Game-theoretic analysis of international climate agreements: The design of transfer schemes and the role of technological change

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Thesis

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Contents

Preface

When I joined the Stability of Coalitions (STACO) research project in 2004 as a guest researcher, I never thought about pursuing a Ph.D. research here in Wageningen. The one-year fruitful research life highly motivated me to continue with the project and to pursue further research. During my Ph.D. research which started in 2006, I was privileged to be surrounded by respectable and fantastic people in both my research and private life. I cannot find appropriate words to express my sincere gratitude to all those people who contributed to the completion of my Ph.D. thesis.

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Chapter 1

Introduction

This thesis examines the formation of international climate agreements (ICAs) in a game-theoretic framework. I analyse strategic behaviour of a number of regions or countries in the world (hereafter referred to as regions) to reduce CO_2 emissions. In the application, I use data that reflect regional characteristics, such as costs and benefits of emission abatement[1], and this enables me to explore the regional incentives for signing an ICA. This research was carried out in the context of the STACO project[2] at Wageningen University.

This introductory chapter commences with the research background and a very brief assessment of the current major scientific insights into global warming, and provides a literature review on the analysis of ICAs. This is followed by the problem definition, the objectives and novel contributions of the thesis, the research questions and the methodologies used. Finally, an outline of the thesis is presented.

1.1. Background of the global warming issue

Global warming has been considered one of the major environmental challenges that the world is facing to date. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) states 'Warming of the climate system is unequivocal' by quoting the observation of changes in the climate system, such as rise in the global average surface temperature and global average sea level (IPCC, 2007a). The global average surface temperature has increased by about 0.74 ± 0.18 °C over the period 1906 to 2005, and global average sea level has risen by 3.1 ± 0.7 mm per year from 1993 to 2003 (IPCC, 2007a). Furthermore, AR4 shows that precipitation increased

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[1] We refer to emission abatement as 'abatement' throughout this thesis.

[2] STACO stands for STAbility of COalitions. The STACO project has first been initiated in 2002 by Prof. E.C. van Ierland, Wageningen University, the Netherlands, and Dr. M. Finus, now at the University of Exeter, U.K. The project is maintained by the Environmental Economics and Natural Resources Group of Wageningen University. For more information, see http://www.enr.wur.nl/UK/staco/.

considerably over the period from 1900 to 2005 in eastern parts of North and South America, northern Europe and northern and central Asia, while it declined in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. There is associated observable evidence of extreme climate events, such as tropical cyclones and increase in the frequency of hot days and heat waves (IPCC, 2007a). The main cause of global warming is considered to be greenhouse gas forcing over the last 50 years and it is 'very likely' that human activities, such as burning of fossil fuels, significantly contributed to the rise in temperature over the last 50 years (IPCC, 2001; IPCC, 2007a).

In the absence of additional climate policy, the baseline global emissions of greenhouse gases (GHGs)[3] are projected to increase by values in the range between 9.7 Gigaton of carbon dioxide-equivalent ($GtCO_2$-eq) and 36.7 $GtCO_2$-eq (25% - 90%) between 2000 and 2030 (IPCC, 2000; IPCC, 2007b). Especially, the fossil fuel originated CO_2 emissions are projected to grow by any rate between 40% and 110% from 2000 to 2030 (IPCC, 2007b). As CO_2 is treated as one of the major GHGs[4], I will focus on CO_2 emissions throughout the thesis.

To tackle the problem of global warming, the Kyoto Protocol was signed in 1997. It mandated that by the period from 2008 to 2012, Annex I countries (composed of developed countries and economies in transition) should reduce their GHGs emissions by approximately 5% compared to their 1990 levels. Annex I countries have initiated their climate change programmes in order to meet their targets. The Protocol came into force in 2005, although the U.S.A., one of the major emitters of CO_2, had not ratified the Protocol. Controlling CO_2 emission encompasses the characteristics of a public good[5]. Benefits derived from abatement by one region are freely available to other countries (non-excludability) and the benefits enjoyed by one region do not diminish the benefits that other countries may obtain (non-rivalry). These features give rise to a free-riding problem, a situation in which regions have few incentives to contribute to the protection of global commons, while they can enjoy benefits derived from abatement efforts by others. It has been widely acknowledged that cooperation on abatement is likely to be difficult to achieve, because of the existence of free-riding. The main obstacle to an implementation of a successful agreement is that the agreement must be ratified on a voluntary basis. There are no international institutions and international laws that implement binding ICAs for all countries involved. Thus, we have to rely on individual voluntary participation in an ICA. It remains a crucial research topic how such a voluntary agreement could be established and how regional incentives to participate in the agreement would change according to different forms and designs of the agreement.

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[3] Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Sulfur hexafluoride (SF_6), Hydrofluorocarbons (HFCs) and Perfluorocarbons (PFCs) are the greenhouse gases listed in Kyoto Protocol (United Nations, 1998).

[4] The share of global mean radiative forcing of GHGs stated in AR4 is about 63% (1.66 W m^{-2}) for CO_2, 18% (0.48 W m^{-2}) for CH_4, 6% (0.16 W m^{-2}) for N_2O, and 13% (0.34 W m^{-2}) for Halocarbons (IPCC, 2007a).

[5] For the theory of public goods, see Cornes and Sandler (1996).

1.2. Literature review

Game-theoretic approaches have been widely used to examine an interaction between countries in the negotiation on climate change, and have emphasised difficulties in designing such a voluntary agreement. A number of studies on ICAs have investigated the formation of climate coalitions in a theoretical framework with symmetric or asymmetric countries (e.g. Hoel, 1992; Barrett, 1994, 1997; Carraro and Siniscalco, 1993; Hoel and Schneider, 1997). These studies show that self-enforcing ICAs can be successful only when the difference between the non-cooperative outcome and the full-cooperative outcome is sufficiently small. The studies with asymmetric countries reveal that it is hard to achieve self-enforcing agreements with a large number of signatories because of asymmetries among countries in the context of benefits and costs from abatement (Carraro, 1999). Other studies, such as Fankhauser and Kverndokk (1996), Tol (2001) and Finus et al. (2006) derive similar results from game-theoretic models with empirical inputs. There are substantially larger global net benefits achieved in the full-cooperative case than in the non-cooperative case, but some countries are worse off because they contribute more to reduce emissions than is in their own interest. This will eventually lead to free-riding. Given the fact that each region's net benefits derived from abatement depend heavily on the arrangements enacted by the ICAs and the design of mechanisms, ICAs should be individually rational (Carraro and Siniscalco, 1993; Finus, 2002) for participants in the agreement, i.e. each member of an ICA is at least as well off as in the non-cooperative case.

1.2.1. Transfer schemes

To curtail the free-riding incentives, some of the policy regimes apply the concept of transfer schemes between countries in the form of side payments, emission permit trading or surplus sharing (e.g. Carraro and Siniscalco, 1993; Edmonds et al., 1995; Rose et al., 1998; Altamirano-Cabrera and Finus, 2006; Weikard et al., 2006). Transfer schemes are especially suitable to compensate regions that contribute relatively more to abatement in the coalition, but that have relatively low benefits from abatement. Carraro and Siniscalco (1993) conclude in an analytical framework that transfer schemes may successfully increase the number of signatories. In a model with five asymmetric regions, Botteon and Carraro (1997) confirm the results obtained by Carraro and Siniscalco (1993) that ICAs can consist of at most three countries, and conclude that transfer schemes exist that may succeed in stabilising larger coalitions. Tol (2001) empirically investigates the impact of side payments and suggests that with side payments, the largest stable coalitions do not include either the large emitters or the most vulnerable countries from climate change.

In the literature on coalition formation it has been shown that transfer schemes will be effective when regions have different structures of costs and benefits of abatement, and the design of the transfer schemes will highly affect the incentives to join the agreement. Both cost-effectiveness and equity issues have been treated as focal points when abatement burdens are distributed among regions. Rose et al. (1998) investigate the impacts of rules for allocating emission permits on the abatement costs of achieving the targeted emission level. They categorise transfer schemes into two types: (i) allocation-based rules and (ii) outcome-based rules. In allocation-based rules, emission permits are initially distributed to the coalition members according to certain criteria. In outcome-based rules, on the other hand, net benefits from cooperative abatement efforts are distributed to the coalition members based on certain criteria. For allocation-based rules, such as permit trading, Altamirano-Cabrera and Finus (2006) examine the impact of different allocation schemes on the success of ICAs, focusing on what they call 'pragmatic schemes' and 'equitable schemes'. In the pragmatic schemes, emission permits are allocated based on certain baseline emission levels, either in the form of Business as Usual (BAU) emissions or emissions in the absence of cooperation (Nash equilibrium)[6]. In the equitable schemes, emission permits are allocated by considering equity aspects, such as ability to pay for abatements, historical responsibility for accumulated emissions, and the level of technology. They conclude that pragmatic schemes perform better than equitable ones in terms of the success of self-enforcing agreements. For outcome-based rules, Weikard et al. (2006) explore the impact of surplus sharing rules where net benefits from cooperating are distributed to the coalition members either on an equitable basis or on an emission basis. They find that equitable sharing rules are inferior to emission-based sharing rules in terms of global net benefits of controlling climate change.

The findings of previous studies, have established that the success of ICAs with transfer schemes largely depends on how emission permits or net benefits are allocated among coalition members. To improve the design of transfer further, another type of transfer scheme called 'optimal sharing' has been explored. Optimal sharing, suggested by Carraro et al. (2006), McGinty (2007), Weikard (2009) and Fuentes-Albero and Rubio (2010), offers two main advantages. These are: (i) if the coalition payoff is sufficiently large and distributed in such a way that each member obtains at least its outside-option payoff, no incentives to leave a given coalition remain and (ii) all coalitions that are possibly internally stable under some sharing rule are internally stabilised. By taking a systematic approach to examine the role of transfer schemes, Carraro et al. (2006) attests that an 'appropriate' transfer scheme (optimal transfer scheme) can maximise cooperation on abatement.

1.2.2. Technology spillovers

Although well-designed transfer schemes are promising, full cooperation on abatement is still hard to attain. Another mechanism, known as issue linkage, that has been proposed may reduce incentives to

[6] Under a Business as Usual (BAU) scenario, no additional climate policy or measure is taken for each region to abate emissions, while in a Nash equilibrium, each region chooses the best abatement strategy domestically, taking abatement in other countries as given.

free-ride and expand coalitions in the global warming game. Carraro (1999) suggests that the grand coalition seems to be unattainable if cooperation on emission reductions alone is considered in the negotiations. The main idea of issue linkage is that countries negotiate not only on emission reductions, but also negotiate on another economic issue, for instance on technology cooperation. Barrett (1997) proposes linking environmental negotiations to international trade negotiations. Carraro and Siniscalco (1997) show that the number of signatories may increase by linking the negotiation on abatement to the negotiation on R&D cooperation. They assume that signatories enjoy a larger degree of spillover from technological cooperation than singletons. Similarly, Kemfert (2004) combines cooperation on abatement and technological innovation to explore the possibility of inducing participation from non-cooperative countries, such as the USA. This approach suggests that an increase in R&D expenditures will lead to technological innovation through technology spillovers and an increase in energy efficiency through technology spillovers and trade in goods among signatories. Buonanno et al. (2003) define spillovers of *knowledge* which affect both the production function and the emission-output ratio. Similarly, Golombek and Hoel (2005) assume that the technology level of the region is determined by its own R&D investments and the investments of other signatories. It has been shown that the technology spillovers from other regions will increase productivity and lower emission intensities, or lower marginal abatement costs.

1.2.3. Induced technological change

There are a number of studies on technological change (TC) and its links to economic growth. In neoclassical theory, TC is treated as given and it is not driven by any market forces (Solow, 1957). Basically, technological change is considered to shift the production function which leads to a reduction in capital per unit of labour (e.g. Kennedy, 1962; Uzawa, 1965) or to an increase in total factor productivity (Arrow et al., 1961). In economy-environment models, prominent studies are by Peck and Teisberg (1994) and Nordhaus and Yang (1996) who numerically examine the optimal paths of emissions with exogenous TC. These studies do not fully explain the drivers of the *steady-state*[7] growth of the economy as the growth rate is exogenously given. A new strand of growth theory, which is sometimes called 'new growth theory' (or 'endogenous growth theory'), aims to answer questions about the drivers of technological improvement over time. New growth theory places more emphasis on the potential role of investment in new knowledge and effects of technological innovation that drives the economic growth (seminal studies are Lucas, 1988 and Romer, 1990). Concerning the definitions of 'endogenous TC' and 'induced TC', Jaffe et al. (2001) point out that models of endogenous TC generally focus on neutral TC while models of induced TC analyse the direction of

[7] This is a situation in which per capita production and per capita consumption are constant due to constant per capita stock of capital and constant per capita labour supply.

R&D investments. In this thesis, R&D investments determine the speed of TC, but not its direction. Technology is endogenously determined, following the definition by Jaffe et al. (2001). In economy-environment models, endogenous TC can be specified in different ways to fit the purpose of the analysis (see Weyant and Olavson, 1999; Löschel, 2002; Clarke et al., 2006; Sue Wing, 2006 for excellent reviews). There are three main sources of TC: (i) R&D investments (e.g. Goulder and Mathai, 2000; Buonanno et al., 2003), (ii) technology spillovers (e.g. Griliches, 1992; Bosetti et al., 2008), and (iii) learning by doing (e.g. Manne and Richels, 2004; Castelnuovo et al., 2005).

Looking at an economy-environment model Goulder and Mathai (2000) theoretically and numerically examine the impact of knowledge accumulation through R&D investments and learning by doing to investigate the optimal timing of abatement. Their finding is that R&D investments will postpone the optimal timing of abatement. In an economy-environment model called R&DICE, Nordhaus (2002) incorporates an improvement in carbon intensity (CO_2 emissions per unit of GDP) that is derived from technological change through R&D investments into the energy sector, leading to fewer emissions. He finds that the role of R&D on model results is somewhat limited.

In a coalition formation game, Buonanno et al. (2003) employ an induced environmental TC model to study the stability of selective coalitions. Technological change through R&D investments will increase production and lower the emission-output ratio. Buonanno et al. (2003) conclude that the existence of induced environmental TC will lower the abatement costs much more than in the case of exogenous environmental TC. Among the studies focusing on regional incentives to participate in a climate coalition, Kemfert (2004) incorporates improvement in energy efficiency derived from R&D investments into her model, and concludes that incentives to join a coalition tend to be stronger if the agreement includes cooperation both on abatement and technological innovation, since the benefits are higher when technology cooperation is included.

1.3. Problem definition

Integrated assessment models (IAMs) are suitable for evaluating the optimal level of abatement by taking dynamic features of the global warming problem into consideration. The original model STACO-1 (Finus et al., 2006; the model will be discussed in detail in Chapter 2) entails important dynamic aspects of climate change; it assumes, however, that levels of annual abatement and thus also annual (undiscounted) abatement costs are constant over time, which indicates that the strategic timing of abatement efforts throughout the planning horizon is not adequately considered. The first problem to be dealt with is related to the implementation of dynamic aspect of abatement efforts. Since each region's abatement level differs from period to period by balancing benefits and costs of abatement, the model needs to be extended from a static setting to a dynamic setting to evaluate optimal abatement strategies over time. To compute optimal levels of abatement, all future impacts of abatement should be considered. More precisely, the benefits at a current period should be influenced by both current abatement and past abatement.

The second problem concerns the design of transfer schemes that influences incentives to cooperate on abatement. As discussed above, a number of studies have explored various flexible mechanisms to increase the environmental effectiveness and stimulate cooperation on global abatement. Some of the regimes apply transfer schemes to affect burden-sharing for abatement efforts among countries based on criteria such as equity or efficiency. In most of the studies transfer schemes for allocation of abatement burdens are based on a single year. In reality, abatement targets for Annex I countries in the Kyoto protocol are assigned according to the emission level in 1990. As Germain and Steenberghe (2003) pointed out, a grandfathering rule based on the emission level in 1990 does not always satisfy the individual rationality requirement along the time path. The static schemes do not take into account that the future growth paths of emissions are expected to diverge substantially between regions. This leads to assignments where historically large emitters obtain a relatively large share of the permits or surplus, while fast-growing developing countries, such as China or India, obtain relatively small shares, resulting in increasing burdens on these developing countries to reduce their emissions; an issue brought forward by many developing countries in their argumentation on why they do not agree on any reduction targets in the Kyoto protocol. To enhance participation of developing countries, some alternative allocation schemes are necessary to set incentives to join an agreement especially for those regions whose economies are expected to grow faster in the future. This problem can be solved by transfer schemes in which the allocation of emission permits generates benefits for these developing countries.

The third problem to be considered is how different channels of technology spillovers and the level of a region's own technology influence incentives to cooperate. If we consider that knowledge is a pure public good, each region can freely enjoy the benefits of knowledge spillovers, which is modelled as 'a world stock of knowledge' in the existing studies. However, if the linkage between cooperation on abatement and cooperation on technology makes the knowledge exclusive to coalition members, the spillovers should be treated as coalitional spillovers (Carraro and Siniscalco, 1997). Therefore, coalition members may benefit not only from the world stock of knowledge, but also from coalitional spillovers generated by cooperation. The question is: are those knowledge spillovers powerful enough to induce incentives to join the agreement.

In addition, knowledge spillovers for environment-related technologies can be formulated in different ways, following studies on the provision of public goods (Hirshleifer, 1983; Holzinger, 2001; Sandler and Tschirhart, 1997; Sandler, 2006). These studies discuss the concept of 'an aggregation technology' as one of the properties of public good besides non-rivalry and non-excludability. According to the definition by Sandler (2006), the aggregation technology, referred to as the social composition function by Hirshleifer (1983), indicates '*how individual contributions to the public good contribute to the overall quantity of the public good available for consumption*' (Sandler, 2006, p.9).

The ways of aggregation in the literature have been categorised according to the characteristics of the public good. If the contribution by one region is a perfect substitute for that of others, the total amount of the public good is defined as the *sum* of all regions' contributions. On the other hand, if the contributions are not perfect substitutes, the total amount of the public good will depend on the smallest contribution (*weakest-link*) or the largest contribution (*best-shot*). The knowledge for environment-related technologies can be considered a regional public good when technology cooperation is established among countries located in that region. An important question is how the aggregation technology affects the incentives to join an agreement.

As shown in Section 1.3, the drivers of TC and spillovers can be determined endogenously through R&D investments. The fourth problem relates to the driver of technological change and its impact on coalition formation. In most studies, knowledge spillovers have been defined as a certain rate of accumulated R&D investments summed over all (coalitional) regions. As the level of reduction of abatement costs with induced TC differs compared to the case of exogenous TC, the question is how R&D investments affect the success of an international agreement and how international cooperation on abatement may induce the incentives for countries to invest in R&D on abatement.

Lastly, it has been widely recognised that one of the main determinants for the result of cost-benefit analysis is a discount rate. The choice of an appropriate discount rate used in the cost-benefit analysis has long been a controversial issue and has been ongoingly debated in literature on climate change as it is a question of value judgement regarding how to deal with the welfare of future generation (e.g. Weitzman, 1994; Azar and Sterner, 1996; Schelling, 1995; Weitzman, 2001). Weitzman (1998) shows the rationale behind the use of the lowest possible discount rate for activities or events in the far-distant future. Given the fact that the 'far future' has greater uncertainties about economic and non-economic features such as the rate of economic growth, the level and rate of technological progress and the amount of capital accumulation compared to the 'near future', he proposes to use a declining discount rate over time and shows the 'certainty equivalent discount factor' as a weighted average of a wide range of possible discount rates for the far future, which is proved to be equal to the lowest possible discount rate. This approach is called 'Hyperbolic discounting', supported by Cropper et al. (1994) and Henderson and Langford (1998). Weyant (2008) also proposes that the discount rate in the short term would be consistent with the market rate of interest, and the discount rate in the long term would consider the intergenerational equity. The Stern Review on the Economics of Climate Change (Stern, 2006) has drawn further attention on discounting in the context of climate change. A major criticism and suggestion for improvement on the Stern review is that the Stern Review applies a low rate of discount rate (e.g. Nordhaus, 2007; Tol and Yohe, 2006, 2009). The low discount rate will lead to the situation where benefits of taking early action of reduction outweigh the costs of reduction efforts. Nordhaus (2007) argues that discount rate should be consistent with the observed rate of return on capital, and Mendelsohn (2008) argues that low discount rates are equitable because that makes each generation equally worse off, as each generation is burdened by the following generations.

In this thesis, I do not put an emphasis on the choice of the discount rate, however, I conduct a sensitivity analysis with different discount rates by following the ongoing discussion by economists.

1.4. Objectives and novel contributions

This section presents the objectives of my analysis based on the problems defined above. The first purpose of the analysis of transfer schemes is to compare the impacts of different transfer schemes on the regional incentive structures and stability of climate coalitions. Following the categorisation by Rose et al. (1998), I begin by examining two types of transfer schemes: allocation-based and outcome-based transfer schemes. For allocation-based schemes, I introduce a dynamic transfer scheme where the initial allocation for emission permits is based on future emissions paths rather than on (static) emissions in some initial years. I compare the impacts of two types of allocation for emission permits in the grandfathering schemes. Dynamic transfer schemes can overcome obstacles that occur under static transfer schemes and can, therefore, contribute to the stability of international climate agreements (cf. Böhringer and Lange, 2005). Under outcome-based rules, gains from cooperation are distributed among coalition members. It has been proven that outcome-based rules are superior to allocation-based rules in terms of stability (Weikard et al., 2006). Furthermore, although less plausible for practical implementation, transfer rules can be improved by introducing an optimal sharing rule where a coalition member can secure at least a payoff equivalent to his outside-option payoff. Therefore, the novel contributions of my analysis of transfer schemes are: (i) in the model with 12 heterogeneous regions, I derive the optimal abatement levels each year and introduce dynamic transfer schemes where the initial allocations of the permits are based on the projections of emissions, and (ii) I conduct a systematic comparison of different transfer schemes.

Secondly, the objective of the analysis of technology spillovers is to examine the implications of various technology spillover mechanisms on the formation and stability of climate coalitions. As shown briefly in Section 1.3, there are different channels through which technology spillovers affect incentives to cooperate. They are categorised into three types: (i) global spillovers from a 'world stock of knowledge', (ii) spillovers that are directly derived from participation in the agreement (coalitional spillovers) and (iii) spillovers to outsiders. I investigate the impacts of the different aggregation technologies on the success of a climate coalition. Furthermore, I examine how strongly technology spillovers affect stability by varying the relative magnitude of spillovers between coalition members and spillovers to outsiders.

Finally, the objective of analysis on induced TC is to investigate how R&D influences the success of an international climate agreement and how international cooperation on abatement effort triggers R&D activities for signatories. The role of region-specific R&D investments in reducing abatement costs is examined by studying different scenarios in which no technological change, exogenous technological change and induced technological change are considered, respectively. From the outcomes of the scenario analyses I can determine the impacts of endogenous technological change. Furthermore, I examine which mechanism of TC (exogenous or induced) dominates the other in successfully forming coalitions.

Besides mitigation actions, adaptation to climate change is crucial to reduce the impacts of climate change and to strengthen resilience to the future climate impacts. The costs and benefits of adaptation have been investigated in the literature on climate change (e.g. De Bruin et al., 2009a; De Bruin et al., 2009b). It should be noted that this thesis focuses on the benefits and costs of mitigation. In addition, this thesis focuses on CO_2 emissions among GHG emissions due to the data availability and reliability for future emissions.

1.5. Research questions and approaches

To achieve the objectives of my research discussed above, I will deal with the following four research questions.

Q1 *How can I implement the dynamic aspects of abatement efforts and incentives to join an international climate agreement into an applied game-theoretical analysis and which stable coalitions would occur if no transfer scheme is considered?*

The first research question indicates how I obtain optimal strategies for abatement levels over time. I relax the assumption of constant abatement levels applied in the original version of STACO model (Dellink et al., 2004; Finus et al., 2006).

Q2 *How does the design of transfer schemes affect the stability of an international climate agreement?*

The second research question investigates the impacts of different designs of transfer schemes, which are ‘pragmatic’ and ‘optimal’ transfer schemes, on the stability of voluntary-based international climate agreement. Furthermore it tackles the current ineffective transfer schemes and considers how we can identify superior transfer schemes. To answer this question, I will examine dynamic transfer schemes and optimal transfers. These might overcome major obstacles in ICAs, and contribute to the stability of climate coalitions.

Q3 *How do different technology spillover mechanisms among regions influence the incentive structures to join and stabilise an international climate agreement?*

The third research question deals with the impacts of technology spillovers on coalition formation. It also explores how different channels of technology spillovers and specifications of aggregation of technology can affect the regional incentive structures. In addition, I will examine whether the net benefits from technology spillovers are large enough to stabilise more ambitious coalitions by offsetting the incentives to free-ride.

Q4 *How do R&D investments influence the success of an international agreement on abatement and how does international cooperation on abatement induce incentives to carry out R&D investments that are socially optimal?*

Finally, the fourth research question indicates how R&D investments influence regional strategies for abatement and stability of climate coalitions. By extending the model with exogenous TC or technology spillovers to incorporate an induced TC, investigation of linking cooperation on abatement to technology cooperation will be further improved, since cooperation affects R&D investments.

1.6. Methodology

There are two approaches to policy evaluation. One is cost-effectiveness analysis that may be used to consider achieving a certain given climate target at minimum costs. The other is cost-benefit analysis where a social planner implements a welfare maximising climate target (optimal abatement levels). I follow the second approach throughout the following chapters where the abatement levels and other economic variables are optimally determined in our model.

Regarding the first research question, I consider a two-stage, non-cooperative game of coalition formation. At the first stage, countries decide to join a coalition or not (membership of the coalition), and then at the second stage, those announcing to join the coalition implement their jointly optimal abatement levels over the planning horizon. The abatement strategies are based on the payoff function of each region. I derive optimal abatement paths over time by building the STACO-2.1 model, a combined game-theoretic and integrated assessment model in a dynamic setting, that is an updated and dynamic extension of the STACO-1 model described in Finus et al. (2006). This will be discussed in detail in Chapter 2. All research questions will be answered by using this STACO-2.1 model. With regard to the stability concept, I follow the standard concept of stability applied in a non-cooperative game: internal stability and external stability, originally defined by d'Aspremont et al. (1983). If a coalition structure satisfies both internal and external stability, it is called stable. In the thesis, I apply the concept of open membership where there is no restriction for new members, because it seems in line with the current procedures of the Kyoto protocol and previous analysis has suggested that the role of restricted membership is limited (e.g. Finus et al., 2005).

So far, little systematic work has been done on the interaction between coalition formation and optimal abatement paths, and on testing the stability of all partial coalitions theoretically and empirically. In the framework of a non-cooperative game, Tol (2001) tested stability for all possible coalitions, applying a fixed path of abatement instead of deriving the optimal abatement path. In the framework of a cooperative game with a dynamic, multi-regional integrated assessment model, Eyckmans and Tulkens (2003) calculated the optimal path of abatement and aggregated discounted welfare for each region. STACO-2.1 is capable of identifying the regional optimal abatement paths based on the stream of benefits and costs of abatement. As each region's abatement strategy depends on its abatement costs and benefits in each period, each region can simultaneously decide by what amount its CO_2 emissions should be reduced and when. I assume that undiscounted benefits in each period depend not only on current abatement but also on abatement in previous periods through reduced concentrations of CO_2 and correspondingly lower damage levels. The model calculates related economic variables such as benefits, abatement costs and payoffs per year.

Regarding the second research question, I incorporate an emission trading system in the model to allow for transfers among regions in the coalition. The annual transfer schemes, referred to as '*dynamic transfer schemes*', which are based on expected paths of emissions, can overcome obstacles associated with grandfathered emission permits and can therefore contribute to the stability of international climate agreements. In Chapter 3, I investigate the implications of a dynamic transfer scheme and take further steps to examine the stability of all possible climate coalitions. Firstly, I focus on the transfer scheme that distributes permits in proportion to emissions. This allocation scheme is presented in the Kyoto protocol as 'Grandfathering' where the allocation of permits is based on the historical emissions of each region. To take the future growth of emissions in developing countries into account, I implement a dynamic transfer scheme that bases the distribution of emission permits on the whole path of reference emissions. Then, I investigate the implication of outcome-based transfer schemes that distribute the gains from cooperation among signatories in such a way that the share of coalition surplus is distributed proportional to initial and future emissions. Finally, the optimal sharing rule is applied.

To answer the third research question, I extend the STACO-2.1 model in Chapter 4 by embedding different types of technology spillovers in the abatement cost function. Basically, technology spillovers are assumed to create an externality to a region by reducing marginal abatement costs. Beside the different channels of technology spillovers discussed above, the size of spillovers depends on ICA membership and the nature of signatories in terms of their state of technology. Under a summation aggregation technology, the spillovers are assumed to be higher both when more regions are members of the coalition, and when regions with an advanced 'state of technology' are members of the coalition. On the other hand, under a best-shot aggregation technology, technology spillovers are higher when the region with the most advanced technology is a member of the coalition, irrespective of the number of signatories. The state of technology is expressed by indicators, such as emissions, carbon intensity or energy intensity for each region.

Regarding the fourth research question, I extend the model used in Chapters 2, 3, and 4 to determine the rate of TC endogenously by introducing R&D investment efforts in Chapter 5. The major difference from the analysis in previous chapters is that each region determines the optimal strategy both for R&D investments and for abatement in the second stage. The stock of knowledge on abatement increases with R&D investments, which leads to lower abatement costs. The regional abatement cost functions are assumed to depend on two variables, abatement level and the stock of knowledge. Here I assume R&D investments are carried out by individual regions with no knowledge spillovers. I analyse the interaction between regional R&D investment efforts and cooperation on abatement in this setting.

1.7. Outline of the thesis

The remainder of this thesis comprises five chapters.

Chapter 2 provides the basic structure of the STACO-2.1 model, composed of a game-theoretic framework and applied features, with specifications and calibrations of the functions used in the model. I report the base case of the simulation that will be used in the following chapters. To address the problem of uncertainty, I conduct a sensitivity analysis by changing crucial model parameters. The first two chapters together form the basis for the investigation of the individual research questions in the following three chapters.

Chapter 3 investigates the features of a dynamic transfer scheme where the distribution of emission permits is based on the whole path of reference emissions. I analyse the impact of implementing dynamic transfer schemes on the stability of coalitions in the dynamic setting presented in Chapter 2. The model incorporates several transfer schemes, based on different allocation rules, such as surplus sharing and optimal sharing rules. Results are discussed for each transfer scheme.

Chapter 4 presents the model extended with technology spillovers both between coalition members and between the coalition and outsiders. Additional simulations are constructed to explore the impacts of alternative specifications of technology in terms of who generates and receives the spillovers, the aggregation and indicators of the technology, and the related impacts on the marginal abatement costs.

Chapter 5 examines the impacts of R&D investments on regional incentives to join the agreement. I extend the model used in previous chapters 2, 3, 4 to implement the development of TC through R&D investments.

Finally, Chapter 6 provides a summary and the main conclusions of the research. All research questions defined in Chapter 1 will be answered in brief. Implications for policy and further research will be discussed.

Chapter 2

Theoretical & empirical background of STACO-2.1

2.1. Extension of the original STACO model (STACO-1)

This chapter presents the theoretical and empirical background of the STACO model in a dynamic setting, STACO-2.1. The STACO model is a combined game-theoretic and integrated assessment model created to examine the formation and stability of international climate agreements. The model is a tool for analysing which coalitions are stable and which kinds of mechanisms can increase incentives to cooperate on reduction of CO_2 emissions. The STACO model captures interactions between countries and the effects their abatement strategies have on the stock of CO_2 in the atmosphere. Each country's payoff from abatement is assessed for each coalition structure, based on regional benefits (avoided damages) and costs from abatement. The original STACO model (STACO-1) as introduced by Finus et al. (2006) and described in detail by Dellink et al. (2004) has been used to investigate several research topics such as membership rules (Finus et al., 2005), multiple coalition formation (Sáiz et al., 2006), transfer schemes (Altamirano-Cabrera and Finus, 2006; Weikard et al., 2006), and stability likelihood of coalition under uncertainty (Dellink et al., 2008b).

In STACO-1 it is assumed that the level of annual abatement and annual undiscounted abatement costs are constant over time. In a model including discounting and a stock pollutant, however, a constant abatement path will generally be inefficient. Therefore we have constructed a model for the stability of coalitions, STACO-2.1, that represents a Ramsey-type dynamic extension of the STACO-1 model. STACO-2.1 identifies the regional dynamically optimal abatement paths based on the discounted future stream of benefits and costs of abatement. As each region's strategy choice depends on its abatement costs and benefits (avoided damages) in each period, each region can simultaneously decide how much CO_2 emissions should be reduced and when. As we deal with a stock pollutant we assume that undiscounted benefits in each period depend not only on current abatement but also on abatement in previous periods through reduced concentrations of CO_2 and correspondingly lower damage levels. The model includes economic variables, such as benefits, abatement cost and payoffs (expressed yearly) and the corresponding discounted aggregates. We consider 12 heterogeneous regions in the model which have individual abatement strategies. We calculate the optimal abatement level each year and check the stability of the coalition over the time horizon of the model. Our analysis is thus based on a one-shot game through considering the total discounted payoffs. We focus on the individual strategic behaviour for reducing emissions at the moment of the negotiation, taking future impacts into consideration. In this thesis, renegotiations, multiple deviations and multiple coalitions are abstracted from the analysis.

This chapter is organised as follows. Section 2.2 provides the game theoretical framework of the model. Section 2.3 presents the calibration of the equations used in the model. In Section 2.4 the general features of the model are discussed. Section 2.5 reports the main results for benchmark scenarios without any transfer schemes and technology spillover effects. Results of the sensitivity analysis are presented in Section 2.6. Section 2.7 concludes.

2.2. Theoretical background of STACO-2.1

We consider a two-stage, non-cooperative game of coalition formation. Countries or regions (hereinafter referred to as regions) are denoted by $i = 1,...,N$. At the first stage, regions decide to join a coalition or not (membership decision). Regions announcing not to join a coalition, the non-signatories, remain singleton players, and those announcing to join, the signatories, form a unique coalition. In our model, which comprises twelve regions, we can obtain 4084 (2^{12} -12) different coalition structures. Coalitions with only one member are not effective. At the second stage, regions adopt their abatement strategies over the planning horizon T . The strategies are based on the following payoff function (π):

$$\pi_i(\mathbf{q}) = \sum_{t=1}^{T} \left\{ (1+r)^{-t} \cdot (b_{it}(\mathbf{q}) - c_{it}(\mathbf{q}_i)) \right\} + \sum_{t=T+1}^{\infty} \left\{ (1+r)^{-t} \cdot b_{it}(\mathbf{q}) \right\} \qquad \forall i \in N \qquad (2.1)$$

where the model horizon accounting for future benefits is infinity, r is the discount rate on the payoff, and $\mathbf{q}$ is an abatement matrix of dimension $N \times T$ [1]. b_{it} is a concave benefit function of past and current global abatement and c_{it} is a strictly convex abatement cost function of regional current abatement given per region and time period. Benefit and abatement cost functions are specified in detail in Section 2.3. The infinite horizon for benefits from abatement ensures a proper reflection of the long-term aspects of climate change, while the period for which the international agreement holds (the planning horizon) is limited. Essentially, in 2010 (t =0) the signatories strike an agreement that sets their abatement path until 2110 (T =100), while taking into account all future benefits and costs

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

from that abatement path. We calculate the optimal abatement paths over the planning horizon. The abatement strategy space for each region is defined as $q_{it} \in [0, \bar{e}_{it}]$, where $\bar{e}_{it}$ denotes regional emission levels in the business-as-usual scenario with no abatement. Note that benefits for each region depend on *aggregate global emission reductions* and that abatement costs depend on the *regional emission reduction*.

