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ORIGINAL PAPER

Stability of climate coalitions in a cartel formation game

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Abstract This paper analyses the formation and stability of coalitions to form international environmental agreements. We present and apply the Stability of coalitions model to assess the internal and external stability of all possible coalition structures in a cartel formation game; first under the assumption that no transfers take place and second for a transfer scheme. One important novelty of this paper is the analysis of the incentive structure of twelve regions for all possible combinations of (cartel) coalitions in an empirical setting with asymmetric regions. We show that stable coalitions can emerge only if benefits from global abatement are sufficiently high or if an appropriate transfer scheme is introduced.

Keywords International environmental agreements · Kyoto-Protocol · Cartel formation · Stability of coalitions · Non-cooperative game theory

JEL Classification Numbers C72 · H41 · Q25

1. Introduction

An important topic in environmental economics is how to reach agreements on environmental policies. This does not only apply to local, regional and national problems but also to transboundary problems (like acid rain), and global problems (like climate change). For many local, regional and national problems, solutions have been introduced based on public

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decision making on environmental standards or policy goals, and the ways and means to reach them. For *international* problems, like the problem of global warming, serious problems arise because a supra-national body for governance and decision making that can impose binding rules for the policies to be implemented (including monitoring of compliance and enforcement) is not available, and we therefore have to rely on voluntary international agreements.

Greenhouse gases have accumulated in the atmosphere for centuries and the decay of most greenhouse gases takes at least 50 years. Countries continue to emit greenhouse gases and the global warming problem will persist for at least the next century. Consequently, it is important to design efficient long-term climate policies in an international setting. This implies that a detailed understanding of the incentives that countries and regions have to cooperate is of utmost importance.

Two game theoretical approaches of the formation of international environmental agreements (IEAs) have stressed the difficulties of designing self-enforcing treaties because of free-riding. The *cooperative approach* has focused on transfer schemes ensuring stability of the efficient grand coalition implementing socially optimal abatement levels (e.g., Chander and Tulkens 1995, 1997; Germain et al. 2003).[1] Empirical studies include Eyckmans and Tulkens (2003), Germain et al. (2003) and Kaitala et al. (1995). The *non-cooperative approach* that we follow in this paper has focused on explaining the problems of forming large and effective coalitions. A coalition is *internally stable* if no coalition member has an incentive to leave the coalition to become a singleton and *externally stable* if no singleton has an incentive to join the coalition.[2] Key results that emerge from this literature (e.g., Barrett 1994, 1997, Bauer 1992, Carraro and Siniscalco 1993, Hoel 1992, Hoel and Schneider 1997, Jeppesen and Andersen 1998 and Rubio and Ulph 2001) are: (a) only small coalitions are stable and (b) whenever full cooperation (social optimum) would generate large global welfare gains compared to no cooperation (Nash equilibrium), stable coalitions achieve only little.

The non-cooperative approach helps to explain the problems of cooperation in international pollution control and most results in the literature rely on simulations and have been derived for very specific assumptions, such as a static payoff structure and/or symmetric players. There are only few empirical studies and most are simplified either on the dynamics (e.g., Botteon and Carraro 1997, 1998; Tol 2001) or on the regional disaggregation of the climate problem (i.e., number of players; e.g., Bosello et al. 2003; Buchner et al. 2002; Eyckmans and Finus 2003).

The aim of this paper is to empirically investigate the incentive structure of world regions in the negotiations on an international climate agreement. For this, we analyze the formation and stability of possible coalition structures in a cartel formation game and discuss some policy implications of our results. The paper tries to answer the following questions in particular: How much emission reduction would occur if countries do not cooperate in an international agreement? Would a coalition of industrialized countries be stable? What are the global gains of full cooperation in the grand coalition and will this coalition be stable? Do transfer mechanisms contribute to the formation of larger stable coalitions?

Our paper adds to the tradition of empirical studies based on the non-cooperative approach in several ways. First, our model captures some important features of the dynamic nature of greenhouse gas accumulation by including the accumulation of greenhouse gases over a period of hundred years under stationary abatement strategies. Second, the effect of hetero-

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[1] For an overview, see Finus (2001, 2003a). A more general discussion of cooperative and non-cooperative coalition theory is provided in Bloch (1997).

[2] Recent advances in non-cooperative coalition theory are discussed in Bloch (1997) and Yi (1997). Applications in the context of IEAs are found in Finus (2003b) and Finus and Rundshagen (2003a,b)

geneity for coalition formation is expressed by estimated abatement costs and damage costs of climate change based on well-known sources. Third, the analysis comprises twelve world regions that render the interactions between actors more interesting than studies that consider fewer regions. In this paper, we limit ourselves to cartel coalitions, i.e., we only allow for one coalition.[3]

In the following, we lay out the building blocks of the model in section 2. In section 3, we discuss the environmental and economic implications of coalition formation for our base case. Section 4 provides a sensitivity analysis and includes results on introducing monetary transfers. Section 5 summarizes the main findings and concludes with a discussion of policy implications. Details on the calibration of the model can be found in the Appendix.

