (2006) have investigated the impact of different permit distribution schemes, for example distribution according to population, ability to pay and initial emissions (based on grandfathering). Their finding is that only a grandfathering scheme can stabilise a non-trivial coalition of at least two members. However, they note that coalitions are small, consisting of no more than three members, and do little to improve greenhouse gas abatement. These results are derived for an essentially static model. For dynamically optimal emission paths and a grandfathering scheme of permits based on projections of future emissions the incentives to participate in a climate agreement improve, particularly for countries that expect large emission growth in the future; cf. Böhringer and Lange (2005). Nagashima *et al*. (2009) investigate this issue using an updated version of the STACO model, and compare different transfer schemes. They find that static grandfathering of emission permits may lead to counterintuitive international transfer flows, as fast-growing economies such as China have a sharply increasing demand for permits.

Permit trading – although prominent among policy-makers – does not guarantee the best incentives for participation. Outcome-based rules that distribute not emission permits but the gains from cooperation are in general superior. The public goods character of greenhouse gas abatement implies that enlarging a coalition always improves the payoffs. This superadditivity condition allows that each coalition member receives at least the non-cooperative payoff. If an ad-hoc rule that distributes the coalition surplus proportional to (initial and future) emissions is introduced better incentives for membership and larger coalitions can be observed.

Transfer design can be improved even further. Relevant for the participation decision of a country are the country's share of the coalition payoff and its outside-option payoff. Hence, if the coalition payoff is distributed in such a way that each member gets at least its outside-option payoff, then no incentives to leave a given coalition remain. This concept is elaborated by Fuentes-Albero and Rubio (2005), Carraro *et al*. (2006), McGinty (2007) and Weikard (2009). Weikard (2009) has shown that surplus sharing according to outside option payoffs internally stabilises all coalitions that are possibly stable under any sharing rule. Hence, this set of coalitions includes one that cannot be improved upon. Therefore, it can be referred to as 'optimal sharing'. It is important to note here that the public goods character of abatement gives rise to positive spillovers. If a coalition forms, it will not reap all the gains from cooperation, as singletons will also benefit from increased abatement. Positive spillovers provide incentives to free-ride and they are larger for larger coalitions. Hence, a grand coalition that would internalise all externalities and implement efficient abatement will be faced with large outside option payoffs and will usually not be stable. Nagashima *et al*. (2009) use the STACO model to investigate the potentially stable coalitions using optimal transfers and compare these results to other transfer schemes. Results from the STACO model for different transfer schemes are presented in the summary table (Table 2.2) below, drawing upon Nagashima *et al*. (2009).

2.3.2 Access rules

The Kyoto Protocol is an agreement open to all. Countries are free to join or not. Open membership seems in line with evidence on IEAs in general. Almost all protocols of major IEAs have no provision that restricts membership. Moreover, intuition and results of the public goods literature suggest that global welfare increases with participation in an agreement and therefore any restriction on membership would hamper the effectiveness of IEAs. However, those results have been derived without considering the restriction that IEAs have to be self-enforcing. Hence, in the presence of free-rider incentives, it seems worthwhile to study the effect on coalition formation when membership is restricted. For instance from the empirical study of Botteon and Carraro (1997) on global warming it appears that some coalitions are internally but not externally stable. This suggests that some of these coalitions could be stabilized if coalition members had the opportunity to deny accession of new potential entrants. Moreover, recent theoretical results by Finus and Rundshagen (2003) obtained from a general framework suggest that exclusive membership may help to stabilize IEAs. The reason is that - though still internal instability poses a problem to IEAs - external instability is less of a problem because members of an IEA under exclusive membership can better control the accession of non-signatories that may upset a coalition equilibrium. However, Finus and Rundshagen (2003) point out that it is not possible to conclude at a general level what “more stability” means in terms of the success of IEAs. Therefore, the implications of exclusive membership in terms of global welfare and global emissions and stock of greenhouse gases matter. We report STACO results on two exclusive membership rules: (i) simple majority voting (ii) unanimity voting cf. Finus, Altamirano-Cabrera and Van Ierland (2005). The latter implies that each member can block the entry of any additonal country.

First, note that all coalitions stable under open-membership are also stable under simple majority voting and all coalitions stable under simple majority voting are also stable under unanimity voting. The empirical results of Finus *et al.* (2005) show that more and larger coalitions can be stabilised. Whereas no non-trivial coalition is stable under open membership, one non-trivial coalition is stable under exclusive membership and majority voting and two other additional coalitions are stable under unanimity voting. However, a more interesting fact is that those additional coalitions are superior in net benefit and in environmental terms. The findings are report in the summary table (Table 2.2) below.

2.3.3 Technological change

The long time horizon of the climate change problem calls for the inclusion of technological change into considerations of coalition stability. Studies by Weyant and Olavson (1999), Löschel (2002) and Clarke *et al.* (2008) provide an overview of the different sources of Technological Change (TC) and illustrations of how these are implemented in different energy and economic models of responses to climate change. Three main sources of TC can be defined: (i) R&D investment (Goulder and Mathai 2000, and Buonanno *et al.* 2003), (ii) R&D spillovers (Griliches 1992, and Bosetti *et al.* 2008), and (iii) learning by doing (Manne and Richels 2004, and Castelnuovo *et al.* 2005).