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 (PANE) between signatories and singletons (Chander and Tulkens, 1995, 1997). Non-signatories choose their abatement level by maximising their own payoffs, taking the other regions' abatement levels as given. On the other hand, signatories choose the abatement levels that maximise the sum of the payoffs of the signatories, taking the abatement levels of non-signatories as given. We call a situation where none or just one of the regions signs the agreement 'All Singletons' and the coalition of all regions the 'Grand Coalition'. In the Grand Coalition, the highest global abatement levels and payoffs are obtained, as all externalities of abatement are taken into account. We call a coalition $K \subseteq \{1,...,N\}$ stable, if the coalition satisfies both *internal* and *external* stability. Internal stability of a coalition requires that no signatories have an incentive to withdraw from the coalition as a lower payoff is obtained by changing their strategies to not join the coalition. Similarly, external stability of a coalition means an equilibrium where no non-signatories have an incentive to participate in the coalition as a lower payoff is achieved by changing their strategies to join a coalition. In the definition of external stability, it is implicitly assumed that non-signatories can join the coalition freely whenever they can obtain the higher payoffs by joining the coalition, without the approval of other signatories. We call this 'stability under open membership' [2] (cf. Finus et al., 2005). Although different membership rules as described in Finus et al. (2005) are available as a choice in the STACO simulations, in this thesis we apply the concept of open membership, mainly because it seems in line with the procedures of the Kyoto protocol.

2.3. Calibration of STACO-2.1

In this section, we explain the specification and calibration of the equations used in our model, which we label STACO-2.1; the full model description is given in Appendix 2A. The model is an update and extension of the original STACO-1 model, described in Dellink et al. (2004) and Finus et al. (2006). We consider twelve world regions; USA (USA), Japan (JPN), European Union-15 (EU15), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil

[2] An alternative membership rule is called 'exclusive membership', see Finus et al. (2005).

(BRA) and the rest of the world (ROW). We set the model horizon which accounts for benefits from abatement to infinity, but adopt a shorter planning horizon of 100 years, ranging from 2011 to 2110 ($t = 1,\ldots,100$), for determining abatement levels[3]. Together, this ensures a proper reflection of the intertemporal aspects of climate change, while the period for which the international agreement holds is limited. Essentially, in 2010, the signatories reach an agreement that sets their abatement paths until 2110, while taking into account all future benefits and costs from these abatement paths.

2.3.1. Emissions

In contrast to STACO-1, we use data for CO_2 emission projections derived from the EPPA model (Paltsev et al., 2005) to calibrate the regional Business As Usual (BAU) emission paths[4] ($\bar{e}_{it}$) with no abatement effort from 2010 (t_0) to 2110 in our model expressed as:

$$\bar{e}_{it} = \frac{\mathrm{a}_i}{\{1+\exp(\mathrm{b}_i \cdot (t_0 + t - \mathrm{d}_i))\}} + \mathrm{c}_i \,, \tag{2.2}$$

where a, b, c, and d are parameters. Details of this approximation are given in Appendix 2B. Table 2.1 shows each region's average emission growth rate from 2010 to 2110.

Table 2.1: Average emission growth rate from 2010 to 2110

Region	Average emission growth rate (%)
USA	1.35
JPN	1.01
EU15	1.13
OOE	1.46
EET	1.19
FSU	0.93
EEX	1.12
CHN	1.27
IND	1.58
DAE	1.09
BRA	1.21
ROW	1.17

In terms of the reference projections, absolute values of emission and average growth rates are substantially larger for USA and China than for other regions. India also has a high average emission

[3] In general, these future benefits also depend on future abatement. However, in this application, such an assumption is not necessary due to the constant marginal benefits assumed.

[4] We use data from World Bank (2003) to match the regional aggregation in EPPA to STACO.

growth rate (1.58%) over the planning horizon. The growth rate (but not the emission levels) will reach their peaks for China and India around 2020 and for USA, Japan and EU15 around 2040, and their emissions will stabilise in later decades.

2.3.2. Stock of CO_2

We adopt the original version of the DICE model developed by Nordhaus (1994) as the basis for stock of CO_2 in our model. The DICE model relates to CO_2 emissions (BAU emission minus abatement level) to the stock of CO_2. The annual stock of CO_2 is a function of the past stock of CO_2 and the annual global emission level from t_0=2010 up to period t. In Eq. (2.3) the stock of CO_2 is composed of three elements. The first term is the pre-industrial stock of CO_2 ($\bar{M}$), which is equal to 590 GtC. This pre-industrial stock of CO_2 is assumed to be an equilibrium, which implies that natural emissions equal natural decay at that level of stock. The second term reflects the excess amount of stock of CO_2 in 2010 compared to the pre-industrial level, which decays with a constant annual rate δ=0.00866. The last term is the sum of global emissions after abatement from 2011 to the year t. Some fraction of the annual emissions during the period remains in the atmosphere at the end of the period at a constant rate ω=0.64 and the rest of the emissions decays over time with the rate δ.
Then, the stock of CO_2 in the atmosphere in period t can be described by the following equation:

$$M_t(q_1,...,q_t) = \bar{M} + (1-\delta)^t \cdot (M_{t_0} - \bar{M}) + \sum_{s=1}^{t}\left((1-\delta)^{t-s} \cdot \omega \cdot \sum_{i=1}^{n} (\bar{e}_{is} - q_{is}) \right) \tag{2.3}$$

The dynamics of the stock of CO_2 can be written as a difference equation:

$$M_t(M_{t-1}, q_t) = \bar{M} + (1-\delta)\cdot(M_{t-1} - \bar{M}) + \omega \cdot \sum_{i=1}^{n} (\bar{e}_{it} - q_{it}) \tag{2.4}$$

The stock of CO_2 in 2110 with no abatement efforts is projected to be 1,493 GtC, in line with the projections of the original version of DICE (Nordhaus, 1994); the associated concentration level of CO_2 equals 700 ppm.

2.3.3. Damages

To derive the damage function applied to our model, we first look at the damage function in the DICE model. The increase in the temperature causes damage by the following equation (Nordhaus, 1994):

$$d_t = \gamma_D \cdot \left[\frac{\Delta T_t}{3}\right]^2 \cdot y_t, \tag{2.5}$$

where d_t denotes global damages in billion US$, γ_D represents the impact on GDP due to the increase in temperature of $3\,^{o}C$, ΔT_t is the increase in global temperature, and y_t gives global GDP.

As we need to relate the stock of CO_2 to the damages, we follow the climate module by Germain and Van Steenberghe (2003), where the stock of CO_2 influences the global temperature with regard to pre-industrial temperature as follows:

$$\Delta T_t = \eta \cdot \ln\left(\frac{M_t}{\overline{M}}\right) \tag{2.6}$$

where η is an exogenous parameter. We substitute Eq. (2.6) into (2.5) to obtain the global damages as a function of the stock of CO_2 as follows:

$$d_t = \left(\frac{\gamma_D}{9}\right) \cdot \left[\eta \cdot \ln\left(\frac{M_t}{\overline{M}}\right)\right]^2 \cdot y_t \tag{2.7}$$

In the DICE model, it is assumed that a doubling of the stock leads to increase in global temperature by 3 degrees Celsius. Then, Eq. (2.6) reads $3 = \eta \cdot \ln(2)$ and $\eta = \frac{3}{\ln(2)}$. The damage function is thus described by the following equation:

$$d_t = \left[\frac{1}{\ln(2)} \cdot \ln\left(\frac{M_t}{\overline{M}}\right)\right]^2 \cdot (\gamma_D \cdot y_t) \tag{2.8}$$

where γ_D represents impact on GDP due to a doubling of the stock by the definition in Eq. (2.5). We apply the estimate by Tol (1997) that damage costs amount to 2.7% of GDP for a doubling of concentrations over pre-industrial levels, that is, $\gamma_D = 0.027$.

Global GDP growth is modelled as an annual incremental increase that is equivalent to about 2.3% of the global GDP in 2010. We follow Nordhaus (1994) and Germain and Van Steenberghe (2003) and approximate the climate system by a linear system of three equations (for concentrations, radiative forcing and atmospheric temperature increase, respectively) and ignore the non-linear feedbacks between the atmosphere and the oceans. Thus, we can calculate damages as a linear function of accumulated past and current abatement, which is required to ensure dominant strategies for our regions. Then, the linearised damage function is:

$$d_t = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t}{\overline{M}}\right)\right] \cdot (\gamma_D \cdot y_t) \tag{2.9}$$

where γ_1 and γ_2 are estimated by OLS-regression (Dellink et al., 2004).

2.3.4. Regional disaggregation of the benefits

We assume that global benefits b_t from abatement are defined as avoided damages as follows:

$$b_t(q_1,...,q_t) = d_t(M_t(0)) - d_t(M_t(q_1,...q_t)). \quad (2.10)$$

Global benefits with numerical specification are described in Appendix 2C. Global benefits are allocated to each region according to the share θ_i based on the estimates by Fankhauser (1995) and Tol (1997). Their absolute numbers and the associated shares are represented in Table 2.2 and Table 2.3.

Table 2.2: Distribution of annual damage costs over different regions in absolute amounts and shares according to Fankhauser (1995)

Region	Fankhauser (1995) Billion US$ (%)
USA	61.0 (22.6%)
European Union	63.6 (23.6%)
Other OECD	55.8 (20.7%)
Former Soviet Union	18.2 (6.8%)
China	16.7 (6.2%)
Rest of the world	54.2 (20.1%)
World	269.5 (100%)
Subtotal OECD	180.4(66.9%)
Subtotal non-OECD	89.1 (33.1%)

Table 2.3: Distribution of annual damage costs over different regions in absolute amounts and shares according to Tol (1997)

Region	Tol (1997) Billion US$ (%)
OECD-America	68.4 (13.1%)
OECD-Europe	35.3 (6.7%)
OECD-Pacific	62.9 (12.0%)
Other Europe	-11.6 (-2.2%)
Middle East	15.9 (3.0%)
Latin America	109.9 (21.0%)
South & Southeast Asia	134.3 (25.6%)
Centrally planned Asia	69.6 (13.3%)
Africa	39.1 (7.5%)
World	523.8 (100%)
Subtotal OECD	166.6 (31.8%)
Subtotal non-OECD	357.2 (68.2%)

Comparing the numbers of Fankhauser and Tol is not straightforward. For instance, Fankhauser's numbers are based on purchasing-power-parity exchange rates, while Tol uses market exchange rates. Moreover, the categorisation in regions varies significantly between Fankhauser and Tol. For instance, Tol provides numbers for USA and Canada together, while Fankhauser puts Canada in the category 'Other OECD'. Therefore, it was unavoidable to make some ad-hoc decisions. Two alternative sets of regional shares were constructed. The first alternative ('STACO calibration I') is primarily based on the estimates of Fankhauser, which have relatively high shares of the OECD regions and relatively low shares of the non-OECD regions. As Fankhauser does not provide information for all regions in the STACO model, some additional assumptions have to be made. The second ('STACO calibration II'), is based as far as possible on Tol's estimates; again additional assumptions are required. The resulting calibrated absolute regional damage costs and the associated shares for both calibration alternatives are given in Table 2.4 and will be discussed below.

Table 2.4: Distribution of annual damage costs over different regions in absolute amounts and shares according to the two calibration alternatives

Region	STACO calibration I Billion US$ ((%) = $\theta_i \cdot 100$)	STACO calibration II Billion US$ ((%) = $\theta_i \cdot 100$)
USA	61.0 (22.6%)	64.8 (12.4%)
JPN	46.5 (17.3%)	59.6 (11.4%)
EU15	63.6 (23.6%)	33.5 (6.4%)
OOE	9.3 (3.5%)	8.7 (1.7%)
EET	3.5 (1.3%)	6.8 (1.3%)
FSU	18.2 (6.7%)	18.2 (3.5%)
EEX	8.1 (3.0%)	15.9 (3.0%)
CHN	16.7 (6.2%)	32.5 (6.2%)
IND	13.4 (5.0%)	89.5 (17.1%)
DAE	6.7 (2.5%)	44.8 (8.5%)
BRA	4.1 (1.5%)	27.5 (5.2%)
ROW	18.3 (6.8%)	122.0 (23.3%)
World	269.4 (100%)	523.8 (100%)
Subtotal OECD	180.4 (66.9%)	166.6 (31.8%)
Subtotal non-OECD	89.1 (33.1%)	357.2 (68.2%)

In STACO calibration I, the data for USA are directly taken from Fankhauser. Damages for JPN are disaggregated from OOE assuming five times as much damage in Japan as in the other countries (roughly based on the share of Japan in total GDP of OOE+JPN). For EU15, the European Union estimate of Fankhauser is used. The damages for OOE are 1/6th of Fankhauser's estimate for Other OECD. The total damages in the OECD for STACO calibration I match Fankhauser: 180.4 billion US$.

For EET, no damage estimate is available. Based on the share of this region in global GDP, we assume the damage share of this region to be 1.3% of global damages. Fankhauser provides an estimate for FSU that can be directly used. The estimate of the damage share for EEX is based on Tol's estimate for Middle East, 3.0%, as Fankhauser does not provide an estimate. The absolute level of damages for this region is calculated using this share of 3% in global damages. The value for CHN is directly taken from Fankhauser. For the last four regions, IND, DAE, BRA and ROW, Fankhauser does not provide sufficient regional information. To match global damages with Fankhauser's estimate, the sum of the damages for these four regions have to equal 42.5 billion US$. These damages are attributed to the four separate regions using their relative shares calculated in the STACO calibration II as discussed below.

In STACO calibration II, the estimates of Tol are the basis for our numbers. Tol provides estimates for Northern America (USA and Canada), a wider range of countries in Europe and Pacific OECD countries. The shares for USA, JPN and EU15 are derived by rescaling Tol's estimates such that total OECD damages equal 166.6 billion US$. The share of STACO region OOE is taken from the first calibration alternative and equals 5.2% of total OECD damages. The calibration of EET in alternative II is based on the same assumption as in alternative I: 1.3% of global damages. For FSU, the negative estimate of Tol is rejected and the absolute damage estimate of Fankhauser is used. The EEX estimate can be directly taken from Tol. For CHN, the share of the region in global damages is taken from calibration alternative I. Tol's estimate for Asia is divided into two-thirds for IND and one-third for DAE. Tol gives damages for the whole of Latin-America, and we assume that the contribution of Brazil is 25% of that estimate. Finally, the share of ROW is calibrated such that the total damage estimate for non-OECD countries corresponds to that of Tol. Note that the share of this region is much higher than in Tol's estimate, since in the STACO classification, ROW also includes all centrally planned Asian countries except China (i.e. Vietnam, Laos, Mongolia, North Korea) and all Latin-American countries except Brazil.

Then, regional benefits are defined as the share of the region times global benefits by the following equation:

$$b_{it}(q_1,...,q_t) = \theta_i \cdot b_t(q_1,...,q_t)\,. \tag{2.11}$$

For the base case, we apply Calibration I which implies relatively higher share for OECD regions, and relatively lower share for non-OECD regions. We conduct sensitivity analysis using Calibration II which implies lower share for OECD countries and higher share for India, dynamic Asian economies, Brazil and rest of the world.

2.3.5. Abatement Costs

We specify an abatement cost function following Marginal Abatement Cost (MAC) curves in 2010 generated by MIT's Emissions Prediction and Policy Analysis (EPPA) model reported by Ellerman and Decaux (1998). EPPA model incorporates two backstop technologies; however, those technologies are excluded when marginal abatement cost curves are calculated because these technologies are assumed not to play a role in 2010. To match our dynamic specification for the period 2010-2110, in our model, we assume exogenous technological progress which is modelled as a reduction of current abatement costs at 0.5% annually (ς =0.005) expressed as follows:

$$c_{it}(q_{it}) = \frac{1}{3} \cdot \alpha_i \cdot (1-\varsigma)^t \cdot q_{it}^3 + \frac{1}{2} \cdot \beta_i \cdot (1-\varsigma)^t \cdot q_{it}^2 \tag{2.12}$$

where α and β are regional cost parameters described in Table 2B-3, Appendix 2B. The role of technological change is further explored in Chapter 4.

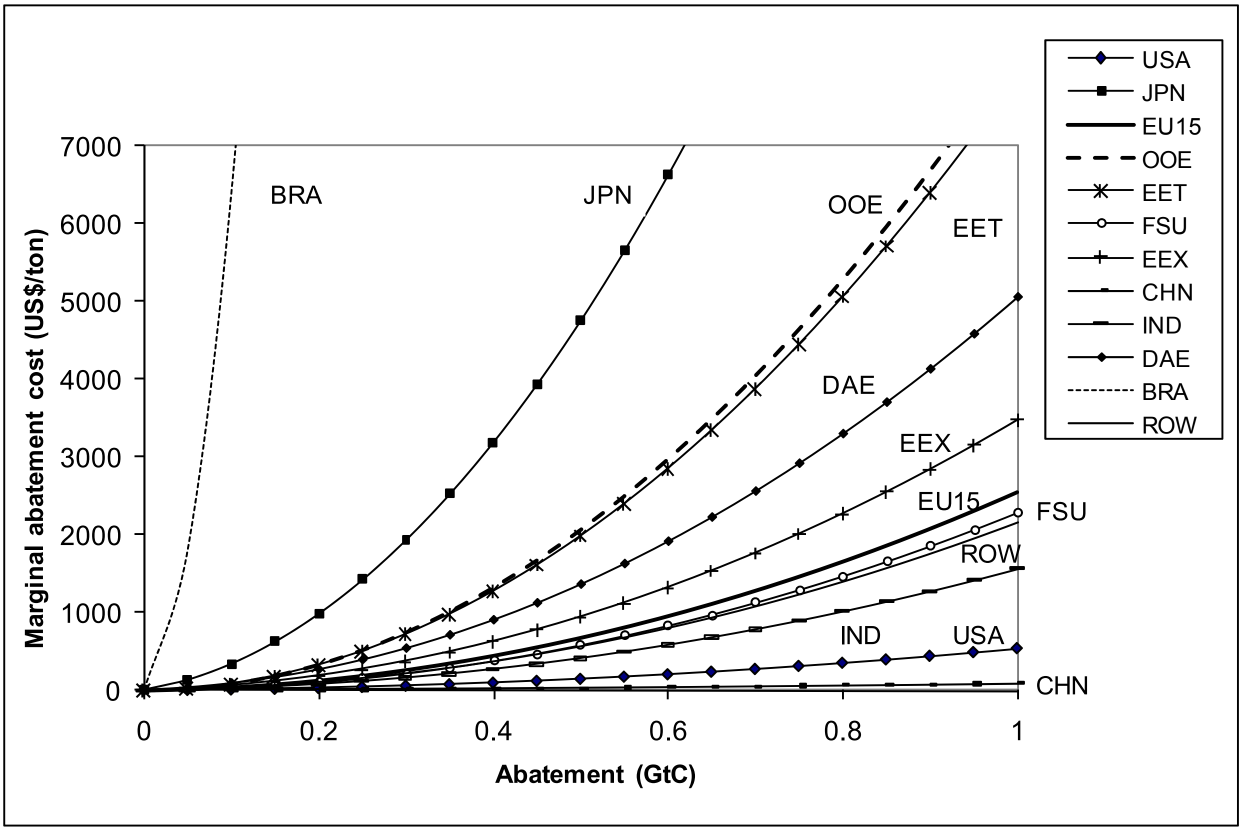

Figure 2.1: Undiscounted marginal cost curves in 2011

Figure 2.1 represents undiscounted marginal cost curves in 2011. The USA and China have flatter marginal cost curves, which implies that those countries can reduce their emissions at a lower cost. On the other hand, Brazil and Japan have steeper marginal cost curves. Since we assume exogenous technological progress, each curve will move downward over time.

2.3.6. Objective function and derivation of optimal abatement

We calibrate the objective function which is the payoff function for each region expressed in Eq. (2.1). Payoff for region i in t period, π_{it}, depends on the abatement path until t. We assume that marginal global benefits reflect all current and future benefits from abatement in period t, discounted back to period t.

Next we calculate optimal abatement levels without cooperation and with cooperation. Regional abatement levels for each period are endogenously determined in the model by maximising the net present value (NPV) of the stream of payoffs. Each region has perfect foresight of the future and can plan its abatement path for the current and all future years within the planning period. Signatories choose the abatement levels that maximise the sum of their payoffs. The first order condition is given by

$$\sum_{j \in K} \sum_{s=t}^{\infty} (1+r)^{t-s} \cdot b'_{js}(q_1, ..., q_s) = c'_{it}(q_{it}) \qquad (2.13)$$

where primes denote derivatives and K denotes a coalition structure.

Non-signatories choose the abatement levels that maximise their own individual payoff. By taking the derivative of the payoff function with regard to the abatement level in period t, the first order condition is derived as follows:

$$\sum_{s=t}^{\infty} (1+r)^{t-s} \cdot b'_{is}(q_1, ... q_s) = c'_{it}(q_{it}) \qquad \forall i \notin K \qquad (2.14)$$

For the detailed derivation of optimal abatement, see Appendix 2C.

2.4. General features of the STACO-2.1

This section provides the general features of the STACO-2.1 model with regard to the game theoretical and the empirical aspects. Our specification of the regional benefit functions is linear in abatement, which leads to constant marginal benefits with regard to abatement (see Appendix 2C). The specification of regional marginal abatement cost is a quadratic function of a region's own abatement. Since marginal benefits are constant, they are independent of other regions' abatements. Therefore, every region has a dominant abatement strategy. Thus, the optimal abatement strategy of some region can be determined regardless of those of other regions; see Eq. (2.13) and (2.14).

When a region j joins a coalition K, the aggregate payoff in the coalition including j will be larger than the aggregate payoff in the coalition excluding j, plus the payoff of region j in a singleton structure (superadditivity) , $\sum_{i \in K} \pi_i + \pi_j < \sum_{i \in K \cup j} \pi_i$. However, individual payoffs do not always increase, and depend on the characteristics of the benefit and cost functions of both the region and the members of the coalition. Global payoff will increase as the number of signatories increases. When a region j joins a coalition K, payoffs of regions outside the coalition will increase. Thus benefits from free-riding increase (positive spillovers).

As discussed earlier, each region has constant marginal benefit and quadratic marginal cost. In a coalition, the burden of abatement and hence the distribution of the gains of cooperation do not only depend on coalition members' characteristics, but also the non-signatories' characteristics of both marginal benefits and marginal costs. Taking the example of a coalition composed of a region with high marginal benefits (MB) and high marginal costs (MC) and another region with a low MB and low MC. Figure 2.2 shows marginal benefits and marginal costs in 2011 for EU15 and China, respectively. Under All Singletons, the abatement level for EU15 is q_{EU} and for China is q_{CHN}. Once both regions form a coalition, China with a flat MC function has to contribute more to abatement (q_{CHN}^{K}) than the EU15, which has a steeper MC function (q_{EU}^{K}). China with lower marginal benefits might be worse off than under All Singletons. Payoffs depend on the characteristics of MB and MC of both regions.

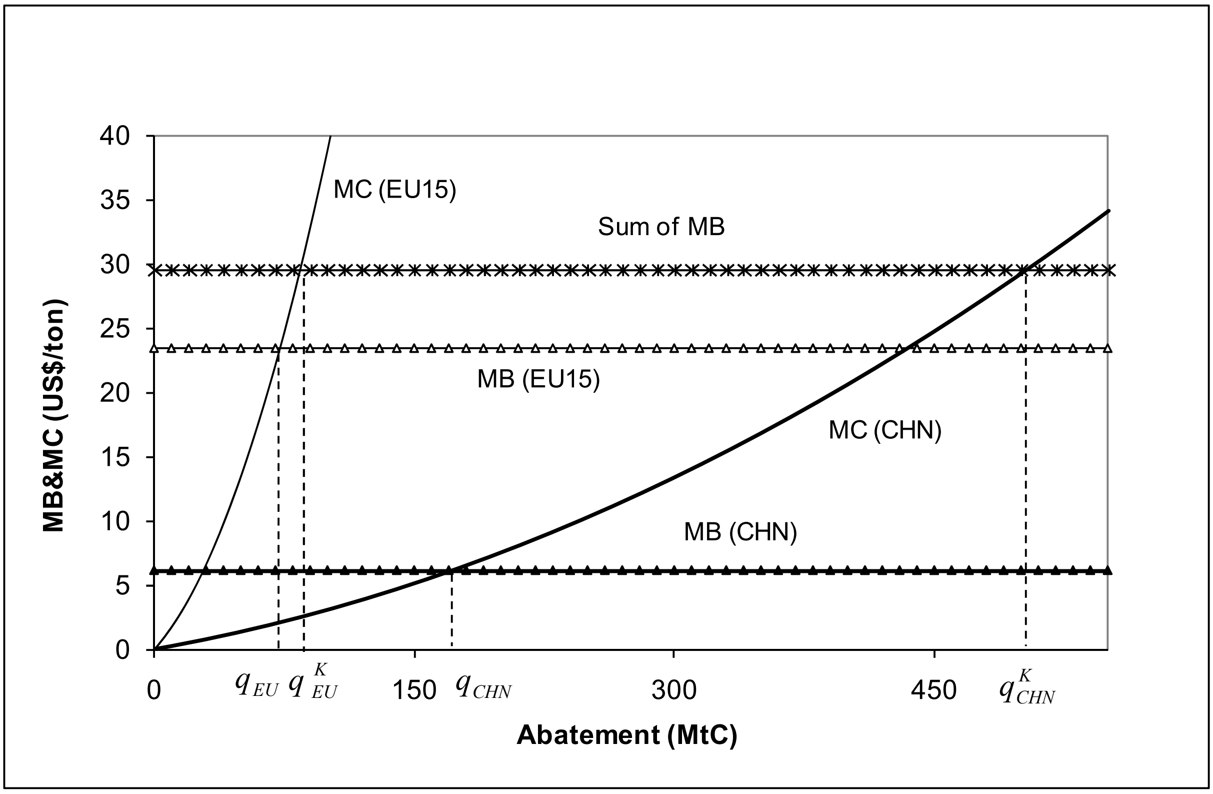

Figure 2.2: Marginal benefits and marginal costs in 2011 for EU15 and China in All Singletons and coalition of EU15 and China

2.5. Results of STACO-2.1 without transfer schemes

In this section, we analyse the results for (i) the All Singletons coalition structure, (ii) the Grand coalition structure, and (iii) all stable coalition structures (if any)[5]. This case can serve as a suitable reference point for the analysis of the various mechanisms in the following chapters. We also test stability for each coalition that may arise from partial cooperation. As the payoff for each region depends on the shares of global benefits, θ_i, the discount rate r and the scale parameter of global damages, γ_D, and we have only imperfect information to calibrate these parameters, we conduct a sensitivity analysis in Section 2.6.

2.5.1. All Singletons coalition structure

Table 2.5 shows the results of the non-cooperative case where all players act as singletons. Under the All Singletons structure, marginal abatement costs equal marginal benefits for each region. The results for this case give good insights into the incentive structure of the different regions. The percentage of annual abatement compared to BAU emission tends to be decreasing over time and leads to a stock of CO_2 of 1,448 GtC by the year 2110. This is about 1.7 times the stock level in 2010.

Table 2.5: All Singletons structure

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Marginal benefits from abatement in 2011
	2011	2110	Billion US$ over 100 years	US$/ton	US$/ton
USA	9.9	5.5	1,117	22.4	22.4
JPN	2.5	3.0	943	17.1	17.1
EU15	7.6	5.6	1,240	23.4	23.4
OOE	5.6	2.6	188	3.4	3.4
EET	4.4	2.9	71	1.3	1.3
FSU	6.7	5.3	362	6.7	6.7
EEX	1.9	2.0	164	3.0	3.0
CHN	14.8	10.8	298	6.1	6.1
IND	10.5	5.3	268	4.9	4.9
DAE	1.9	2.1	136	2.5	2.5
BRA	0.1	0.2	84	1.5	1.5
ROW	6.3	4.5	365	6.7	6.7
Global	8.0	5.5	5,238		

Global stock of CO_2 in 2110 = 1,448 GtC

[5] It should be noted that there is no guarantee that there will be one non-trivial stable coalition.

At the individual region level, abatement differs from region to region, as the abatement level is determined by marginal benefits and marginal costs and we have heterogeneous regions. The USA, a region with a low marginal abatement cost, and high share of global benefits, has an incentive to make substantial abatement efforts even in the All Singletons case, and according to our calculations in 2011 USA reduces 9.9% of BAU emissions. Regions with higher marginal abatement cost and a lower share of global benefits, such as energy exporting countries, Brazil, and dynamic Asian economies, have hardly any incentive to reduce emissions on their own. Japan, which has a relatively high share of global benefits, makes comparatively little abatement efforts due to its high marginal cost. In 2011, it only reduces about 2.5% of emissions in the BAU case and total abatement amounts to 2 GtC over time.

2.5.2. Grand coalition structure

Table 2.6 displays the results for the Grand Coalition. In this case, marginal abatement costs equal the sum of marginal benefits among all regions at the level of 99.0 US$/ton. The abatement allocation varies widely from region to region. In the Grand Coalition, total gain from cooperation in terms of the NPV of payoff compared to All Singletons case is 9,973 billion US$ (15,211 billion US$ - 5,238 billion US$). Even though at the global level, substantially higher NPV of payoff can be achieved, some regions are worse off when Grand Coalition is formed. For instance, China, which has the lowest abatement costs, has to contribute considerably to reduce emissions.

Table 2.6: Grand Coalition structure

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Incentive to change membership (NPV)
	2011	2110	Billion US$ over 100 years	US$/ton	Billion US$ over 100 years
USA	22.8	12.2	4,158	99.0	52
JPN	11.7	11.4	3,930	99.0	-281
EU15	18.3	12.5	5,062	99.0	-432
OOE	29.9	13.7	518	99.0	261
EET	47.6	28.8	-1	99.0	297
FSU	26.2	20.5	1,031	99.0	423
EEX	28.4	20.7	248	99.0	420
CHN	89.3	53.9	-1,777	99.0	2,727
IND	65.8	28.6	482	99.0	588
DAE	34.7	25.9	209	99.0	352
BRA	6.2	4.7	333	99.0	27
ROW	30.7	19.6	1,019	99.0	442
Global	36.6	22.5	15,211		

Global stock of CO_2 in 2110 = 1,304 GtC

This leads to a substantial difference in the NPV of payoff, from 298 billion US$ in the All Singletons case to -1,777 billion US$ in the Grand Coalition. This situation violates individual rationality. Here, incentives to change membership are simply the gains from changing membership given that the other regions do not change their membership. Regions with a positive incentive can benefit from leaving the Grand Coalition. Regions with a negative incentive would lose when leaving. Only Japan and EU15 have no incentive to leave the Grand Coalition – all other regions have a strong incentive to leave and take a free-rider position.

Looking at the path of net benefits over time[6] (Figure 2.3), every region except China is better off in the later periods over the planning horizon. The absolute net benefits of China are substantially lower than other regions, moreover they are decreasing over time.

Figure 2.4 depicts the emission paths for BAU, All Singletons and the Grand Coalition. In the BAU scenario, no abatement takes place. BAU emissions grow in the form of an S-shaped curve, and the pace of growth slows down at the end of the century, reaching a level of almost 25 GtC by 2110. In the case of All Singletons, emissions reach approximately 24 GtC by 2110. Emissions in the Grand Coalition are about 20% lower than in the All Singleton case, and reach approximately 19 GtC by 2110.

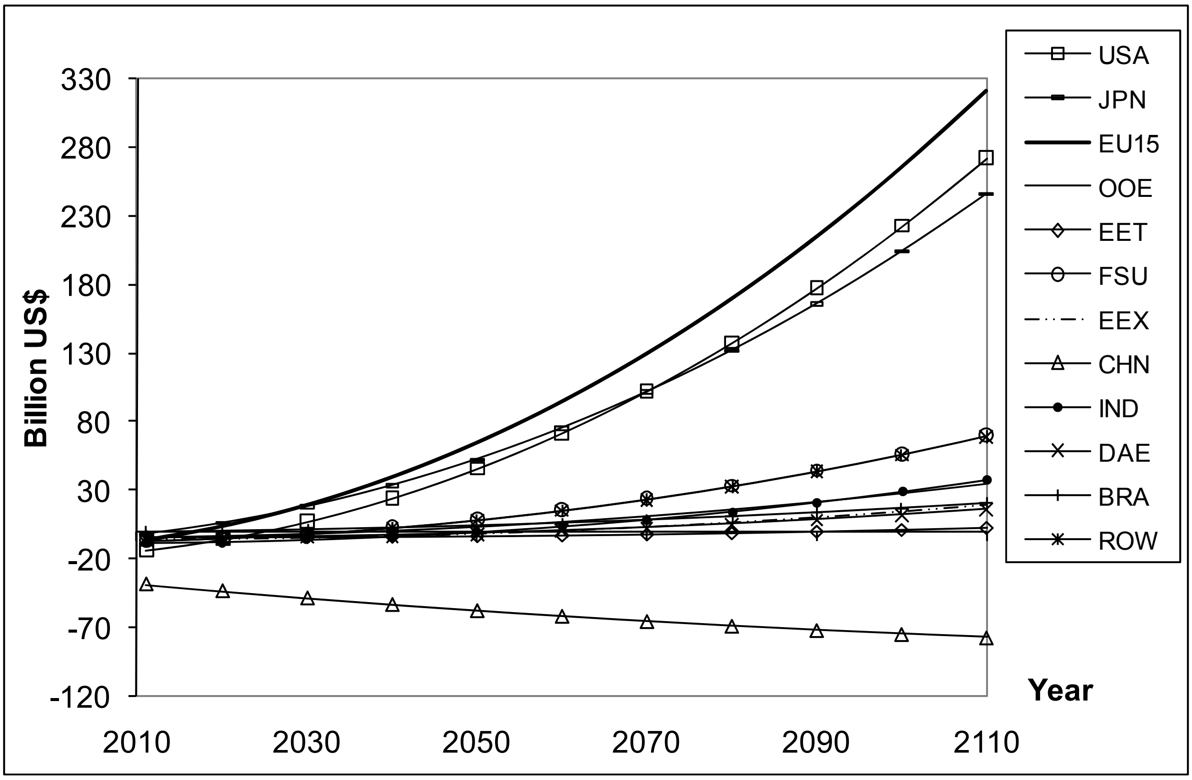

Figure 2.3: Annual regional net benefits in Grand Coalition (Undiscounted)

[6] These are the net benefits from past and current abatement that arise in period t and represent a cash flow.