2. Description of the main structure of STACO

2.1. Description of the game

In the STAbility of COalitions model (STACO) that we employ, coalition formation is modeled as a *two-stage game* (Bloch 1997). In the *first stage*, countries or regions[4] decide on their *membership* in a coalition; in the *second stage*, coalition members choose their *abatement strategies*.

In the *first stage*, we assume that there are two membership strategies available to regions: "I do not want to sign the agreement" and "I want to become a member of the climate treaty". Technically, this implies that regions that announce not to sign become a singleton and those that announce to sign become a member of a cartel coalition. For 12 world regions, this gives rise to 4084 different *coalition structures*.

In the *second stage*, regions choose their abatement strategies based on the following payoff function for each region i, $i = 1, \ldots, N$:[5]

$$\pi_i(q) = \sum_{t=1}^{T} (1 + r_i)^{-t} (B_{it}(q_t) - \mathrm{AC}_{it}(q_{it})), \tag{1}$$

where T denotes the time horizon, $t = 1, 2, \ldots, T$, r_i is the discount rate of country i, B_{it} are benefits from global abatement $q_t = \sum_{i=1}^{N} q_{it}$, AC_{it} are abatement costs from individual abatement q_{it} and q is an abatement matrix of dimension $N \times T$. Benefits from global abatement are derived from reduced environmental damages caused by greenhouse gas emissions. (Details on the calibration of the payoff function are given in the Appendix.)

Following the literature (cf. Bloch 1997), we assume that the coalition and single regions play a Nash equilibrium in terms of abatement strategies. This has also be called a partial

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[3] This assumption is in line with the observation that all existing IEAs are single coalition agreements. Nevertheless, recent approaches in coalition theory have investigated the theoretical possibility of multiple coalitions (see the reference cited in footnote 2 and additionally Bosello et al. 2003; Eyckmans and Finus 2003 for instance). The main finding is that if coalition formation is not restricted to a single coalition, coalition structures with multiple coalitions may well emerge in equilibrium that may perform better than single coalitions in terms of global welfare and global abatement. However, the results are not innocuous in terms of real world interpretations as explained for instance in Finus (2003a).

[4] In the remainder of the paper, we will refer to "regions".

[5] We make the standard assumptions: $\forall$i $\in$ I, $q_{it} \in [0, e_{it}^{\mathrm{BAU}}]$ and at each time t: $B'_{it} > 0$, $B''_{it} \leq 0$, $\mathrm{AC}'_{it} > 0$, and $\mathrm{AC}''_{it} > 0$, where primes denote derivatives and e_{it}^{BAU} is the emission level in the business-as-usual scenario (BAU). Our calibration of these functions results in a unique interior solution for optimal abatement levels.

Nash equilibrium between the coalition and single regions by Chander and Tulkens (1997). That is, non-signatories choose their abatement strategies such as to maximize their own payoff, taking the abatement strategies of all other regions as given. Signatories choose their abatement such as to maximize the aggregate payoff to their coalition, taking the abatement strategies of all outsiders as given. Consequently, the "All Singletons Coalition Structure", where none of the regions signs the agreement, implies an equilibrium abatement strategy vector corresponding to the "classical" Nash equilibrium; similarly, the "Grand Coalition Structure", where all regions are member of the coalition, reflects the "classical" social optimum. The highest global welfare will be obtained in the Grand Coalition Structure.

We call a coalition structure c^* *stable* if no country has an incentive to change its membership strategy, given the strategies of all other regions. This corresponds to the definition of internal stability and external stability mentioned in the Section 1.

For the dynamic aspects of the model we note the following. The STACO model considers a time period of 100 years in which emissions of the various regions will increase under business as usual when no emission reduction occurs. Regions decide on the basis of the discounted net benefits over this period by which percentage they will reduce their emissions as compared to the base year level for 2010. In order to simplify the analysis, we impose that this emission reduction percentage remains stable for the entire time period. Net benefits of each region depend on the abatement cost and the benefits of reduced damages of climate change. These damages are calculated on the basis of the accumulation of greenhouse gases, the resulting temperature change and the expected impacts on the various regions in the world. We consider this specification to be useful because we are primarily interested in the overall impact of the long-term stationary abatement policies of regions. To this end, an analysis of the net present value of the discounted stream of future pay-offs from stationary abatement strategies suffices.[6]

Though we do not pay special attention to the policy instruments that should be used to implement the IEA at a regional level (i.e., whether the policies are implemented by means of carbon taxes or tradable permits or direct regulation), our calculation of the optimal allocation of abatement efforts implicitly assumes that an efficient policy instrument, such as tradable permits or carbon taxes, is implemented within the coalition to achieve the targets formulated in the agreement. Similarly, efficient policy instruments are implicitly underlying the singletons behavior. In this context, it is important to note that we assume initially in our analysis that no transfers take place between members of the coalition, and that no transfers occur between other regions. In section 4 on sensitivity analysis and transfers, we will include a transfer mechanism.