Nordhaus (2002) incorporates endogenous TC into his DICE-99 model: the R&DICE model. The original DICE-99 model is a global model that assumes exogenous Hicks neutral TC in the production function; a reduction in carbon intensity (carbon emissions per unit of output) is achieved by substitution of capital and labor inputs for carbon energy. On the other hand, the R&DICE model assumes that an improvement in carbon intensity is driven by technological change via R&D inputs into the energy sector, and this “carbon-energy-saving technological change” is finally embedded in the emission function. In the R&DICE model, a price increase for carbon energy will induce firms to invest in new knowledge by developing environmentally-friendly new processes and products which will lead to lower emissions. Nordhaus concludes that the substitution effect as present in the DICE-99 model is likely to be larger than the effect of ITC on CO2 abatements, mainly due to the small social returns to R&D.

The studies that have investigated the role of TC on coalition formation and stability are few. Buonanno *et al.* (2003) use an endogenous environmental technical change model called ETC RICE model with six regions to study the case of a “Kyoto” agreement without or with emission permit trading among Annex I or worldwide where regions play a non-cooperative Nash game. TC is specified in three ways: (i) endogenous technological change and exogenous environmental technological change (the stock of knowledge is a production factor), (ii) endogenous technological change and policy-induced environmental technological change (R&D affects both productivity and the emission-output ratio), (iii) technological spillovers. In their model, a stock of knowledge is accumulated over time through R&D investment and it is embodied in a production function and the emission-output ratio. Endogenous TC is driven by regional spillovers within sectors and increasing returns to scale from human capital. In Buonanno *et al.* the incentive to invest in R&D depends on regional marginal costs and the option of emission trading. The region with lowest marginal abatement costs has a strong incentive to carry out R&D to maximize social welfare by selling emission permits. The presence of spillovers leads to an increase of incentives to free-ride, thus the overall R&D efforts are reduced.

In the context of linkage of climate control with increased R&D expenditures, Kemfert (2004) examines incentives for cooperation and stability of all possible coalitions by using a world integrated assessment model (WIAGEM) with four regions. ITC is defined in a way that an increase in R&D investments leads to an improvement in energy efficiency (an increase in energy productivity). Kemfert concludes that incentives to join a coalition tend to be stronger in the case of cooperation on both climate control and technological innovation than in the absence of cooperation, due to lower abatement costs which brings higher profits. In addition, issue linkage increases incentives to join a coalition.

Tol *et al.* (2000) examine the role of the issue linkage with restricted technology diffusion for stabilising a larger climate coalition in which abatement-specific technologies are developed by learning-by-doing or R&D investments in a similar framework as Goulder and Mathai (2000). Tol *et al.* conclude that the threat of restricting technology diffusion may prevent the coalition member from deviating, however, the coalition may lose by restricting technology diffusion. The effectiveness of the restriction increases with the size of the coalition.

Nagashima and Dellink (2008) examine the stbility of international climate agreements in the presence of exogenous technological change and spillovers. In their model TC implies declining abatement cost and technological spillovers imply that innovations in one region will trigger innovations elsewhere. Using the STACO model for a scenario where spillovers are stronger between coalition members, Nagashima and Dellink (2008) find that while technology spillovers increase global abatement and welfare they do not help to stabilise larger coalitions. Nagashima and Weikard (2009) examine the the link between R&D investment to improve abatement technologies and the incentives to join an ICA. Their finding is that on the one hand coalition formation will drive investment pattern, but on the other hand investment opportunities will affect abatement costs and therefore the willingness to join an ICA. Comparing models of exogenous and endogenous TC, the latter will concentrate R&D investments and TC in regions that are characterised by low marginal abatement costs such as China and India. Endogenous TC gives larger payoffs to any given coalition compared to exogenous TC, however the best stable coalition does not reap a higher percentage of what a grand coalition would gain. The latter result is also reported in Table 2.2 below.

2.3.4 Uncertainty and learning

Recently, Na and Shin 1998, Ulph 2004, Kolstad and Ulph 2006, Kolstad 2007 and Dellink *et al*. (2008) have studied coalition formation under uncertainty and learning. They assume uncertainty about parameter values of the payoff function where probability distribution functions are assumed to be known to all regions. In the climate coalition formation game, where countries choose their membership in the first stage and their abatement strategies in the second stage, Kolstad and Ulph (2006) and Kolstad (2007) distinguish three cases: (i) Uncertainty is resolved before the first stage. This corresponds to the case of *full learning*. (ii) Uncertainty is resolved after the first stage but before the second stage. This corresponds to the case of *partial learning*. (iii) Uncertainty is never resolved. This is the case with *no learning*. In the modelling approach of Kolstad and Ulph (2006) learning takes the form of perfect learning, i.e. all players learn the true values of all uncertain parameters. All papers in this domain are stylised models with ex-ante identical players, except Dellink *et al*. (2008). The general conclusion is that learning has a negative impact on the success of coalition formation. Na and Shin (1998) compare cases (ii) and (iii), but they do not consider stock pollution effects. Moreover their analysis is restricted to only three countries. The first restriction is removed in Ulph (2004), who compares all three cases and considers a two period model with a stock pollutant. Due to this complication, results are based on simulations and conclusions are not always clear-cut. Moreover, regions' strategy space in the abatemment game is restricted to either 'no abatement' or 'full abatement',and uncertainty concerns the benefits from global abatement, with only two states (low and high benefits) and uncertainty is correlated between players. This means that in the case of learning all countries are also ex-post identical; either all countries are low or high benefit countries. Kolstad (2007) adopts the same set of assumptions, but considers a flow pollutant. In this case the unambiguous result is that when comparing case (i) and (iii), learning increases the size of a stable ICA but has a negative impact on global welfare, as proven in Kolstad and Ulph (2006). Case (ii) is ambiguous; learning may have a positive or negative impact on participation and welfare. Finally, in the case of uncorrelated uncertainty, Kolstad and Ulph (2006) confirm the negative impact of learning, but again have to resort to simulation, despite the assumption that all countries are ex-ante identical and that there are only two states in the world. Dellink *et al*. (2008) formulate a stochastic version of the STACO model to test the theoretical results in an applied setting. They find that in most cases learning has indeed a negative impact, but this is always the case. Furthermore, they illustrate that a stochastic approach can shed much more light on the stability of coalitions than a deterministic setting.