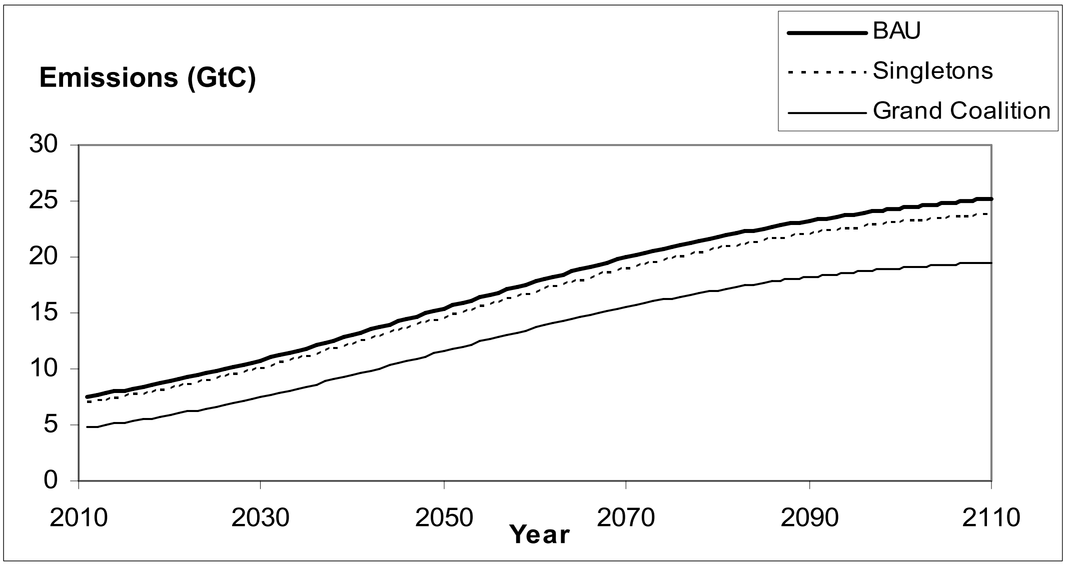

Figure 2.4: Emission paths for BAU, All Singletons, and Grand Coalition

2.5.3. Stable coalitions

We compute regional payoffs for all possible cartel coalitions and examine stability for all 4084 coalition structures with an algorithm programmed in MATLAB. It is found that 14 non-trivial coalitions are internally stable[7], of which only the one between Japan and EU15 is also externally stable. There is a tendency that coalitions comprising regions with similar characteristics in terms of benefits and costs are internally stable.

Table 2.7 shows the results for the unique stable coalition of Japan and EU15. When comparing the results in Table 2.7 with those in Table 2.5, it can be established that EU15 reduces emissions about 30% more than in the All Singletons structure. Japan's abatement efforts are twice as high as in the All Singletons structure. As a result of their cooperation, both regions can obtain slightly higher NPV of payoff than in the All Singletons case.

Incentives to change membership are shown in the last column of Table 2.7 and are expressed as the gains from changing membership in a situation where all other regions do not change their membership, i.e. we consider single deviations. For singletons, it thus reflects the incentive to join the coalition of Japan and EU15. Japan and EU15 have an interest in cooperation, because of their higher marginal benefits from abatement, while none of the other regions want to join, as their abatement costs would increase considerably if they have to take the benefits in Japan and EU15 into account and

[7] These coalitions are: [EU15&JPN], [OOE&EEX], [EEX&CHN], [OOE&IND], [EEX&IND], [OOE&DAE], [EEX&DAE], [CHN&DAE], [IND&DAE], [FSU&BRA], [OOE&IND&BRA], [FSU&ROW], [BRA&ROW], [FSU&BRA&ROW].

compensation payments are not available. Other coalitions are not stable, implying that free-rider incentives are strong and regions are often better off not joining a coalition.

Table 2.7: Stable coalition of Japan and EU15

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Incentive to change membership (NPV)
	2011	2110	Billion US$ over 100 years	US$/ton	Billion US$ over 100 years
USA	9.9	5.5	1,199	22.4	-143
JPN	***5.5***	***6.0***	***975***	***40.4***	***-32***
EU15	***10.7***	***7.6***	***1,244***	***40.4***	***-4***
OOE	5.6	2.6	201	3.4	-70
EET	4.4	2.9	76	1.3	-78
FSU	6.7	5.3	386	6.7	-121
EEX	1.9	2.0	175	3.0	-107
CHN	14.8	10.8	321	6.1	-725
IND	10.5	5.3	286	4.9	-159
DAE	1.9	2.1	145	2.5	-89
BRA	0.1	0.2	90	1.5	-7
ROW	6.3	4.5	389	6.7	-126
Global	8.6	5.8	5,486		

Global stock of CO_2 in 2110 = 1,445 GtC

2.6. Sensitivity analysis

As simulation results depend on parameter values which are subject to uncertainties associated with the quantitative model, we conduct a sensitivity analysis to examine how these uncertainties affect the model results. We believe that crucial parameters in the model are the scale parameter of damage and benefit function (γ_D) and the discount rate (r). Therefore, we change the base value of γ_D and r to 50% less and 50% more, respectively. In addition, we vary the shares of global benefits (θ_i) using Calibration II with a lower share for OECD countries and higher shares for India, dynamic Asian economies, Brazil and ROW.

Table 2.8 presents the results of the sensitivity analysis. With regard to the level of global emission abatement and NPV of global payoffs, results are sensitive to both the discount rate and scale parameter for damage. The low discount rate increases the total abatement by about 40% in All Singletons and by about 35% in Grand Coalition compared to the base case, because future benefits from abatement will have a higher present value. Conversely, a higher discount rate will decrease the total abatement as current payoffs have higher value. Regarding the scale parameter γ_D, a lower value will decrease total abatement by 36% in All Singletons and by 32% in Grand Coalition, and a higher value will increase total abatement by 30% in the All Singletons case and the Grand Coalition, compared to the base case. Changing the discount rate and scale parameter will increase or decrease absolute values of the results, but relative values between regions remain almost unchanged.

Table 2.8: Sensitivity analysis

Scenario		Global emission abatement	Net present value (NPV) of payoff	Stable coalition
		GtC over 100 years	Billion US$ over 100 years	
1. Base case				
	All Singletons	98	5,238	Yes
	Grand Coalition	418	15,211	No
	Stable coalition	104	5,486	[JPN-EU15]
2. Change in the regional benefit shares				
Calibration II	All Singletons	96	5,154	Yes
	Grand Coalition	418	15,211	No
	Stable coalition	103	5,461	[JPN-BRA-ROW]
3. Change in the scale parameter for damage				
50% less	All Singletons	63	1,673	Yes
	Grand Coalition	285	5,106	No
	Stable coalition	-	-	No
50% more	All Singletons	125	10,108	Yes
	Grand Coalition	520	28,625	No
	Stable coalition	133	10,578	[JPN-EU15]
4. Change in the discount rate				
50% less	All Singletons	136	20,998	Yes
	Grand Coalition	560	58,695	No
	Stable coalition	145	21,966	[JPN-EU15]
50% more	All Singletons	78	1,854	Yes
	Grand Coalition	342	5,559	No
	Stable coalition	83	1,943	[JPN-EU15]

In all these scenarios, the Grand Coalition is never stable even though it increases the global payoff compared to the All Singleton case. In the scenario of Calibration II we find one stable coalition which consists of Japan, Brazil and ROW. These regions have a higher share of benefits from global abatement and higher marginal abatement costs under Calibration II. From this sensitivity analysis with regard to parameters examined, we may conclude that results of stability depend on the parameters which change regional payoff relatively, but do not depend on the scale parameter for damage and discount rate.

2.7. Final remarks

The purpose of this chapter is to set the stage for an in depth discussion of the formation and stability of climate coalitions under several mechanisms. We introduce the structure of our model, STACO-2.1 and its functional specifications in detail. We present some key results for benchmark scenarios which will serve as reference points for the analysis in the following chapters.

The results suggest that regions with relatively lower marginal abatement costs and lower marginal benefits would be worse off when they cooperate as they bear the largest burden of abatement but obtain the least benefits. This already suggests that transfer schemes can be effective to stabilise larger coalitions. We examine this in detail in Chapter 3. Chapter 4 investigates the role of international technology spillovers, and Chapter 5 takes this one step further and introduces induced technological change into the STACO model.

Appendix 2A

Box 2A-1: Equations in STACO-2.1

Payoff function (objective function)

$$\max\ \pi_i(q_1,...,q_T) = \sum_{t=1}^{T}\left\{(1+r)^{-t}\cdot(b_{it}(q_1,...,q_t) - c_{it}(q_{it}))\right\} + \sum_{t=T+1}^{\infty}\left\{(1+r)^{-t}\cdot b_{it}(q_1,...,q_T)\right\} \qquad \forall i \in \boldsymbol{N}$$

Stock of CO_2

$$M_t(M_{t-1},q_1,...,q_t) = \overline{M} + (1-\delta)\cdot(M_{t-1}(q_1,...,q_{t-1}) - \overline{M}) + \omega\cdot\sum_{i=1}^{n}\left(\overline{e}_{it} - q_{it}\right) \qquad t = 1,...,\infty$$

$$M_{t_0} = 835\text{ GtC}$$

Damages

$$d_t(M_t) = \left[\gamma_1 + \gamma_2\cdot\left(\frac{M_t(q_1,...,q_t)}{\overline{M}}\right)\right]\cdot(\gamma_D\cdot y_t)$$

Benefits

$$b_t(q_1,...,q_t) = d_t(M_t(\mathbf{0})) - d_t(M_t(q_1,...,q_t))$$

$$b_{it}(q_1,...,q_t) = \theta_i\cdot b_t(q_1,...,q_t)$$

Abatement costs

$$c_{it}(q_{it}) = \tfrac{1}{3}\cdot\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^3 + \tfrac{1}{2}\cdot\beta_i\cdot(1-\varsigma)^t\cdot q_{it}^2$$

Discounted benefits

$$B_i(\mathbf{q}) \equiv \sum_{t=1}^{\infty}\left\{(1+r)^{-t}\cdot b_{it}(\mathbf{q})\right\}$$

Discounted abatement costs

$$C_i(\mathbf{q_i}) \equiv \sum_{t=1}^{\infty}\left\{(1+r)^{-t}\cdot c_{it}(q_{it})\right\}$$

Marginal benefits from current abatement

$$B'_{it}(q_t) \equiv \sum_{s=t}^{\infty}\left\{(1+r)^{t-s}\cdot\frac{\partial b_{is}(q_1,...,q_s)}{\partial q_t}\right\}$$

Marginal abatement costs

$$C'_{it}(q_{it}) \equiv \frac{\partial c_{it}(q_{it})}{\partial q_{it}}$$

Discounted marginal benefits

$$B'_i(\mathbf{q}) \equiv \frac{\partial B_i(\mathbf{q})}{\partial q_t} = (1+r)^{-t}\cdot B'_{it}(q_t)$$

Discounted marginal abatement costs

$$C'_i(\mathbf{q_i}) \equiv \frac{\partial C_i(\mathbf{q_i})}{\partial q_{it}} = (1+r)^{-t}\cdot C'_{it}(q_{it})$$

Appendix 2B

Table 2B-1: Global parameters

Symbol	Description	Value	Unit	Source
$\overline{M}$	Pre-industrial level of CO_2 stock	590	GtC	Nordhaus (1994)
M_{t_0}	Stock of CO_2 in 2010, starting point for calculations	835	GtC	Nordhaus (1994)
δ	Natural annual removal rate of CO_2 stock	0.00866	-	Nordhaus (1994)
ω	Airborne fraction of emissions remaining in the atmosphere	0.64	-	Nordhaus (1994)
r	Discount rate	0.02	-	Assumption
θ_i	Share of region i in global benefits	see Table 2.4		Own calculation based on Fankhauser (1995) and Tol (1997)
α_i	Abatement cost parameter of region i	see Table 2B-3, column 2		Own calculation based on Ellerman and Decaux (1998)
β_i	Abatement cost parameter of region i	see Table 2B-3, column 3		Own calculation based on Ellerman and Decaux (1998)
ς	Technological progress parameter	0.005	-	Assumption
γ_D	Scale parameter of damage and benefit function	0.027	-	Tol (1997)

Table 2B-2: Regional parameters in the emission function

Regions	Emission in 2010	Parameters			
	GtC (share)	a	b	c	d
USA	1.763 (0.238)	6530	-0.04	1112	2065
JPN	0.344 (0.046)	687	-0.052	292	2058
EU15	0.943 (0.127)	2580	-0.04	589	2056
OOE	0.360 (0.049)	1383	-0.05	240	2057
EET	0.226 (0.030)	623	-0.05	141	2047
FSU	0.774 (0.104)	2196	-0.03	-97	2024
EEX	0.469 (0.063)	1282	-0.04	246	2049
CHN	1.127 (0.152)	3467	-0.06	525	2036
IND	0.344 (0.046)	1591	-0.05	108	2045
DAE	0.316 (0.043)	700	-0.06	251	2048
BRA	0.122 (0.016)	336	-0.054	82	2047
ROW	0.637 (0.086)	1889	-0.04	287	2047
World	7.425 (1)	-	-	-	-

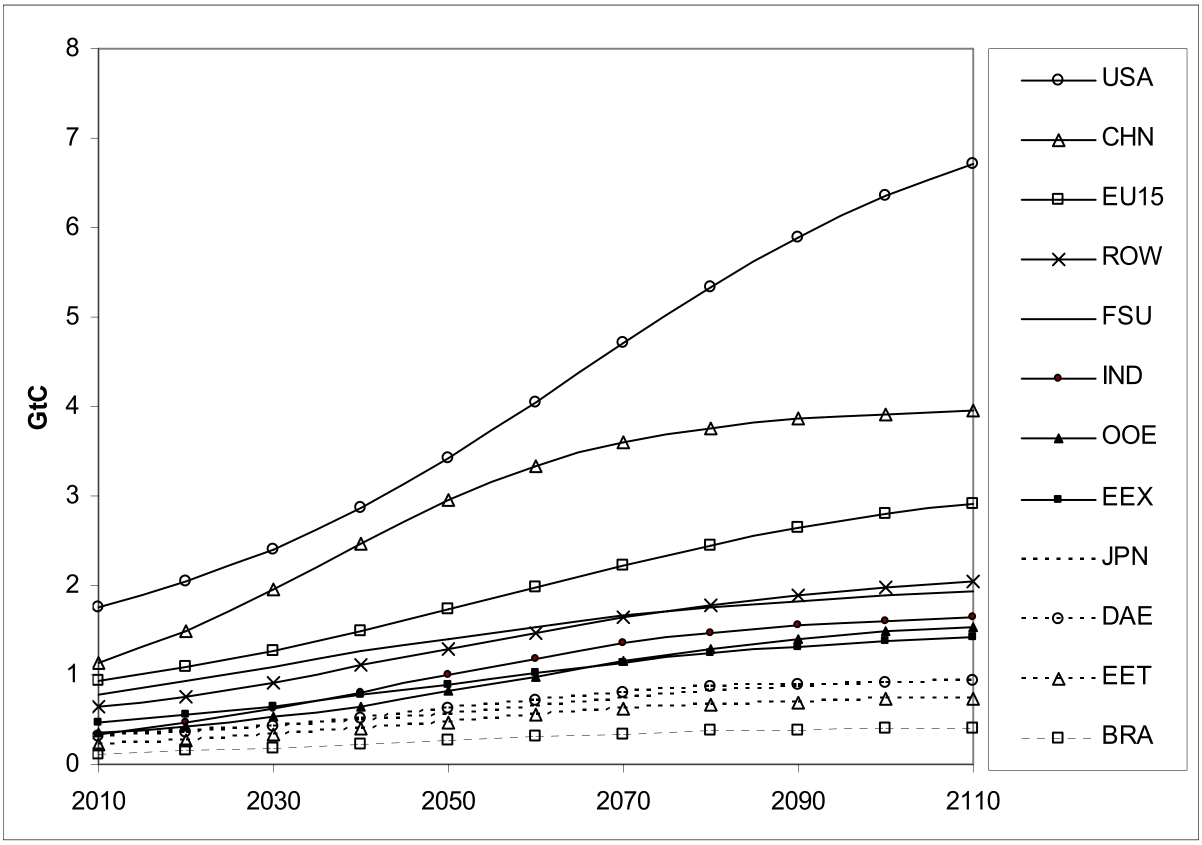

Figure 2B-1: Regional BAU emission paths

Source: Own calculations based on projections from the MIT-EPPA model (Paltsev et al, 2005)

Table 2B-3: Regional parameters in the abatement cost function

Regions	Parameter of abatement cost α_i	Parameter of abatement cost β_i
USA	0.0005	0.0398
JPN	0.0155	1.8160
EU15	0.0024	0.1503
OOE	0.0083	0
EET	0.0079	0.0486
FSU	0.0023	0.0042
EEX	0.0032	0.3029
CHN	0.00007	0.0239
IND	0.0015	0.0787
DAE	0.0047	0.3774
BRA	0.5612	8.4974
ROW	0.0021	0.0805

Appendix 2C

Derivation of the global benefit function and optimal abatement

Global benefit function

$$b_t(q_1,...,q_t) = d_t(M_t(0)) - d_t(M_t(q_1,...q_t))$$

$$b_t(q_t) = \left(\gamma_1 + \gamma_2 \cdot \frac{M_t(0)}{\overline{M}}\right) \cdot \gamma_D \cdot y_t - \left(\gamma_1 + \gamma_2 \cdot \frac{M_t(q_1,...,q_t)}{\overline{M}}\right) \cdot \gamma_D \cdot y_t$$

$$= \gamma_2 \cdot (\gamma_D \cdot y_t) \cdot \left(\frac{M_t(0)}{\overline{M}} - \frac{M_t(q_1,...,q_t)}{\overline{M}}\right)$$

$$= \gamma_2 \cdot (\gamma_D \cdot y_t) \cdot \left(\frac{M_t(0)}{\overline{M}} - \frac{M_t(0) - \sum_{s=1}^{t} (1-\delta)^{t-s} \cdot \omega \cdot q_s}{\overline{M}}\right)$$

$$= \gamma_2 \cdot (\gamma_D \cdot y_t) \cdot \left(\frac{\sum_{s=1}^{t} (1-\delta)^{t-s} \cdot q_s}{\overline{M}} \cdot \omega\right)$$

Optimal abatement (without cooperation)

$$\max_{q_{it}} \quad \pi_i(q_1,...,q_T) = \sum_{t=1}^{T} \left\{(1+r)^{-t} \cdot (b_{it}(q_1,...,q_t) - c_{it}(q_{it}))\right\} + \sum_{t=T+1}^{\infty} \left\{(1+r)^{-t} \cdot b_{it}(q_1,...,q_t)\right\}$$

F.O.C

$$\frac{\partial \pi_i(q_1,...,q_T)}{\partial q_{it}} = \left\{\sum_{t=1}^{\infty} (1+r)^{-t} \cdot b'_{it}(q_1,...,q_t)\right\} - (1+r)^{-t} \cdot c'_{it}(q_{it}) = 0$$

$$\sum_{t=1}^{\infty} (1+r)^{-t} \cdot b'_{it}(q_1,...,q_t) = (1+r)^{-t} \cdot c'_{it}(q_{it})$$

$$\sum_{s=t}^{\infty} (1+r)^{t-s} \cdot b'_{is}(q_1,...,q_s) = c'_{it}(q_{it})$$

Non-signatories

Non-signatories choose their abatement level by maximising their own payoffs. Following Eq. (2.14), the optimal abatement of region i in t period can be derived as follows;

$$\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot\{d_s(M_s(0))-d_s(M_s(q_1,...,q_s))\}'=\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^2+\beta_i\cdot(1-\varsigma)^t\cdot q_{it}$$

$$\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot\left\{\theta_i\cdot\gamma_2\cdot\gamma_D\cdot y_s\cdot\left(\frac{M_s(0)}{\overline{M}}-\frac{M_s(0)-\sum_{s=t}^{\infty}(1-\delta)^{s-t}\cdot q_s}{\overline{M}}\right)\right\}'=\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^2+\beta_i\cdot(1-\varsigma)^t\cdot q_{it}$$

$$\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot(1-\delta)^{s-t}\cdot\theta_i\cdot\gamma_2\cdot\gamma_D\cdot y_s\cdot\omega\cdot\frac{1}{\overline{M}}=\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^2+\beta_i\cdot(1-\varsigma)^t\cdot q_{it}$$

$$q_{it}^*=\frac{-(\beta_i\cdot(1-\varsigma)^t)+\sqrt{(\beta_i\cdot(1-\varsigma)^t)^2+4\cdot\alpha_i\cdot(1-\varsigma)^t\cdot\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot(1-\delta)^{s-t}\cdot\theta_i\cdot\gamma_2\cdot\gamma_D\cdot y_s\cdot\omega\cdot\frac{1}{\overline{M}}}}{2\cdot\alpha_i\cdot(1-\varsigma)^t}$$

Coalition members

Signatories choose the abatement levels that maximise the sum of the payoffs of the signatories. Following Eq. (2.13), the optimal abatement of region i in the coalition K in t period is written as;

$$\sum_{j\in K}\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot(1-\delta)^{s-t}\cdot\theta_j\cdot\gamma_2\cdot\gamma_D\cdot y_s\cdot\omega\cdot\frac{1}{\overline{M}}=\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^2+\beta_i\cdot(1-\varsigma)^t\cdot q_{it}$$

$$q_{it}^*=\frac{-(\beta_i\cdot(1-\varsigma)^t)+\sqrt{(\beta_i\cdot(1-\varsigma)^t)^2+4\cdot\alpha_i\cdot(1-\varsigma)^t\cdot\sum_{j\in K}\sum_{s=t}^{\infty}(1+r)^{t-s}\cdot(1-\delta)^{s-t}\cdot\theta_j\cdot\gamma_2\cdot\gamma_D\cdot y_s\cdot\omega\cdot\frac{1}{\overline{M}}}}{2\cdot\alpha_i\cdot(1-\varsigma)^t}$$

Chapter 3

Stability of international climate coalitions – A comparison of transfer schemes*

This paper studies the impact of pragmatic and optimal transfer schemes on the incentives for regions to join international climate agreements. With an applied model that comprises twelve world regions we investigate: (i) a benchmark without transfers, (ii) scenarios with allocation-based rules where coalition members receive tradable emission permits proportional to initial or future emissions, (iii) scenarios with outcome-based rules where the coalition surplus is distributed proportional to emissions, and (iv) a scenario based on an optimal sharing rule where the coalition surplus is distributed proportional to outside option payoffs.

We find that well-designed transfer schemes can stabilise larger coalitions and increase global abatement levels. In our applied setting we find that for allocation-based and outcome-based rules only small coalitions are stable, and, in the case of grandfathered emission permits, there is no stable coalition at all. Some obstacles associated with grandfathered emission permits can be overcome by incorporating the expected growth of emissions in developing countries in the distribution of emission permits. For the optimal transfer scheme we find that larger coalitions, which include key players such as the United States and China, can be stable, but no transfer scheme is capable of stabilising the Grand Coalition.

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3.1. Introduction

The literature on the formation and stability of international environmental agreements (IEAs) has emphasised that transfers will strengthen incentives to join agreements. Two main insights have been established. First, if countries are identical, transfers will not be effective (Carraro and Siniscalco, 1993), whereas if countries differ in their costs and benefits of pollution abatement, transfers will be effective. Transfers can be used to obtain the cooperation of countries with low marginal costs of abatement. Hence, agreements between countries with high marginal abatement benefits and countries with low marginal abatement costs will be particularly successful (Barrett, 2001; Weikard et al., 2006). Secondly, it is evident from a number of studies that the incentives to join an IEA will be very sensitive to the way the transfer rule is designed (e.g. Botteon and Carraro, 1997; Tol, 2001; Carraro et al., 2006; Altamirano-Cabrera and Finus 2006; Weikard et al., 2006). However, with the exception of Carraro et al. (2006), there is no study which systematically compares different transfer schemes with respect to participation incentives, global welfare and abatement efforts.

The purpose of this paper is to provide a comparison of different transfer schemes and relate these to results for an optimal transfer scheme suggested by Eyckmans and Finus (2004) and Weikard (2009). Our analysis employs a two-stage cartel game as introduced by d'Aspremont et al. (1983) which has been widely used for the analysis of the stability of IEAs. At the first stage an announcement game is played where players (regions) choose to sign or not to sign an IEA. At the second stage the signatories and the remaining singletons play a non-cooperative abatement game where the signatories maximise joint welfare. This establishes a 'partial agreement Nash equilibrium' (Chander and Tulkens, 1995). A stable agreement is a Nash equilibrium of the first stage announcement game where payoffs are derived from the (unique) second stage equilibrium and a transfer scheme. A stable agreement is internally stable as no signatory wants to leave and externally stable as no singleton wants to join.

Our analysis is devoted to international climate coalitions and the prospects for international cooperation on mitigation to achieve an efficient policy response to climate change. We employ the Stability of Coalitions model (STACO) comprising twelve world regions. To provide a proper representation of the long run impacts of climate change we have constructed a model version, STACO-2.1, to identify regionally optimal abatement paths based on the benefits and costs of abatement. The model is an update and dynamic extension of the STACO-1 model described by Finus et al. (2006). As each region's strategy depends on its abatement costs and benefits (avoided climate change damages) in each period, our abatement game is a difference game. Because we assume constant marginal benefits we have a unique dominant strategy equilibrium. We assume that current benefits in each period depend not only on current abatement but also on abatement in previous periods through reduced concentrations of CO_2 and the corresponding lower damage levels. The decisions to sign or not to sign an agreement are based on the net present value (NPV) of regional payoffs.

Following Rose et al. (1998) we distinguish *allocation*-based and *outcome*-based transfer schemes. The former implement transfers by distributing emission permits, and the latter distribute the gains from cooperation. Altamirano-Cabrera and Finus (2006) have investigated the impact of different permit distribution schemes such as, 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, i.e. a coalition with 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. As these results are derived for an essentially static model, we examine and compare dynamically optimal emission paths for a grandfathering scheme based on initial emissions with a scheme based on projections of future emissions.[1] As we discuss below, this improves the incentives to participate in a climate agreement particularly for countries that expect large emission growth in the future; cf. Böhringer and Lange (2005). Although prominent among policy-makers, permit trading does not guarantee the best incentives for participation. Outcome-based rules that distribute the gains from cooperation instead of the emission permits are in general superior. The public goods character of greenhouse gas abatement implies that enlarging a coalition always improves payoffs. This characteristic allows each coalition member to receive at least the non-cooperative payoff. In this study we apply an ad-hoc rule stating that the coalition surplus is distributed proportional to (initial and future) emissions. But 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 no incentives to leave a given coalition remain if the coalition payoff is sufficiently large and distributed in such a way that each member gets at least its outside-option payoff. Weikard (2009) has shown that surplus sharing according to outside option payoffs internally stabilises all coalitions that are possibly stable under any sharing rule. We refer to this sharing rule as 'optimal sharing'. It should be noted, however, that even optimal sharing does not guarantee participation in the Grand Coalition, *i.e.* it cannot ensure that the efficient solution is achieved, because outside option payoffs increase with an enlargement of the coalition.

This chapter is organised as follows. Section 3.2 provides the game-theoretical framework of the STACO-2.1 model and its numerical specification. Section 3.3 introduces the transfer schemes that we examine in our model. Section 3.4 reports the main results, followed by a sensitivity analysis in Section 3.5. Section 3.6 concludes. The Appendix provides the model parameters.

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[1] The warning from Kydland and Prescott (1977) applies that dynamically 'optimal' policies may fail if agents revise their expectations.

3.2. The stability of coalitions model (STACO-2.1)

3.2.1. *Game-theoretic background*

We model a climate agreement as a two-stage game consisting of a coalition formation stage and an abatement decision stage. The set of players (hereafter referred to as regions) is denoted by $N = \{1,...,n\}$. In the first stage, every region announces whether to sign the agreement or not. Formally the strategy space of each region i is the set $\{sign, \ not\ sign\}$. Signatories (those who sign) form a unique coalition K. Regions that do not sign remain singleton. We refer to the case where no region signs as 'All Singletons'; the case where all regions sign is called the Grand Coalition.

In the second stage, the coalition K and the singletons $i \in N \setminus K$ adopt their abatement strategies simultaneously. An abatement strategy for a singleton $i \in N \setminus K$ is defined as a vector (*i.e.* time-path) of abatements $(q_{i1},...,q_{iT})$. Abatement in period t is restricted to $q_{it} \in [0, \bar{e}_{it}]$ where $\bar{e}_{it}$ denotes regional emission levels in the business-as-usual (BAU) scenario with no abatement efforts. The coalition K adopts an abatement path that specifies period-t abatements for all coalition members $i \in K$ and all periods $t \in \{1,...,T\}$ such that period-t abatements are from the Cartesian-product space $\prod_{i \in K} [0, \ \bar{e}_{it}]$.

We assume that membership and abatement decisions are taken only once, and remain fixed throughout a planning horizon T.[2] Each region obtains benefit b_{it} which depend on global emission reductions and bears costs c_{it} which depend on the region's own emission reduction. The benefit function b_{it} is linear in past and current global abatement. Abatement costs c_{it} are convex in regional current abatement. Benefit and abatement cost functions are specified in detail in Section 3.2.2. Not considering transfers for the moment, the payoff for each region π_i is the net present value of benefits and costs that accrue over time:

$$\pi_i(\mathbf{q}) = \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (b_{it}(q_1,...,q_t) - c_{it}(q_{it})) \right\} \tag{3.1}$$

where the model horizon accounting for future benefits is infinity, r is the discount rate, and $\mathbf{q}$ is an abatement matrix of dimension $N \times T$.[3]

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[2] The impact of renegotiations on the stability of a climate agreement is investigated in a separate paper by Weikard et al. (2010).

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

The equilibrium concept we employ is subgame perfect equilibrium. We solve our two-stage game by backward induction. We start the analysis at the second stage, where the abatement decisions are taken. Following Chander and Tulkens (1995, 1997) and Bloch (1997) we assume that the coalition, acting as a single player, and the singletons play a Cournot-Nash game.[4] More precisely, as the relevant strategy space is not an abatement level but an abatement path, we determine open-loop Nash equilibria in which each player's abatement path is a best response to the paths adopted by all other players (cf. Dockner et al., 2000, p.86). Hence, regional abatement paths are endogenously determined in the model.[5] We assume that the coalition $K \subseteq N$ sets abatement paths for its members that maximise the coalition payoff defined as the sum of all members' payoffs while singletons $i \in N \setminus K$ choose their abatement level to maximise their own payoffs. For every coalition $K \subseteq N$ the abatement game has a unique interior solution $(\mathbf{q}_1^*(K),...,\mathbf{q}_n^*(K))$ under the STACO specification of benefit and cost functions (see Section 3.2.2). The uniqueness of the equilibrium abatement paths allows us to specify the payoffs directly as function of the coalition structure.

Now we can move to the first stage. First, we formally introduce transfer schemes that redistribute the coalition payoff (determined at the second stage) among signatories. A financial transfer $F_i(K)$ is a payment made or received such that $\sum_{i \in K} F_i = 0$ and $F_i(K) = 0$ for all singletons $i \in N \setminus K$. The transfer schemes will be specified in Section 3.3. We obtain a valuation function $V_i(K)$ that specifies the payoff for every region $i \in N$ and every coalition $K \subseteq N$, using the unique optimal abatement level $\mathbf{q}^*(K)$ in the calculation of payoffs. The payoffs of singletons and signatories are as follows:

$$V_i(K) \equiv \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (b_{it}(\mathbf{q}^*(K)) - c_{it}(\mathbf{q}_i^*(K))) \right\} \qquad \text{for } i \notin K, \tag{3.2}$$

$$V_i(K) \equiv \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (b_{it}(\mathbf{q}^*(K)) - c_{it}(\mathbf{q}_i^*(K))) \right\} + F_i(K) \qquad \text{for } i \in K, \tag{3.3}$$

At the first stage, given these payoffs, players decide whether to sign an abatement agreement or not. Those who sign form a coalition *K*. The Nash equilibria of the coalition formation game at the first stage can be derived from the valuation function given in Eq. (3.2) and (3.3). We will refer to the Nash equilibria as stable coalitions. A coalition *K* is stable if no signatory has an incentive to withdraw from the coalition (internal stability) and no non-signatory has an incentive to participate (external stability); cf. d'Aspremont et al. (1983). Formally, stability is defined as:

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[4] This equilibrium concept has been defined as 'Partial Agreement Nash Equilibrium (PANE)' by Chander and Tulkens (1995).

[5] Although the strategy space is a set of time paths of abatement, the paths are determined once and for all.

Internal stability: $V_i(K) \geq V_i(K \setminus \{i\})$ $\forall i \in K$,

External stability: $V_j(K) \geq V_j(K \cup \{j\})$ $\forall j \notin K$.

3.2.2. The STACO-2.1 model

In this section, we explain the numerical specification of our model, which we label STACO-2.1. The model is an update and extension of the original STACO-1 model, described in Dellink et al. (2004) and Finus et al. (2006). Here, we focus on the main features of the model. Equations are presented in Box 3.1. We consider twelve world regions: USA (USA), Japan (JPN), European Union-15 (EU15), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and rest of the world (ROW). We set the model horizon to account for benefits from abatement to infinity, but adopt a shorter planning horizon of 100 years, ranging from 2011 to 2110, to determine abatement levels. With respect to abatement levels after the planning horizon *T*, we do not need to make any assumptions: they do not affect the costs and benefits that accrue to abatements in periods $t \leq T$ in our model specification. Together, this ensures a reflection of the most relevant intertemporal aspects of climate change. The first term on the right hand side of Eq. (3.4) in Box 3.1 indicates the net present value of the stream of payoffs over the planning horizon. The second term captures future impacts after the planning horizon. Therefore, marginal global benefits reflect all current and future benefits from abatement in period t, discounted back to period t. Essentially, in 2010 (t_0) the signatories set their abatement paths up to 2110 (T=100), taking into account all future benefits and costs of abatement. We calculate the payoff function for each region and each possible coalition. Recall that payoff for region i in period t, π_{it}, depends on the abatement path until t.

We use the data for CO_2 emissions derived from the EPPA model (Babiker et al., 2001; Paltsev et al., 2005) to calibrate the regional BAU emission paths[6] in our model; these paths are presented in the Appendix. It should be noted that our calibration of BAU emissions is based on EPPA model simulations that include damages from climate change. Thus, any feedback from the climate to the economy in the case of inaction (i.e. in absence of any climate policy) is implicitly included in the calibration. Benefit b_{it} from abatement is a function of the avoided damage, which in turn depends on global atmospheric temperature change. We follow Nordhaus (1994) and Germain and Van

[6] We use data from World Bank (2003) to match the regional aggregation in EPPA to STACO. As we use multiple sources to calibrate the baseline, some inconsistencies may arise. We expect, however, that these are relatively minor compared to the uncertainties regarding the other parameter values, especially since we focus on stability issues, rather than forecasting optimal abatement trajectories.

Steenberghe (2003) and approximate the climate system by a linear system of three equations (for concentrations, radiative forcing and atmospheric temperature increase, respectively) and ignore the non-linear feedbacks between the atmosphere and the oceans. Thus, we can calculate damages as a linear function of accumulated past and current abatement, which is required to ensure dominant strategies for our regions.[7] In Eq. (3.5), as defined in Chapter 2, M_t is the stock of CO_2 in year t, $\overline{M}$ denotes the pre-industrial stock of CO_2, y_t denotes global GDP in year t as given in Nordhaus (1994), and γ_1 and γ_2 are estimated by OLS-regression (Dellink et al., 2004). For the global damage parameter γ_D, we apply the estimate by Tol (1997) that damages amount to 2.7% of GDP for a doubling of concentrations over pre-industrial levels, that is, $\gamma_D = 0.027$. Note that marginal benefits change over time due to the assumption that damages increase linearly with GDP.