2.2. Calibration of the model

In this section, we describe payoff functions (1) and their constituting elements. Our analysis takes 2010 as the base year and covers a period of 100 years (2011–2110) in order to capture the long-run effects of the global warming problem.

The philosophy behind the construction of our empirical model comprises two items. First, the model must be simple enough to be tractable for a game theoretical analysis and it should reflect important results and features of optimal growth models in terms of the development of global emissions and concentration of greenhouse gases over the relevant period. Therefore, we base our calibration of global emissions, the stock of greenhouse gases

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[6] We acknowledge that the path of abatement influences the outcomes of the model, as earlier abatement implies lower future damages. This strengthens the importance of carrying out a sensitivity analysis on the level of (future) damages.

Table 1 Emissions, benefit and abatement cost parameters

Regions	Emissions in 2010 (Gton)	Share of global benefits s_i		Abatement cost parameter	
		Calibration I	Calibration II	α_i	β_i
USA	2.42	0.226	0.124	0.0005	0.00398
JPN	0.56	0.173	0.114	0.0155	0.18160
EEC	1.4	0.236	0.064	0.0024	0.01503
OOE	0.62	0.035	0.017	0.0083	0
EET	0.51	0.013	0.013	0.0079	0.00486
FSU	1	0.068	0.035	0.0023	0.00042
EEX	1.22	0.030	0.030	0.0032	0.03029
CHN	2.36	0.062	0.062	0.00007	0.00239
IND	0.63	0.050	0.171	0.0015	0.00787
DAE	0.41	0.025	0.085	0.0047	0.03774
BRA	0.13	0.015	0.052	0.5612	0.84974
ROW	0.7	0.068	0.233	0.0021	0.00805
World	11.96	$\sum s_i = 1$	$\sum s_i = 1$		

and resulting temperature change on the widely known DICE-model by Nordhaus (1994). Second, our model uses the most disaggregate data currently available for accuracy but also to render the strategic interaction between regions (i.e., players) interesting. This implies that in our model the world is divided into 12 regions: USA (USA), Japan (JPN), European Union (EEC), Other OECD countries (OOE), Central and 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).[7]

For the calibration of the model, we rely on damage cost estimates of Fankhauser (1995) and Tol (1997) and abatement cost estimates of Ellerman and Decaux (1998). Global damages are calibrated to equal 2.7% of GDP when a doubling of CO_2 concentrations occurs. Regional shares in total benefits are displayed in Table 1, together with the parameter values of the abatement cost functions (recalibrated to reflect our model horizon, see Appendix). For reference, we also include expected regional emissions in 2010 in this table.

Marginal abatement cost functions are graphically represented in Figure 1. From the graph, it is evident that CHN and USA have the flattest curves while BRA and JPN have the steepest. Combining the information on abatement costs and benefits, it can easily be conjectured that as the USA has relatively low abatement costs and high damages, the regional payoff from abatement is higher than in other regions. BRA that is facing high abatement costs and a relatively low share in global damages has small incentives to reduce emissions.

Together with the payoff functions and the functions that describe the accumulation of greenhouse gases and concentrations, the benefit and abatement cost functions constitute the empirical part of STACO.

Though STACO captures important dynamic aspects of climate change, it is *de facto* a one-shot game because of stationary abatement strategies (i.e., the emission reduction percentage for a region once it has been chosen, remains constant over the full time period).

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[7] EEC comprises the 15 countries of the European Union as of 1995. OOE includes among other countries Canada, Australia and New Zealand. EET includes for instance Hungary, Poland, and Czech Republic. EEX includes for example the Middle East Countries, Mexico, Venezuela and Indonesia. DAE comprises South Korea, Philippines, Thailand, and Singapore. ROW includes for instance South Africa, Morocco and many countries in Latin America and Asia. (For details, see Babiker et al. 2001.)