2.3.5 Renegotiations

Examining renegotiations seems important for at least two different reasons. First, the commitment period 2008-2012 agreed in the Kyoto protocol is closing in a few years time and, hence, there is a need to take a look beyond. Secondly, the prospect of renegotiations at a later stage changes the incentives to join a coalition at earlier stages and, therefore, changes the negotiation results. The issue is to examine whether renegotiations hamper or help the formation of stable coalitions: whether renegotiations lead to agreements with higher or lower abatement targets. The Conference of Parties meetings of the United Nations Framework Convention on Climate Change (UNFCCC) clearly illustrate that negotiating GHG emission controls is a process rather than a matter of striking an agreement. Hence, the formation of an ICA is probably best understood in a sequential game framework.

In the theoretical literature on games of coalition formation Bloch (1996), Ray and Vohra (2001) and Konishi and Ray (2003) have developed such sequential models. These modelling approaches, being general and highly abstract, have not yet found their way into applied work. From an applied modelling perspective the theoretical literature on international environmental agreements suffers from a serious drawback. It is generally assumed that countries are identical and coalitions can be fully characterised by the number of participating countries. Barrett (1994 and 1999) considers an infinitely repeated game. Contrary to what a folk theorem would suggest, full participation cannot generally be achieved because the option to renegotiate limits the threats of punishment. Asheim *et al.* (2006) use a similar model but allow for regional agreements. The finding is that several regional agreements increase GHG abatement over one global agreement but, again, full participation is not achieved. Ulph (2004) and Rubio and Ulph (2007) have studied renegotiations of international environmental agreements with a stock pollutant. They find that as the gains from cooperation increase over time, participation declines. This reinforces Barrett's (1994) findings. In a recent paper de Zeeuw (2008) considers farsighted stability in a dynamic membership game and finds small as well as large stable coalitions. However, all these approaches are confined to symmetric countries and do not capture abatement cost differences and the impact of transfers to stabilise agreements.

Using the STACO model that comprises 12 heterogeneous regions Weikard, Dellink and van Ierland (2007) and Weikard and Dellink (2008) have explored the impact of renegotiations. They argue that, because fossil fuels are finite, ICA renegotiations are a finite game and punishment strategies can be effective. Weikard and Dellink (2008) have adapted the optimal transfer rule (see section 2.3.1) to make it applicable in a setting with renegotiations. They find that a grand coalition may be stabilised in early commitment periods.

2.3.6 Summary of findings from the STACO research:

Table 2.2 summarises findings from the STACO model for various scenarios. The "Percentage gap closure" last column is the percentage of the possible welfare gains that the best stable coalition (in a given scenario) achieves. The grand coalition, which is usually unstable would close the gap by 100 percent.

Table 2.2. Summary of best performing stable coalitions under various policy options.

Scenario / Policy	Coalition	Percentage gap closure
None	All singletons	0
Permit trading[a),f)]	EU-15, China	24
Optimal sharing [b)]	USA, EET, CHN, IND, DAE	46
Majority voting [c)]	FSU, Brazil, ROW	4.2
Unanimity voting [c)]	China, EEX	5.6
Exogenous technological change [d)], no transfers	JPN, EU-15	3.5
Exogenous technological change [d)], optimal transfers	USA, EET, EEX,CHN, IND	44.5
Endogenous technological change [e)], optimal transfers	EU-15, EET,CHN, IND, DAE	44.8
Renegotiations with optimal sharing (2 periods) [b)]	All but EU, after 30 years: USA, EET, CHN, IND, DAE	62

a) Altamirano-Cabrera and Finus (2006)
b) Weikard and Dellink (2008)
c) Finus, Altamirano-Cabrera and van Ierland (2005)
d) Nagashima and Dellink (2008)
e) Nagashima and Weikard (2009)
f) Nagashima *et al*. (2009)

2.3.7 Summary of issues for further research:

(i) Given the possibility to renegotiate, will countries join an ICA all at once or would there be a sequence of accessions?

(ii) Can ICAs consisting of a small number of countries contribute to mitigation by taking a lead in shaping policies and policy instruments, and to what extent? Does a leader-follower negotiation structure generate smaller or larger coalitions, less or more successful emissions control? This is of particular importance given the possibility of rapid climate change and a potential urgency to take action.

(iii) Will the possibility of renegotiations lead to larger coalitions because members hope to improve their stakes in the future without making long-term commitments in the present; or rather to smaller coalitions because renegotiations open the option to "wait and see"?

(iv) How does uncertainty and learning impact the coalition formation process? What is the precise nature of the tradeoff between uncertain benefits from early abatement and improved abatement decisions at a later stage?

(v) How are equilibrium abatement paths affected by the possibility to renegotiate and by the possibility of sequential accessions? What are the implications for climate change related damages and welfare.

(vi) The results obtained by answering these questions will be useful to evaluate policy options on the national and EU-level such as, e.g.

(vii) Is it better to negotiate a global agreement or rather (several) small bilateral agreements (e.g. EU-China)?

(viii) What is the role of side-payments (direct transfers or distribution of tradable emission permits) in the formation of ICAs in a framework of sequential accessions?

(ix) How can emission rights be assigned to improve stability under sequential accession?