Eq. (3.6) shows the regional benefits expressed as a regional share of avoided damages. Thus, global benefits are allocated according to the constant share θ_i for each region, as displayed in the Appendix. These regional benefit shares are calibrated to regional damage estimates by Fankhauser (1995), as explained in detail in Dellink et al. (2004). We specify an abatement cost function following the estimates of the EPPA model by Ellerman and Decaux (1998); these abatement costs reflect the welfare costs of a cost-minimising mixture of possible mitigation responses (primarily fuel switch and changes in capital accumulation). In Eq. (3.7) we define α and β as regional cost parameters. We assume exogenous technological progress which is modelled as a reduction of current abatement costs at an annual rate ς=0.005.

The STACO-1 model (as used in Finus et al., 2006; Altamirano-Cabrera and Finus, 2006; Weikard et al., 2006) assumed that each region chooses a constant abatement level over the planning time horizon. Here, we use a specification in which abatement levels for each period are endogenously determined in the model by maximising the net present value of the stream of payoffs. Each region has perfect foresight into the future and can plan its abatement path for the current and all future years until the planning horizon. In our numerical simulations with twelve regions we thus investigate 4084 ($2^{12} - 12$) different coalition structures.

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[7] We acknowledge that this is a bold assumption, but econometric analysis reported in Dellink et al. (2008a) reveals that for our purposes the linearisation fits the larger non-linear model very well. Furthermore, the focus of our analysis is not on presenting the most up to date specification of the carbon cycle but on how costs and benefits of abatement influence the incentives for coalition formation. Note that our analysis abstracts from non-linearities arising from climate thresholds (see IPCC, 2007a).

Box 3.1. Equations in STACO-2.1

Payoffs

$$\pi_i(\mathbf{q}) = \sum_{t=1}^{T}\left\{(1+r)^{-t}\cdot(b_{it}(\mathbf{q})-c_{it}(\mathbf{q}_i))\right\} + \sum_{t=T+1}^{\infty}\left\{(1+r)^{-t}\cdot b_{it}(\mathbf{q})\right\} \tag{3.4}$$

Damages

$$d_t = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t}{\overline{M}}\right)\right]\cdot(\gamma_D \cdot y_t) \tag{3.5}$$

Benefits

$$b_{it}(q_1,...,q_t) = \theta_i \cdot \left\{d_t(\mathbf{0}) - d_t(q_1,...,q_t)\right\} \tag{3.6}$$

Abatement costs

$$c_{it}(q_{it}) = \tfrac{1}{3}\cdot\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^3 + \tfrac{1}{2}\cdot\beta_i\cdot(1-\varsigma)^t\cdot q_{it}^2 \tag{3.7}$$

3.3. Transfer schemes

In this section we introduce different transfer schemes. Section 3.3.1 presents an allocation-based transfer scheme, namely the emissions-based tradable emission permits scheme. Sections 3.3.2 and 3.3.3 introduce outcome-based transfer schemes: emissions-based surplus sharing and optimal sharing. For a consistent comparison of the different transfer schemes, we implement all schemes as a stream of financial transfers between coalition members over the model horizon. Note that Eq. (3.3) implies that only the differences in net present values of these transfers are relevant in the stability analysis.

3.3.1. Emissions-based tradable emission permits

An allocation-based transfer rule describes a distribution of permits and incorporates a permit trading system. Altamirano-Cabrera and Finus (2006) compare several allocation-based rules for distributing the permits.[8] We focus on the most common transfer scheme which distributes permits in proportion to a base year level of a full path of emissions. This allocation scheme can be considered as 'grandfathering' where the allocation of permits is based on the initial emissions for each region in a base year. Emission permits can be traded only among signatories. The payoff ($V_{it}^{P}(K)$) for a signatory i in period t after the permit trading is calculated as

[8] For criteria of rules for allocating permits see Edmonds et al. (1995) and Rose et al. (1998).

$$V_{it}^{P}(K) \equiv V_{it}(K) - p_t \cdot (\tilde{q}_{it} - q_{it}^{*}(K)) \quad , \tag{3.8}$$

where p_t is the (market clearing) permit price in period t and $\tilde{q}_{it}$ is the required abatement level for signatory i in period t to comply with the assigned emission level under the permit trading system in coalition K. The first term on the right hand side of Eq. (3.8), $V_{it}(K)$, indicates the payoff of signatory i in period t without permit trading in coalition K. The second term implies that if a region reduces emissions more than assigned ($q_{it}^{*} > \tilde{q}_{it}$), the region can sell the permits to other signatories. On the other hand, if a region reduces emissions less than the assigned level ($q_{it}^{*} < \tilde{q}_{it}$), the region has to compensate the difference by purchasing permits. In the equilibrium of the permits market the price of a permit, p_t, equals marginal abatement costs.

In the permits market, the initially allocated emission permits to region i in period t, $\tilde{e}_{it}$, are calculated as a fraction $\lambda_{it}(K)$ of the total amount of permits allocated to the signatories in a coalition K with $\sum_{i \in K} \lambda_{it}(K) = 1$, such that

$$\tilde{e}_{it} = \lambda_{it}(K) \cdot \sum_{i \in K} e_{it}^{*} \tag{3.9}$$

The total amount of emission permits for signatories is equal to the emission level in equilibrium, $\sum_{i \in K} \tilde{e}_{it} = \sum_{i \in K} e_{i}^{*}$, expressed as $\sum_{i \in K} \tilde{e}_{it} = \sum_{i \in K} \bar{e}_{it} - \sum_{i \in K} q_{it}^{*}$, where $\bar{e}_{it}$ denotes BAU emissions of region i in period t.

The required abatement level can be defined as

$$\tilde{q}_{it} = \bar{e}_{it} - \lambda_{it}(K) \cdot \left(\sum_{j \in K} \bar{e}_{jt} - \sum_{j \in K} q_{jt}^{*} \right). \tag{3.10}$$

Under permit trading based on *initial emissions*, the fraction $\lambda_{it}(K)$ is calculated based on the ratio of 2010 emissions for region i ($\bar{e}_{i,t_0}$) over the total 2010 emissions of all signatories. Thus, the fraction is constant over time:

$$\lambda_{it}(K) = \lambda_{i}(K) = \frac{\bar{e}_{i,t_0}}{\sum_{j \in K} \bar{e}_{j,t_0}} \quad . \tag{3.11a}$$

Under permit trading based on *future emissions*, we use the full path of BAU emissions to determine the time-dependent fractions:

$$\lambda_{it}(K) = \frac{\bar{e}_{it}}{\sum_{j \in K} \bar{e}_{jt}} \quad . \tag{3.11b}$$

The initial-emissions-based permit trading does not take into account projections of emissions. Hence, regions with growing emissions in the future have to buy permits from other signatories. The future-emissions-based permit trading gives regions permits which are fully adjusted to their expected emissions.

It should be stressed that membership decisions are only made once, before the first period. The players base their decisions on the net present value of their payoff including transfers.

3.3.2. Emissions-based surplus sharing

Transfer schemes based on surplus sharing are proposed for instance by Weikard et al., (2006), who consider various sharing rules for the gains of cooperation. One of the main advantages of surplus sharing is that individual rationality is always satisfied as long as a coalition is at all profitable.[9] The sharing rule assigns a fraction $\lambda_{it}(K)$ (with $\sum_{i \in K} \lambda_{it}(K) = 1$) of the coalition surplus $S_t(K)$ at time t (as defined below in Eq. (3.12)) to every signatory $i \in K$. The coalition surplus $S_t(K)$ is defined as the difference between the joint gain of the signatories and the sum of the payoffs in the situation of the All Singletons structure, *i.e.*

$$S_t(K) = \sum_{i \in K} V_{it}(K) - \sum_{i \in K} V_{it}(\varnothing) . \tag{3.12}$$

The final payoff of a signatory after the surplus sharing is then given by its payoff in the All Singletons structure plus its share of the coalition surplus:

$$V_{it}^{S}(K) = V_{it}(\varnothing) + \lambda_{it}(K) \cdot S_t(K) . \tag{3.13}$$

Although it is possible to apply many different rules to the sharing problem (such as equal sharing, proportional sharing and combinations), we adopt a proportional sharing rule based on emission levels. Therefore, the fraction of the coalition surplus is equivalent to the fraction under the emissions-

[9] Profitability means that coalitional payoff is larger than the sum of payoffs of coalition members in the All-Singletons case. The STACO specification, in particular the functional form of the benefit function, guarantees profitability of every coalition, as singletons have dominant strategies, and thus there is no leakage effect.

based permit trading as defined in Section 3.3.1. Under the initial-emissions-based transfer scheme, the fractions are based on 2010 emission levels:

$$\lambda_{it}(K) = \lambda_i(K) = \frac{\bar{e}_{i,t_0}}{\sum_{j \in K} \bar{e}_{j,t_0}}. \tag{3.14a}$$

Under the future-emissions-based surplus sharing, we use the full path of reference emissions (BAU) to determine time-dependent fractions:

$$\lambda_{it}(K) = \frac{\bar{e}_{it}}{\sum_{j \in K} \bar{e}_{jt}}. \tag{3.14b}$$

3.3.3. Optimal surplus sharing

We now apply the optimal sharing rule suggested by Carraro et al., (2006), McGinty (2007), Weikard (2009) and Fuentes-Albero and Rubio (2010). Optimal sharing requires that each signatory's payoff in net present value terms is at least as much as what it could have obtained by deviating from coalition K, namely the outside option payoff (cf. Weikard 2009). Outside option payoffs at time *t* can written as $V_{it}(K \setminus \{i\})$. We can define the per-period residual as $V_{Kt}(K) - \sum_{i \in K} V_{it}(K \setminus \{i\})$ which is distributed in proportion to the outside option payoffs.[10] The payoff function $V_i^o(K)$ is defined as:

$$V_{it}^o(K) \equiv \frac{V_{it}\left(K \setminus \{i\}\right)}{\sum_{j \in K} V_{jt}\left(K \setminus \{j\}\right)} \cdot V_{Kt}(K). \tag{3.15}$$

Rearranging the right hand side shows that under an optimal sharing rule a coalition K is internally stable if and only if in net present value terms it holds that

$$\frac{V_K(K)}{\sum_{i \in K} V_i(K \setminus \{i\})} \geq 1, \tag{3.16}$$

for all $i \in K$ and all $K \subseteq N$. Hence, *K* is internally stable if the coalition payoff (weakly) exceeds the sum of the outside option payoffs, and if not, *K* cannot be internally stable. Inequality (3.16) is a

[10] Note that the residual can be shared by each coalition member in any way desired, because it does not affect internal stability (Weikard 2009).

necessary condition for stability. It is a sufficient condition for internal stability if transfers are arranged according to Eq. (3.15).

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 which 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.

3.4. Results

In this section we present our results, starting in Section 3.4.1 with an examination of the benchmark case without transfers. Sections 3.4.2 and 3.4.3 discuss the emissions-based permit trading and emissions-based surplus sharing, respectively. Section 3.4.4 presents results of an optimal sharing scheme.

3.4.1. No transfers

Table 3.1 illustrates the incentive structures of the different regions for the non-cooperative case where all players act as singletons. In this All Singletons structure marginal abatement costs equal marginal benefits within each region. The difference between annual abatement in the All Singletons case and in BAU decreases over time and leads to a stock of CO_2 of 1,448 GtC (Gigaton carbon) by the year 2110. This corresponds to about 1.7 times the stock level in 2010.

Abatement differs across regions as the abatement level is determined by regional marginal benefits and marginal costs. In our model, developed regions have a higher share of global benefits than developing regions (cf. the Appendix). The USA, a region with a low marginal abatement cost curve and high share of global benefits, has an incentive to make substantial abatement efforts even in the All Singletons case, and in 2011 USA reduces 9.9% of their BAU emissions. Regions with higher marginal abatement costs and lower shares of global benefits, such as the energy exporting countries, Brazil, and dynamic Asian economies, have hardly any incentive to reduce emission on their own. Japan has a relatively high share of global benefits, but does not make large abatement efforts due to their high marginal costs of abatement. In 2011, Japan reduces only about 2.5% of its emissions in the BAU case.

With a Grand Coalition marginal abatement costs equal the sum of marginal benefits among all regions at 99.0 US$/ton (See Table 3.2). The abatement allocation differs widely between regions. In the Grand Coalition, the total gain from cooperation in terms of the net present value of payoffs compared to the All Singletons case is almost 10 trillion US$ (15,211 billion US$ − 5,238 billion US$). Even though substantially higher global payoffs can be achieved, some regions are worse off when the Grand Coalition is formed. For instance, China, which has the flattest abatement cost curve in our setting, has to contribute a lot to reduce emissions.[11]

Table 3.1: All singletons structure

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Marginal benefits from abatement in 2011
	2011	2110	Billion US$ over 100 years	US$/tC	US$/tC
USA	9.9	5.5	1,117	22.4	22.4
JPN	2.5	3.0	943	17.1	17.1
EU15	7.6	5.6	1,240	23.4	23.4
OOE	5.6	2.6	188	3.4	3.4
EET	4.4	2.9	71	1.3	1.3
FSU	6.7	5.3	362	6.7	6.7
EEX	1.9	2.0	164	3.0	3.0
CHN	14.8	10.8	298	6.1	6.1
IND	10.5	5.3	268	4.9	4.9
DAE	1.9	2.1	136	2.5	2.5
BRA	0.1	0.2	84	1.5	1.5
ROW	6.3	4.5	365	6.7	6.7
Global	8.0	5.5	5,238		

Global stock of CO_2 in 2110 = 1,448 GtC

This leads to a large reduction in the net present value of China's payoff, from 298 billion US$ in the All Singletons case to -1,777 billion US$ in the Grand Coalition. The incentive to leave the coalition, i.e. the increase in payoffs by unilaterally changing the membership decision, is shown in the last column of Table 3.2. In the case of the Grand Coalition where all regions are signatories, a positive number indicates an incentive to leave the coalition, while a negative number indicates the benefit from membership. Only Japan and EU15 have no incentive to leave the Grand Coalition, that is, all

[11] The marginal abatement cost curve of China in our model is very flat because there is a lot of scope for energy efficiency improvement, fuel switch and introduction of renewables in the Chinese energy system which is mainly based on coal. Forecasts of the development of China's marginal abatement costs over a century are, of course, subject to large standard errors. Chen (2005) offers forecasts, based on MARKAL, until the year 2030. Chen's bottom-up assessments are not directly comparable to top-down assessments. However, a top-down framework is more appropriate for our analysis as it provides consistent estimates for all regions, *cf.* Ellerman and Decaux (1998).

other regions have stronger free-rider incentives and wish to leave. The global stock of CO_2 in 2110 is projected to be 1,304 GtC in the Grand Coalition.

Table 3.2: Grand coalition structure (without transfers)

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Incentive to change membership (NPV)
	2011	2110	Billion US$ over 100 years	US$/tC	Billion US$ over 100 years
USA	22.8	12.2	4,158	99.0	52
JPN	11.7	11.4	3,930	99.0	-281
EU15	18.3	12.5	5,062	99.0	-432
OOE	29.9	13.7	518	99.0	261
EET	47.6	28.8	-1	99.0	297
FSU	26.2	20.5	1,031	99.0	423
EEX	28.4	20.7	248	99.0	420
CHN	89.3	53.9	-1,777	99.0	2,727
IND	65.8	28.6	482	99.0	588
DAE	34.7	25.9	209	99.0	352
BRA	6.2	4.7	333	99.0	27
ROW	30.7	19.6	1,019	99.0	442
Global	36.6	22.5	15,211		

Global stock of CO_2 in 2110 = 1,304 GtC

We compute all possible cartel coalitions and examine stability of all 4084 coalition structures with an algorithm programmed in MATLAB. Without transfers, 14 non-trivial coalitions are internally stable, of which only the one between Japan and EU15 is also externally stable. Larger coalitions are not stable because free-rider incentives are strong and most regions are better off when they stay outside a coalition. Table 3.3 shows the results for the stable coalition, Japan and EU15. Both Japan and EU15 make larger abatement efforts than in the All Singletons structure. As a result of their cooperation, both regions can obtain slightly higher payoffs than in the All Singletons case.

In equilibrium, the signatories have an interest in cooperating, because of their higher marginal benefits from abatement, while none of the singletons have an interest in joining, as their abatement costs would increase too much if they have to take the benefits of Japan and EU15 into account.

Table 3.3: Coalition of Japan and EU15 (without transfers)

Regions	Annual abatement (% of BAU emissions)		Net present value (NPV) of payoff	Marginal costs in 2011	Incentive to change membership (NPV)
	2011	2110	Billion US$ over 100 years	US$/tC	Billion US$ over 100 years
USA	9.9	5.5	1,199	22.4	-143
JPN	***5.5***	***6.0***	***975***	***40.4***	***-32***
EU15	***10.7***	***7.6***	***1,244***	***40.4***	***-4***
OOE	5.6	2.6	201	3.4	-70
EET	4.4	2.9	76	1.3	-78
FSU	6.7	5.3	386	6.7	-121
EEX	1.9	2.0	175	3.0	-107
CHN	14.8	10.8	321	6.1	-725
IND	10.5	5.3	286	4.9	-159
DAE	1.9	2.1	145	2.5	-89
BRA	0.1	0.2	90	1.5	-7
ROW	6.3	4.5	389	6.7	-126
Global	8.6	5.8	5,486		

Global stock of CO_2 in 2110 = 1,445 GtC

3.4.2. Emissions-based tradable emission permits

3.4.2.1. Initial-emissions-based permit trading

We now incorporate a transfer scheme based on emission permit trading across coalition members, as explained in Section 3.3.1. Under the initial-emissions-based permit trading, emission permits are divided among the signatories based on their respective emissions in the base year 2010.[12] We find that no non-trivial coalition is stable under initial-emissions-based permit trading. It, thus, leads to the most undesirable outcome among all the cases that we consider. When we compare the results with those under no transfers, EU15 no longer desires to stay in the coalition with Japan, as the costs of purchasing emission permits from Japan outweigh the benefits of collaboration. A stable coalition is more likely if a region with high marginal benefits, such as Japan or EU15 collaborates with a region with low marginal abatement costs, such as China or India. The basic idea is that the former regions could finance emission reductions in the latter regions. The problem is, however, that under the initial-

[12] Using 1990 emission levels instead of 2010 does not influence the main qualitative results (results are available from the authors upon request).

emissions-based permit trading scheme, the number of permits issued to China and India is relatively small. As their reference emissions grow relatively fast, these regions will need large abatement efforts in order to reach their targets. In contrast, a region like Japan will obtain a relatively large number of permits under the initial-emissions-based scheme, whereas their emissions are expected to hardly grow over the next century.

3.4.2.2. Future-emissions-based permit trading

A possible way out of the just described dilemma is to base the distribution of emission permits on the entire path of reference emissions, that is, to apply a transfer scheme based on future emissions. This will overcome the situation obtained in the initial-emissions-based transfer scheme as fast-growing regions such as India will obtain more permits over time. Under the future-emissions-based permit trading twelve coalitions are internally stable of which two are also externally stable: (a) EU15 and China, and (b) Japan and India (cf. Table 3.4).

Table 3.4: Stable coalitions (with future-emissions-based permit trading)

Regions	Abatement in 2110		Net present value (NPV) of payoff		Incentive to change membership (NPV)	
	(% of BAU emissions)		Billion US$ over 100 years		Billion US$ over 100 years	
	(a) EU15 & China	(b) Japan & India	(a) EU15 & China	(b) Japan & India	(a) EU15 & China	(b) Japan & India
USA	5.5	5.5	1,780	1,240	-654	-126
JPN	3.0	***3.7***	1,448	***975***	-23	***-32***
EU15	***6.4***	5.6	***1,512***	1,368	***-272***	-71
OOE	2.6	2.6	289	207	-176	-44
EET	2.9	2.9	109	78	-63	-7
FSU	5.3	5.3	559	398	-251	-52
EEX	2.0	2.0	252	180	-197	-56
CHN	***27.6***	10.8	***401***	332	***-103***	-13
IND	5.3	***12.7***	415	***287***	-105	***-18***
DAE	2.1	2.1	209	150	-123	-33
BRA	0.2	0.2	129	93	-84	-31
ROW	4.5	4.5	564	402	-235	-52
Global	8.2	6.0	7,667	5,709	-2,284	-536

Global stock of CO_2 in 2110 = 1,425 GtC (EU15 and China) and 1,444 GtC (Japan and India)

Under the initial-emissions-based permit trading, China and India have incentive to leave the coalition because of higher abatement burden compared to Japan and EU15, respectively, and therefore have lower payoffs than outside the coalition. This makes the coalition internally unstable. The situation improves under the future-emissions-based permit trading as China and India have lower required abatement levels (more emission permits), and they can sell their permits to their partners, Japan and EU15, respectively. These transfers would encourage China and India to enter a coalition.

Figure 3.1 shows how the transfer schemes affect the stream of payoffs for China in a coalition of EU15 and China. Without transfers, the payoff for China is slightly negative for the first two decades, but it is clearly positive for the later decades (as Chinese emissions are expected to stabilise), leading to a small but positive NPV of payoffs (9 billion US$). With initial-emissions-based permit trading the payoff decreases rapidly and becomes negative after two decades. This is due to the fast growth of reference emissions and thus the need for large emission reductions by China. In these periods, China buys permits from EU15. In later decades, the payoffs become positive again, as Chinese emissions stabilise and China is able to sell some permits. In net present value terms, the coalition is not beneficial for China (NPV of payoff equals -5 billion US$). Note that the stream of transfers from EU15 to China can be read from the figure by subtracting the payoffs without transfers from the payoffs with transfers.

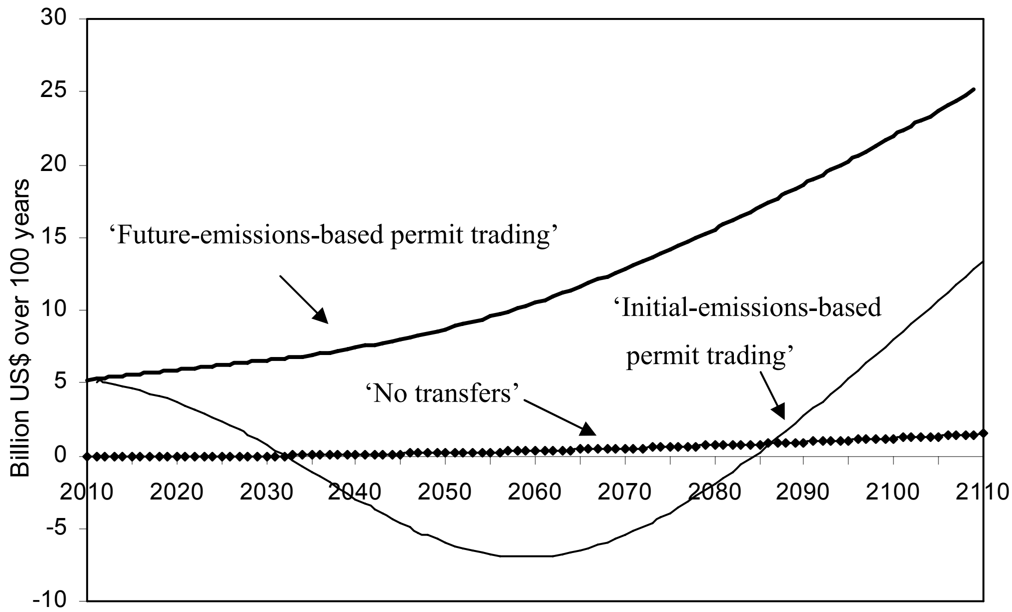

Figure 3.1: Undiscounted payoff paths for China in the coalition of EU15 and China

With future-emissions-based permit trading, China is able to sell permits to the EU15 in all periods, as the difference in growth rates between the two regions is considered in the allocation of the emission permits. Thus, negative payoffs in the middle of the century are prevented and China earns a NPV of almost 400 billion US$ on the sale of excess permits. These additional earnings overcome the free-rider incentives of China and, while they reduce the gains from cooperation for EU15, the outcome is beneficial for both. Thus the coalition is internally stable. Entry of another permit buyer (seller) violates the interests of some signatories, because the emission permit price will be too high (low). Thus, the coalition of EU15 and China is also externally stable.

3.4.3. Emissions-based surplus sharing

Table 3.5 presents the main results of the emissions-based surplus sharing scheme for the only stable coalition consisting of USA and China. This coalition is stable under both the initial-emissions-based and future-emissions-based surplus sharing. When transfers are based on a division of the gains from cooperation rather than a division of tradable emission permits, internal stability is less of a problem. Therefore, although the initial-emissions-based surplus sharing does not entirely match the development of the regions, the scheme is sufficient to stabilise this coalition. Most regions have less incentive to change membership under the future-emissions-based surplus sharing, indicating that the future-emissions-based surplus sharing is more robust than initial-emissions-based surplus sharing.

Under surplus sharing the outcome in terms of net present value of global payoff and the associated CO_2 concentration improves compared to the no transfers and permit trading case.

Table 3.5: Coalition of USA and China (with surplus sharing)

Regions	Abatement in 2110	Share of the coalition surplus in 2110		Net present value (NPV) of payoff		Incentive to change membership (NPV)	
	(% of BAU emissions)	Billion US$		Billion US$ over 100 years		Billion US$ over 100 years	
		Initial-emissions-based	Future-emissions-based	Initial-emissions-based	Future-emissions-based	Initial-emissions-based	Future-emissions-based
USA	***6.3***	***11***	***12***	***1,332***	***1,319***	***-215***	***-201***
JPN	3.0	-	-	1,454	1,454	-399	-421
EU15	5.6	-	-	1,940	1,940	-350	-388
OOE	2.6	-	-	290	290	-45	-42
EET	2.9	-	-	110	110	-5	-7
FSU	5.3	-	-	562	562	-58	-78
EEX	2.0	-	-	253	253	-15	-23
CHN	***27.1***	*7*	*7*	***436***	***449***	***-137***	***-151***
IND	5.3	-	-	417	417	-80	-64
DAE	2.1	-	-	210	210	-25	-30
BRA	0.2	-	-	130	130	-29	-30
ROW	4.5	-	-	566	566	-79	-87
Global	8.2	19	19	7,700	7,700	-1,437	-1,523

Global stock of CO_2 in 2110 = 1,425 GtC

3.4.4. Optimal sharing

Under the optimal sharing transfer scheme, 182 non-trivial stable coalitions emerge, of which 108 are Pareto undominated. As discussed in Section 3.3.3, optimal sharing guarantees that a coalition is always internally stable if Eq. (3.16) holds. Table 3.6 presents outcomes for the top five stable coalitions according to the net present value of global payoffs.

Table 3.6: Top five stable coalitions with optimal sharing

	Net present value (NPV) of payoff (Billion US$ over 100 years)				
	{USA, EET, CHN, IND, DAE}	{EU15, EET, EEX, CHN, IND}	{EU15, OOE, EET, CHN, IND}	{EU15, EET, CHN, IND, DAE}	{USA, EET, EEX, CHN, DAE, BRA}
USA	***1,603***	2,413	2,386	2,378	***1,566***
JPN	1,933	1,930	1,910	1,904	1,883
EU15	2,595	***1,778***	***1,769***	***1,762***	2,527
OOE	386	386	***354***	380	376
EET	***138***	***138***	***136***	***137***	***134***
FSU	749	748	740	738	730
EEX	336	***310***	332	331	***300***
CHN	***415***	***413***	***403***	***410***	***401***
IND	***485***	***487***	***479***	***484***	541
DAE	***261***	279	276	***260***	***253***
BRA	172	172	170	170	***165***
ROW	755	754	746	744	736
Global	9,830	9,810	9,701	9,697	9,613

We discuss three main observations from our results. First, Barrett (1994) has shown that stable coalitions will be small in a model with symmetric players if the gains from cooperation (the payoff difference between All Singletons and the Grand Coalition) are large. Here we consider asymmetric regions and we obtain large stable coalitions compared to the outcomes without transfers, even though gains from cooperation are large. We find stable coalitions of up to six regions. Those that include China and one of the major OECD regions (USA or EU15) generate the highest global payoffs. In such coalitions regions with cheap abatement options match with regions with high marginal benefits.

Secondly, we can obtain a significantly higher net present value of global payoffs compared to the outcomes under other transfer schemes. While we find that 25% of the potential gains from cooperation are obtained under emissions-based surplus sharing, an optimal transfer scheme can reap 46%.[13] Under optimal sharing transfers are arranged to minimise free-rider incentives by giving each region its outside option payoff if that is feasible; see Eq. (3.15). Every coalition that is internally

[13] The percentages of potential gains from cooperation are 0% for All Singletons and 100% for the Grand Coalition.

stable under some sharing rule is also internally stable under optimal sharing. Hence it is expected from theory and does not come as surprise that optimal sharing can stabilise coalitions which perform better than the stable coalitions under other transfer schemes. However, the degree to which optimal sharing helps to bridge the gap between the All Singletons and the Grand Coalition performance is remarkable.

Thirdly, ambitious coalitions will generate large positive externalities to non-cooperative regions, such as USA and EU15. The USA can obtain higher payoffs in a free-rider position when EU15 joins others; likewise EU15 can obtain higher payoffs in a free-rider position when the USA joins others (see Table 3.6).

3.5. Sensitivity analysis

As simulation results depend on parameter values which are subject to uncertainties associated with the numerical model, we conduct a sensitivity analysis to examine how the main assumptions affect the model results. The crucial parameters in this model are the abatement cost parameters α, β, the scale parameter of the benefit function γ_D, and the discount rate r. First, for the abatement costs, we simultaneously double or halve the base value of α and β for all regions. Second, for the scale parameter of the benefit function, we double the base value of γ_D; this higher level is roughly equivalent to the estimate by Tol (2005). Similarly, we scale it down to one-half the original value, which roughly resembles the estimate of Nordhaus (1994). Finally, we change the base value of the discount rate r from 2% to 1% and 3%, respectively.

Table 3.7 presents the results of the sensitivity analysis under no transfers and with the different transfer schemes. Under the emissions-based permit trading and surplus sharing schemes we obtain the same stable coalitions using the alternative parameter values as in the base case. Similarly, under the optimal transfer scheme we find the same five stable coalitions that are performing best in terms of the net present value of global payoff and CO_2 concentration as in the base case. Changing each parameter value will increase or decrease absolute values of the results, but ratios between regions remain almost unchanged. This indicates that for the transfer schemes that we analysed results in terms of stability are robust with respect to the investigated changes in the values of these key parameters.

Table 3.7: Sensitivity analysis

Scenario	No transfers	Permit trading		Surplus sharing		Optimal sharing
		Initial- emissions-based	Future- emissions-based	Initial- emissions-based	Future- emissions-based	
Base case	{JPN, EU15}	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
Marginal abatement cost						
Double	None	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
One-half	{JPN, EU15}	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
Marginal benefit						
Double	{JPN, EU15}	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
One-half	None	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
Discount rate						
1%	{JPN, EU15}	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}
3%	{JPN, EU15}	None	{EU15, CHN} {JPN, IND}	{USA, CHN}	{USA, CHN}	{USA, EET, CHN, IND, DAE} {EU15, EET, EEX, CHN, IND} {EU15, OOE, EET, CHN, IND} {EU15, EET, CHN, IND, DAE} {USA, EET, EEX, CHN, DAE, BRA}

3.6. Discussion and conclusions

In this paper we examine the stability of all possible climate coalitions in a cartel game under different transfer schemes using a numerical analysis. We investigate to what extent different types of transfer schemes can contribute to the stability of an international climate agreement, using our applied model STACO-2.1.

The results of our model analysis should always be interpreted with the specific settings of the model and the underlying assumptions in mind; we emphasise that our analysis does not focus on multiple coalitions or on renegotiations, and that our conclusions only refer to one-shot cartel games. Nonetheless, our numerical analysis with a larger number of heterogeneous regions allows the identification of some general features that cannot be analysed in models with symmetric players.

First, when the transfer scheme is poorly designed in the sense that it increases incentives to free-ride, the best performing stable coalition may be worse than in the case of no transfers. In our setting, this occurs for the initial-emissions-based tradable permit system (grandfathering).

Secondly, improvements of the initial-emissions-based tradable permit system, such as a tradable permit system based on the full path of emissions or a surplus sharing scheme, do enhance stability of coalitions, i.e. lead to stable coalitions that perform better in terms of emission reduction. The resulting stable coalitions, however, remain small and rather ineffective in comparison to the Grand Coalition.

Thirdly, well-designed transfer schemes, including the optimal transfer scheme, can stabilise larger coalitions. Our paper shows in a calibrated setting that optimal transfers perform much better than more pragmatic transfer schemes: the most ambitious stable coalition under optimal transfers is at least twice as effective (in terms of reaping the potential gains from cooperation) as under any of the pragmatic schemes we have considered. This remarkable result implies that it is important in actual negotiations to design appropriate transfer schemes. But such schemes require detailed insight into the incentive structures of the regions. Thus, there is a trade-off between more pragmatic schemes that may be easier to implement but are hardly effective, and more elaborate schemes, that would be more effective but which may be hard to achieve in actual negotiations.

Fourthly, large asymmetries between regions imply not only that the gains from cooperation are large, but also that free-rider incentives are large (cf. Barrett, 1994). Whereas transfer schemes can play a major role in mitigating the free-rider incentives, the financial flows involved may be huge (in our setting annual transfers may be several billions of US$). The political implications of such huge flows are daunting and may complicate negotiations.

Finally, it turns out that even with optimal transfers ambitious coalitions consisting of e.g. USA, EU and China are not stable. We can conclude that transfer schemes can play a role in aligning regional incentives to induce larger and more effective stable coalitions, but other mechanisms are required to overcome the strong remaining free-rider incentives. Although it may be difficult to estimate future emission paths and outside option payoffs and to implement a formal 'optimal sharing' scheme, we show that for enhancing stability it is essential to be aware of the incentives for regions to participate. Incentives can be set either through the allocation of permits or through the design of the transfer mechanisms (or compensation payments). Bringing the idea of optimal sharing and the outside option payoffs to the attention of negotiators may help to identify an allocation of costs and benefits over the various regions that provides incentives to join a climate agreement and to contribute to global abatement of greenhouse gases.