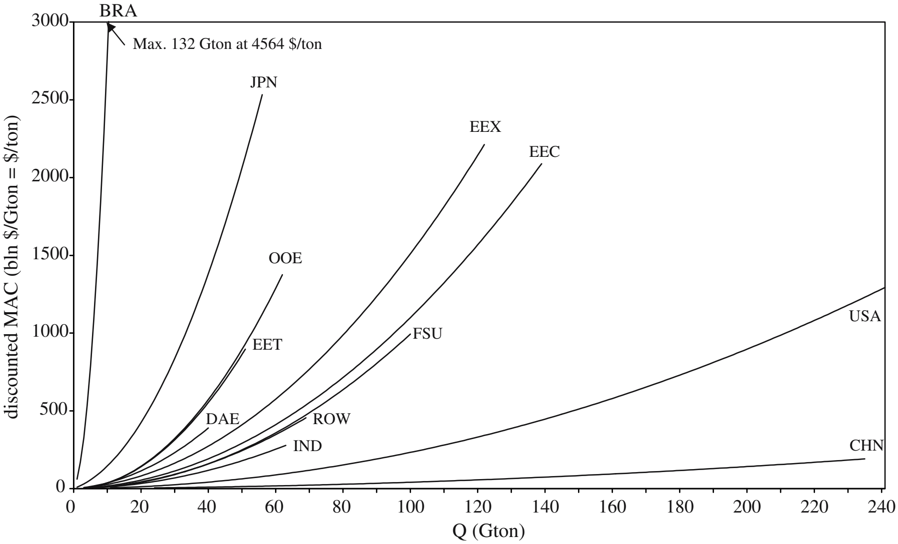

Fig. 1 Discounted marginal abatement cost functions

We choose this specification to simplify the model structure. This simplification seems to be justified because we also assume that the decision to join a coalition or to remain a singleton is based on discounted payoffs. Hence, only aggregate magnitudes matter in our simple model which are very close to more sophisticated models (see also footnote 6). In other words, in our analysis, we focus on the stability of coalition structures, not on detailed predictions of economic growth and welfare in the various regions. The calibration on the basis of the DICE model and the EPPA model ensures that the model mimics larger models on the focal issues of the stock of GHGs, abatement costs and benefits.

The value of the discount rate cannot be taken from data. The discount rate is assumed to be 2%, which implies that future costs and damages get more emphasis than under higher discount rates. A sensitivity analysis would allow to analyze the impact of different levels of the discount rate, but that is not the primary focus of our paper.

Details of the calibration of the STACO model are given in the Appendix, including the development of concentrations of greenhouse gases, the regional benefit and abatement cost functions and all parameter values; a more detailed description of the model and details on the calibration procedure are available from Dellink et al. (2003).

2.3. Some basic implications of the model

For the incentive structure of regions, our payoff functions imply the following, assuming Calibration I in the following illustration.[8] First, in any coalition, the flatter a country's marginal abatement cost curve, the higher will be its contribution to joint abatement. Thus, we expect that USA, CHN and ROW will carry a relatively large portion of joint abatement whereas BRA and JPN will carry a low portion. Second, the individual contribution of a country will rise with the number of coalition members with high marginal benefits

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[8] Note that these characteristics of the payoff function depend crucially on the calibrated parameter values of the benefit and abatement cost functions. Hence, the implications on a regional level will vary between Calibrations I and II.

(i.e., high regional shares s_i). Hence, other things being equal, if USA, JPN and the EEC are members of a coalition, this will require higher abatement efforts of individual regions than if for instance EEX, BRA and Dynamic Asian countries are members of a coalition. Third, and trivially, regions with high marginal benefits benefit more from cooperation in terms of reduced damages than those with low marginal benefits. Fourth, as a tendency, regions with relatively high marginal benefits and relatively steep marginal abatement cost curves, like for instance JPN and the EEC, will receive *in the absence of transfers* a high share from the gains from cooperation where the opposite holds for regions with relatively low marginal benefits and flat marginal abatement cost curves like CHN and EET. It is not unrealistic that large abatement efforts are undertaken in developing countries such as CHN, and only little is done in countries such as JPN. The question is, however, who will bear the financial burden for these efforts? It seems likely that in an international climate agreement some compensation payments will become available. Though these are not commonplace in existing IEAs, they are likely to become more popular. The Kyoto Protocol contains several so-called flexible mechanisms for international compensations, including tradable permits, Joint Implementation and the Clean Development Mechanism. These transfers are not included in the analysis and the results that we present in section 3, but will be analyzed using an extended model version in section 4.

3. Results: base case

3.1. Introduction

In order to understand the incentive structure for regions, we start by considering the characteristics of a set of three coalition structures in terms of emission reduction, cost and benefits and net discounted payoff for the various regions. In our base case, we use a global benefit parameter $\gamma_D = 0.027$ as in Tol (1997), regional benefit shares of Calibration I, and abatement parameters as listed in Table 1, subsection 2.2. We discuss first the characteristics of three "benchmark coalition structures": (1) The "*All Singletons Coalition Structure*" with no cooperation (subsection 3.2). (2) The "*Grand Coalition Structure*" with full cooperation (subsection 3.3). (3) The "*Industrialized Countries Coalition Structure*" as an example of partial cooperation (subsection 3.4). In the latter, we assume that the industrialized countries USA, JPN, EEC, OOE, EET and FSU form a coalition. Subsequently, we report on the incentive structure and the stability of all possible coalition structures (subsection 3.5).

3.2. All Singletons Coalition Structure

Table 2 reports results if each region acts as a singleton and no coalition is established. This corresponds to the "classical" Nash equilibrium with no cooperation. Hence, for each country marginal abatement costs are equated to marginal benefits. Annual global emission reduction amounts to only 4.6% which implies a stock of carbon dioxide of 1,561 Gton of CO_2 in 2110. This is about 2.5 times the pre-industrial level. The fact that for the *first tons of abatement* benefits are higher than the costs of abatement explains that even in the absence of any cooperation total emission reductions equal 55 Gton.