2.4 Alternative stability concepts

So far little work has been done to systematically explore alternative solution concepts in the context of IEA games. There are two main alternatives. The first is to consider multiple deviations, the second is to consider a deviator's concern about best responses of others to a deviation. We briefly explain both ideas below.

(i) Multiple deviations: It is reasonable to assume that players can coordinate their strategies in a negotiation process. Hence, if it pays for a subgroup of players to deviate collectively, the considered strategy profile is not coalition proof. Bernheim *et al*. (1987) and Farrell and Maskin 1989) develop a concept coalition proof equilibrium. Because of its complexity this concept has not in applied to ICAs in any published work.

(ii) Farsightedness: A Nash equilibrium is characterised by the fact that deviations do not pay given that others stick to their strategy. However, a player considering a deviation should also take other's reaction into account. A farsightly stable equilibrium recognises this. It is assumed that a deviation would only occur if it is beneficial to the deviator when other play best responses to the deviation (Chwe 1994, de Zeeuw 2008).

3. Quickscan of Integrated Assessment Models

The multifaceted aspect of climate change makes it a fascinating, but complex issue to study. Climate change is a global issue that stretches across borders, scientific disciplines and time. It involves many interrelated processes each belonging to a different discipline. Human processes create Greenhouse Gas (GHG) emissions; atmospheric, oceanic and biological processes link emissions to atmospheric concentrations of GHGs. Climatic and radiative processes link these concentrations to the climate. Finally economic, ecological and socio-political processes link the changed climate to valued impacts and policies.

To comprehend the whole issue at hand these different disciplines need to be combined in a comprehensive manner. Integrated assessment was developed to fulfil this need and advise policy and decision making. The third assessment report (IPCC, 2001) defines integrated assessment as: "*an interdisciplinary process of combining, interpreting, and communicating knowledge from diverse scientific disciplines in such a way that the whole set of cause-effect interactions of a problem can be evaluated*". IAMs attempt to advance understanding by constructing a formal representation, i.e. a model. IAMs can be divided into two broad categories: policy evaluation models, also known as simulation models, and policy optimisation models (Weyant *et al.*, 1995).

3.1 Quickscan of existing Integrated Assessment Models

To facilitate the selection of suitable candidate models for a coalition formation analysis, several key criteria are identified to evaluate the models. First, only global models or models including several regions that together represent the globe are included. That is, specific regional models are not considered as their results would be of limited applicability for our purposes.

Secondly, the model should include monetised damages from climate change. By monetising damages the effects of the economy on climate change and the effects of climate change on the economy are linked. The advantage of such IAMs is that they can deal with important issues such as the efficient allocation of abatement burdens and accepted damages, by specifying the costs and benefits of various abatement strategies. Moreover, one can analyse what the optimal climate strategy (mitigation) should be, by trading off the damages due to climate change and mitigation costs.

Thirdly, the model selected should be contemporary. That is, it should be a model that is still actively used and reasonably up to date with new estimates in the literature. Many models are outdated or are no longer being worked on.

Table 2.1 shows an overview of 30 prominent IAMs. Their scale is given and whether they are still actively used. The damage functions are reviewed. In the table PU denotes physical units and refers to damages functions that are not monetised. MON refers to monetised damage functions. These are monetised based on literature, N refers to Nordhaus (1994), T refers to Tol (1996a), F refers to Fankhauser (1995), H refers to Hertel (1993) and D&M refers to Dowlabadati and Morgan(1993). Finally the models are characterised as optimisation models (OP) or evaluation models (EV).

Table 3.1 Overview of Integrated Assessment Models.

Model	Regions	Active	Damage module	Literature	Type
AD-DICE	GLOBAL	A	MON based on N	De Bruin *et al* 2009	OP
AIM	countries/grid	I	PU	Morita *et al* (1994)	EV
AS/Exm	GLOBAL	I	MON	Lempert *et al* (1996)	EV
CETA	GLOBAL	I	MON adjusted from N/F	Peck and Teisberg (1992)	OP
Connecticut	GLOBAL	I	MON based on N	Yohe and Wallace (1995)	OP
CSERGE	GLOBAL	I	MON based on F	Maddison (1995)	OP
DIAM	GLOBAL	I	MON	Chapuis *et al* (1995)	OP
DICE	GLOBAL	A	MON based on N	Nordhaus(1994)	OP
FAIR	17 regions	A	MON based on N	den Elzen *et al*. (2007)	EV
FARM	8 regions	I	PU and MON based on H		
FUND	16 regions	A	MON based on T	Tol (2005)	OP
ICLIPS		I	Tolerable window apraoch	Bruckner *et al* (2003)	EV
ICAM	continent/coun	?	MON based on D&M	Dowlatabadi and Morgan (1995)	EV
IIASA	GLOBAL	I	none	WEC/IIASA (1995)	OP
IMAGE	Grid	A	PU	Alcamo(1994)	EV
MAGICC		I	none	Wigley *et al* (1993)	EV
MARIA	GLOBAL/conti	?	MON based on F	Mori (1995)	OP
MERGE	continental	A	MON adjusted from N	Manne *et al* (1995)	OP
MiniCAM	countries/grid	?	MON based on Manne *et al*		EV?
MIT/EPPA	countries/grid	A	none	MIT(1994),Reilly (2005)	EV
PAGE	continent/coun	A	MON based on CRU/ERL/F/T	Hope *et al*. (1993)	EV
PEF	continent/coun	I	PU	Cohan *et al* (1994)	EV
PGCAM		I	PU		EV?
PROCAM	countries/grid	I	MON based on Manne *et al*	Edmonds *et al* (1994)	EV
RICE	continental	I*	MON based on N	Nordhaus and Boyer (2000)	OP
SLICE	continental	I	MON based on N	Kolstad (1996)	OP?
STACO	12 regions	A	MON based on N, T, F	Finus *et al*. (2006)	OP
TARGETS	GLOBAL	I	?	Rotmans (1995)	EV
WAGEM	11 regions	A	none	Kemfert (2005)	OP
WITCH	12 Regions	A	MON based on N	Bosello (2000)	OP

Note: * Nordhaus does have plans to update RICE, but the currently available version is outdated and therefore the model is labelled as “inactive”.