Appendix 3A

Table 3A-1: Main model parameter values

Symbol	Description	Value	Unit	Source
$\overline{M}$	Pre-industrial level of CO_2 stock	590	GtC	Nordhaus (1994)
δ	Natural annual removal rate of CO_2 stock	0.00866	-	Nordhaus (1994)
ω	Airborne fraction of emissions remaining in the atmosphere	0.64	-	Nordhaus (1994)
r	Discount rate	0.02	-	Assumption
θ_i	Share of region i in global benefits	see Table 3A-2, column 3		Own calculation based on Fankhauser (1995)
α_i	Abatement cost parameter of region i	see Table 3A-2, column 4		Own calculation based on Ellerman and Decaux (1998)
β_i	Abatement cost parameter of region i	see Table 3A-2, column 5		Own calculation based on Ellerman and Decaux (1998)
ς	Technological progress parameter	0.005	-	Assumption
γ_D	Scale parameter of damage and benefit function	0.027	-	Tol (1997)

Table 3A-2: Regional parameter values

Regions	Emission in 2010	Share of global benefits	Parameter of abatement cost	Parameter of abatement cost
	GtC (share)	θ_i	α_i	β_i
USA	1.763 (0.238)	0.226	0.0005	0.0398
JPN	0.344 (0.046)	0.173	0.0155	1.8160
EU15	0.943 (0.127)	0.236	0.0024	0.1503
OOE	0.360 (0.049)	0.035	0.0083	0
EET	0.226 (0.030)	0.013	0.0079	0.0486
FSU	0.774 (0.104)	0.068	0.0023	0.0042
EEX	0.469 (0.063)	0.030	0.0032	0.3029
CHN	1.127 (0.152)	0.062	0.00007	0.0239
IND	0.344 (0.046)	0.050	0.0015	0.0787
DAE	0.316 (0.043)	0.025	0.0047	0.3774
BRA	0.122 (0.016)	0.015	0.5612	8.4974
ROW	0.637 (0.086)	0.068	0.0021	0.0805
World	7.425 (1)	$\left(\sum\theta_i = 1\right)$		

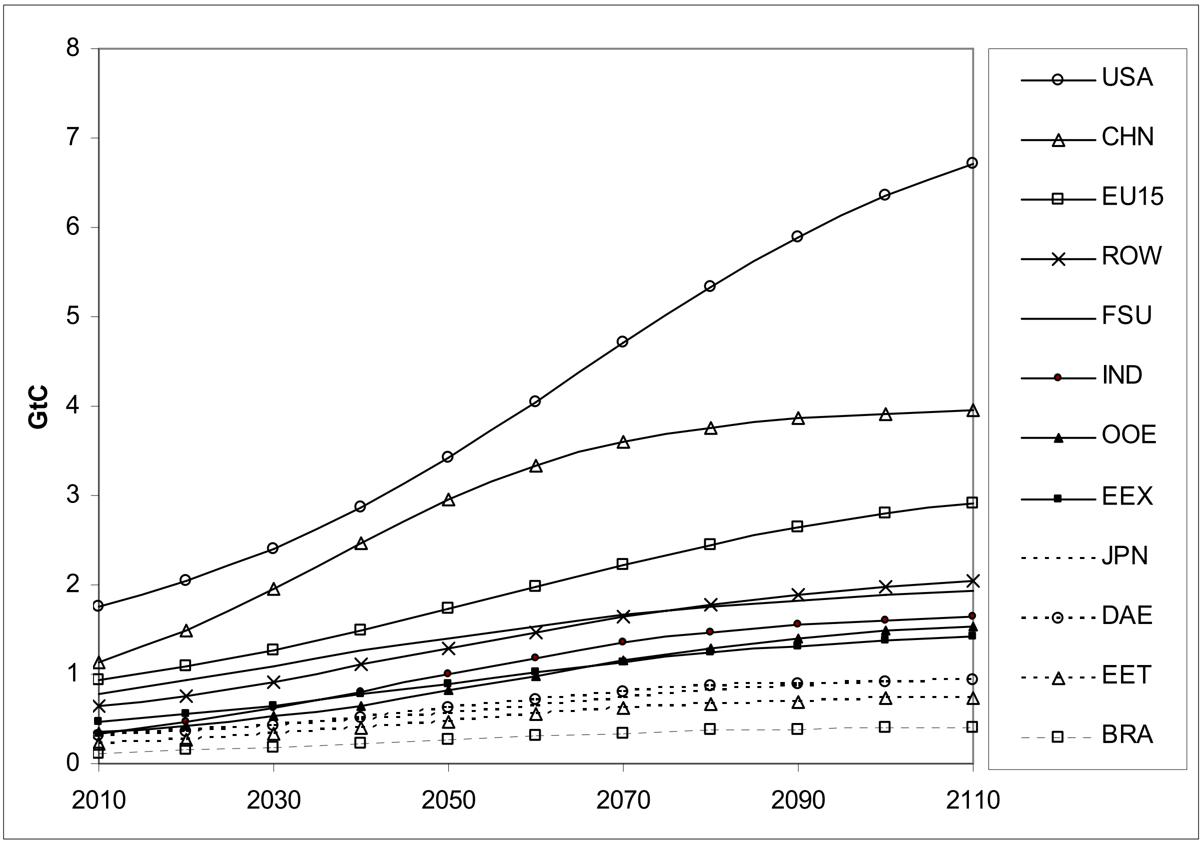

Figure 3A-1: Regional BAU emission paths

Source: Own calculations based on projections from the MIT-EPPA model (Paltsev et al., 2005)

Chapter 4

Technology spillovers and stability of international climate coalitions*

Cooperation in international environmental agreements appears difficult to attain because of strong free-rider incentives. This paper explores how different technology spillover mechanisms among regions can influence the incentives to join and stabilise an international agreement. We use an applied modelling framework (STACO) that enables us to investigate the stability of partial climate coalitions. Several theories on the impact of technology spillovers are evaluated by simulating a range of alternative specifications. We find that spillovers are a good instrument to increase the abatement efforts of coalitions and reduce the associated costs. In our setting, however, they cannot overcome the strong free-rider incentives that are present in larger coalitions, i.e. technology spillovers do not substantially increase the success of international environmental agreements. This conclusion is robust with respect to the specification of technology spillovers.

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4.1. Introduction

Successful CO_2 emission abatement requires international cooperation. However, full cooperation in the international environmental agreements (IEAs) seems to be difficult to achieve because of free-riding incentives. Game-theoretic approaches are widely used to explore the properties of IEAs. For example, Barrett (1994) proves that stable coalitions will achieve little if the difference between the non-cooperative outcome and the full-cooperative outcome for each region is large. In order to solve this problem, numerous studies examine the effects of institutional settings aimed to stimulate voluntary participation in the IEAs, for example, through transfers (e.g. Carraro and Siniscalco, 1993; Bloch, 1997; Hoel and Schneider, 1997; Weikard et al., 2006). A general observation from this literature is that rather inefficient partial coalitions tend to emerge and the coalition with all the members may not be attained. De Zeeuw (2008) widens the scope to a dynamic context and confirms that large stable coalitions can only emerge when the gains from cooperation are small. Thus, even with transfers, full cooperation on emission abatement is hard to establish.

The purpose of this paper is to systematically investigate how various technology spillover mechanisms affect the formation and stability of climate coalitions in a non-cooperative game. To do this, we use an integrated assessment model, STACO (Finus et al., 2006; Nagashima et al., 2009). We explore how technology spillovers that depend on the coalition that is formed influence the incentive structures to join the coalition. Moreover, we examine whether the effects of technology spillovers are large enough to stabilise more ambitious coalitions by offsetting the incentive to free-ride. We simulate several spillover mechanisms and specifications that are available in the literature to investigate the robustness of these links.

The paper is organised as follows. The remainder of this section sketches the main insights from the literature on technology cooperation and coalition formation. Section 4.2 provides the game-theoretic and empirical framework of the STACO model, and introduces technology spillovers in the model. Section 4.3 reports the main results with technology spillovers, followed by an analysis of the impact of the level and direction of spillovers between coalition members and to outsiders in Section 4.4. Section 4.5 provides an analysis of alternative specifications of technology, and Section 4.6 concludes. The Appendix provides the model parameter values.

4.1.1 Technology and coalition formation

It has been commonly recognised that technological change plays a significant role in controlling climate change costs. In traditional neoclassical models, technological change is determined exogenously, where it increases factor productivity (e.g. for analytical studies, Arrow et al., 1961; Kennedy, 1962; Uzawa, 1965, and for empirical studies, Peck and Teisberg, 1994; Nordhaus, 1994;

Nordhaus and Yang, 1996). New growth theory places more emphasis on the endogenous role of technology and its positive externalities that drive economic growth (Romer, 1990; Griliches, 1992; Grossman and Helpman, 1994). Endogenous technological change can be measured in different ways (see Weyant and Olavson, 1999 and Löschel, 2002 for excellent surveys in the domain of climate change modelling). Löschel (2002) and Clarke et al. (2008) present three main factors in endogenous technological change models: (i) research and development (R&D) investment, (ii) technology spillovers (between countries, industries or firms) and (iii) learning-by-doing.

In this paper, we focus on the role of technology spillovers between countries (cf. Coe and Helpman, 1995) for the success of international climate agreements. As our framework is a cost-benefit analysis of climate policy, technology spillovers are not derived from R&D investment, but they are treated as factors that lead to cost reductions stemming from the level of knowledge in other regions.[1] In short, technology spillovers depend on the 'state of technology' to reduce greenhouse gas emissions.

In the domain of coalition formation, a number of studies have proposed to link the agreements on emissions abatement with technological cooperation. The main idea of this mechanism is that each region negotiates not only on emissions abatement but also negotiates on technological cooperation, which might induce regions to join a coalition. For example, Carraro and Siniscalco (1994), Cesar and De Zeeuw (1996) and Barrett (2003) indicate that linkage of the IEAs on climate control and technological cooperation may stabilise an IEA, as payoffs of signatories will increase due to increased technological spillovers from other signatories. Carraro and Siniscalco (1997) show that linkage of the environmental agreement with an agreement on technological cooperation may overcome free-riding problems due to the fact that the negotiation on both climate control and technology is more profitable to signatories when benefits from technological cooperation are exclusive to them than the negotiation on climate control only. Tol et al. (2000, 2001) investigate the diffusion of abatement technology and argue that when diffusion can be restricted to coalition members, this may reduce free-rider incentives, although countries prefer to cooperate only on technology and not on abatement. Kemfert (2004) shows in an applied coalition formation game with four regions that signatories can profit more when they cooperate on emissions abatement and technological innovation than in the case of non-cooperation. Furthermore, there exist incentives for non-cooperating countries, such as U.S.A., to join an agreement in which countries cooperate both on emission abatement and technological innovations, because they can obtain technology spillovers, which improve energy efficiency through trade in goods with signatories; international trade effects are further investigated in Kemfert et al. (2004).

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[1]Growth theory considers spillovers as positive externalities, while innovation theory does not. For a detailed discussion, see Weyant and Olavson (1999).

Buonanno et al. (2003) define the international spillovers of knowledge generated by a stock of world knowledge. In their setting, international knowledge spillovers affect both the production function and the emission to output ratio. Golombek and Hoel (2005) assume that the technology level of the region depends on own investments in R&D and R&D investment in other countries (signatories) using a certain rate of technology diffusion, and R&D activities in cooperating countries will lower abatement costs in non-cooperating countries due to technology diffusion. Bosetti et al. (2009) have recently taken up this issue in an applied setting, using the multi-regional endogenous growth model WITCH.

Buchner and Carraro (2005a, 2005b, 2006) explore the interactions between technology and coalition formation using the FEEM-RICE model. While their analysis touches upon the same topic as ours, they focus on a subset of possible coalitions and investigate stability issues only for those. This means that they cannot show the general implications of technology spillovers on coalition formation nor address which regions will participate in the most ambitious stable coalitions.

Most existing models assume that the level of environmental technology can be approximated by looking at the emission intensity of production, that knowledge can be aggregated over regions through summation and that spillovers have the effect of pivoting the marginal abatement cost (MAC) curve down. Recent literature suggests, however, that a ‘best-shot’ aggregation of technology may be more appropriate (Sandler, 2006). Furthermore, alternative indicators of technology, based on for example energy intensity or carbon intensity, are also found in the applied literature (e.g. Kemfert, 2004). Finally, Baker et al. (2008) and Bauman et al. (2008) challenge the conventional specification that spillovers (or learning, for that matter) pivot down the MAC curves. Baker et al. (2008) suggest two alternatives: an extension of the MAC curve to the right, and a change in the curvature of the MAC curve.

The general insight that emerges from these studies is that there are a number of different channels through which technology spillovers may affect the payoffs of regions and thus the incentives to cooperate: (i) global spillovers from a ‘world stock of knowledge’, (ii) spillovers that are directly derived from participation in the agreement (coalitional spillovers) and (iii) spillovers to outsiders. Furthermore, technology spillovers can be specified in different ways, depending on the answer to the essential questions of how to measure technology and how to specify the effects of spillovers on the MAC curve.

What all these studies lack, however, is a systematic analysis of the influence of technology spillovers on the stability of international climate agreements with heterogeneous players in an applied setting. Moreover, these studies do not shed light on the influence of the relative magnitude of spillovers between coalition members versus spillovers to outsiders, which can be a significant element for the success of climate coalitions.

4.2. The stability of coalitions model (STACO)

4.2.1. Game-theoretic background

In this section, we describe the game-theoretic model. Our analysis uses a two-stage, one shot game. In the first stage, regions denoted by $i \in N$, $N = \{1,...,n\}$ decide whether they sign the agreement or not. Signatories form a coalition and non-signatories remain singletons in the second stage of the game. Then, all regions simultaneously determine their emission abatement levels. The payoff for each region π_i is a function of regional benefits B_{it} and regional abatement costs AC_{it} at period t . Formally, we have:

$$\pi_i(\mathbf{q}) = \sum_{t=1}^{\infty} \left\{ (1+r)^{-t} \cdot (B_{it}(q_1,...,q_t) - AC_{it}(q_{it})) \right\} \tag{4.1}$$

where $\mathbf{q}$ is an abatement matrix of dimension $N \times \infty$, and r is the discount rate. The payoff is calculated as the net present value (NPV) of the stream of net benefits. We assume that the regional benefits depend on past and current global emission abatement, and the regional abatement costs depend on a region's own current abatement. The regional abatement levels are determined within the abatement strategy space $q_{it} \in [0, \bar{e}_{it}]$, where $\bar{e}_{it}$ denotes emission levels in the business-as-usual (BAU) scenario.

We apply the solution concept of a partial agreement Nash equilibrium between the signatories and singletons (Chander and Tulkens, 1995, 1997). We assume that signatories determine their abatement level by maximising the sum of the payoffs of the signatories taking the abatement levels of non-signatories as given. Non-signatories 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 Section 4.2.2).

We apply the optimal sharing rule developed by Carraro et al. (2006) and Weikard (2009). Optimal sharing requires that each signatory obtains at least the payoff that can be secured when it deviates from coalition K . This is called the outside option payoff. In addition, the residual is distributed in proportion to the outside option payoffs[2]. Weikard (2009) shows that surplus sharing according to outside option payoffs internally stabilises all coalitions that are possibly stable under any sharing rule. That is, if the coalition payoff is distributed in such a way that each member gets at least its outside-

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[2] The residual can be shared by each coalition member in any way desired, because it does not affect internal stability as long as these shares are non-negative.

option payoff, then no region has incentives to leave the coalition. Hence, the coalition is internally stable whenever the coalition payoff (weakly) exceeds the sum of the outside option payoffs.

We refer to the situations where none or one of the regions joins a coalition as 'All Singletons', and a coalition where all regions cooperate as 'Grand Coalition'. Following d'Aspremont et al. (1983), we call a coalition K stable if the coalition satisfies both internal and external stability. Internal stability of a coalition means that no signatory has an incentive to withdraw from the coalition. External stability of a coalition means that no singleton has an incentive to join the coalition.

4.2.2. The STACO model

In this section, we present the main issues in the numerical specification of our model in a dynamic setting described in Nagashima et al. (2009), which is an extension of the original static STACO-1 model explained in Finus et al. (2006). We consider twelve world regions: USA (USA), Japan (JPN), European Union-15 (EU15), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and rest of the world (ROW). Payoffs from abatement are given as the NPV of benefits minus abatement costs over the model horizon. We set the model horizon to infinity to capture future benefits from abatement, while adopting a planning horizon for abatement and coalition formation of 100 years, ranging from 2011 to 2110. Calibration of the regional BAU emission paths,[3] represented in the Appendix 4A (Figure 4A-1), is based on the data for CO_2 emissions derived from the EPPA model (Babiker et al., 2001; Paltsev et al., 2005) and the GDP path is also derived from the EPPA model. Our benefit function is based on a linearised approximation of avoided damages, calculated by using the damage module of the DICE model (Nordhaus, 1994) and the climate module by Germain and van Steenberghe (2003). For global damages, we apply the estimate by Tol (1997) that damages amount to 2.7% of GDP for a doubling of concentrations over pre-industrial levels. Global benefits are allocated according to a fixed share for each region, as displayed in Appendix (Table 4A-2). We specify a regional abatement cost function based on the estimates of the EPPA model by Ellerman and Decaux (1998).

4.2.3. Technology spillovers

In our base model, we adopt the (common) assumption that technology spills over to region i in period t (ς_{it}) by reducing marginal abatement costs through pivoting of the MAC curve[4]:

[3] We use data from World Bank (2003) to match the regional aggregation in EPPA to STACO.

[4] We investigate alternative assumptions in Section 4.5.

$$MAC_{i,t+1} = (1-\varsigma_{i,t}) \cdot MAC_{i,t} \tag{4.2}$$

Or equivalently,

$$MAC_{i,t} \equiv \frac{\partial AC_{it}}{\partial q_{it}} = \alpha_i \cdot \left(\prod_{s=1}^{t-1} \left(1-\varsigma_{is}\right) \right) \cdot q_{it}^2 + \beta_i \cdot \left(\prod_{s=1}^{t-1} \left(1-\varsigma_{is}\right) \right) \cdot q_{it}, \tag{4.3}$$

where $\prod_{s=1}^{t-1} \left(1-\varsigma_{is}\right)$ reflects the product of technological spillovers until period *t*, and α and β are the abatement cost parameters in our base year 2010 .

The size of the technology spillover depends on which regions are member of the coalition. We assume that the spillovers will be higher when more regions are member of the coalition, and when regions with an advanced state of technology are member of the coalition, but the size of the spillover cannot be controlled by the coalition members, as their state of technology is exogenous. Spillovers to region j in period t (ς_{jt}) are expressed through a summation over all players of the regional spillover effect times the state of technology:

$$\varsigma_{jt} = \sum_{i=1}^{N} \xi_{ij} \cdot SoT_{it} \tag{4.4}$$

with $0 \le \xi_{ij} < 1$ the spillover effect from region *i* to region *j*. In different scenarios, the value of ξ_{ij} varies, depending on whether *i* and/or *j* are member of the coalition. Unfortunately, there is no strong empirical base to calibrate the values of ξ_{ij} . Therefore, we conduct a robustness analysis by changing the values of these spillover coefficients in Section 4.4.

The 'state of technology' (SoT) used in Eq. (4.4) is the inverse of the regional emission intensity in the reference path, calculated as the business-as-usual amount of CO_2 emission per unit of GDP.[5] The rationale for this definition is that regions that have low emission intensities have a high level of knowledge on GHG abatement strategies. To investigate the robustness of this definition, we compare some alternative definitions in Section 4.5. As we use the state of technology as an indicator of the level of knowledge, we refer to the emission intensity in the reference path and do not adjust for changes in the emission intensity due to abatement. This is because we interpret abatement primarily as a movement along the technology curve, i.e. adoption of existing knowledge, rather than a shift of the curve, i.e. creation of new knowledge. As for the state of technology, Table 4.1 shows that Japan

[5] We scale the SoTs such that global SoT equals 1 in 2110.

has the highest state of technology throughout the century, followed by EU15. On the other hand, U.S.A. and China have relatively low states of technology.

Table 4.1: State of technology based on emission intensity

Year	USA	JPN	EU15	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
2011	0.02	0.06	0.04	0.02	0.01	0.00	0.01	0.01	0.01	0.02	0.03	0.02
2060	0.05	0.12	0.08	0.04	0.01	0.01	0.03	0.02	0.02	0.05	0.07	0.04
2110	0.07	0.21	0.14	0.06	0.03	0.02	0.06	0.04	0.03	0.11	0.16	0.08

Note: The state of technology is based on the inverse of BAU emissions over GDP for each region (ton/US1000$) and we scale the state of technology such that the global state of technology equals 1 in 2110.

To investigate the role of spillovers on coalitional stability in a systematic manner, we investigate five scenarios, which differ with respect to the type of spillover between regions.

In the *first* or reference scenario, we consider coalition formation in the absence of technology spillovers, and do not assume any technological progress. We assume no technology spillovers among regions: $\xi_{ij} = 0$.

In the *second* scenario, we assume regional spillovers that depend only on the own state of technology, i.e. internal spillovers. Therefore, we have $\xi_{ii} = \overline{\xi^{own}} > 0$, $\xi_{ij} = 0 \; \forall j \neq i$. Although we have no solid empirical basis for the size of this internal spillover, we assume $\overline{\xi^{own}} = 0.01$. As the regional state of technology will always be smaller than unity, this implies technology spillovers of less than 1% per annum.

In the *third* scenario, we assume global spillovers, which mimics international spillovers of knowledge generated by 'the stock of world knowledge' as in Buonanno et al. (2003), although our model is much simpler and thus cannot capture the knowledge creation aspect. We rather focus on the link between technology spillovers and incentives to cooperate in an IEA. In this context, the essence of the global spillovers is that every region obtains technology spillovers, irrespective of membership of the coalition or not: $\xi_{ij} = \overline{\xi^{global}} > 0$. We assume that this global spillover replaces the internal spillover from scenario 2 ($\overline{\xi^{own}} = 0$). Assuming the same spillover rate, that is, $\overline{\xi^{global}} = 0.01$, leads to technological progress slowly increasing over the century to 1% per annum.

In the *fourth* scenario, in addition to the global spillovers, signatories to the climate agreement gain spillovers from the other coalition members (cf. the 'coalition information exchange parameter' in Carraro and Siniscalco, 1997); this scenario also refers to the mechanism in Kemfert (2004) that participants cooperate on technological innovation. With coalitional spillovers, in addition to global spillovers, signatories can obtain higher spillovers from other signatories, that is,

$$\begin{cases} \xi_{ij} = \overline{\xi^{C}} + \overline{\xi^{global}} > 0 \ \forall i, j \in K; \\ \xi_{ij} = \overline{\xi^{global}} > 0 \qquad else. \end{cases}$$

We calibrate coalitional spillovers to $\overline{\xi^{C}}$ =0.005 and still $\overline{\xi^{global}}$ =0.01.

This scenario is expected to provide a stimulus for regions to join a coalition, as membership brings technology benefits, although the effect is assumed to be moderate, as it is on top of the global spillover effect.

In the *fifth* scenario, following Golombek and Hoel (2005), we consider all possible technology spillovers, i.e., we extend the mechanism of the third scenario with spillovers to singletons (which we label 'extended spillovers'). In this setting, not only signatories benefit from internal coalition spillovers, but also singletons can obtain spillovers from signatories, that is

$$\begin{cases} \xi_{ij} = \overline{\xi^{C}} + \overline{\xi^{global}} > 0 \ \forall i, j \in K; \\ \xi_{ij} = \overline{\xi^{NC}} + \overline{\xi^{global}} > 0 \ \forall i \in K; \forall j \notin K; \\ \xi_{ij} = \overline{\xi^{global}} > 0 \qquad else, \end{cases}$$

where extended spillovers ($\overline{\xi^{NC}}$) equal 0.001 and still $\overline{\xi^{C}}$ =0.005 and $\overline{\xi^{global}}$ =0.01. In this case, we assume that a region can also benefit from its own contribution to the coalitional spillovers not as in the case of internal coalitional spillovers, and that outsiders can get some ratio of spillovers from the coalition. Following Carraro and Siniscalco (1997), we assume that the diffusion rate among coalitions is larger than the one towards outsiders.

4.3. Results

As we cannot properly estimate the values of different ξ, our analysis of the results focuses on the impact of varying levels of spillovers on stability of climate coalitions (Section 4.4), and a comparison of different specifications (Section 4.5). Nonetheless, it is instructive to start with an analysis of the stability for all 4,084 coalition structures for the five scenarios.

In order to improve comparison of the results across scenarios, we need normalisation as larger technology spillovers imply larger NPV of payoffs (through lower abatement costs). We calculate the percentage of the gap between Grand Coalition and All Singletons that is closed by a coalition, which can be interpreted as a normalised indicator of success of the coalition.[6] Table 4.2 shows the best-performing stable coalitions in all scenarios of technology spillovers, the associated NPV of global payoffs in billion dollars and the associated indicator of success. We obtain 185 stable coalitions in the cases of no spillovers and internal spillovers, and 182 stable coalitions in the case of global spillovers. Clearly, global spillovers lead to higher absolute payoffs than no spillovers and internal spillovers for any given coalition structure. While marginal abatement costs are lower and payoffs are higher in the presence of technology spillovers, the incentives to join or leave a coalition are not significantly influenced. The best performing coalition, in terms of global payoff and indicator of success, is formed by the USA, EET, CHN, IND and DAE. While absolute payoffs increase with global spillovers, the indicator of success remains virtually unchanged: the spillovers affect all coalitions and also the gap between Grand Coalition and All Singletons. As the incentives to change membership depend on a comparison of different coalitions, the absolute values are much less important than the relative differences. The indicator of success shows that these relative differences hardly change, which implies that the incentives to change membership hardly change. A first conclusion can therefore be that internal and global technology spillovers are not successful instruments to enhance the stability of climate coalitions.

Under coalitional spillovers, where coalition members benefit from partners through technology spillovers, we have 193 stable coalitions. There are two mechanisms at work here. First, the indicator of success for any given coalition is lower than in the case of no, internal and global spillovers (although absolute payoffs are higher). This is due to the fact that the rate of technology spillovers depends on the coalition formation and these spillovers work best in the Grand Coalition, i.e. they increase the gap between the Grand Coalition and All Singletons. Secondly, new coalitions stabilise that are more ambitious; in this case, the coalition of USA, EET, EEX, CHN and IND. That these two mechanisms counteract each other is confirmed by the small decrease in the average indicator of success.

In the case of extended spillovers, global payoffs and the associated indicator of success are slightly higher than in the case of coalitional spillovers. The reason is that the spillovers to outsiders are not reflected in the Grand Coalition; therefore, the gap between the NPV of global payoffs in Grand Coalition and in All Singletons is the same for coalitional spillovers and extended spillovers, while the NPV of global payoffs for any given coalition is larger in the case of extended spillovers as singletons can benefit from the spillovers generated by the coalition members. In our setting, however, the extended spillovers are not sufficiently strong to substantially alter the set of stable coalitions. We will investigate this finding in more detail in Section 4.4.

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[6] The indicator of success for a coalition is calculated as the difference between the NPV of global payoff when a coalition is formed and in All Singletons divided by the difference between the NPV of global payoff in the Grand Coalition and in All Singletons.

Table 4.2: NPV of global payoffs in the selected stable coalitions

Coalition	No spillovers		Internal spillovers		Global spillovers		Coalitional spillovers		Extended spillovers	
	Indicator of success (%)	NPV of global payoff (billion $)	Indicator of success (%)	NPV of global payoff (billion $)	Indicator of success (%)	NPV of global payoff (billion $)	Indicator of success (%)	NPV of global payoff (billion $)	Indicator of success (%)	NPV of global payoff (billion $)
[USA, EET, CHN, IND, DAE]	46.0	8590 (1)	45.9	8645 (1)	46.0	9655 (1)	43.4	9783 (2)	43.4	9789 (2)
[EU15, EET, EEX, CHN, IND]	45.8	8571 (2)	45.7	8624 (2)	45.8	9635 (2)	43.2	9761 (3)	43.2	9769 (3)
[EU15, OOE, EET, CHN, IND]	44.8	8486 (3)	44.7	8538 (3)	44.8	9530 (3)	42.2	9662 (5)	42.3	9671 (5)
[EU15, EET, CHN, IND, DAE]	44.6	8472 (4)	44.6	8526 (4)	44.7	9525 (4)	42.3	9665 (4)	42.3	9675 (4)
[USA, EET, EEX, CHN, DAE, BRA]	43.7	8386 (5)	43.6	8442 (5)	43.8	9440 (5)	42.0	9639 (7)	42.1	9650 (7)
[USA, EET, EEX, CHN, IND]	NS		NS		NS		44.3	9882 (1)	44.3	9886 (1)
Total number of stable coalitions	185		185		182		193		195	
Indicator of success (average %)	21.1		21.1		21.1		21.0		21.3	

Note: The number in the bracket shows ranking in terms of NPV of global payoff. NS denotes 'not stable coalition'

Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

Indicator of success (average %): ((Average NPV of global payoffs in all stable coalitions – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

In the coalitional and extended spillover scenarios, the number of stable coalition increases and new stable coalition between USA, EET, EEX, CHN, and IND emerges, which ranks first. That the stable coalition consisting of six regions between USA, EET, EEX, CHN, DAE, BRA does not rank in the top five shows that the size of the coalition does not necessarily dictate the ambitious level of the coalition: in the setting with heterogeneous regions, a smaller coalition of 'key players' may be more successful than a large coalition.

For these five scenarios, we can conclude that only moderately small stable coalitions emerge, which close the gap between the Grand Coalition and All Singletons by less than 50%. Furthermore, while coalitional spillovers do increase payoffs and stabilise somewhat more ambitious coalitions, they also increase the gap between Grand Coalition and All Singletons, making the indicator of success smaller.

In the fourth and fifth scenarios, the coalition is assumed to be able to control the technology spillovers, albeit only partially in the extended spillover case. This setting can be interpreted as a model in which the public good (abatement) is coupled with a club good (technological knowledge; for details on club goods, see Sandler and Tschirhart, 1997). The provision of the public good is affected by the presence of the club good. In our setting, the coalition may be able to control which regions share in the club good, but it does not deliberately choose the level of provision of the club good: it is not an independent choice variable. This is due to our assumption that spillovers are linked to the exogenous state of technology of the coalition members. Thus, the public good game does not affect the provision of the club good for any given coalition. Still, the model does of course capture the effect that when more regions join the coalition, both the level of abatement (the public good) and the level of technology spillovers (the club good) increase.

4.4. Disentangling the impact of coalitional spillovers

As shown in the previous section, coalition spillovers can enhance stability to some extent, although the indicator of success is lower than in the other scenarios. To understand the main elements which stabilise the coalition, we address the following questions: Does the magnitude of the technology spillovers created by the coalition (the 'level effect') matter? Does the relative rate of the coalitional spillovers between the coalition members and outsiders (the 'asymmetry effect') influence the success of climate coalitions? In order to explore the main driving forces, we explore these two questions by varying the *level* of coalitional and extended spillovers in Section 4.4.1 and by varying the *ratio* between coalitional and extended spillovers in Section 4.4.2. We consider the case of extended spillovers examined in Section 4.3 as the 'base case' in the following sections.

4.4.1. Analysis of the impact of the level effect

In the first analysis, we explore the level effect on the stability of coalitions by increasing the magnitude of the coefficient of coalitional and extended technology spillovers. We examine the stability of all coalitions using different values of coalitional spillovers to coalitional members ($\overline{\xi^C}$) and to outsiders ($\overline{\xi^{NC}}$), moving from 0.005 to 0.05 for coalition members and from 0.001 to 0.01 for outsiders in five steps, while the ratio of the coalitional spillovers to coalitional members over spillovers to outsiders remains the same.

The results of these calculations are summarised in Table 4.3, which shows the NPV of global payoffs and associated indicator of success for the best-performing stable coalitions.

Table 4.3: NPV of global payoffs in the selected stable coalitions for the analysis of level effects

	$\overline{\xi^C}$ / $\overline{\xi^{NC}}$					
Coalition	Base case	0.01/0.002	0.02/0.004	0.03/0.006	0.04/0.008	0.05/0.01
USA, EET, EEX, CHN, IND	**9886 (44.3)**	**10004 (41.6)**	10247 (36.7)	NS	NS	NS
USA, EET, CHN, IND, DAE	**9789 (43.4)**	9926 (40.9)	10209 (36.4)	NS	NS	NS
EU15, EET, EEX, CHN, IND	**9769 (43.2)**	9906 (40.8)	NS	NS	NS	NS
EU15, EET, CHN, IND, DAE, BRA	NS	**10112 (42.5)**	**10593 (39.1)**	11114 (36.1)	11678 (33.5)	NS
EU15, EEX, CHN, IND, DAE	NS	**10065 (42.1)**	10430 (38.0)	NS	NS	NS
EU15, EET, EEX, CHN, IND, BRA	NS	NS	**10634 (39.4)**	11110 (36.0)	11624 (33.2)	NS
EU15, OOE, EET, EEX, CHN, DAE	NS	NS	**10604 (39.2)**	11080 (35.9)	NS	NS
EU15, EEX, CHN, IND, DAE, BRA	NS	NS	NS	**11469 (38.2)**	12103 (35.7)	NS
USA, EU15, EET, CHN, BRA	NS	NS	NS	**11380 (37.7)**	11947 (34.9)	NS
EU15, EET, CHN, DAE, BRA, ROW	NS	NS	NS	**11228 (36.8)**	11861 (34.4)	12555 (32.5)
JPN, EU15, EET, CHN, DAE, BRA	NS	NS	NS	NS	**12751 (39.0)**	13741 (37.7)
EU15, OOE, EET, EEX, CHN, DAE, BRA	NS	NS	NS	NS	**12495 (37.7)**	13324 (35.9)
USA, EU15, CHN, DAE, BRA	NS	NS	NS	NS	**12438 (37.4)**	NS
JPN, EU15, EEX, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14294 (40.1)**
JPN, EU15, OOE, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14173 (39.6)**
USA, EU15, EET, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14140 (39.4)**
Total number of stable coalitions	195	203	233	250	274	267
Indicator of success (average %)	21.3	21.1	21.1	21.6	22.0	23.6

Note: NS denotes 'not stable coalition'. The numbers in bold show three best-performing stable coalitions in terms of NPV of global payoffs (billion US$)
The number in bracket denotes indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100
Indicator of success (average %): ((Average NPV of global payoffs in all stable coalitions – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

The results show that the best-performing stable coalitions substantially change with the magnitude of spillovers. It is likely that Brazil and Japan, who have higher marginal abatement costs, have incentives to join the coalition as spillovers increase. For example, the coalition of EU15, EET, CHN, IND and DAE, which ranks fourth in the base case model (in the last column of Table 4.2), is not stable anymore as spillovers increase, whereas these regions complemented by Brazil form a new stable coalition. In line with the analysis in Section 4.3, the indicator of success for each stable coalition decreases with higher spillovers, as is clearly shown in Table 4.3. Higher spillovers imply higher global payoffs in the Grand Coalition, while the global payoff in the All Singletons remains the same across all spillover levels. This difference is so large that the indicator of success decreases substantially with increasing spillovers for a given stable coalition. The conclusion can be drawn that larger spillovers tend to increase the size of stable coalition (up to seven members), and largely change the structure of the stable coalitions, but the level effect may not have large effects on the indicator of success.

4.4.2. Analysis of the impact of the asymmetry effect

In the second analysis, we focus on the effects of the relative rate of the coalitional spillovers between the coalition members in comparison to spillovers to outsiders on the stability of coalitions. We explore this asymmetry effect in two ways. First, we increase the coefficient of coalitional spillovers to outsiders in four steps while keeping those to coalition members the same as in the base case. Second, we increase the coefficient of coalitional spillovers to coalition members while those to outsiders remain the same. We suspect that larger asymmetry between technology spillovers among signatories versus outsiders may enhance larger stable coalitions. The larger spillovers induce signatories to stay in the coalition, and thus additional internally stable coalitions are expected to emerge. The large coalitional spillovers attract potential new entrants because coalition members can get higher benefits from increased abatement by reducing emissions at lower costs than in the base model.

Table 4.4(a) shows the results of the asymmetry effects when the coefficient of coalitional spillovers to outsiders increases. The results suggest that the four best-performing stable coalitions remain the same, regardless of the level of extended spillovers. Thus, while the numbers change slightly, the Table clearly shows that the asymmetry effect is of little importance for the stability of climate coalitions.[7]

[7] This conclusion may not hold for much larger values of the extended spillovers, but we feel that much higher values would not be realistic.