At the level of individual regions, it is evident that annual emission reductions vary widely. The reason is large differences between regions in marginal abatement cost curves (see Figure 1 and Table 1) and marginal benefits from abatement (see Table 1). Even in the absence of cooperation, USA has an incentive to annually reduce emissions by 16 Gton; similarly,

Table 2 All Singletons Coalition Structure

Regions	Total emission reduction Gton (over 100 years)	Annual emission reduction percentage of emissions in 2010	Total abatement costs billion US$ over 100 years	Total benefits from abatement billion US$ over 100 years	Payoff billion US$ over 100 years	Marginal abatement costs US$/ton	Marginal benefits US$/ton
USA	16	6.7	53	468	415	8.5	8.5
JPN	1	1.4	2	357	354	6.5	6.5
EEC	7	4.7	24	488	464	8.8	8.8
OOE	2	3.1	1	71	71	1.3	1.3
EET	1	1.8	0	27	27	0.5	0.5
FSU	5	4.9	4	140	135	2.5	2.5
EEX	1	0.7	0	62	62	1.1	1.1
CHN	15	6.6	16	128	112	2.3	2.3
IND	3	5.3	3	103	101	1.9	1.9
DAE	1	1.3	0	52	51	0.9	0.9
BRA	0	0.1	0	32	32	0.6	0.6
ROW	4	5.3	4	141	137	2.5	2.5
World	55	4.6	109	2,069	1,960		

Global stock of carbon dioxide in 2110 equals 1,561 Gton

the low marginal abatement costs of CHN imply relatively large incentives to abate unilaterally. In contrast, regions like BRA, the Dynamic Asian countries and the EEX have virtually no incentive at all to conduct emission reductions by themselves because of steep marginal abatement cost curves and low marginal benefits from abatement. Overall, it is evident that marginal benefits and costs remain at a moderate level.

3.3. Grand Coalition Structure

Table 3 displays results for the Grand Coalition Structure that corresponds to the "classical" global or social optimum with full cooperation. Thus, marginal abatement costs are equal across regions and amount to 37.4 US$/ton – a value that is in the range of many other empirical studies (e.g., Weyant 1999). At the aggregate level, annual emission reduction amounts to 21.4%, exceeding those in the All Singletons Case by a substantial amount. However, not total emissions implied by emission reductions from BAU-emission are important for damages and hence for the benefits from emission reduction but greenhouse gas concentration. Here we find that the difference in concentration in 2110 is more moderate and amounts to a reduction of only 5.5% compared to the All Singletons Case. This is a feature reminiscent also to most integrated assessment models. The reason is that the airborne fraction of CO_2-emissions that remains in the atmosphere is only 64% and the annual natural removal rate of 0.86% levels off differences between both cases over a period of 100 years. However, the total payoff (benefits minus abatement costs) in the Grand Coalition Structure is 6,031 billion US$, more than 3 times the level in the All Singletons Coalition Structure, which implies substantial gains from cooperation. This stresses the importance of cooperation in the case of global warming.

It is evident that USA and CHN have to contribute substantially more than other regions to a globally optimal solution due to their flat marginal abatement cost curves. For EET and CHN a globally optimal solution would not be profitable, as is indicated by bold faced figures in column 6, Table 3. Those regions have to contribute much to cooperation but benefit

Table 3 Grand Coalition Structure

Regions	Total emission reduction	Annual emission reduction	Total abatement costs	Total benefits from abatement	Payoff	Marginal abatement costs	Marginal benefits	Incentive to leave coalition
	Gton (over 100 years)	percentage of emissions in 2010	billion US$ over 100 years	billion US$ over 100 years	billion US$ over 100 years	US$/ton	US$/ton	billion US$ over 100 years
USA [a]	38	15.7	513	2,169	1,656	37.4	8.5	23.6
JPN [a]	4	6.5	63	1,653	1,590	37.4	6.5	−123.8
EEC [a]	16	11.5	229	2,262	2,033	37.4	8.8	−180.1
OOE [a]	10	16.5	127	331	203	37.4	1.3	109.6
EET [a]	10	19.6	130	125	**−6**	37.4	0.5	124.9
FSU [a]	19	19.3	242	647	405	37.4	2.5	178.1
EEX [a]	12	10.2	188	288	99	37.4	1.1	169.9
CHN [a]	96	40.6	1,348	594	**−754**	37.4	2.3	1133.2
IND [a]	22	33.8	295	479	184	37.4	1.9	245.8
DAE [a]	10	25.1	155	239	84	37.4	0.9	142.1
BRA [a]	1	5.5	12	147	135	37.4	0.6	10.0
ROW [a]	19	26.5	250	652	401	37.4	2.5	185.1
World	256	21.4	3,553	9,584	6,031			

Global stock of carbon dioxide in 2110 equals 1,475 Gton

[a] indicates that the region is a coalition member

only little in the form of reduced damages. Thus, we can immediately conclude that without transfers the Grand Coalition cannot be a stable coalition structure.