Looking at models that fulfil the previously described criteria we see that there are 6 candidates: FAIR, FUND, MERGE, PAGE, STACO, and WITCH. PAGE does not deal with coalition formation issues; STACO has been discussed extensively above. The other models are discussed in more details below.

3.2 Coalition formation in existing IAMs

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) was developed in Tol (1996b). FUND is one of the few IAMs that includes an extensive impact module. Impacts are monetised for several impact sectors. Tol (2001) uses an "analytically tractable approximation" of the FUND model to derive incentives of regions to cooperate.

Kemfert (2004) and Kemfert, Lise and Tol (2004) use the WAGEM model to investigate coalition formation. WAGEM does not contain a full damage module, and therefore the analysis is restricted to scenarios where coalition members realize pre-determined Kyoto-type targets. Babiker (2001) adopts a similar strategy to overcome the absence of damage estimates in the MIT-EPPA model.

WITCH (World Induced Technical Change Hybrid model) and it predecessor, FEEM-RICE, were developed by the Fondazione Eni Enrico Mattei (FEEM) Climate Change Modelling and Policy Research Programme (Bosetti *et al*., 2006). This optimal growth model has been developed with the aim of studying policies for climate change control. It contains 12 world regions. The damage function is adopted from Nordhaus and Boyer (2000). A full stability analysis is not possible with WITCH, or at least has never been carried out. Rather, Buchner and Carraro (2007) restrict the analysis to a few given coalition structures and compare the payoffs of regions for these.

3.3 Identifying suitable IAMS for coalition formation analysis

As mentioned above, the models should contain marginal abatement costs and marginal damage costs for several world regions, and should not be outdated. While there are several suitable candidates, only one existing model, STACO, is currently able to deal with coalition formation and stability.

The analysis of the current attempts to study coalition formation in IAMS reveals that the models all compromise on some essential elements: STACO reduces the underlying economic model to just a payoff function; FUND is approximated by a simple analytical model; WITCH excludes stability analysis and MIT/EPPA and WAGEM have exogenous reduction targets (as they do not contain a full damage module).

4. Prospects for coalition formation in FAIR and MERGE

4.1 Basic setup of the FAIR model[4]

The extended FAIR 2.1 model consists of 17 world regions; USA, OECD-Europe Eastern Europe, Japan, Oceania, FSU, Central America, South America, Middle East and Turkey, East Asia (incl. China) South-East Asia, Northern Africa, Southern Africa, Western Africa, Eastern Africa and South Asia.

Furthermore, it integrates the following sub-modules:

1. The emissions pathway module, calculating the multi-gas emission pathways;
2. The climate module, calculating temperature implications of greenhouse gas emissions.

The MAGICC 4.1 climate model (Wigley, 2003; Wigley & Raper, 2001, 2002) is used for to calculate radiative forcing and temperature increase. The MAGICC model allows exploring the impact of different settings of the climate sensitivity, i.e. the equilibrium global mean surface temperature increase due to a doubling of pre-industrial atmospheric CO2. For alternative calculations either the UNFCCC-ACCC climate model or the IRF functions based on simulation experiments with various Atmosphere-Ocean General Circulation Models (AOGCMs) can be used, e.g. Den Elzen *et al*. (2002), Den Elzen *et al*. (1999) and Den Elzen and Schaeffer (2002).

3. The abatement cost module, combined with a simple macroeconomic growth model for calculating the GDP losses as a result of abatement. To calculate the abatement costs for each region Marginal Abatement Cost curves (MACs) are used. Using the emissions targets of the regimes over the different regions and a least-cost approach. The model calculates the tradable emission permits, the international permit price and the total abatement costs up to 2030, with or without emission trading.

MAC curves reflect the additional costs of abating a unit of GHG emissions and are used to derive permit supply and demand curves under different regulation schemes in any emission trading market using the same methodology as Ellerman and Decaux (1998) and Criqui *et al*. (1999). These schemes could include constraints on imports and exports of emission permits, non-competitive behaviour, transaction costs associated with the use of emissions trading, less than fully efficient supply (related to the operational availability of viable CDM projects) and the banking of surplus emission allowances.

4. The burden-sharing module calculates the distribution of mitigation costs for different allocation regimes.

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[4] Based on information provided by Andries Hof, MNP.

4.2 Possibilities and bottlenecks for coalition formation and stability analysis in FAIR

FAIR is different than most models discussed above because it is a simulation (evaluation) model, and not an optimization model. In principle, when first order conditions for optimal actions are specified, and when these are independent of other variables, simulation models can also assess the consequences of optimal actions, but the model is not directly aimed at this.

A major drawback of FAIR for climate-economy analysis is its lack of a general equilibrium framework. The model misses the general equilibrium feedback mechanisms that have revealed to be important in top-down assessments of the costs of climate policies. For instance, in FAIR there is no impact of the policies on relative prices, and thus the reactions of producers and consumers to the changed circumstances can only be roughly approximated. This may especially be problematic when more far-reaching climate policies are investigated, i.e. for larger coalitions, as the general equilibrium effects will be more pronounced there. When payoffs from climate policies and coalition formation are based on costs and benefits as projected by FAIR, only a first-order approximation can be given, and important indirect effects that are present in most IAMs cannot be taken into account.