Table 4.4(a): NPV of global payoffs in the selected stable coalitions for the analysis of asymmetry effects

Coalition	$\overline{\xi^{C}}$ / $\overline{\xi^{NC}}$				
	Base case	0.005/0.002	0.005/0.003	0.005/0.004	0.005/0.005
USA, EET, EEX, CHN, IND	**9886 (44.3)**	**9891 (44.4)**	**9896 (44.4)**	**9901 (44.5)**	**9906 (44.5)**
USA, EET, CHN, IND, DAE	**9789 (43.4)**	**9795 (43.5)**	**9800 (43.5)**	**9806 (43.6)**	**9812 (43.6)**
EU15, EET, EEX, CHN, IND	**9769 (43.2)**	**9778 (43.3)**	**9786 (43.4)**	**9795 (43.5)**	**9804 (43.6)**
EU15, EET, CHN, IND, DAE	**9675 (42.3)**	**9685 (42.4)**	**9695 (42.5)**	**9705 (42.6)**	**9715 (42.7)**
EU15, OOE, EET, CHN, IND	**9671 (42.3)**	**9680 (42.4)**	**9690 (42.5)**	9699 (42.6)	9709 (42.7)
EU15, EET, CHN, DAE, ROW	9655 (42.2)	9677 (42.4)	9689 (42.5)	**9700 (42.6)**	**9712 (42.7)**
Total number of stable coalitions	195	194	201	200	204
Indicator of success (average %)	21.3	21.7	21.6	21.9	22.1

Note: The numbers in bold rank in top five in terms of NPV of global payoff (billion US$)
The number in bracket denotes indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100
Indicator of success (average %): ((Average NPV of global payoffs in all stable coalitions – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

Table 4.4(b): NPV of global payoffs in the selected stable coalitions for the analysis of asymmetry effects

Coalition	$\overline{\xi^{C}}$ / $\overline{\xi^{NC}}$					
	Base case	0.01/0.001	0.02/0.001	0.03/0.001	0.04/0.001	0.05/0.001
USA, EET, EEX, CHN, IND	**9886 (44.3)**	**10000 (41.6)**	10233 (36.6)	NS	NS	NS
USA, EET, CHN, IND, DAE	**9789 (43.4)**	**9920 (40.9)**	NS	NS	NS	NS
EU15, EET, EEX, CHN, IND	**9769 (43.2)**	9898 (40.7)	NS	NS	NS	NS
USA, OOE, EET, CHN, IND	NS	**9919 (40.9)**	10170 (36.1)	10432 (32.0)	NS	NS
USA, EET, CHN, IND, DAE, BRA	NS	NS	**10663 (39.6)**	11129 (36.2)	11631 (33.3)	12172 (30.8)
EU15, EET, EEX, CHN, IND, BRA	NS	NS	**10595 (39.2)**	11046 (35.7)	11532 (32.7)	NS
EU15, OOE, EET, EEX, CHN, DAE	NS	NS	**10563 (38.9)**	11011 (35.4)	NS	NS
EU15, EEX, CHN, IND, DAE, BRA	NS	NS	NS	**11469 (38.2)**	11998 (35.1)	NS
USA, EU15, EET, CHN, BRA	NS	NS	NS	**11380 (37.7)**	11885 (34.6)	NS
EU15, EET, EEX, CHN, BRA, ROW	NS	NS	NS	**11153 (36.3)**	11703 (33.6)	12304 (31.4)
USA, EU15, CHN, DAE, BRA	NS	NS	NS	NS	**12367 (37.0)**	NS
EU15, OOE, EET, EEX, CHN, DAE, BRA	NS	NS	NS	NS	**12365 (37.0)**	13156 (35.1)
USA, EU15, EEX, CHN, BRA	NS	NS	NS	NS	**12294 (36.6)**	12966 (34.3)
USA, JPN, OOE, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14304 (40.2)**
JPN, EU15, EEX, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14082 (39.2)**
USA, EU15, EET, CHN, DAE, BRA	NS	NS	NS	NS	NS	**14048 (39.0)**
Total number of stable coalitions	195	199	225	245	272	261
Indicator of success (average %)	21.3	21.0	20.6	20.6	21.1	22.3

Note: NS denotes 'not stable coalition'. The numbers in bold show three best-performing stable coalitions in terms of NPV of global payoff (billion US$)
The number in bracket denotes indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100
Indicator of success (average %): ((Average NPV of global payoffs in all stable coalitions – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

Table 4.4(b) presents the results of the asymmetry effect when the coalitional spillovers increase, keeping the extended spillovers constant (thereby making the wedge between both larger). The Table largely combines the insights from Tables 4.3 and 4.4(a): the level effect dominates the asymmetry effect, and thus, Table 4.4(b) looks very similar to Table 4.3. While the level effect does stabilise larger (although not necessarily more ambitious) coalitions, as it increases the gap between Grand Coalition and All Singletons, the indicator of success does not increase with increasing spillovers. Again, we can draw the conclusion that the asymmetry effect is of minor importance. The main explanation for the limited importance of the asymmetry effect is that for the stability of climate coalitions, internal stability (i.e. no coalition member wants to leave the coalition) is a much more important condition than external stability (i.e. no outsider wants to join the coalition): increasing coalitional spillovers can be associated with increasing the internal stability (to some extent at the expense of weakening external stability), as they increase the surplus generated by the coalition. Spillovers to outsiders have a more complicated impact, as they increase the incentives to free-ride (and thus increase external stability and reduce internal stability), but they also imply higher global abatement levels and thus increase payoffs for coalition members as well. Furthermore, if an outsider decides to join the coalition, its membership will increase the technology spillovers created by the enlarged coalition, again leading to higher benefits for the region itself and for other regions. Consequently, these effects mitigate each other and the result emerges that increasing spillovers to outsiders does increase abatement levels and payoffs but does not stabilise larger coalitions.

4.5. Alternative specifications and sensitivity analysis

In order to investigate the robustness of our results, we simulate various alternative specifications of technology spillovers by (i) varying the aggregation of technology, (ii) using different indicators for the state of technology, and (iii) changing the impact of spillovers on the MAC curve. In addition, as we believe that a crucial parameter in the model is the discount rate r, this is subjected to a sensitivity analysis. For ease of comparison, we use the base model with extended spillovers as the reference case. Table 4.5(a) presents the results of the alternative specifications and the sensitivity analysis on the discount rate; these results will be discussed in the next sections.

Table 4.5(a): Sensitivity analysis (using extended spillovers)

Coalition	Base case	Best-shot	Alternative state of technology		Alternative effect on MAC		Discount rate 1%	Discount rate 3%
			Energy intensity	Carbon intensity	Extend to right	Change curvature		
USA, EET, EEX, CHN, IND	**9886** **(44.3)**	**9665** **(45.5)**	**9914** **(44.6)**	**11906** **(42.0)**	**9501** **(44.9)**	NS	**38774** **(44.0)**	**3562** **(44.6)**
USA, EET, CHN, IND, DAE	**9789** **(43.4)**	**9553** **(44.4)**	**9785** **(43.4)**	**11898** **(41.9)**	**9400** **(43.9)**	**8799** **(45.9)**	**38414** **(43.2)**	**3525** **(43.7)**
EU15, EET, EEX, CHN, IND	**9769** **(43.2)**	**9653** **(45.4)**	**9781** **(43.4)**	11740 (40.8)	**9374** **(43.6)**	**8783** **(45.7)**	**38355** **(43.0)**	**3516** **(43.4)**
EU15, EET, CHN, IND, DAE	**9675** **(42.3)**	**9526** **(44.2)**	**9657** **(42.2)**	NS	**9277** **(42.7)**	**8685** **(44.6)**	**38005** **(42.2)**	**3480** **(42.5)**
EU15, OOE, EET, CHN, IND	**9671** **(42.3)**	**9541** **(44.3)**	**9680** **(42.4)**	11609 (39.8)	**9301** **(42.9)**	**8680** **(44.6)**	37879 (41.9)	**3489** **(42.8)**
USA, EET, EEX, CHN, DAE, BRA	9650 (42.1)	9409 (43.0)	9645 (42.1)	11778 (41.0)	9209 (42.0)	**8625** **(43.9)**	**38056** **(42.3)**	3458 (42.0)
EU15, EET, CHN, IND, DAE, BRA	NS	NS	NS	**12035** **(42.9)**	NS	NS	NS	NS
EU15, EEX, CHN, IND, DAE	NS	NS	NS	**11982** **(42.5)**	NS	NS	NS	NS
USA, EET, CHN, DAE, ROW	NS	NS	NS	**11911** **(42.0)**	NS	NS	NS	NS
Total number of stable coalitions	195	200	194	201	188	184	194	190
Indicator of success (average %)	21.3	21.1	21.1	21.0	21.0	21.6	21.5	21.2

Note: NS denotes 'not stable coalition'. The numbers in bold rank in top five in terms of NPV of global payoff (billion US$)
The number in bracket denotes indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100
Indicator of success (average %): ((Average NPV of global payoffs in all stable coalitions – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

4.5.1. Alternative aggregation of technology

In the simulations above, the assumption is that knowledge ('state of technology' in our terminology) can be summed over regions to identify the size of the spillovers. According to Sandler (2006), however, 'Knowledge is the quintessential best-shot or better shot public good, where breakthroughs come from concentrating effort and building up research centers of excellence'. Therefore, we can construct an alternative spillover formulation where we follow Sandler's definition and define spillovers through a best-shot aggregation of technology. The implication of the best-shot aggregation (Hirshleifer, 1983; Sandler, 2006) is that the technology spillovers depend on the maximum state of technology in a coalition, rather than the sum of technologies. In the field of GHG abatement technologies, the rationale for the best-shot aggregation is that the technologies that regions have to reduce emissions will have substantial (or even full) overlap with the technologies in other regions. Consequently, the region with the highest state of technology will not learn from others. In this section, we explore the effects of best-shot aggregation on the stability of coalitions under the internal and extended coalitional spillovers. To reflect a region's capability of adopting advanced technology, we modify the spillover specification in Eq. (4.4) such that the spillover depends on the difference between the highest state of technology and the region's own state of technology. Hence, the spillovers[8] can be defined as follows:

$$\begin{cases} \varsigma_{it} = \overline{\xi^{C}} \cdot \left\{ \max\limits_{j \in K}(SoT_{j,t}) - SoT_{i,t} \right\} + \overline{\xi^{global}} \cdot \left\{ \max\limits_{j \in N}(SoT_{j,t}) - SoT_{i,t} \right\} \ \forall i \in K; \\ \varsigma_{it} = \overline{\xi^{NC}} \cdot \left\{ \max\limits_{j \in K}(SoT_{j,t}) - SoT_{i,t} \right\} + \overline{\xi^{global}} \cdot \left\{ \max\limits_{j \in N}(SoT_{j,t}) - SoT_{i,t} \right\} \ \forall i \notin K. \end{cases} \tag{4.5}$$

The 'Best-shot' column in Table 4.5 (a) shows the NPV of global payoffs for the best-performing stable coalitions with the best-shot technology aggregation (assuming extended coalitional spillovers). We can observe that the five best-performing stable coalitions remain the same but the indicators of success for these coalitions are slightly higher than in the base model, which can be explained by the fact that the level of spillovers is somewhat smaller than in our base case. The results suggest that the aggregation method does not change the qualitative outcomes of the analysis.

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[8] All spillover coefficients are unchanged, and in the best-shot aggregation, we rescale the SoTs such that the maximum SoT equals 1 in 2110.

4.5.2. Alternative indicators for state of technology

In this section, we consider alternative indicators for state of technology, using energy intensity or carbon intensity instead of emission intensity. Energy intensity is calculated as energy use[9] per unit of GDP, whereas carbon intensity is calculated as the amount of CO_2 emitted per unit of energy. Emission intensity is used among others by Carraro and Siniscalco (1997), while Kemfert (2004) uses energy intensity. The fourth and fifth columns in Table 4.5(a) show the best-performing stable coalitions with these alternative indicators of state of technology. With the state of technology based on energy intensity, we obtain the same five best-performing stable coalitions as in the base case. This is because the regional trends of energy intensity are similar to the trends of the emissions-output ratio. In contrast, with the state of technology based on carbon intensity, most of the stable coalitions are the same but additionally other stable coalitions emerge. In our model, emission and energy intensities decrease over time, but this is not the case with carbon intensity. This shows that while emission intensity and energy intensity are more or less interchangeable as an indicator of the state of technology in addressing climate change, carbon intensity is a very different indicator, which leads to different stable coalitions.

4.5.3. Alternative levels of spillovers on the MAC curve

The effect of technology spillovers (and learning) on the shape of the marginal abatement cost (MAC) curve is hardly ever subjected to a thorough analysis, even though suspicion of the effect of technical change on marginal abatement costs was already put forward more than 20 years ago by Downing and White (1986). Recently, two papers emerged, Baker et al. (2008) and Bauman et al. (2008), which challenge the conventional assumption that technological change will pivot the MAC curve down. Bauman et al. (2008) take up the argumentation of Downing and White (1986) and show that in certain circumstances, technological change may even increase marginal abatement costs. Baker et al. (2008) review the literature and derive that different technology options will have a different impact on marginal abatement costs. Following Baker et al. (2008), we adopt two alternatives to our base model: (i) technology spillovers will extend the MAC curve to the right, and (ii) technology spillovers will affect the curvature of the MAC curve.

In model terms, this implies that we separate the effects of the spillovers on the two parts of our MAC function (Eq. (4.3) in Section 4.2.3). In the base case, a spillover will reduce both parameters α and β. We approximate an extension of the curve to the right as a spillover effect that will only affect parameter α (to the same extent as in the base model), leaving parameter β unchanged. This implies that the initial slope of the MAC curve is unchanged, but the curvature is reduced. In the alternative

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[9] The trajectory of final energy is based on the EPPA model (Paltsev et al., 2005).

with a changed curvature, we assume that technology spillovers will reduce the initial slope of the MAC curve, but increase the curvature (where we assume the effect is smaller but not insignificant). In mathematical notation, we have:

Base model:
$$MAC_{i,t} \equiv \frac{\partial AC_{it}}{\partial q_{it}} = \alpha_i \cdot \left(\prod_{s=1}^{t-1} \left(1 - \varsigma_{is}\right) \right) \cdot q_{it}^2 + \beta_i \cdot \left(\prod_{s=1}^{t-1} \left(1 - \varsigma_{is}\right) \right) \cdot q_{it} \qquad (4.3)$$

Extension:
$$MAC_{i,t} \equiv \frac{\partial AC_{it}}{\partial q_{it}} = \alpha_i \cdot \left(\prod_{s=1}^{t-1} \left(1 - \varsigma_{is}\right) \right) \cdot q_{it}^2 + \beta_i \cdot q_{it} \qquad (4.6)$$

Change curvature:
$$MAC_{i,t} \equiv \frac{\partial AC_{it}}{\partial q_{it}} = \alpha_i \cdot \left(\prod_{s=1}^{t-1} \left(1 + 0.1 \cdot \varsigma_{is}\right) \right) \cdot q_{it}^2 + \beta_i \cdot \left(\prod_{s=1}^{t-1} \left(1 - \varsigma_{is}\right) \right) \cdot q_{it} \qquad (4.7)$$

where Π denotes the product over time.

The main results of these alternative specifications can be found in the sixth and seventh columns of Table 4.5(a). In the alternative specifications, the total spillover effect is somewhat smaller than that in the base model (as the effect on β is missing, and the effect on α is reversed, respectively), and as expected, the indicator of success for each coalition is generally larger and the payoff smaller than in the base model. In the first alternative, the ranking of the best-performing stable coalitions is unaffected. In the second alternative, the level of spillovers is substantially smaller (as can be seen from the lower payoffs for a given coalition), and consequently, the coalition (USA, EET, EEX, CHN, and IND) that ranks first in the base model is not stable, but there are not many other changes in the stability of coalitions. Thus, we conclude that while the impact of the shape of the MAC curve cannot be ignored, the qualitative conclusions still hold.

4.5.4. Changing discount rate

We change the base value of discount rate r from 2% to 3% and 1%, respectively, reflecting a higher (lower) rate of time preference. As shown in the eighth and ninth columns of Table 4.5(a), increasing (decreasing) the value of r will decrease (increase) the NPV of global payoffs as future benefits from abatement are valued lower (higher), but the set of best-performing stable coalitions and the indicator of success for these coalitions remain largely the same as the base case: the relative comparison between different coalitions, which is what matters for stability analysis, is not substantially affected by the discount rate.

4.5.5. Alternative transfer schemes

The purpose of this section is to explore to what extent our finding of very limited asymmetry effects is influenced by the adopted type of transfer scheme, by comparing coalitional spillovers (i.e. no spillovers to outsiders) with full spillovers to outsiders (i.e. equal to spillovers to coalition members). Table 4.5(b) shows that the best performing stable coalitions vary with the type of transfer scheme (conform to the expectations and earlier results for a setting without spillovers reported in Nagashima et al., 2009). The results also show that the asymmetry effect does not matter for which coalition emerges as best-performing, given the transfer schemes. There is a tendency that less efficient transfer schemes imply a larger positive effect of spillovers to outsiders, but this is because less efficient transfer schemes imply smaller and less ambitious stable coalitions, and thus a larger number of outsiders. Thus, we can conclude that the conclusion on the limited asymmetry effect is not directly related to the choice of transfer scheme.

Table 4.5(b): Sensitivity analysis (using extended spillovers)

	Coalitional spillovers ($\overline{\xi^{NC}}=0$)			Full extended spillovers ($\overline{\xi^{NC}}=\overline{\xi^{C}}$)		
	Best performing coalition	NPV of global payoff (billion $)	Indicator of success (%)	Best performing coalition	NPV of global payoff (billion $)	Indicator of success (%)
Base case (optimal transfers)	[USA, EET, EEX, CHN, IND]	9882	44.3	[USA, EET, EEX, CHN, IND]	9906	44.5
Emission permits	[EU15, CHN]	7578	22.8	[EU15, CHN]	7611	23.1
No transfers	[JPN, EU15]	5404	2.5	[JPN, EU15]	5513	3.5

Note: Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

4.6. Discussions and conclusions

In this paper we explore the effects of technology spillovers among heterogeneous regions on the stability of possible climate coalitions with optimal transfer scheme. We identify technology spillovers through three major channels, and investigate how technology spillovers can influence the region's incentive structure to join the coalition. It should be noted that we leave the issues of a separate technology agreement and endogenous learning effects for further analysis; thus, the spillovers we investigate are exogenous. For future research, it will also be worthwhile to examine endogenous feedback effects from abatement on the state of technology and those impacts on the stability of climate coalitions.

Our main finding is that while global and coalitional spillovers can generate higher payoffs and boost global abatement levels, technology spillovers do not substantially increase the success of international climate agreements.

By and large, technology spillovers exclusive to coalitional members do increase their incentive to stay in the coalition and their efforts to reduce emissions, which leads to increased stability. However, as the gap between full cooperation (the Grand Coalition) and no cooperation (All Singletons) also increases with the size of coalitional spillovers, the relative success of a coalition, measured in terms of the percentage of the gap between Grand Coalition and All Singletons that is closed by the coalition, mostly decreases with the level of coalitional spillovers.

Furthermore, spillovers to outsiders have a mixed influence on the incentives to free-ride, and thus the set of stable coalitions remains largely unchanged. This also leads to the surprising finding that the ratio (asymmetry) between spillovers to coalition members and to outsiders is hardly important for the stability of coalitions. Thus, the analysis in this paper shows that spillovers between coalition members may be much less effective in overcoming the strong free-rider incentives that prevail in the international climate negotiations than is commonly assumed.

Appendix 4A

Table 4A-1: Main model parameter values

Symbol	Description	Value	Unit	Source
$\overline{M}$	Pre-industrial level of CO_2 stock	590	GtC	Nordhaus (1994)
δ	Natural annual removal rate of CO_2 stock	0.00866	-	Nordhaus (1994)
ω	Airborne fraction of emissions remaining in the atmosphere	0.64	-	Nordhaus (1994)
r	Discount rate	0.02	-	Assumption
θ_i	Share of region i in global benefits	see Table 4A-2, column 3		Own calculation based on Fankhauser (1995)
α_i	Abatement cost parameter of region i	see Table 4A-2, column 4		Own calculation based on Ellerman and Decaux (1998)
β_i	Abatement cost parameter of region i	see Table 4A-2, column 5		Own calculation based on Ellerman and Decaux (1998)
γ_D	Scale parameter of damage and benefit function	0.027	-	Tol (1997)

Table 4A-2: Regional parameters in the benefit and abatement cost function

Regions	Emission in 2010	Share of global benefits	Parameter of abatement cost	Parameter of abatement cost
	GtC (share)	θ_i	α_i	β_i
USA	1.763 (0.238)	0.226	0.0005	0.0398
JPN	0.344 (0.046)	0.173	0.0155	1.8160
EU15	0.943 (0.127)	0.236	0.0024	0.1503
OOE	0.360 (0.049)	0.035	0.0083	0
EET	0.226 (0.030)	0.013	0.0079	0.0486
FSU	0.774 (0.104)	0.068	0.0023	0.0042
EEX	0.469 (0.063)	0.030	0.0032	0.3029
CHN	1.127 (0.152)	0.062	0.00007	0.0239
IND	0.344 (0.046)	0.050	0.0015	0.0787
DAE	0.316 (0.043)	0.025	0.0047	0.3774
BRA	0.122 (0.016)	0.015	0.5612	8.4974
ROW	0.637 (0.086)	0.068	0.0021	0.0805
World	7.425 $\left(\sum = 1\right)$	$\left(\sum \theta_i = 1\right)$		

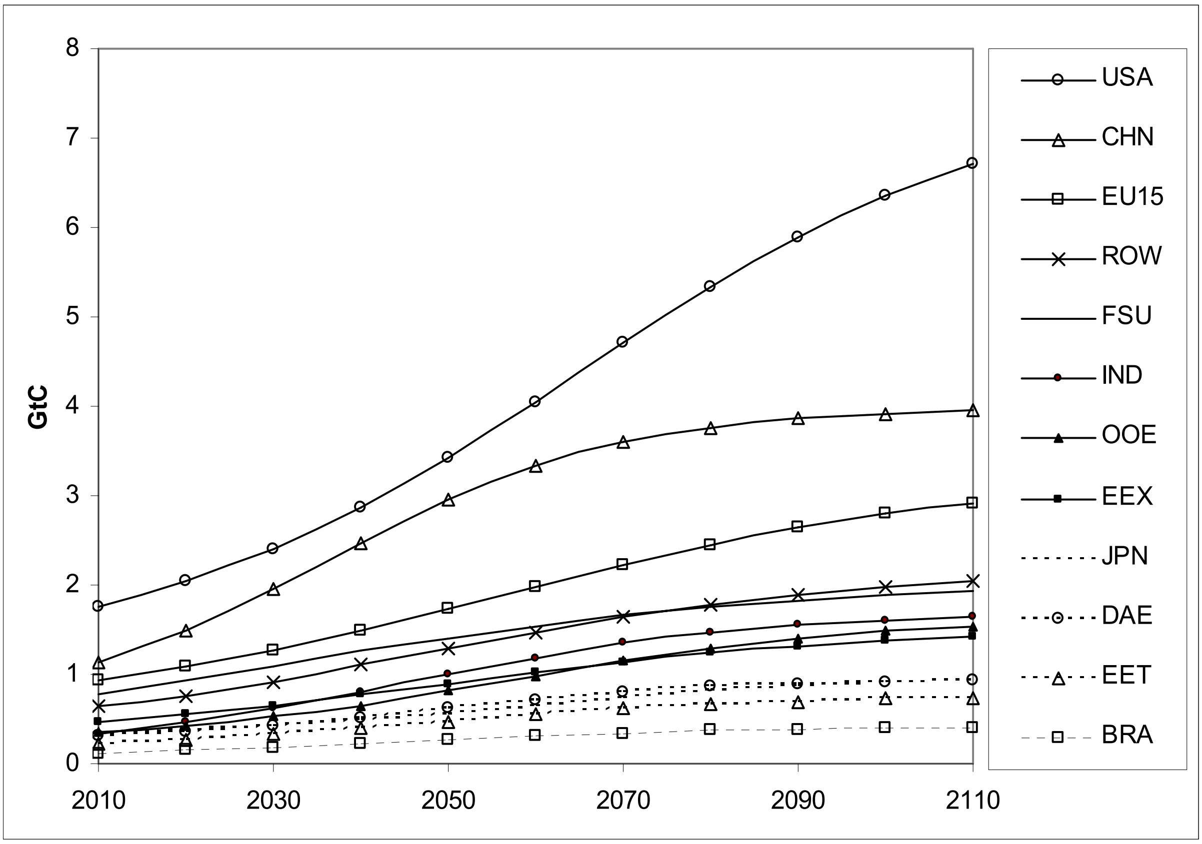

Figure 4A-1: Regional BAU emission paths

Source: Own calculations based on projections from the MIT-EPPA model (Paltsev et al., 2005).

Chapter 5

International climate agreements with induced technological change*

Technological change plays a crucial role in controlling climate change. Over the past two decades, a number of theoretical and empirical studies have been devoted to understand the drivers of technological change. This paper examines the impact of R&D investments on the stability of climate coalitions with an optimal transfer scheme and it explores how international cooperation on abatement affects the incentives of signatories to invest in R&D to reduce emissions. With an applied model we investigate the role of three different specifications of technological change for regions' incentives to join an international climate agreement. Specifically we compare the effects of (i) no technological change, (ii) exogenous technological change, and (iii) induced technological change (ITC). In the latter case, the stock of knowledge for reducing emissions develops through regional R&D investments.

We find that the set of best performing stable climate coalitions hardly changes between the scenario of no technological change and exogenous technological change, but we find a different set of stable coalitions for induced technological change. Coalitions that are stable in all three scenarios can achieve the highest payoffs in the case of induced technological change.

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5.1. Introduction

Following the definition of technological change (TC) developed in neoclassical economics, a previous chapter (Chapter 3) has examined the stability of international climate agreements (ICAs) in the presence of exogenous technological change (ExTC). In our specification, ExTC lowers abatement costs of CO_2 at a constant rate over time. Over the past two decades, a number of theoretical and empirical studies have been devoted to understand the drivers of TC (e.g. Binswanger and Ruttan, 1978; Romer, 1990; Griliches, 1992; Grossman and Helpman, 1994; Coe and Helpman, 1995). This work has led to new types of models where TC is price or policy induced and determined endogenously.[1] In this Chapter, we introduce induced TC (ITC) into the analysis of the stability of international climate agreements.

As discussed in Chapter 4, studies by Weyant and Olavson (1999), Löschel (2002) and Clarke et al. (2008) provide an overview of the different sources of 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; Buonanno et al., 2003), (ii) R&D spillovers (Griliches, 1992; Bosetti et al., 2008), and (iii) learning by doing (Manne and Richels, 2004; Castelnuovo et al., 2005). It has been widely acknowledged that different sources of TC have different economic and environmental impacts. We provide a brief overview of the state of the art of the studies on induced technological change (ITC) to understand how ITC is specified and implemented in economic models of climate change. Most of the work on TC focuses on the rate of TC while ITC models aim to explain not only the rate but also the direction of TC (Ruttan, 2001; Acemoglu, 2002; Otto et al., 2007). Goulder and Mathai (2000) explore the effects of ITC and clarify the implications of different types of ITC and the associated impacts on economy and environment by considering both cost-effectiveness and cost-benefit criteria. Their analysis of the impact of knowledge accumulation through R&D investment reveals that abatement tends to be shifted to later stages due to the availability of more advanced technologies derived from a larger accumulated stock of knowledge in the future.

Nordhaus (2002) incorporates ITC into his DICE-99 model: the R&DICE model. The original DICE-99 model is a global model that assumes exogenous Hicks-neutral technological change in the production function. A reduction in carbon intensity (carbon emissions per unit of output) is achieved by substitution of capital and labour 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

[1] According to Jaffe et al. (2001) the analysis of 'endogenous TC' focuses on the rate of TC, while the analysis of 'induced TC' focuses on the direction of TC through strategic R&D investments.

the emission function. In the R&DICE model a price increase for carbon based energy will induce firms to invest in the development of low carbon 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 CO_2 abatements, mainly due to the small social returns to R&D.

Few studies have investigated the role of ITC in the formation of international climate agreements. 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), and (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 technological change is driven by regional spillovers within sectors and increasing returns to scale from human capital. On the other hand, endogenous TC appears through improvements of the emission-output ratio via R&D investments. Buonanno et al. (2003) conclude that abatement costs are lower in the presence of endogenous TC with induced environmental TC than in the presence of only endogenous TC. The incentives to invest in R&D depend 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 maximise 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 increase in energy productivity. Kemfert concludes that incentives to join a coalition tend to be stronger if cooperation includes both climate control and technological innovation because the benefits resulting from technological improvement outweigh free-rider incentives.

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 through learning-by-doing or R&D investments in a similar framework as Goulder and Mathai (2000). Tol et al. (2000) conclude that the threat of restricting technology diffusion may prevent the coalition member from deviating, although the coalition may lose by restricting technology diffusion. The effectiveness of the restriction increases with the size of the coalition.

Previous chapters examine the stability of international climate agreements in the presence of technological change and spillovers. In these modelling approaches drivers of TC and spillovers are exogenous. Abatement costs fall over time either through an autonomous improvement or through knowledge spillovers from other regions. This chapter extends this analysis by relaxing the assumption of exogenous technological change. In our model, R&D investments improve a stock of knowledge that lowers abatement costs. In this respect we follow the analytical framework developed by Goulder and Mathai (2000). But we combine an ITC model with a game of coalition formation.

The main aim of this chapter is to examine how R&D influences the success of an international agreement on greenhouse gas abatement and how international cooperation on abatement may trigger the incentives for signatories to invest in R&D to reduce emissions. To study the effects of region-specific investment on technological change, we investigate three scenarios: (i) no technological change, (ii) exogenous technological change, and (iii) induced technological change. We do not consider technology spillovers.

The remainder of this chapter is organised as follows. Section 5.2 provides the theoretical framework for incorporating ITC into a game of coalition formation. Section 5.3 explains the empirical features of our model. Section 5.4 presents the main results. Section 5.5 reports the results of a sensitivity analysis. Finally, Section 5.6 offers conclusions.

5.2. Induced technological change and coalition formation

As in previous chapters, we assume that only a single international climate agreement (ICA) can be formed and that each region is free to join. This type of coalition formation game is called a cartel formation game with open membership. The solution concept employed here is internal-external stability. Seminal papers in this domain are Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). We consider two stages; at the first stage the ICA forms. At the second stage R&D investment and abatement paths are chosen. We allow for transfers between signatories of a climate agreement.

Let N denote a set of n regions with individual regions $i \in N$. At the first stage, each region decides about its membership in the agreement. Regions announcing that they will not join the coalition remain singletons. Regions announcing that they will join become signatories of the agreement. A coalition K is a set of k coalition members. We refer to a coalition structure as 'All Singletons' if $k \leq 1$. The coalition with $k = n$ members is called 'Grand Coalition'.

We call a coalition K stable if the coalition satisfies both internal and external stability. Internal stability of a coalition means that no signatory has an incentive to withdraw from the coalition, and external stability denotes that none of the singletons has an incentive to join the coalition, while others do not change their membership (single deviation). We denote region i's payoff under coalition K by $V_i(K)$.

The stability concepts are defined as follows:

Internal stability: Coalition K is internally stable if and only if

$$V_i(K) \geq V_i(K \setminus \{i\}) \qquad \forall i \in K \,. \tag{5.1}$$

External stability: Coalition K is externally stable if and only if

$$V_j(K) \geq V_j(K \cup \{j\}) \qquad \forall j \notin K \,. \tag{5.2}$$

At the second stage of the game, each region determines the optimal strategies for R&D investments and abatements. We now identify these strategic choices for each region in the All Singletons case and for the case with a given coalition.

Let $B_{i,t}(q_1,...,q_t)$ be a regional benefit function at time t. It is a function of past and current global abatements $(q_1,...,q_t)$ with $\frac{\partial B}{\partial q} > 0$ and $\frac{\partial^2 B}{\partial q^2} = 0$. Let $C_{i,t}(q_{i,t}, H_{i,t})$ be the regional abatement cost function, where $q_{i,t}$ is regional abatement at time t and $H_{i,t}$ is the regional stock of knowledge at time t. The regional abatement cost function has the following properties widely used in the literature (e.g. Goulder and Mathai, 2000): $\frac{\partial C}{\partial q} > 0$, $\frac{\partial^2 C}{\partial q^2} > 0$, $\frac{\partial C}{\partial H} < 0$, and $\frac{\partial^2 C}{\partial H \, \partial q} < 0$. The implication here is that regional marginal costs increase with regional abatements (the first two properties), and that regional abatement costs and regional marginal abatement costs are both reduced through an increased stock of knowledge (the last two properties). The benefit and abatement cost functions are specified in detail in Section 5.3.

The optimal paths of the emission abatements and R&D investments $I_{i,t}$ over the time horizon maximise the net present value (NPV) of payoff π_i for region i. The objective function is,

$$\pi_i(q_{i,1},...,q_{i,T}; I_{i,1},...,I_{i,T}) = \sum_{t=1}^{\infty} (1+r)^{-t} \cdot \left[B_{i,t}(q_1,...,q_t) - C_{i,t}(q_{i,t}, H_{i,t}) - I_{i,t} \right], \tag{5.3}$$

where r is the discount rate and T is a planning horizon. The regional benefit B_i is the NPV of future benefits, which enables us to consider benefits from current abatement for an infinite time horizon.

We apply the notion of Partial Agreement Nash Equilibrium (PANE) where we assume that signatories act jointly as a single player and singletons act individually (Chander and Tulkens, 1995, 1997; Bloch, 1997). Under this notion, the singletons $i \notin K$ determine their strategic choices by maximising their own payoffs taking the other regions' strategies as given, while signatories $i \in K$ choose their strategies by maximising the sum of the payoffs of the signatories taking the strategies of singletons as given. With our specification of benefit and cost functions, we obtain a unique interior solution of abatements and investments. This justifies to write the payoff function as a function of the coalition structure, usually called a partition function $V_i(K)$. The partition function specifies payoffs for every coalition $K \subseteq N$ and the singleton players under K.

The optimisation problem for singletons is

$$V_i(K) \equiv \max_{q_{i,1},\ldots,q_{i,T};I_{i,1},\ldots,I_{i,T}} \pi_i \tag{5.4}$$

$$\text{s.t.} \quad H_{i,t+1} - H_{i,t} = f(I_{i,t}), \tag{5.5}$$

$$\text{given} \quad H_{i,1}.$$

Eq. (5.5) presents the advancement of the stock of knowledge for abatement technology with $f(\cdot) > 0$, $\frac{\partial f}{\partial I} > 0$, and $\frac{\partial^2 f}{\partial I^2} < 0$ (cf. Goulder and Mathai, 2000). The stock of knowledge at time t ($H_{i,t}$) is accumulated through the investment in R&D, which leads to increased abatements compared to the situation without any R&D investments. For the sake of simplicity, we assume that regional abatement costs are affected by regional R&D investment. The rate of change in the stock of knowledge may differ between regions as the investment path may differ.

Given Eq. (5.3), the discrete-time current value Hamiltonian for singletons is defined as follows;

$$\mathcal{H}_{i,t} = \left[B_{i,t}(q_1,\ldots,q_t) - C_{i,t}(q_{i,t},H_{i,t}) - I_{i,t}\right] + (1+r)^{-1} \cdot \lambda_{i,t+1} \cdot f(I_{i,t}) \qquad \forall i \notin K, \tag{5.6}$$

where $\lambda_{i,t+1}$ is the costate variable that expresses a shadow value of the stock of knowledge at time $t+1$. The shadow value of the stock of knowledge is positive and decreasing over time, which implies that additional knowledge is always useful for the region and the effectiveness of a unit of investment is higher in an earlier period than in a later period. Without loss of generality, the stock of knowledge is normalised to be unity in the initial period. The abatement strategy space for each region is defined as $q_{i,t} \in \left[0, \, \overline{e}_{i,t}\right]$, where $\overline{e}_{i,t}$ denotes regional emission levels in the business-as-usual (BAU) scenario with no abatement.