The last column of Table 3 shows the absolute amount of the gains from leaving the grand coalition, based on single deviations. For example, if the USA were to leave the Grand Coalition, but the other 11 regions were to remain, the payoff to USA would increase with almost 24 bln US$, almost 1.5% of their total payoff. For most regions, these free-rider gains are very high, sometimes even larger than their payoff, indicating a strong free-rider incentive. Only JPN and the EEC have no interest in leaving the Grand Coalition. As these two regions have high marginal benefits from abatement, they have the highest interest in full cooperation, and – as will be apparent below – also in partial cooperation. A detailed explanation of the underlying mechanisms will be provided below where we report on our stability analysis (subsection 3.5).

3.4. Industrialized Countries Coalition Structure

Table 4 displays results for the Industrialized Countries Coalition Structure. The first six regions (indicated in italics in Table 4) jointly maximize the aggregate payoff to their coalition and therefore marginal abatement costs of these regions are equal. Annual abatement is substantially lower than in the Grand Coalition Structure but almost twice as high as in the All Singletons Coalition Structure. Also, the net benefits of climate policies (3140 billion US$) is 60% higher than without cooperation, showing smaller gains from partial cooperation than from global cooperation.

However, also the Industrialized Countries Coalition Structure is not stable. Three regions, i.e., OOE, EET and FSU, would be worse off in this coalition than if they would leave and they actually have a lower payoff than in the All Singleton Coalition Structure (as indicated by bold faced numbers in Table 4, column 5). Moreover, not only these regions but also the

Table 4 Industrialized Countries Coalition Structure

Regions	Total emission reduction	Annual emission reduction	Total abatement costs	Total benefits from abatement	Payoff	Marginal abatement costs	Marginal benefits	Incentive to change membership strategy
	Gton (over 100 years)	Percentage of emissions in 2010	billion US$ over 100 years	billion US$ over 100 years	billion US$ over 100 years	US$/ton	US$/ton	billion US$ over 100 years
USA^a	32	13.4	332	906	574	28.0	8.5	65.3
JPN^a	3	5.2	38	691	653	28.0	6.5	−46.9
EEC^a	14	9.7	147	945	798	28.0	8.8	−52.8
OOE^a	9	14.3	83	138	**55**	28.0	1.3	70.5
EET^a	9	16.9	85	52	**−33**	28.0	0.5	80.3
FSU^a	17	16.7	157	270	**113**	28.0	2.5	114.6
EEX	1	0.7	0	120	120	1.1	1.1	−113.5
CHN	15	6.6	16	248	232	2.3	2.3	−794.9
IND	3	5.3	3	200	197	1.9	1.9	−172.7
DAE	1	1.3	0	100	99	0.9	0.9	−93.9
BRA	0	0.1	0	61	61	0.6	0.6	−6.5
ROW	4	5.3	4	272	268	2.5	2.5	−137.8
World	107	8.9	865	4,005	3,140			

Global stock of carbon dioxide in 2110 equals 1,539 Gton

[a] indicates that the region is a coalition member

USA have an incentive to leave the coalition, as it is evident from the last column in Table 4.[9] Thus, in this respect, our results illustrate the difficulties of ratifying a coalition in which industrialized countries agree on emission reduction targets, like the Kyoto protocol, but we emphasize that the rules in the Kyoto protocol on CDM and joint implementation make the Kyoto Protocol much more complex than our setting where no transfers or cooperation outside the coalition is considered. Nevertheless, our results may give an intuition for the decision of President Bush to withdraw from the Kyoto Protocol and his announcement to pursue, nevertheless, an "active" national climate policy by recalling our finding that the USA will already conduct relative large emission reductions without any cooperation (see Table 2).

Not surprising, all six outsiders are better off than in the All Singletons Coalition Structure since they benefit from the abatement efforts of the Industrialized Countries Coalition. The fact that none of the outsiders has an incentive to join the coalition is more surprising, which follows from the negative number in the last column in Table 4. The reason is that if already six regions have formed a coalition, joining would imply a substantial increase of abatement efforts for a potential entrant but only a marginal additional benefit from reduced emissions. The finding explains at least partially why it has proven so difficult to encourage developing countries to participate in the Kyoto protocol as advocated in particular by the USA.

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[9] Our finding that the Industrialized Countries Coalition Structure is not profitable for some participants, and hence also not stable, is confirmed by Bosello et al. (2003) in the context of the Kyoto Protocol.