From a technical perspective, there may be some complications due to a mismatch between the software used for FAIR and STACO. Given the relatively simple nature of the underlying mathematical model, this complication should however not pose critical problems. Obviously, a substantial effort may be needed for the researcher(s) involved in the integration to become acquainted with both software languages.

One of the major strengths of the FAIR model is its flexibility with respect to the input data: compared to most models, it is very easy to switch between different marginal abatement cost or damage estimates. Furthermore, this set-up of the FAIR model fits very nicely with the STACO approach, and facilitates the integration of both models. STACO assumes a simple, linear relation between global abatement efforts and avoided damages. This simplicity allows the model to directly link the costs and benefits of abatement and express a single function for payoffs as a function of regional and global abatement efforts. Thus, assessments made with the FAIR model can be used to change the payoff functions of STACO. This allows for a thorough robustness analysis of the payoff function used in STACO, and thus for an enhanced insight into the drivers of coalitional stability.

Because the determination of payoffs and the stability assessment can be separated, a major first step can be taken by using FAIR to project abatement efforts and payoff functions for all possible coalition structures. These can be stored in a database for all possible coalition structures, and the stability of coalitions can then be assessed using the existing STACO stability assessment module. The revision of this STACO module to read payoffs from a database rather than directly from the other STACO module is rather straightforward.

In this first step, exogenous decisions need to be assumed with respect to the division of abatement efforts over regions (in the FAIR emission pathway module) and the financial transfers between coalition members (in the FAIR burden-sharing module). Thus, the more advanced features of STACO, including the concept of optimal transfers, cannot be included in this step. Note also that in this stage a consistent comparison with the original STACO code is not feasible, as this approach does not entail full welfare maximization of the different regions, but rather fixed abatement targets.

A second step may involve the construction of a new module to integrate the stability assessment into the FAIR framework: the only restriction is that the software that is used is relatively efficient in doing a large number of comparisons in a big database/matrix. It is unlikely that the software used for FAIR will pose any problems in this respect.

Finally, further revisions of the FAIR model to allow more complex optimization routines would be useful for more realistic and advanced model simulations, such as renegotiations and optimal transfers. Such efforts should be coordinated with other projects at MNP on the further development of FAIR. Separate research at MNP in collaboration with Wageningen University and the Institute for Environmental Studies of VU University Amsterdam (IVM-VU) to include adaptation costs into the FAIR model, and plans at Wageningen University to include adaptation costs into the STACO model, may present an excellent opportunity to create synergies between these different activities. The strategic aspects of adaptation make this extension of the model very interesting: adaptation can be regarded as a private response to climate change (with local benefits), whereas abatement (mitigation) is a public response in the sense that it creates global benefits.

4.3 Basic setup of the MERGE model

MERGE, "A Model for Estimating the Regional and Global Effects of greenhouse gas reductions", is an intertemporal general equilibrium model of the global economy. We investigate the MERGE 5.1 version available online (http://www.stanford.edu/group/MERGE/). The world is divided into 9 geo-political regions: (1) USA, (2) Western Europe, (3) Japan, (4) Canada, Australia and New Zeeland, (5) Eastern Europe and former Soviet Union, (6) China, (7) India, (8) Mexico and OPEC countries and (9) the rest of the world. Each regional economy is modelled as a Ramsey model of optimal long-term growth (Manne and Richels, 2000). Discounted utility is maximized and output is a function of capital, labour and energy inputs. Energy is divided into electric and non electric energy. Separate technologies are defined for each source of electric energy. Each region has a consumption and savings choice. Investments are equal to savings and build up the capital stock. Emissions translate into global concentrations which in turn impact mean global indicators such as temperature change. MERGE is calibrated to the base year 2000. The model uses 10-year intervals. The model can find the optimal policy but also the most cost-effective way of achieving a policy target.

MERGE includes both market and non-market damages of climate change. Market damages include such damages as agricultural losses, coastal erosion etc. whereas non-market damages include species losses, human health and catastrophic risk. Generally high income regions are willing to pay more to avoid these damages than low income regions. Market damages are implemented such that they reduce output that is available for consumption and savings. MERGE focuses also on non-market damages. This relation is assumed to be quadratic and the authors acknowledge that the parameter estimates for non-market damages are highly speculative due to the uncertainties involved. One peculiarity of the MERGE model deserves mention here: the market damages as assessed by MERGE are approximated as a percentage of GDP in the Business-as-Usual scenario, and there is no feedback from a change in GDP as a result of damages or abatement costs on the level of damages. This lack of feedback implies a small overestimation of damages (as climate change is likely to lower GDP levels), but facilitates the numerical solution of the model. Note furthermore that the MERGE team are intending to update the damage module of their model using more recent insights from e.g. Richard Tol (Geoffrey Blanford, personal communication February 2008).

A limited number of internationally uniform goods can be traded across regions. Trade in oil, gas energy intensive sectors and carbon emissions can be traded in various versions of this model. MERGE contains carbon emission coefficients for both current and prospective future technologies. Some of these technologies such as nuclear and hydroelectric energy create no emissions. Non-electric energy sources all cause emissions. MERGE also considers that oil and gas reserves are limited. Non-energy emissions of GHGs are also included such as methane from agriculture. Climate change is summarized by a change in global mean temperature. The emissions-radiation link is summarized according to the IPCC guidelines.

4.4 Possibilities and bottlenecks for coalition formation and stability analysis in MERGE

The MERGE model can handle two types of solution concepts: (i) the Pareto optimum, and (ii) exogenous targets. In the first approach, marginal abatement costs are weighed against marginal damages to find the optimal level of climate emission control.