The Hamiltonian is assumed to be differentiable. Formally, we obtain the following set of first order conditions as follows (cf. e.g., Conrad and Clark, 1987):

$$\frac{\partial \mathcal{H}_{i,t}}{\partial I_{i,t}} = 0 \tag{5.7}$$

$$(1+r)^{-1} \cdot \lambda_{i,t+1} - \lambda_{i,t} = -\frac{\partial \mathcal{H}_{i,t}}{\partial H_{i,t}}, \tag{5.8}$$

$$H_{i,t+1} - H_{i,t} = f(I_{i,t}), \tag{5.5}$$

$$B'_{i,t}(q_1,...,q_t) = C'_{i,t}(q_{i,t}, H_{i,t}) \qquad \text{for } i \notin K. \tag{5.9}$$

Next, we move to the optimisation problem for signatories as follows,

$$V_i(K) \equiv \max_{I_{i,t}, q_{i,t}} \sum_{j \in K} \pi_j \qquad \forall i \in K \tag{5.10}$$

$$\text{s.t.} \qquad H_{i,t+1} - H_{i,t} = f(I_{i,t}) \tag{5.5}$$

given $H_{i,1}$.

The discrete-time current value Hamiltonian for signatories is,

$$\mathcal{H}_{i,t} = \sum_{j \in K} \left[B_{j,t}(q_1,...,q_t) - C_{j,t}(q_{j,t}, H_{j,t}) - I_{j,t} \right] + \lambda_{i,t+1} \cdot f(I_{i,t}) \qquad \forall i \in K. \tag{5.11}$$

The set of first order conditions for signatories is,

$$\frac{\partial \mathcal{H}_{i,t}}{\partial I_{i,t}} = 0, \tag{5.7}$$

$$(1+r)^{-1} \cdot \lambda_{i,t+1} - \lambda_{i,t} = -\frac{\partial \mathcal{H}_{i,t}}{\partial H_{i,t}}, \tag{5.8}$$

$$H_{i,t+1} - H_{i,t} = f(I_{i,t}), \tag{5.5}$$

$$\sum_{j \in K} B'_{j,t}(q_1,...,q_t) = C'_{i,t}(q_{i,t}, H_{i,t}). \tag{5.12}$$

As formulated above, technological progress is endogenously determined; therefore, no autonomous technological change is considered. We consider a difference game where the paths of regional abatement and investment are mutually best responses to those of other regions. We solve the model from the last period of the time horizon, assuming that investments and abatement costs beyond the last period of time horizon go to zero for each region. Hence, the transversality condition for each region is,

$$\lambda_{i,T} = -\frac{\partial \mathcal{H}_{i,t}}{\partial H_{i,t}}, \tag{5.13}$$

and $\lambda_{i,T+1} = 0$.

To analyse the role of TC on coalition formation, we investigate three scenarios. In the first scenario, we consider coalition formation in the absence of technological change (no TC), i.e. where there is no R&D investment which lowers marginal abatement costs. In the second scenario, to capture the effects of ITC on the stability of coalitions, we incorporate exogenous technological change (ExTC) which evolves at a given annual rate over time. Under ExTC coalition formation does not influence the path of stock of knowledge and investments. To make this exogenous approach comparable to the endogenous one, the annual rate of exogenous TC for each region is the average rate over the time horizon obtained in the case of ITC under All Singletons. In the third scenario, we consider ITC through R&D investments as formulated above.

For each scenario, an optimal sharing rule (Carraro et al., 2006; McGinty, 2007; Weikard, 2009; Fuentes-Albero and Rubio, 2010) is applied. Optimal sharing compensates regions for their abatement efforts in order to set incentives to join the agreement. Under an optimal sharing rule each coalition member obtains at least its outside-option payoff $V_i(K \setminus \{i\})$, i.e. the payoff the region receives when deviating from coalition K (Weikard, 2009). The residual $V_K(K) - \sum_{i \in K} V_i(K \setminus \{i\})$, which is the difference between the coalitional payoff under coalition K and the sum of all members' outside option payoffs, can be distributed between coalition members in any way desired without an effect on internal stability. In our analysis, the residual is distributed proportional to the outside option payoffs.

Therefore, the partition function $V_i^O(K)$ with optimal sharing rule is defined as:

$$V_i^O(K) \equiv \frac{V_i(K \setminus \{i\})}{\sum_{j \in K} V_j(K \setminus \{j\})} \cdot V_K(K). \tag{5.14}$$

Rearranging Eq. (5.14) indicates that under optimal sharing a coalition K is internally stable if and only if

$$\frac{V_K(K)}{\sum_{i \in K} V_i(K \setminus \{i\})} \geq 1, \tag{5.15}$$

for all $i \in K$ and all $K \subseteq N$. Hence, K is internally stable if the coalition payoff (weakly) exceeds the sum of the outside option payoffs, else K cannot be internally stable. Eq. (5.15) is a necessary condition for stability. It is sufficient for internal stability if transfers are arranged according to Eq.

(5.14). The optimised paths of R&D investments and abatements are not affected by the transfers, while the transfers are affected by the R&D investments and the abatements.

5.3. Calibration of the model

In this section, we explain the main lines of the numerical specification of our model that is based on STACO-2.1 (Nagashima et al. 2009) with an emphasis on modifications that we adopt for the purpose of our study. The main equations are described in Box 5.1. We consider twelve world regions: USA (USA), Japan (JPN), European Union-15 (EU15), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and rest of the world (ROW). In line with earlier Chapters, we set the planning horizon of 100 years from 2011 ($t=1$) to 2110, and derive payoffs for 100 years which depend on future benefits from abatements within 100 years. As results depend on future values of decision variables, we need additional assumptions on these values and therefore we assume that regions will adopt a path of abatement and R&D based on the assumption that the coalition will continue for another 200 years. This additional time is sufficient to avoid interactions of the terminal constraint on the payoffs for the first 100 years.

It should be noted that our model does not aim at accurate forecasts for such long time-horizon, rather we want to avoid 'last-period effects' within the first century caused by the finite time-horizon of the model. The payoff for region i, π_i, is a function of benefits B_i, abatement costs C_i and investments I_i as described in Section 5.2. The first term on the right hand side of Eq. (5.16) denotes the NPV of the stream of payoffs over the planning horizon. The discount rate is assumed to be 2%. In Section 5.5, the base value of the discount rate is changed from 2% to 1% and 3%, respectively, for a sensitivity analysis. The second term indicates future impacts by abatements after the planning horizon. Each region determines an optimal path of the abatements and investments. We impose the assumption that the coalition established at the initial period lasts for 300 years. Based on the DICE model developed by Nordhaus (1994), the stock of CO_2 is calibrated, as shown in Eq. (5.17). The stock of CO_2 depends on the stock in the previous period M_{t-1}, pre-industrial stock $\overline{M}$, a natural annual removal rate of the stock δ, emissions in the BAU scenario $\overline{e}_{i,t}$, abatement $q_{i,t}$ and the airborne fraction of emissions remaining in the atmosphere ω. The benefit function follows the damage module of the DICE model (Nordhaus, 1994) and the climate module by Germain and Van Steenberghe (2003). In Eq. (5.18), y_t denotes global GDP in year t as given in Nordhaus (1994), and γ_1 and γ_2 are estimated by OLS-regression (Dellink et al., 2004). For the global damage parameter γ_D, we apply the estimate by Tol (1997) that damages amount to 2.7% of GDP for a doubling of concentrations over pre-industrial levels, that is, $\gamma_D = 0.027$. Eq. (5.19) shows the global benefits expressed as avoided damages. In Eq. (5.20), global benefits are allocated according to the share θ_i for each region, as displayed in the Appendix. These regional benefit shares are calibrated to regional damage estimates by Fankhauser (1995). As the time horizon is extended to 300 years, we modify the specification of the future damages in a way that the marginal global benefits grow with GDP until 2110 (as assumed in the earlier chapters) and remain constant afterwards.

We use the data from the EPPA model (Babiker et al., 2001; Paltsev et al., 2005) to calibrate the regional BAU emission paths in our model, adjusted to our regional aggregation using additional data from World Bank (2003). It should be noted that an estimation of the regional BAU emission paths is only available until 2110, but we extrapolate using the same formula, which leads to almost constant BAU emission paths after 2110. The regional abatement cost function (Eq. 5.21) is based on the basic formula with regional cost parameter α and β (as described in Appendix), estimated by Ellerman and Decaux (1998), where we additionally incorporate the impacts of the stock of knowledge as a reduction of abatement costs. Eq. (5.22) denotes the development of the regional stock of knowledge. Each region can obtain the fraction of γ of its own investment[2]. The scale parameter γ is assumed to be constant over time and region.

As for the first order condition, Eq. (5.7) and (5.8) can be described as follows:

$$I_{i,t}^{*} = \left[\frac{(1+r)^{-1} \cdot \lambda_{i,t+1} \cdot \gamma}{2} \right]^2 \qquad (5.7')$$

$$(1+r)^{-1} \cdot \lambda_{i,t+1} - \lambda_{i,t} = -\left(\frac{\frac{1}{3} \cdot \alpha_i \cdot q_{i,t}^3 + \frac{1}{2} \cdot \beta_i \cdot q_{i,t}^2}{(H_{i,t})^2} \right) \qquad (5.8')$$

As shown in Eq. (5.7') and (5.8'), the incentive to carry out R&D investment depends on a costate variable (a shadow value of the stock of knowledge) in the next period $\lambda_{i,t+1}$ which depends on the shadow value of the stock of knowledge, the stock of knowledge itself and abatements in the period of t.

For no TC we assume $\gamma = 0$, and each region does not carry out any investment, and, hence H_i is constant over time. For ExTC we assume that the stock of knowledge for each region grows at a constant rate and the rate is chosen such that the stock of knowledge in the last period $H_{i,T}$ is equal to $H_{i,T}$ in the ITC-All Singletons case. Regional investment in ExTC is a function of $H_{i,t}$, an annual

[2] This is similar to the assumptions by Goulder and Mathai (2000) and Tol et al. (2000) for their specifications of knowledge accumulation function.

growth rate of $H_{i,t}$, and γ which is the same rate as in ITC.

Box 5.1: Equations in STACO-2.1

Payoffs

$$\pi_i = \sum_{t=1}^{T} (1+r)^{-t} \cdot \left[B_{i,t}(q_1,...,q_t) - C_{i,t}(q_{i,t}, H_{i,t}) - I_{i,t} \right] + \sum_{t=T+1}^{\infty} (1+r)^{-t} \cdot B_{i,t}(q_1,...,q_T) \tag{5.16}$$

Stock of CO_2

$$M_t(M_{t-1}, q_1,...,q_t) = \bar{M} + (1-\delta) \cdot (M_{t-1}(q_1,...,q_{t-1}) - \bar{M}) + \omega \cdot \sum_{i=1}^{n} \left(\bar{e}_{i,t} - q_{i,t} \right) \tag{5.17}$$

Damages

$$d_t(M_t) = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t(M_{t-1}, q_1,...,q_t)}{\bar{M}} \right) \right] \cdot (\gamma_D \cdot y_t) \tag{5.18}$$

Benefits

$$B_t(q_1,...,q_t) = d_t(M_t(M_{t\text{-}1}, \mathbf{0})) - d_t(M_t(M_{t\text{-}1}, q_1,...,q_t)) \tag{5.19}$$

$$B_{i,t}(q_1,...,q_t) = \theta_i \cdot B_t(q_1,...,q_t) \tag{5.20}$$

Abatement costs

$$C_{i,t}(q_{i,t}) = \frac{\frac{1}{3} \cdot \alpha_i \cdot q_{i,t}^3 + \frac{1}{2} \cdot \beta_i \cdot q_{i,t}^2}{H_{i,t}} \tag{5.21}$$

Stock of knowledge

$$H_{i,t+1} - H_{i,t} = \gamma \cdot I_{i,t}^{\frac{1}{2}} \tag{5.22}$$

5.4. Results

This results section starts with an examination of All Singletons for each scenario. Then, Section 5.4.2 examines stability of climate coalitions for each scenario mentioned above with optimal transfer schemes.

5.4.1. All Singletons

Table 5.1 shows the results of the All Singletons case for each scenario, where marginal abatement costs equal marginal benefits for each region. The results obtained in All Singletons give good insights into the incentive structure of the different regions. As mentioned in Section 5.3, the results until 2110 are presented while the model covers 300 years. It should be noted that due to our method of calibration, the results in the case of ExTC and ITC are approximately identical.

Table 5.1: All Singletons

Region	Annual abatement (% of BAU emissions)				NPV of payoff (Billion US$ over 100 years)		
	2011	2110			noTC	ExTC	ITC
		no TC	ExTC	ITC			
USA	9.7	3.7	3.8	3.9	854	858	858
JPN	2.5	1.6	1.6	1.6	724	730	731
EU15	7.4	3.6	3.7	3.7	951	958	958
OOE	5.5	1.8	1.8	1.8	144	146	146
EET	4.3	1.9	1.9	1.9	55	55	55
FSU	6.6	3.7	3.7	3.7	277	280	280
EEX	1.8	1.1	1.1	1.1	126	127	127
CHN	14.5	6.7	6.8	6.8	229	231	231
IND	10.2	3.4	3.4	3.4	206	208	208
DAE	1.9	1.1	1.1	1.1	105	106	106
BRA	0.1	0.1	0.1	0.1	65	65	65
ROW	6.2	2.9	2.9	2.9	280	282	282
World	7.9	3.5	3.6	3.6	4,016	4,046	4,047

Global stock of CO_2 in 2110 = 1,458 GtC (no TC, ExTC, ITC)

As shown in Table 5.1, the percentage of abatement differs across regions as the abatement level is determined by marginal benefits and marginal costs. Regions with flatter marginal abatement cost curves, such as USA, China and India, tend to have an incentive to make substantial abatement efforts even in the All Singletons case. Among these three regions, the USA can obtain the highest NPV of payoffs of almost 860 billion US$ (in the case of ExTC and ITC) due to its higher marginal benefits from global abatements. The EU15 with a moderately flat marginal abatement cost curves has also strong incentives to reduce emissions as they can obtain a higher share of marginal benefits. Regions with steeper marginal abatement cost curves and lower marginal benefits (energy exporting countries, Brazil, and dynamic Asian economies etc.) have hardly any incentive to reduce emissions on their own.

Next we focus on the optimal path of R&D investments which drives the development of the stock of knowledge in the case of ITC. Figure 5.1 presents the paths of R&D investment for the top three regions with respect to R&D effort when ITC is considered.

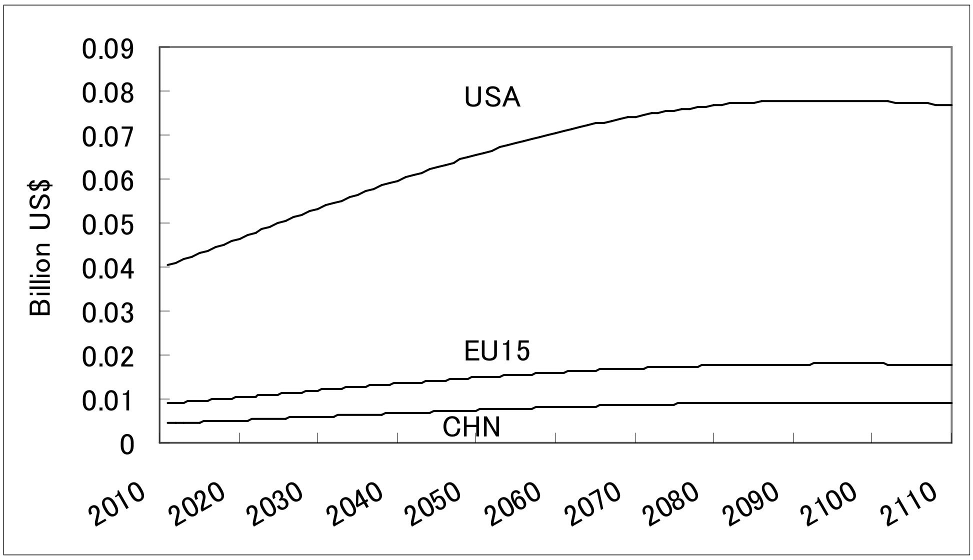

Figure 5.1: Investment paths in the presence of ITC (billion US$) in All Singletons for the top three regions

As shown in Figure 5.1, the level of R&D investments (and technological change) differs significantly across regions and USA has a stronger incentive to carry out R&D investments than other regions even without any cooperation on abatement. In All Singletons, regions with strong incentives to reduce emissions have stronger incentives to carry out R&D, as investments at time t depend on abatement and stock of knowledge in future periods. Regions with larger investments have a larger stock of knowledge; see Eq. (5.22). Overall, the effort for R&D investments is directed to regions where it pays to abate emissions.

5.4.2. Stable coalitions

In this section, we explore how coalition formation affects the outcomes for the different specifications of TC. We compute R&D investments, abatement and payoffs for all possible cartel coalitions ($2^{12}-12=4084$) and examine their stability with an algorithm programmed in MATLAB. Table 5.2 shows the results for the best performing stable coalitions for each scenario with optimal transfers. We use the same indicator of success[3] as in Chapter 4, in order to compare the outcomes across scenarios. As shown in Table 5.2, the NPV of global payoffs slightly increases when ExTC is considered compared with those obtained in the case of no TC. Due to our calibration the assumed rates of TC are small and the resulting effects on payoffs are too small to substantially affect stability. The set of best performing stable coalitions and the associated indicator of success between the scenario of no TC and ExTC are very close to each other. When we consider ITC, four of the top five stable coalitions under noTC are no longer stable. Furthermore, the number of internally stable coalitions, and therefore the number of stable coalitions, decreases.

Generally coalitions can achieve the highest NPV of payoffs in the case of ITC even though regions are paying for investments while in the ExTC scenario TC is assumed to come at no cost. Note that coalition members, as they take their coalition partners' benefits into account, increase their abatement levels. This, in turn, triggers additional investments by signatories in R&D as compared to the All Singletons case. However, coalition formation does not affect abatement and R&D of non-signatories in our specification with linear benefits and no knowledge spillovers. Table 5.3 shows the amount of R&D investments by the members of the best performing coalition (EU15, EET, CHN, IND, DAE) compared to All Singletons. The results show that all coalition members increase their investments substantially. As the investment levels depend on the shadow value of the stock of knowledge which in turn depends on abatement levels, regions with lower abatement costs have to make larger efforts to abate and invest more than other regions.

R&D investments carried out by coalition members lead to lower regional abatement costs, and cooperation on abatement drives each coalition member to carry out more abatement compared with All Singletons. As a result of increased abatement in a coalition, not only coalition members but also singletons can obtain higher benefits in the case of ITC, which leads to a decrease (increase) in the number of internally (externally) stable coalitions. ITC thus makes a coalition more 'productive'. However, the public good nature of abatement increases free-rider incentives and reduces stability. This finding is in line with Barrett's (1994) results that large coalitions can form when little is at stake, but only small coalitions can form if a lot is at stake.

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[3] Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition – NPV of global payoff in All Singletons))*100

Table 5.2: Stable coalitions with optimal transfer scheme (top five in terms of NPV of global payoff)

Signatories	no TC			ExTC			ITC		
	Rank	Indicator of success (%)	NPV of global payoff (billion $)	Rank	Indicator of success (%)	NPV of global payoff (billion $)	Rank	Indicator of success (%)	NPV of global payoff (billion $)
USA, EET, CHN, IND, DAE	1	45.9	7,652	1	46.0	7,697	NS*	46.2	7,967
EU15, EET, EEX, CHN, IND	2	45.7	7,634	2	45.7	7,677	NS*	46.0	7,949
EU15, OOE, EET, CHN, IND	3	44.8	7,562	3	44.8	7,605	NS*	45.1	7,879
EU15, EET, CHN, IND, DAE	4	44.6	7,546	4	44.6	7,588	1	44.8	7,854
USA, EET, EEX, CHN, DAE, BRA	5	43.6	7,466	5	43.6	7,510	NS*	43.8	7,767
USA, OOE, EET, EEX, CHN	8	42.3	7,366	8	42.4	7,410	2	42.6	7,660
EU15, EET, EEX, CHN, DAE, BRA	9	42.3	7,362	9	42.3	7,403	3	42.5	7,656
USA, EEX, CHN, IND	11	42.0	7,339	11	42.0	7,383	4	42.4	7,643
EU15, OOE, EEX, CHN, DAE	14	41.7	7,320	14	41.8	7,362	5	42.1	7,621
Internally stable coalitions		627			628			581	
Externally stable coalitions		3584			3584			3628	
Stable coalitions		185			186			179	

Note: NS indicates that the coalition is not stable coalition.

Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition– NPV of global payoff in All Singletons))*100

Table 5.3: Comparison of investments (in million US$) in All singletons (AS) and in a coalition between EU15, EET, CHN, IND and DAE

		2011	2035	2060	2085	2110
EU15	AS	10	10	20	20	20
	Coalition	40	60	70	80	80
EET	AS	0.0	0.0	0.0	0.0	0.0
	Coalition	10	20	20	30	30
CHN	AS	4	6	8	9	9
	Coalition	1190	1600	1910	2000	1900
IND	AS	0.1	0.2	0.2	0.3	0.3
	Coalition	70	90	120	130	120
DAE	AS	0.0	0.0	0.0	0.0	0.0
	Coalition	20	30	30	40	40

5.5. Sensitivity analysis

Due to the unavailability or uncertainty of data for calibration of the main parameter values, we conduct a sensitivity analysis to explore the effects of alternative parameter values on the results for the case of ITC. We focus on two crucial parameters used in our model. First, we change the parameter for the productivity of R&D investment γ by increasing (decreasing) its value in incremental steps, which examines the case of a higher (lower) effectiveness of R&D. Second, we change the base value of discount rate r from 2% to 1% and 3%, respectively. As the NPV of global payoffs increases with γ due to higher effectiveness of R&D investment, it makes more sense to compare the results of the indicator of success among scenarios with different values of γ instead.

Table 5.4 shows the ranks and the indicator of success for the best-performing stable coalitions in terms of NPV of global payoff under each scenario for different values of γ. As shown in Table 5.4, when the same stable coalitions appear across scenarios (e.g. a coalition of USA, EEX, CHN and IND), the indicator of success is quite robust with respect to changes of the value of γ. Only stability and the rank in the set of stable coalitions differ. It should be noted that only stable coalitions are ranked according to their indicator of success. The shift of ranks with increasing values of γ is due to the following mechanisms. First, increasing productivity of R&D investments increases both coalition payoff and positive spillovers from abatement, as larger productivity of R&D means that more is at stake when regions consider membership. Second, as noted before, the larger the stakes, the larger the free-rider incentives. Finally, the top-ranked coalitions lose stability as γ increases, and coalitions with a lower indicator of success become the new top-ranked coalitions.

The last three rows of Table 5.4 show the number of internally stable coalitions, externally stable coalitions and stable coalitions, respectively. The results show that the number of internally (externally) stable coalitions decreases (increases) with the value of γ, which implies that the free-riding incentives increase with higher values of γ.

Sensitivity analysis with respect to the discount rate shows that the NPV of global payoffs decreases with the value of the discount rate. The results for the indicator of success are compared across scenarios. Table 5.5 presents the rankings and the indicator of success for the five best-performing stable coalitions under each scenario for different discount rates. As shown in Table 5.5, a higher discount rate leads to lower indicator of success. Furthermore, the number of stable coalitions increases with the discount rate. Here we observe a similar pattern as with changes in γ. As the discount rate falls (and more is at stake), the best-performing coalitions are no longer stable. It is interesting to observe that the indicator of success of the best-performing stable coalition is fairly robust (around 45%) among different scenarios.

Table 5.4: Sensitivity analysis with different values of the R&D productivity parameter γ for the ITC model specification

Signatories	$\gamma=0$ (No TC)		$\gamma=5\cdot10^{-5}$		$\gamma=10^{-4}$ (Base case)		$\gamma=1.5\cdot10^{-4}$		$\gamma=2\cdot10^{-4}$	
	Rank	Indicator of success (%)	Rank	Indicator of success (%)	Rank	Indicator of success (%)	Rank	Indicator of success (%)	Rank	Indicator of success (%)
USA, EET, CHN, IND, DAE	1	45.9	1	46.1	NS	46.2	NS	46.2	NS	46.1
EU15, EET, EEX, CHN, IND	2	45.7	2	45.9	NS	46.0	NS	46.0	NS	45.9
EU15, OOE, EET, CHN, IND	3	44.8	NS	45.0	NS	45.1	NS	45.2	NS	45.2
EU15, EET, CHN, IND, DAE	4	44.6	3	44.8	1	44.8	1	44.8	NS	44.8
USA, EET, EEX, CHN, DAE, BRA	5	43.6	4	43.7	NS	43.8	NS	43.8	NS	43.8
USA, CHN, IND, DAE, BRA	7	42.4	5	42.6	NS	42.9	NS	43.1	NS	43.3
USA, OOE, EET, EEX, CHN	8	42.3	6	42.5	2	42.6	2	42.6	NS	42.6
EU15, EET, EEX, CHN, DAE, BRA	9	42.3	7	42.4	3	42.5	NS	42.5	NS	42.5
USA, EEX, CHN, IND	11	42.0	10	42.2	4	42.4	3	42.5	1	42.6
EU15, OOE, EEX, CHN, DAE	14	41.8	12	41.9	5	42.1	NS	42.2	NS	42.2
USA, EET, EEX, CHN, DAE	NS	42.0	NS	42.1	6	42.1	5	42.1	3	42.0
USA, EET, CHN, IND, BRA	15	41.6	13	41.8	7	42.0	4	42.1	2	42.2
USA, OOE, EET, CHN, DAE	19	41.2	18	41.3	10	41.4	7	41.4	5	41.4
USA, CHN, IND, DAE	NS	40.8	NS	41.0	13	41.2	8	41.4	4	41.5
Internally stable coalitions	627		612		581		552		527	
Externally stable coalitions	3584		3597		3628		3657		3674	
Stable coalitions	185		179		179		173		164	

Note: NS indicates not stable coalition.
Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition– NPV of global payoff in All Singletons))*100

Table 5.5: Sensitivity analysis with different values of the discount rate for the ITC model specification

Signatories	Discount rate 1%		Discount rate 2% (Base case)		Discount rate 3%	
	Rank	Indicator of success (%)	Rank	Indicator of success (%)	Rank	Indicator of success (%)
USA, EET, CHN, IND, DAE	NS	50.9	NS	46.2	1	45.4
EU15, EET, EEX, CHN, IND	NS	50.6	NS	46.0	2	45.2
EU15, EET, CHN, IND, DAE	NS	49.4	1	44.8	3	44.1
USA, EET, EEX, CHN, DAE, BRA	NS	48.6	NS	43.8	4	42.8
USA, CHN, IND, DAE, BRA	NS	47.8	NS	42.9	5	41.9
USA, OOE, EET, EEX, CHN	NS	47.0	2	42.6	6	41.8
EU15, EET, EEX, CHN, DAE, BRA	NS	47.2	3	42.5	9	41.5
USA, EEX, CHN, IND	NS	47.1	4	42.4	10	41.5
EU15, OOE, EEX, CHN, DAE	NS	46.8	5	42.1	15	41.1
USA, EET, CHN, IND	1	44.4	NS	40.2	NS	39.7
EU15, EET, CHN, IND	2	43.3	NS	39.2	NS	38.6
USA, EET, EEX, CHN, BRA	3	42.2	31	38.0	NS	37.2
USA, EEX, CHN, DAE	4	41.7	NS	37.2	NS	36.2
EU15, EET, EEX, CHN, BRA	5	41.1	NS	37.0	NS	36.2
Internally stable coalitions	416		581		622	
Externally stable coalitions	3771		3628		3588	
Stable coalitions	135		179		181	

Note: NS indicates not stable coalition. Non-stable coalitions are not ranked.
Indicator of success (%): ((NPV of global payoff in a coalition – NPV of global payoff in All Singletons) / (NPV of global payoff in Grand Coalition– NPV of global payoff in All Singletons))*100

5.6. Conclusion and scope for future research

In this chapter, we examine the stability of all possible climate coalitions in a cartel game with an optimal transfer scheme under different specifications for technological change. Three scenarios are investigated to explore the role of TC on regional incentive structures: (i) no TC, (ii) exogenous TC, and (iii) induced TC (ITC). ITC is endogenously determined: costly regional R&D investments improve the stock of knowledge which, in turn, lowers abatement costs. We investigate the impacts of ITC on the stability of an international climate agreement, using the STACO-2.1 model.

The set of best performing stable coalitions and the associated indicator of success hardly change between the scenario of no TC and ExTC, but ITC does produce different set of stable coalitions. Coalitions that are stable in all three scenarios can achieve the highest NPV of payoffs in the case of ITC even though regions are paying for investments. Of course, on an optimal R&D investment path every investment made is worthwhile and will cover the cost.

Furthermore, the number of internally (externally) stable coalitions decreases (increases) with ITC relative to the other two cases, and the number of stable coalitions decreases. Our results indicate that in the case of ITC, all coalition members increase their investments substantially when they cooperate. As the investment levels depend on the shadow value of the stock of knowledge which depends on abatement levels and level of stock of knowledge, regions with lower abatement costs have to contribute the most to reduce emissions and, in turn, increase their investments more than other regions. R&D investments carried out by coalition members lead to lower abatement costs in the coalition and cooperation on abatement drives each coalition member to carry out more abatement compared with the All Singletons case. As a result of increased global abatement, not only coalition members but also singletons obtain higher benefits in the case of ITC which leads to decrease (increase) in the number of internally (externally) stable coalitions. Therefore, ITC might improve global payoffs, however, at the same time it tends to increase free-rider incentives due to the public good nature of global warming.

We find that the indicator of success is quite robust with respect to the productivity of R&D (i.e. the value of γ). Furthermore, the number of internally (externally) stable coalitions decreases (increases) with the value of γ , as free-riding incentives increase. We find coalitional stability to be sensitive with respect to changes of the discount rate. The number of stable coalitions increases with the value of discount rate. In both cases, the dominating mechanism is that a higher productivity of R&D or a lower discount rate increase the payoffs of regions, and thus increase the gains from cooperation, but also increase free-rider incentives. The seminal result of Barrett (1994) that stable coalitions are smaller when the stakes are higher applies here.

It is left to future research to investigate other sources of technological change, such as spillovers from R&D investments undertaken by other regions. Among the alternatives to the Kyoto Protocol on emission abatement, technological development and cooperation have been considered in the literature as one of the instruments to control climate change. In reality, a range of technology policies and agreements have been established bilaterally and/or multilaterally in the global climate regime, such as the Asia-Pacific Partnership on Clean Development and Climate. It will be worthwhile to examine whether cooperation on abatement technology may improve the stability of climate coalitions in a framework of ITC.

Appendix 5A

Table 5A-1: Main model parameter values

Symbol	Description	Value	Unit	Source
$\overline{M}$	Pre-industrial level of CO_2 stock	590	GtC	Nordhaus (1994)
δ	Natural annual removal rate of CO_2 stock	0.00866	-	Nordhaus (1994)
ω	Airborne fraction of emissions remaining in the atmosphere	0.64	-	Nordhaus (1994)
r	Discount rate	0.02	-	Assumption
θ_i	Share of region i in global benefits	see Table 5A-2, column 2		Own calculation based on Fankhauser (1995)
α_i	Abatement cost parameter of region i	see Table 5A-2, column 3		Own calculation based on Ellerman and Decaux (1998)
β_i	Abatement cost parameter of region i	see Table 5A-2, column 4		Own calculation based on Ellerman and Decaux (1998)
γ_D	Scale parameter of damage and benefit function	0.027	-	Tol (1997)

Table 5A-2: Regional parameter values

Regions	Share of global benefits	Parameter of abatement cost	Parameter of abatement cost
	θ_i	α_i	β_i
USA	0.226	0.0005	0.0398
JPN	0.173	0.0155	1.8160
EU15	0.236	0.0024	0.1503
OOE	0.035	0.0083	0
EET	0.013	0.0079	0.0486
FSU	0.068	0.0023	0.0042
EEX	0.030	0.0032	0.3029
CHN	0.062	0.00007	0.0239
IND	0.050	0.0015	0.0787
DAE	0.025	0.0047	0.3774
BRA	0.015	0.5612	8.4974
ROW	0.068	0.0021	0.0805
World	$\left(\sum \theta_i = 1\right)$		

Chapter 6

Discussion and conclusions

6.1. Introduction

Mitigating global warming is one of the crucial challenges we are facing. The IPCC (2007a) states that 'Warming of the climate system is unequivocal'. A number of studies have examined the impacts of climate change on agriculture, economic activities, human health, and eco-systems, and have suggested that global cooperation plays a crucial role in achieving significant reduction in global GHG emissions. Achieving global cooperation is, however, a difficult task due to the fact that global warming is a phenomenon with public good characteristics. This situation is reflected in the actual international negotiations on climate change where a global consensus is hard to establish. Therefore, international climate agreements should be self-enforcing as no authority exists to regulate free-riding. Voluntary participation by regions can be realised if signing the agreement is profitable to them; total benefits outweigh the total costs involved in signing the agreement. One of the key elements to attain the success of the agreement is to ensure the participation from major emitters such as the United States and developing countries with growing economies.

The analysis in this thesis reveals that incentives to join the agreement are influenced not only by the type of mechanisms that may promote cooperation, but also by the design of these mechanisms. I examine the impacts of three types of mechanisms: (i) transfer schemes, (ii) technology spillovers and (iii) induced technological change. The aim of this thesis is to explore the impact of these different mechanisms and their designs on the success of an international climate agreement. I consider a two-stage, non-cooperative game on controlling climate change. For the numerical simulations, a dynamic version of the STAbility of COalitions model (STACO-2.1) is used. The basic framework of the STACO is as follows. At the first stage, regions decide whether to join a unique agreement or not (membership decision). Regions announcing that they will not join a coalition become a singleton, and those announcing that they will join become signatories of the agreement. In our model with twelve regions, we obtain 4084 (2^{12} -12) different coalition structures. In the second stage, regions adopt their abatement strategies over the planning horizon. Non-signatories choose their abatement levels by maximising their own payoffs, taking the other regions' abatement levels as given. Signatories choose the abatement levels that maximise the sum of the payoffs of the signatories, taking the abatement levels of non-signatories as given and considering the benefits of other signatories. In the case of R&D investments, the general framework is extended in such a way that regions decide the optimal strategies for abatement and R&D investments in the agreement on abatement over the planning horizon. Furthermore, I assume that decisions for membership are taken at the beginning of the time horizon. The conclusions in this chapter are based on the results obtained by using our stylised model with specific setting. The remainder of this chapter is organised as follows. Section 6.2 provides the answers to the research questions presented in Chapter 1. Section 6.3 presents general conclusions and discussion. Finally, Section 6.4 suggests some lines of further research.

6.2. Answers to the research questions

This section presents in brief the answers to the research questions presented in Chapter 1.

Q1 *How can I implement the dynamic aspects of abatement efforts and incentives to join an international climate agreement into an applied game-theoretical analysis and which stable coalitions would occur if no transfer is considered?*

To derive optimal abatement paths over time, I constructed a model for the stability of coalitions, STACO-2.1, that is an update and dynamic extension of the STACO-1 model. The model enables us to identify the regional optimal abatement paths based on the future stream of benefits and costs of abatement. As each country's abatement strategy depends on its abatement costs and benefits in each period, all countries can simultaneously decide the level and timing of the abatement.