3.5. Stability analysis

We checked all 4,083 non-trivial coalition structures for internal and external stability with an algorithm programmed with the software package Matlab.[10] We found that there is no coalition structure that is both internally and externally stable, under the setting that no transfers are considered. Whereas more than 1,000 coalition structures are externally stable, only 14 coalition structures are internally stable; these are reported in Table 5. All these internally stable coalitions are characterized by low emission reductions and very small gains from cooperation. In all cases, the USA, JPN and the EEC want to join these small internally stable coalitions, making these coalitions externally unstable and hence unstable. This can easily be explained by the high damages in these three regions, which imply large gains from joining a coalition. Consequently, it emerges that the desire of these regions for a stricter climate policy provides an incentive for these regions to join existing small coalitions and hence undermines the stability of these small coalitions. This may seem paradox. Here it is not only the incentive to leave a coalition that undermines stability but also the incentive to join a coalition by "new members": joining means that the enlarged coalition will implement more ambitious abatement targets making it internally unstable for the "old members".

At the other end of the spectrum there are the EET and CHN, which do not want to join any of these internally stable coalitions (except when CHN is already part of the coalition). The incentive structure for EET is such that they have relatively steep marginal abatement costs and very low benefits; especially the low benefits make joining the coalitions unattractive for this region. For CHN, the incentive to stay outside these coalitions can best be explained by the flat marginal abatement costs: if CHN enters a coalition, she would have to agree upon large emission reductions (as this is efficient from a coalitional perspective). This result could be changed when transfer schemes are implemented so that abatement activities in CHN can be funded by other regions.

It is clear that the main problem for cooperation is a lack of internal stability because of strong free-rider incentives. The incentive of a region to join a coalition firstly depends on its contribution to joint abatement, as reflected by its marginal abatement cost curve. The higher the contribution, the higher the incentive to free-ride will be. Secondly, the incentive of a country to join a coalition in terms of its individual benefits from joint abatement is directly linked to its regional share of global benefits s_i. The smaller this value, the less a region benefits from joint abatement and hence the smaller the incentive to cooperate will be. However, not only the absolute values of the free-rider incentives matter, but even more important is the relative difference between regions: only regions with a similar incentive structure form internally stable coalitions.

Though USA, JPN and the EEC have relatively low free-rider incentives, they are not members of any internally stable coalition.[11] All three regions have an incentive to cooperate

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[10] There exist N^2 combinations (i.e., vectors) of announcements whether to join the agreement or not (see section 2). With $N = 12$ regions, this gives 4,096 different announcement vectors. Since there are N announcement vectors where only one region announces to become a member of the agreement and one announcement vector where no region announces to be a member, which all lead to the "All singleton coalition structure", there are $N^2 - N$, i.e., 4,084 different coalition structures and hence 4,083 non-trivial coalition structures. A non-trivial coalition structure means a coalition structure with a coalition with at least two members. In the following, we concentrate in the stability analysis on these coalition structures since the singleton coalition structure is stable by definition. (By construction, if all regions announce not to become a member, a single change of an announcement cannot make a difference).

[11] The USA would like to leave the coalition with JPN and the EEC, as the high damages, especially in the EEC, and relatively low marginal abatement costs in the USA imply high abatement percentages for the USA in this coalition (more than 12%).

Table 5 Internally stable coalitions

Coalitions	Global emission reduction Gton (over 100 years)	Annual emission reduction percentage of emissions in 2010	Global payoff billion US$ over 100 years	Regions with incentive to join
All Singletons	55	4.63	1,960	–
OOE, EEX	57	4.75	2,013	USA, JPN, EEC, FSU, IND, BRA, ROW
EEX, CHN	62	5.18	2,190	USA, JPN, EEC, OOE, FSU, IND, DAE, BRA, ROW
OOE, IND	58	4.84	2,050	USA, JPN, EEC, FSU, BRA, ROW
EEX, IND	58	4.83	2,045	USA, JPN, EEC, OOE, FSU, BRA, ROW
OOE, DAE	57	4.73	2,005	USA, JPN, EEC, FSU, BRA, ROW
EEX, DAE	56	4.72	2,002	USA, JPN, EEC, OOE, FSU, IND IND, BRA, ROW
CHN, DAE	61	5.09	2,153	USA, JPN, EEC, OOE, FSU, EEX, IND, BRA, ROW
IND, DAE	57	4.79	2,032	USA, JPN, EEC, OOE, FSU, BRA, ROW
FSU, BRA	56	4.68	1,981	USA, JPN, EEC, ROW
OOE, IND, BRA	59	4.92	2,081	USA, JPN, EEC, FSU, ROW
FSU, ROW	60	4.98	2,101	USA, JPN, EEC, BRA
BRA, ROW	56	4.68	1,981	USA, JPN, EEC, FSU
FSU, BRA, ROW	60	5.05	2,131	USA, JPN, EEC

with other regions because of relatively high marginal benefits. Moreover, they have a strong incentive to form a coalition with regions that have a flat marginal abatement cost curve as for instance CHN. However, such a coalition would not be internally stable because it violates the interests of CHN.[12] Also, EET are no member of an internally stable coalition and do not wish to join one because their free-rider incentives are higher than those of other regions.