The outcome of the optimisation routine is labelled the “efficient allocation”. This is, however, not identical to a full joint welfare maximization. Rather, Negishi weights are used to provide a market equilibrium. Equalisation of marginal abatement costs across regions is then taken care of through unlimited trading of emission permits. The main reason for this approach is that if full joint welfare maximization would be adopted, the analysis of climate change policy would be clouded with effects caused by the different levels of development of regions. Keller *et al*. (2003) put it as follows: “The Negishi weights are an instrument to account for regional disparities in economic development. They equalize the marginal utility of consumption in each region for each period in order to prevent large capital flows between regions. This technique is descriptive rather than prescriptive; although the choice of utility function implies that such capital flows would greatly improve social welfare, without the Negishi weights the problem of climate change would be drowned by the vastly larger problem of underdevelopment. A detailed exposition of Negishi weights is given in Nordhaus and Yang (1996) and the references cited therein.” As marginal utilities differ between regions, a financial transfer from a rich to a poor region would increase utility in that region more (in terms of global social welfare) than that it would reduce utility in the donor region. Thus, full joint welfare maximization would generate huge financial transfers across the world until marginal utilities are equalised; this is prevented by using Negishi weights.

At first sight, this limited optimization routine may conflict with the assumption of joint welfare maximization of coalitions as used in the game-theoretical models, including STACO. However, one should realise that model such as STACO only specify costs and benefits from climate policy. The larger issue of underdevelopment does not play a role, as the model does not specify a full welfare function. Consequently, in this respect the assumptions made in MERGE match the ones made in STACO.

The complex solution routine in MERGE substantially complicates the possibilities to design model simulations with a partial climate agreement. According to Tom Rutherford (personal communication February 2008), it is very hard to design a procedure to reflect private cost-benefit behaviour by individual regions. Nonetheless, the behaviour of regions that do not participate in the agreement can be approximated through two changes in assumptions: (i) permit trading with outsiders is not allowed, and (ii) global damages are not taken into account by outsiders. An iterative procedure can then be designed in which the model is solved for the outsiders and the coalition keeping the strategies for the other players exogenous. In each simulation, the strategy of one region (or the coalition) is updated. The iterations go on until the strategies are mutually consistent. Note that convergence of the model is not guaranteed in this set-up.

With respect to the second change in assumptions (global damages are not taken into account by outsiders), it is important to note that the original MERGE model assumes that regions that are not participating in international permit trading do not perform a private cost-benefit analysis, but rather do no abatement at all. While this may be a reasonable assumption for the cases investigated with MERGE so far, this assumption becomes untenable when partial coalitions are assumed: the block of outsider regions reflects a too large fraction of global emissions, and the damages to these regions is so substantial that the zero-abatement assumption is not realistic. If this restriction of MERGE can be overcome, regional benefits from reduction of local air pollution can also be captured in the model.

Given the outdated nature of the damage function in the MERGE model, it seems sensible to start the integration of STACO and MERGE by deriving abatement cost functions from MERGE simulations analogous to the procedure in Ellerman and Decaux (1998). These can then be entered into the existing STACO framework and provide interesting insights into the robustness of the STACO model with respect to the specification of abatement costs. Note that this first step implicitly simplifies the many interlinkages between the different regions through international trade in fossil fuels.

A logical second step is then to derive a benefit function from MERGE by varying global abatement levels and calculating regional damage levels. For market damages, this is straightforward, as these only depend on the temperature change. For non-market damages, a more complicated non-linear function is used, and thus, a pure analytical derivation is not possible and numerical simulations are required.

Taking these two steps together, the MERGE model can also be used to assess the net benefits of abatement (i.e. the benefits minus costs, or in STACO terminology the payoff) through a construction that is similar to the way the marginal abatement costs are determined in Ellerman and Decaux: for different levels of abatement the model is run (n.b. assuming a given rule for financial transfers / a given division of emission permits) and the impact on welfare of the region is assessed. A curve can be fitted through the points that these different simulations create to reflect the payoff as a function of abatement for each region.

A more ambitious step towards integration of coalition formation and stability analysis in MERGE is to solve MERGE with singletons. This may be computationally hard and perhaps some stronger assumptions are required on the order of play (e.g. the coalition acts first, the singletons react). Some of these complications are already discussed above. Therefore, it makes sense to start this approach by assuming that outsiders do no abatement at all, and change that assumption to a private cost-benefit analysis at a later stage. One could start by treating one region as an outsider (that does no abatement) and maintaining cooperation for all other regions. Using the iterative approach sketched above, one can then investigate the computational problems involved (e.g. concerning the speed of convergence) before incorporating other partial coalitions.

The stability assessment can be incorporated in much the same manner as with the FAIR model: as the calculation of payoffs is separable from the stability assessment, the payoffs for the different regions in a partial coalition can be stored in a database for all possible coalition structure, and the stability of coalitions can then be assessed using the existing STACO module. From a technical perspective, this may be preferable over integrating the stability assessment into the MERGE framework, as the GAMS software is much less efficient at this type of assessment than the existing Matlab code for STACO; existing routines to link GAMS and Matlab can be used for this. As this advantage only refers to computational speed, it is of course also possible to implement the stability analysis in GAMS.