The case without an international climate agreement (i.e. the case of All Singletons) can serve as a reference point for the analysis of the various mechanisms in the following analysis. Once I have calculated the abatement levels and payoffs for all possible coalitions, I test the stability of each coalition. The outcomes obtained in All Singletons reflect the characteristics of the regions, that is the benefits from abatement as avoided damages and abatement costs over the time horizon. Annual global abatement increases over time, while the percentage of annual global abatement compared to BAU emissions tends to be decreasing over time. At the regional level, differences in marginal benefits and costs among regions drive different paths of abatements.

The USA, a region with low marginal abatement costs and high benefits, reduces emissions substantially even in the All Singletons structure. On the other hand, regions with high marginal abatement costs and lower benefits, such as energy exporting countries, Brazil and dynamic Asian economies, have little incentive to reduce emissions. Although Japan can enjoy a large share of global benefits, it does not take much abatement efforts due to its relatively high marginal abatement costs. It should be noted that for all regions, zero abatement is not an optimal strategy as they can benefit more from abatement than they can benefit by conducting zero abatement.

In the Grand Coalition where all regions sign the agreement, the NPV of global payoff substantially increases compared to the All Singletons case. Some regions are, however, worse off by joining the coalition, such as China with the lowest abatement cost function due to the fact that China has to contribute much to reduce emissions. This feature reflects the difficulties to obtain full cooperation in the actual negotiations on climate change if no appropriate burden sharing mechanism is applied.

The analysis shows that a unique stable coalition between Japan and EU15 emerges if no transfers are applied. Both regions reduce their emissions more than in the All Singletons structure. Both coalition members have an interest in cooperation, because of their higher marginal benefits from abatement, while none of the other regions want to join, as their abatement costs would increase too much if they have to take the benefits of Japan and EU15 into account.

Q2 How does the design of transfer schemes affect the stability of an international climate agreement?

To examine the roles of different types of transfer schemes, I investigate the impacts of a number of 'pragmatic' and 'optimal' transfer schemes on the stability of voluntary-based international climate agreements. The pragmatic transfer schemes are divided into two categories: allocation-based and outcome-based transfer schemes. I simulate the following cases: (i) allocation-based schemes where emission permits are distributed proportional to initial or future reference (BAU) emission levels to coalition members, (ii) outcome-based schemes where the coalition surplus is distributed proportional to the reference emissions, and (iii) an optimal sharing scheme where each signatory receives at least as much as what it could have obtained by deviating from the coalition.

In the case of allocation-based schemes, no stable coalition emerges if the emission permits are distributed based on a single (historical) base year. The observation from this analysis is that historically large emitters get a disproportionately large share of the permits that they can sell while fast-growing regions, such as China and India, need to buy emission permits. This leads to the situation that historically large emitters are permit-sellers, while the developing countries are permit-buyers. Results improve when the permits are distributed based on the full path of future emissions. Two stable coalitions between EU15 & China and between Japan & India are formed. China and India will obtain their increased payoffs due to the increased emission permits compared with those under the initial-emission-based permit trading, so that they can sell their permits to the respective coalition partner. The future-emissions-based permit trading will increase the incentives to join the coalition for the regions with growing emissions because the allocations of the permits are larger than in initial-emission-based permit trading. Hence, future-emissions-based permit trading may be a key determinant in persuading developing countries to sign an international climate agreement.

Turning to outcome-based schemes where transfers are based on a division of the gains from cooperation, one of the main advantages of surplus sharing is that individual rationality is always satisfied as long as a coalition is at all profitable, i.e. countries cannot be worse off in a coalition with a transfer scheme than as a singleton. The only stable coalition formed by the USA and China emerges under both the initial-emissions-based and future-emissions-based surplus sharing. China with a higher growth rate of emission obtains a higher NPV of payoff under the future-emissions-based surplus sharing than the USA does. The global sum of incentives to change membership is less under the future-emissions-based surplus sharing. This implies that the coalition that emerges under future-emissions-based surplus sharing will be possibly more stable than the coalition that emerges under initial-emissions-based surplus sharing due to the smaller incentives to change membership.

The outcomes can be improved further when optimal surplus sharing is introduced. Under optimal surplus sharing, each region can secure its outside-option payoff. There is no incentive to leave a given coalition if the coalitional payoff exceeds the sum of the outside option payoffs. I obtain 182 non-trivial larger stable coalitions which consist of up to six regions and a higher NPV of global payoffs than under any other transfer scheme.

To sum up, I derive the following conclusions from the analysis of transfer schemes. First, the number and the identity of members of a stable coalition are influenced by the design of transfer schemes. The findings show that if the transfer scheme fails to be designed appropriately (e.g. permit trading based on initial emissions), outcome in terms of stability may be worse than in the case without transfers. Second, the Grand Coalition is not stable irrespective of the transfer scheme. The free-rider incentives are huge in the absence of transfers and too large to be overcome by any transfer scheme. Third, as seen in our analysis, the optimal surplus sharing scheme performs best in terms of stability, and economic and environmental outcomes compared to any pragmatic transfer schemes. Examining stability of climate coalitions with different transfer schemes gives significant insights into changes in regional incentives.

Q3 How do different technology spillover mechanisms among regions influence the incentive structures to join and stabilise an international climate agreement?

It is widely recognised that environment-related technological change plays an essential role in reducing emissions and saving abatement costs. A number of studies have proposed to link the agreements on emissions abatement to technological cooperation, where a region signs an agreement on emission controls and on technology cooperation or technology transfers with its partners. Among the main sources of technological change specified in the previous literature, I focus on the role of the spillovers to answer this research question. I systematically investigate how technological spillovers affect the formation and stability of climate coalitions to understand whether the effects of technology spillovers are large enough to stabilise more ambitious coalitions by offsetting the incentive to free-ride.

Technology spillovers and their effects can be described in different ways. Most existing models measure the level of technology by using the emission-output ratio (emissions over GDP) and assume that the stock of knowledge (which is embedded in the production function and the emission-output indicator) can be aggregated over the regions. The spillovers will lower the abatement costs by pivoting the marginal costs down. Technology spillovers can be treated as a club good which is exclusive to the coalition members, and therefore, membership will be profitable to coalition members and help to stabilise coalitions. The level of technology spillovers differs from coalition to coalition, because the rate of spillovers depends on the partners' state of technology. To explore the role of spillovers on stability, I investigated five scenarios: (i) no spillovers, (ii) internal spillovers, (iii) global spillovers, (iv) coalitional spillovers, and (v) extended spillovers (all possible technology spillovers). I use an indicator of success of international climate agreements based on the ratio of the differences of NPV of global payoffs between a coalition and All Singletons over the difference of global NPV between of Grand Coalition and All Singletons.

Three major results are found. First, while global spillovers lead to higher NPV of global payoffs compared to no spillovers and internal spillovers for any given coalition structure, the incentive to change membership does not change significantly because relative differences between different coalitions hardly change, although global spillovers achieve the highest NPV of global payoffs in a given coalition. Second, in the case of coalitional spillovers, while the absolute value of NPV of global payoffs is higher, the indicator of success for any given coalition is lower than in the case of no, internal or global spillovers. This is due to the fact that coalitional spillovers perform best in the Grand Coalition, so that they increase the gap between Grand Coalition and All Singletons as compared to a setting without spillovers. Third, extended spillovers slightly enhance the indicator of success (due to the fact that spillovers to outsiders are not reflected in the Grand Coalition, therefore, the gap between NPV of global payoffs in Grand Coalition and in All Singletons is the same for coalitional spillovers and extended spillovers), however, they are not strong enough to change the set of stable coalitions in our settings.

To explore the main driving forces which influence the success of an agreement, I focus on the impact of different magnitudes of spillovers (level effects) and of different relative rates of coalitional spillovers over spillovers to outsiders (asymmetry effects). The results of the analysis of level effects indicate that as the magnitude of spillovers increases, the best-performing stable coalitions change substantially. Furthermore, the indicator of success is decreasing with increasing spillovers for a given stable coalition, as the gap between Grand Coalition and All Singletons increases as compared to a setting without spillovers. It can be concluded that level effects will enlarge the stable coalition (up to seven members), but they may not increase the indicator of success.

I explore the asymmetry effects on stability and success by increasing spillovers to outsiders (or spillovers to coalition members) while keeping the same value of spillovers to coalition members (or spillovers to outsiders). Increasing the spillovers to coalition members does increase stability of coalitions as expected because they induce signatories to stay in the coalition. The indicator of success, however, decreases with coalitional spillovers. This is again because large coalitional spillovers increase the gap between Grand Coalition and All Singletons.

On the other hand, increasing the spillovers to outsiders, while spillovers to coalition members remain the same, is not important for the stability of climate coalitions, due to the balance between the increase in external stability arising from increased incentives to free-ride and the increase in internal stability arising from increased incentives for signatories to stay in a coalition. Overall, the findings suggest that the spillovers may improve the stability of coalitions, however, they cannot fully overcome the strong incentives to free-ride in larger coalitions.

Q4 *How do R&D investments influence the success of an international agreement on abatement and how does international cooperation on abatement induce incentives to carry out R&D investments that are socially optimal?*

The role of innovation and technological change has received a lot of attention in the climate change debate. Over the past few decades, in depth discussions on the drivers of technological change have been provided in the context of climate change. In general, to reduce abatement costs, a region carries out R&D investment.

To answer this research question, I examine three scenarios: (i) no technological change (noTC), (ii) exogenous technological change (ExTC), and (iii) induced technological change (ITC). In Chapter 5, I extend the model which was used in Chapters 2-4 to determine the rate of technological change *endogenously*, and I apply optimal transfers. Through R&D investments, knowledge about abatement technology is accumulated over time and leads to a reduction in abatement costs. For simplicity, under ITC, the rate of development for the regional stock of knowledge is assumed to be constant over time and across regions. For noTC it is assumed that no region carries out any net investment in R&D, therefore, the stock of knowledge remains constant over time. For ExTC, I assume that the growth rate of the stock of knowledge is constant over time, and the rate is calibrated in such a way that the stock of knowledge in the last period is equal to the one of the last period in the All Singletons case with ITC.

I find that optimal strategies for R&D investments significantly differ across regions in All Singletons, and regions with higher incentives to reduce emissions (regions with lower marginal costs) have relatively higher incentives to carry out R&D investments. Higher investments lead to higher levels of stock of knowledge which enables regions to abate at lower costs. When regions cooperate on abatement, the set of best performing stable coalitions in terms of NPV of payoffs change little between two scenarios of noTC and ExTC. In the case of ITC, the number of stable coalitions decreases. Induced technological change influences incentives to join the coalition in the following way. When a coalition is formed, coalition members increase abatement levels relative to the All Singletons case. Increase in abatement triggers additional investments by coalition members, and especially regions with lower abatement costs make large efforts to abate and eventually to invest in R&D compared with other signatories. Increased investment and abatement levels by signatories bring larger benefits compared with the All Singletons case. As burdens for signatories increase and benefits for singletons increase due to the 'public good' nature of climate control, the number of internally (externally) stable coalition decrease (increase). Therefore, cooperation on abatement in the case of ITC can achieve a high global payoff, but free-riding incentives also increase.

6.3. General conclusions and discussion

Our analysis of international climate agreements reveals that well-designed mechanisms can facilitate successful formation of partial coalitions, although global cooperation is still hard to be achieved. The reason lies in the public good nature of global warming and regional characteristics of benefits and costs. Following insights of transfer schemes obtained in previous studies, our systematic analysis supports the fact that an incentive to join the agreement is highly sensitive to the design of transfer scheme. For different designs of transfer schemes, there is a trade-off between feasibility and effectiveness. Allocation-based transfer schemes are easier to implement than an optimal transfer scheme which can achieve more successful coalition formation in the context of global payoffs and CO_2 emissions.

The role of technological change has received a lot of attentions to reduce a significant amount of emissions. Two types of sources of technological change are investigated in the thesis: (i) technology spillovers and (ii) R&D investment. In our setting, a major difference between two sources is whether cooperating regions have to pay for their own technology improvement. If technology spillovers are treated as private goods, a country with higher abatement technology can be an attractive partner for other countries to cooperate with, as cooperation on abatement will lead to reduction in abatement costs without paying for technology improvement. Within the context of assumptions used here, quantitative results suggest that the spillovers between cooperating regions may not be effective enough to overcome the free-riding incentives for non-cooperative countries, as large emission reduction by cooperating countries will bring large benefits also to non-cooperating countries.

In the case of ITC, regional R&D investments improve the stock of knowledge which leads to low abatement costs. When cooperating with other regions, signatories can obtain higher payoffs than in All Singletons, which is driven by increased investment after cooperation on abatement. ITC plays a significant role in increasing global payoffs, however, it also increases free-rider incentives as non-signatories also benefit from a large reduction made by signatories. As long as R&D investment increases payoffs under cooperation on abatement and the gains from cooperation are large, the difference in the source of technological change will not provide any significant differences in terms of improvement in the success of a climate agreement.

The Kyoto Protocol has provided us with opportunities to search for successful international cooperation on climate change, although there are some issues to be improved. One of the issues lies in the poorly designed setting of stabilisation targets or of allocation for emissions permits for Annex I countries. The settings in which the permits are allocated based on emissions in 1990 levels benefit historically large emitters, so that a country with a higher energy efficiency in 1990 will be worse off than other countries. In addition, this historical emission-based setting may not be attractive for developing countries that expect high economic growth in the 21st century, as examined in Chapter 3. Therefore, ongoing discussion on regional stabilisation targets or allocation of emission permits should take into account that the estimation of the reduction potential by region be based on regional characteristics such as incentive structures, technology levels and structures of industries. It is apparent in the ongoing international negotiations on controlling climate change that achieving global consensus is a difficult task, as regions have different characteristics regarding benefits and costs of global warming. It will be plausible to have a partial cooperation which consists of regions which have significant potentials for controlling climate change cost-effectively, rather than full cooperation. Flexible measures which lead to a win-win cooperation for the countries involved will be necessary to achieve a successful partial cooperation.

In case of technology spillovers, a provider of high technology does not necessarily have benefits from cooperation. The country with more advanced abatement technologies does not really obtain a strong up-grade of its technology from its partners, but the partners may provide potentials to abate emissions at lower costs.

6.4. Scope for future research

Finally, I present some topics for future research in the domains of (i) the applied modelling, (ii) technological change, and (iii) international agreements. First of all, in our climate module, we assume that damage is a linear function of past and current global abatement levels. This assumption is supported by the econometric findings by Dellink et al. (2008a). The linearity of the damage function guarantees dominant abatement strategies for regions. To relax the assumption of the dominant strategies for estimating the degree of carbon leakage among regions, it will be worthwhile to apply the state of the art of carbon cycle and climate system descriptions, which imply a different relationship between carbon cycle and CO_2 concentrations in the atmosphere. Moreover, further examination on regional damage from global warming is needed as the success of a international climate agreement is sensitive to the regional shares of global damages.

Second, regarding drivers of technological change, a possible extension is to examine the impacts of learning-by-doing on the stability of coalitions where abatement costs are a function of the abatement levels, and marginal abatement costs are decreasing through accumulated experience of abatement. Different implication in the context of abatement strategies over time will be obtained relative to the case of R&D investments.

The final extension involves the international framework for controlling climate change. As one of the alternatives to the Kyoto Protocol with cooperation on emission abatement, an agreement on technological cooperation may emerge. The development and diffusion of cleaner technologies is now on the negotiation agenda for a post-2012 climate regime. Parallel to the negotiation on emission abatement under the Kyoto Protocol, technology-oriented agreements have been established bilaterally and/or multilaterally outside the UN framework, such as the Asia-Pacific Partnership on Clean Development and Climate (APP). Although the APP does not provide a cap on total emissions, it has been active in reducing emissions through an improvement of energy efficiency, involving participation from major emitters, such as USA, China and India. A technology-oriented agreement on a voluntary basis can be an effective framework in the sense that it induces participation from developing countries under the cooperation with developed countries, and it considers industries which are exposed to international competition by cooperating across countries.

It is left to future research to investigate the impacts of technology cooperation where signatories work together to invest in R&D for improvement in energy efficiency which contributes to reduction in CO_2 emissions. It will be worthwhile to examine whether this type of agreements on technology cooperation increases incentives to join the agreement and contributes to the stability of climate coalitions.

The reader should be aware that a central assumption in the game-theoretical analysis applied in this thesis is that regions act on the basis of self-interest. An interesting research question is how elements of altruistic behaviour would affect the outcomes.

Summary

Global warming is one of the crucial challenges that the world is facing now. The allocation of reduction efforts among regions has long been negotiated and it will not be an easy task to achieve a full cooperation with stringent targets.

The thesis examines the formation of international climate agreements (ICAs) in a game-theoretic framework. I analyse strategic behaviour of a number of regions to reduce greenhouse gas (GHG) emissions. Game-theoretic approaches have been widely used to examine an interaction between countries in the negotiations on climate change, and have emphasised difficulties in designing such a voluntary agreement. This thesis provides a systematic approach to examine the impacts of designs of the ICAs on the success of ICAs.

In Chapter 2, I present the basic structure of the STACO-2.1 model, composed of a game-theoretic framework and applied features, with specifications and calibrations of the functions used in the model. I analyse the results for (i) the All Singletons coalition structure, (ii) the Grand coalition structure, and (iii) all stable coalition structures. This case can serve as a suitable reference point for the analysis of the various mechanisms in the following chapters. The results show that a coalition of EU15 and Japan is stable. Both regions have an interest in cooperation, because of their higher marginal benefits from abatement. The results suggest that regions with relatively lower marginal abatement costs and lower marginal benefits would be worse off when they cooperate as they bear the largest burden of abatement but obtain the least benefits. This suggests that transfer schemes can be effective to stabilise larger coalitions.

In Chapter 3, I analyse the impact of pragmatic and optimal transfer schemes on the incentives for regions to join international climate agreements. With an applied model that comprises twelve world regions I investigate: (i) a benchmark without transfers, (ii) scenarios with allocation-based rules where coalition members receive tradable emission permits proportional to initial or future emissions, (iii) scenarios with outcome-based rules where the coalition surplus is distributed proportional to the emissions, and (iv) a scenario based on an optimal sharing rule where the coalition surplus is distributed proportional to outside option payoffs.

I find that when the transfer scheme is poorly designed in the sense that it increases incentives to free-ride, the best performing stable coalition may be worse than in the case of no transfers. In our applied setting this occurs for the initial-emissions-based tradable permit system (grandfathering).

Improvements of the initial-emissions-based tradable permit system, such as a tradable permit system based on the full path of emissions or a surplus sharing scheme, do enhance stability of coalitions. For the optimal transfer scheme we find that larger coalitions, which include key players such as the United States and China, can be stable, but no transfer scheme is capable of stabilising the Grand Coalition. The results show that optimal transfers perform much better than more pragmatic transfer schemes. Such schemes, however, require detailed insight into the incentive structures of the regions. Therefore, there is a trade-off between more pragmatic schemes that may be easier to implement but are hardly effective and optimal transfers which may be hard to achieve in actual negotiations.

In Chapter 4, I explore how different technology spillover mechanisms among regions can influence the incentives to join and stabilise an international agreement. Several theories on the impact of technology spillovers are evaluated by simulating a range of alternative specifications: (i) no spillovers, (ii) internal spillovers, (iii) global spillovers, (iv) coalitional spillovers, and (v) extended spillovers (all possible technology spillovers).

I find that spillovers are a good instrument to increase the abatement efforts of coalitions and reduce the associated costs. In our setting, however, they cannot overcome the strong free-rider incentives that are present in larger coalitions. Therefore, technology spillovers do not substantially increase the success of international environmental agreements. This conclusion is robust with respect to the specification of technology spillovers.

In Chapter 5, I relax the assumption of exogenous technological change analysed in the previous chapters and explore the impacts of induced technological change (ITC) on the stability of an international climate agreement. To examine the impacts of different specifications of technological change in reducing abatement costs on regional incentives, three scenarios are investigated: (i) no technological change (noTC), (ii) exogenous technological change (ExTC), and (iii) induced technological change (ITC). Technological change is induced by the abatement targets. It reduces emissions through regional R&D investments, which lowers abatement costs over time. The results reveal that the set of best-performing stable coalitions and the associated indicator of success hardly change between the scenario of noTC and ExTC, but ITC does produce a different set of stable coalitions. Coalitions that are stable in all three scenarios can achieve the highest NPV of payoffs in the case of ITC. The results indicate that coalition members increase their investments and abatement substantially when they cooperate in the case of ITC. As a result of increased global abatement, not only coalition members but also singletons obtain high benefits, which leads to decrease (increase) in the number of internally (externally) stable coalitions. Therefore, ITC might improve global payoffs, however, at the same time it tends to increase free-rider incentives due to the public good nature of global warming. I find that the indicator of success is quite robust with respect to the productivity of R&D. Furthermore, the number of internally (externally) stable coalitions decreases (increases) with the value of the productivity of R&D, as free-riding incentives increase. I find that stability is sensitive with respect to changes of the discount rate. The number of stable coalitions increases with the value of discount rate. In both cases, the dominating mechanism is that higher productivity of R&D or a lower discount rate increase the payoffs of regions, and thus increase the gains of cooperation, but also increase free-rider incentives.

Overall, the main finding of this thesis is that well-designed mechanisms can facilitate successful formation of partial coalitions, although global cooperation is still hard to achieve. The reason lies in the public good nature of global warming and regional characteristics of benefits and costs. Following insights of the current literature on transfer schemes, our systematic analysis supports the fact that an incentive to join the agreement is highly sensitive to the design of transfers. For different designs of transfer schemes, there is a trade-off between feasibility and effectiveness. Allocation-based transfer schemes are easier to implement than an optimal transfer scheme which can achieve more successful coalition formation in the context of global payoffs and CO_2 emissions.

The role of technological change has received significant attentions to reduce a significant amount of emissions. Two types of sources of technological change are investigated in the thesis: (i) technology spillovers and (ii) R&D investment. If technology spillovers are treated as private goods, a country with higher abatement technology can be an attractive partner for other countries to cooperate with, as cooperation on abatement will lead to reduction in abatement costs without paying for technology improvement. Within the context of assumptions used here, quantitative results suggest that the spillovers between cooperating regions may not be effective enough to overcome the free-riding incentives for non-cooperative countries, as large emission reduction by cooperating countries will bring large benefits also to non-cooperating countries.

In the case of induced technological change, regional R&D investments improve the stock of knowledge which leads to low abatement costs. When cooperating with other regions, signatories can obtain higher payoffs than in All Singletons, which is driven by increased investment after cooperation on abatement. ITC plays a significant role in increasing global payoffs, however, it also increases free-rider incentives as non-signatories also benefit from a large reduction made by signatories. As long as R&D investments increase payoffs under cooperation on abatement and the gains from cooperation are large, the difference in the source of technological change will not provide any significant differences in terms of improvement in the success of a climate agreement.

The Kyoto Protocol was the first significant step that provided stimulus for search for successful international cooperation on climate change policies, although there are issues to be improved. Now, negotiation on the post Kyoto framework has been taking place with an aim of large cooperation on tackling climate change among countries. Flexible measures which lead to a win-win cooperation for the countries involved will continue to play a crucial role in achieving a successful cooperation and the search for well-designed mechanisms will be further pursued.

Samenvatting

De opwarming van de aarde is een van de grootste uitdagingen waarmee de wereld op dit moment wordt geconfronteerd. Tussen de verschillende regio's is lang onderhandeld over de verdeling van de inspanningen voor emissiereductie en het blijkt niet eenvoudig te zijn om volledige samenwerking met strikte reductiedoelstellingen te bereiken.

Dit proefschrift analyseert de formatie van internationale klimaatverdragen in een speltheoretisch kader. Ik analyseer het strategisch gedrag van een aantal regio's die gericht zijn op het reduceren van broeikasgasemissies. Speltheoretische modellen worden gebruikt om de interactie tussen landen die onderhandelen over klimaatverandering te analyseren. De modellen benadrukken dat het moeilijk is om tot een vrijwillige overeenkomst te komen. Dit proefschrift gebruikt een systematische methode om de invloed van het ontwerp van internationale klimaatverdragen op het succes van internationale klimaatverdragen te analyseren.

In hoofdstuk 2 presenteer ik de basisstructuur van het model STACO-2.1 (STAbiliteit van COalities), dat bestaat uit een speltheoretische kader en toegepaste modules met specificaties van de in het model gebruikte functies. Ik analyseer de resultaten voor (i) de 'ieder-voor-zich' coalitiestructuur (All Singletons coalition structure), (ii) de mondiale coalitiestructuur (Grand coalition), en (iii) alle stabiele coalitiestructuren. Deze analyse vormt de basis voor het verder onderzoeken van de verschillende mechanismen in de volgende hoofdstukken. De resultaten laten zien dat een coalitie van EU15 en Japan stabiel is. Beide regio's hebben interesse in samenwerking omdat zij beide hoge marginale baten ontvangen van emissiereductie. De resultaten suggereren dat regio's met relatief lage marginale emissiereductiekosten en lage marginale baten slechter af zijn wanneer zij samenwerken, omdat zij dan de grootste last dragen, maar de minste baten ontvangen. Een systeem van financiële herverdeling kan effectief zijn om grotere stabiele coalities te vormen.

In hoofdstuk 3 analyseer ik de invloed van pragmatische en optimale systemen voor financiële herverdeling op het stimuleren van deelname van verschillende regio's aan internationale klimaatverdragen. Ik analyseer met een toegepast model, dat bestaat uit twaalf wereld regio's, de volgende onderdelen: (i) een benchmark zonder financiële herverdeling, (ii) scenario's waar coalitieleden verhandelbare emissierechten ontvangen die proportioneel gelijk zijn aan de emissies in een basisjaar of aan toekomstige emissies, (iii) scenario's waar het surplus van de coalitie (wat alle betrokken landen samen aan extra netto baten genereren) proportioneel verdeeld wordt in relatie tot de hoeveelheid emissies en (iv) een scenario gebaseerd op een optimale verdeelregel, waar het surplus van de coalitie zodanig verdeeld wordt dat de motivatie om niet mee te werken wordt geminimaliseerd.

De resultaten geven aan dat een gebrekkig ontworpen herverdelingsschema mogelijk slechter werkt dan een systeem zonder financiële herverdeling, omdat de prikkels om zwart te rijden (te 'free-riden') stijgen. In de toegepaste setting gebeurt dit wanneer de toedeling van verhandelbare emissierechten gebaseerd wordt op de emissies in een basisjaar ('grandfathering'). De stabiliteit van de coalitie wordt bevorderd door een betere allocatie van emissierechten, door bijvoorbeeld een systeem van verhandelbare emissierechten te baseren op het volledige toekomstige emissiepad of een verdeelschema gebaseerd op het surplus van de coalitie. Met het optimale systeem van financiële herverdeling vinden we grotere coalities die stabiel kunnen zijn, met belangrijke spelers zoals de Verenigde Staten en China. Echter er bestaat geen systeem van financiële herverdeling dat leidt tot een stabilisering van de Grote coalitie. De resultaten laten zien dat de optimale financiële herverdeling beter functioneert dan de meer pragmatische systemen van herverdeling. Deze systemen vereisen echter een meer gedetailleerde kennis van de economische prikkels voor de verschillende regio's. Hierdoor ontstaat er een afweging tussen meer pragmatische systemen die makkelijker zijn te implementeren maar weinig effectief zijn of optimale financiële herverdeling, die echter moeilijker zijn te bewerkstellingen in de huidige onderhandelingen.

In hoofdstuk 4 onderzoek ik hoe de verschillende mechanismen van technologische uitstralingseffecten (spillover) van verschillende regio's invloed kunnen hebben op de stimulans om deel te nemen aan en het stabiliseren van een internationaal verdrag. Ik evalueer meerdere theorieën over de invloed van technologische uitstralingseffecten door het simuleren van de volgende reeks van alternatieve specificaties: (i) geen uitstralingseffecten, (ii) interne uitstralingseffecten (alleen binnen de eigen regio), (iii) mondiale uitstralingseffecten (naar de hele wereld), (iv) coalitionele uitstralingseffecten (alleen tussen samenwerkende landen), en (v) volledige uitstralingseffecten (alle hiervoor genoemde technologische uitstralingseffecten tezamen).

De resultaten laten zien dat uitstralingseffecten een goed instrument zijn om de emissiereductie-inspanning van coalities te verhogen en de gerelateerde kosten te reduceren. In onze setting kunnen uitstralingseffecten echter niet de sterk aanwezige prikkels om zwart te rijden, die aanwezig zijn bij grote coalities, voorkomen. Technologische uitstralingseffecten leiden dus niet automatisch tot een aanzienlijke toename van het succes van international milieuverdragen. Deze conclusie is robuust in relatie tot de specificaties van technologische uitstralingseffecten.

In hoofdstuk 5 versoepel ik de aanname van exogene technologische verandering zoals geanalyseerd in de voorgaande hoofdstukken en onderzoek ik het effect van geïnduceerde technologische verandering (ITC) op de stabiliteit van een internationaal klimaatverdrag. Drie scenario's zijn onderzocht om het effect van verschillende specificaties van technologische verandering op het reduceren van emissiekosten op regionale initiatieven te bepalen. Deze scenario's zijn: (i) geen technologische verandering (noTC), (ii) exogene technologische verandering (ExTC), en (iii) geïnduceerde technologische verandering (ITC). Technologische verandering reduceert emissies doordat regionale R&D investeringen leiden tot een verlaging van de emissiekosten in de toekomst. De resultaten laten zien dat de set van meest effectieve stabiele coalities en de gerelateerde indicator van succes bijna niet veranderen tussen de scenario's noTC en ExTC, echter scenario ITC produceert een andere set van stabiele coalities. De coalities die stabiel zijn in alle drie de scenario's, hebben de hoogste netto contante waarde van de opbrengsten in scenario ITC. Door de toename van mondiale emissiereductie zullen niet alleen de coalitieleden maar ook de buitenstaanders (singletons) hogere baten ontvangen, en dit leidt tot een afname (toename) van het aantal interne (externe) stabiele coalities. ITC kan leiden tot een toename van de mondiale opbrengsten, maar tegelijkertijd tot een toename van de prikkels om zwart te rijden vanwege het publieke goed karakter van klimaatverandering. De resultaten laten zien dat de indicator van succes robuust is ten aanzien van de productiviteit van R&D. Het aantal interne (externe) stabiele coalities daalt (stijgt) met de waarde van de productiviteit van R&D, wanneer de prikkels om zwart te rijden stijgen. Welke coalities stabiel zijn hangt af van de discontovoet. Een stijging van de discontovoet leidt tot een toename van het aantal stabiele coalities. Het dominerende mechanisme is dat een hogere productiviteit van R&D en/of een lagere discontovoet beide leiden tot een toename van de opbrengsten van de regio's, waardoor de winst om samen te werken toeneemt, maar dit leidt ook tot een toename van het zwartrijdergedrag.

De belangrijkste uitkomst van dit proefschrift is dat goed ontworpen mechanismen de succesvolle formatie van gedeeltelijke coalities kunnen faciliteren, alhoewel het ook dan moeilijk is om mondiale samenwerking tot stand te brengen. De redenen hiervoor zijn het publieke goed karakter van klimaatverandering en de kosten en baten die per regio verschillen. In navolging van de inzichten in de huidige literatuur over financiële herverdeling bevestigt onze systematische analyse dat een initiatief om deel te nemen aan een verdrag erg gevoelig is voor het ontwerp van het systeem van financiële herverdeling. Er is een afweging tussen haalbaarheid en effectiviteit voor verschillende ontwerpen van financiële herverdeling. Systemen van financiële herverdeling die gebaseerd zijn op allocatie zijn makkelijker te implementeren dan een optimaal systeem van financiële herverdeling. Hierdoor ontstaan er meer succesvolle coalities in de context van mondiale opbrengsten en CO_2 emissies.

De rol van technologische verandering heeft veel aandacht gekregen als middel om emissies te reduceren. Twee verschillende vormen van technologische verandering zijn onderzocht in dit proefschrift, namelijk (i) technologische uitstralingseffecten, en (ii) geïnduceerde technologische verandering. Wanneer technologische uitstralingseffecten worden gedefinieerd als een privaat goed, dan zal een land met een hoger niveau aan emissiereductie technologie een interessantere partner zijn voor andere landen om mee samen te werken. Voor deze landen zal samenwerking leiden tot een afname van de emissiereductiekosten zonder te betalen voor technologische verandering. Uitgaande van de veronderstellingen in het toegepaste model duiden de kwantitatieve resultaten erop dat uitstralingseffecten tussen samenwerkende regio's mogelijk niet effectief genoeg zijn om prikkels van zwart rijden voor niet-samenwerkende landen te voorkomen, omdat hoge emissiereducties van samenwerkende landen ook grote baten opleveren voor niet-samenwerkende landen.

In het geval van geïnduceerde technologische verandering (ITC) leiden regionale R&D investeringen tot een verbetering van het kennisniveau wat leidt tot lagere emissiereductie kosten. Wanneer ondertekenaars van een verdrag samenwerken met andere regio’s kunnen zij hogere opbrengsten ontvangen dan in het geval van ‘ieder-voor-zich’ (All Singletons), dit komt door een toename van investeringen als gevolg van samenwerking. ITC speelt een belangrijke rol in de toename van de mondiale opbrengsten, maar leidt ook tot een toename van de prikkels om zwart te rijden, omdat niet-ondertekenaars ook de baten ontvangen van de emissiereductie van de ondertekenaars. Als R&D investeringen leiden tot een toename van de opbrengsten van samenwerking en de baten van samenwerking groot zijn, dan heeft de herkomst van de technologische verandering geen invloed op de toename van het succes van een klimaatverdrag.

Het Kyoto Protocol was een belangrijke eerste stap in de zoektocht naar succesvolle internationale samenwerking op het gebied van klimaatbeleid, hoewel er nog verbeteringen mogelijk zijn. Op dit moment vinden er onderhandelingen plaats over een post-Kyoto verdrag, met als doel om klimaatverandering in een nog bredere samenwerking tussen verschillende landen aan te pakken. Flexibele maatregelen blijven daarbij een cruciale rol spelen om succesvolle win-win samenwerking tussen landen te bewerkstellingen en de zoektocht naar goed ontworpen mechanismen zal voortduren.

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Miyuki Nagashima was born on July 16^{th}, 1973 in Tokyo, Japan. In 2001 she obtained a Masters degree in International Public Policy at Osaka School of International Public Policy, Osaka University, with a focus on Environmental Economics. She graduated with Honours, First in Class in 2001 at the Masters Programme. In 2004, she obtained a scholarship from the Rotary Foundation to do research at the Environmental Economics and Natural Resources Group at Wageningen University as a guest researcher. In 2006 she started her Ph.D. research at the Environmental Economics and Natural Resources Group, Wageningen University. During her Ph.D. studies, in 2007 she joined the Young Scientists Summer Programme at the International Institute for Applied Systems Analysis (IIASA), in Laxenburg, Austria, financed by the Netherlands Organisation for Scientific Research (NWO). Between 2008 and 2009, she worked as a researcher at the Systems Analysis Group of the Research Institute of Technology for the Earth (RITE) in Kyoto, Japan. Her Ph.D. research papers have been published in peer-reviewed international journals and presented at international conferences. In 2010 she successfully completed the doctoral training programme at the Research School for Socio-Economic and Natural Sciences of the Environment (SENSE). She is currently employed as a Junior Professional Officer at the Analysis & Methods subprogramme of Adaptation, Technology and Science Programme at the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat in Bonn, Germany.

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