Finally, once a model for stability analysis using the MERGE model is operational, full advantage can be taken from the richness of the MERGE model. International lnis between regions at a sectoral level can be exploited to investigate issue linkage and strategic behaviour in the energy markets. A major opportunity for state-of-the-art research is provided by the enhanced version of MERGE with local air pollution effect that is constructed at MNP. This enhanced model allows the specification of local (private) benefits of abatement efforts, where the original MERGE model and original STACO analyses only incorporate global (public) benefits from abatement. Not only does this feature improve the cost-benefit assessment of climate policy, it also allows for an investigation into the strategic aspects of local versus global environmental policy. It is clear that the activities on strategic aspects of adaptation, mentioned in Section 4.2 has some interesting similarities to the local air pollution module, and an investigation in the combination of both aspects deserves attention.

5. Discussion

This section offers a brief discussion of the prospects for the most relevant future research activities. We also identify major bottlenecks. We close with a preview of a strategy and its potential policy relevance.

5.1 Research agenda and bottlenecks

A clear understanding of the incentives associated with different policy options will facilitate policy-makers who negotiate ICAs. Much of the work on formation and stability of ICAs has been either theoretical or based on much simplified assumptions. In order to arrive at more reliable assessments stability analysis must be combined with more elaborated climate impact assessment models. Such improved ICA- IAMs could address several relevant issues, for example

- Impacts of leakage – reduction of a abatement efforts as a best response to others increased abatement efforts;
- Impacts of rebound effects – increased energy consumption in some sectors or regions as a response to lower energy prices due to increased energy efficiency;
- Impacts of technological change on the timing of abatement and coalition formation;
- The impacts of side-payments (transfers) that can be arranged as
    - Direct payments;
    - Compensation schemes for abatement costs;
    - Issue linking;
- The impacts of technological cooperation;
    - Allowing for knowledge spillovers;
    - Implementing active R&D cooperation;
- The impacts of renegotiations.

To illustrate one particular issue further: Recently, there is substantial interest into the consequences of a “delayed accession” of developing countries in a global climate agreement. Whereas the current models are suited to investigate the economic consequences of a given accession time frame, they are not capable of answering essential questions with respect to the incentives of regions to delay their accession. Thus, they work with exogenous scenarios to reflect different assumptions on which countries will join an agreement and at which date. The existing game-theoretic models have the major flaw that their description of the interactions between the economic system and the climate system are too simplified to make credible sectoral and regional projections of the impacts of climate policies. Integrated coalition formation models, such as the ones proposed here, will be able to provide insights into the changes in incentives of regions over time to join a climate agreement by combining the empirical richness of the IAMs with the game-theoretic mechanisms as explored in STACO. While many argue that costs and benefits will not be the only determinant in international policy-making, they do play a central role in the evaluations that countries make and on which they base their behaviour. Furthermore, the quantitative analysis provided by the coalition formation models can also be used for a more positive analysis: when should certain regions be stimulated to join a coalition and when should a more reactive approach be preferred.

Several bottlenecks can be identified in the different domains:

(i) Game theory

International negotiation processes are complex. In any case a national government or groups of governments that link their climate policies (such as EU) need to adopt a position, come up with suggestions for cooperation, and perhaps make concessions. Moreover, for a successful negotiation process it is not only necessary to know one's own stakes but also what is at stake for others. It is well-known result from bargaining theory that asymmetric information for example about others' payoffs may lead to inefficient bargaining outcomes. The inclusion of uncertainties as well as asymmetric information is a major challenge for applied modelling.

Another issue is the existence of multiple equilibria. Generally, with multiple equilibria, some equilibrium is best for one player while another equilibrium is best for another player. This gives rise to non-trivial equilibrium selection problems.

(ii) Integrated Assessment modelling

Regionalised IAMs provide an insight into what is at stake for different countries/regions. As such they provide an informational basis for the negotiation process.

Stability analysis of the kind a combined STACO-MERGE or STACO-FAIR model would offer is important input for policy-makers/negotiators. Analysis of different model variants unveils the incentives of different regions to participate in an agreement. This may facilitate the search for strategic alliances in climate policy negotiations.

(iii) Data requirements

The quality of results from IAMs always depends on the available data. As data are always incomplete or due measurement error, uncertainty analysis remains an issue for IAMs (see Gabbert and Kroeze (2004) for a survey). The analyses with STACO have revealed that regional damage estimates are especially important for the determination of regional payoffs, and therefore for the stability of coalitions (see Dellink *et al.*, 2008 for an econometric investigation into this issue). Unfortunately, good regional damage estimates are not always available, and the quality of the estimates is often poor. While scattered evidence is available on the impact of specific climate impacts for specific regions, fully integrated assessments of all impacts for all regions are very scarce (most models use the damage estimates of the RICE model, but these have been estimated already 10 years ago, and thus do not reflect recent insights).

(iv) Computations

The most interesting policy questions arise around the issue of timing of abatement measures and accession to an ICA. This involves the analysis of sequential games that can be computationally too demanding.

Similarly models with endogenous technological change will usually involve optimal control problems in a strategic setting, i.e. differential games the solution of which may require huge computing capacities.

5.2 Preview of a research strategy

FAIR can relatively easily be used to (i) update the abatement cost and benefit functions in STACO; (ii) do stability assessments in FAIR for non-optimal regimes; (iii) Further research is required before partial coalition formation can be fully integrated into FAIR. MERGE's damage module is not fully up to date but it might be updated 'soon'. A full integration of MERGE and STACO seems to be difficult. A pragmatic approach would suggest to revise STACO's benefits and cost functions using results from MERGE.

As a final remark we wish to stress some potential policy implications of the efforts to combine game theoretic stability analysis with Integrated Assessment modelling.

- Use of transfers – these may be large. Hence, good communication with the public is needed to explain the needs and purposes of transfers;
- Shaping of industrial policies with respect to green technologies;
- Restriction of technology spillovers to members of an ICA can have negative stability impacts.

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