4. Results: sensitivity analyses and extension to transfers

A typical feature of empirical work is that results depend on parameter values, which are subject to some uncertainty. Given the large number of parameters that enter our model, some selection is necessary. From the discussion in section 3, it became evident that in particular the estimation of benefits from global abatement is associated with large uncertainty. In our model, this concerns the level parameter γ_D that applies to all countries and expresses global benefits as reduction of global damages in terms of GDP and the shares of global benefits of individual regions, s_i. Hence, we conduct the following sets of sensitivity analyses. The first set of sensitivity analyses assumes the same regional shares s_i as in the base case (Calibration I) but lower or higher values of γ_D. Note that this sensitivity analysis can also be interpreted as a change of the discount factor as a higher discount factor works similar to

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[12] The incentives to leave the coalition of USA, JPN, the EEC and CHN are negative for the first three regions (-49, -103 and -163 billion US$, respectively), but highly positive for China (610 billion US$); note that no other region would like to join this coalition – it is externally stable.

Table 6 Sensitivity analysis for calibration I*

Benefits (%)	Coalitions	Total emission reduction Gton (over 100 years)	Annual emission reduction percentage of emissions in 2010	Total abatement costs billion US$ over 100 years	Total benefits from abatement billion US$ over 100 years	Payoff billion US$ over 100 years
50	All Singletons	34	2.9	36	644	608
	Grand Coalition	172	14.4	1,225	3,211	1,986
100	All Singletons	55	4.6	109	2,069	1,960
	Grand Coalition	256	21.4	3,553	9,584	6,031
120	All Singletons	62	5.2	145	2,801	2,655
	Coalition JPN, EEC	67	5.6	203	2,988	2,784
	Grand Coalition	284	23.8	4693	12,746	8,053

The All Singletons Coalition Structure is stable by definition (see section 2); the Grand Coalition is not stable in any of the scenarios; the coalition of JPN and the EEC is only stable for benefits 120% and above; benefits 100% = base case.

lower global damages and hence lower benefits from abatement.[13] The second set assumes the same value of γ_D as in the base case, but considers different regional benefit shares as listed under Calibration II in Table 1.

Third, results of a model version that considers transfers are presented. We opt for a transfer scheme based on grandfathering of emission rights and focus on the influence of introducing transfers on the stability and characteristics of various coalition structures; this means we leave the comparison of different transfer schemes to another paper (Weikard et al. 2004).

4.1. First set of sensitivity analyses (Calibration I)

In the base case, we assumed $\gamma_D = 0.027$ to which we refer now as “benefits 100%”. We start our sensitivity analysis by lowering global benefits to 50% compared to the base case that implies $\gamma_D = 0.0135$; this is almost equal to the value of the DICE model (Nordhaus 1994). We find no stable (non-trivial) coalition structure in this case as indicated in Table 6. The lower benefits imply lower emission reductions (a reduction from 55 to 34 Gton in the All Singletons Coalition Structure), though this relation is clearly non-linear (due to the non-linear abatement cost function). The impact of lower benefits on global payoffs is a combination of the direct impact of the lower benefits and the indirect impact through lower emission reductions.

Subsequently, we raise benefits gradually. This leads to a stable coalition between JPN and the EEC at a level of 120%. Interestingly, in this case, internally stable coalition structures are the same as those listed in Table 5, except that JPN and the EEC also form an internally stable coalition, which is also externally stable. Recalling our discussion in section 3, this is not surprising. First, in the Grand Coalition Structure and the Industrialized Countries Coalition Structure these were the only two regions that had no incentive to leave their coalition (see Tables 3 and 4). Second, JPN and the EEC had a low free-rider incentive. However, the coalition of JPN and the EEC only marginally improves upon the Singleton Case as is evident

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[13] This can be seen from equation (1): under stationary abatement strategies and in the absence of technological progress, the abatement costs are constant over time. In contrast, benefits are increasing over time, as the stock of CO_2 grows. Consequently, a lower global damage parameter scales down the net present value of benefits and thus payoffs. A higher discount rate gives less emphasis on future periods, i.e., periods with relatively high benefits, and thus also scales down the net present value of payoffs.

from Table 6. This is not only because the coalition is small in size, but also because these two regions have a low free-rider incentive index and thus will choose only very moderate abatement targets (as marginal abatement costs are relatively high compared to marginal benefits).

We also compute scenarios where we raise benefits to 200 and 300%, respectively, but no major changes occur.

Summarizing the results of this first sensitivity analysis, we can conclude the following. First, if there are stable coalitions they will be rather small, confirming the results of Barrett (1994, 1997), and Hoel (1992). Second, the analysis of free-rider incentives helps to explain membership in stable coalition structures: if there are stable coalitions, they will be formed among regions with a similar incentive structure. Moreover, it is likely that only coalitions with low abatement targets are stable since otherwise the free-rider incentive would become too strong. Third, our results are in line with a conclusion obtained by Barrett (1994) for symmetric regions: whenever the relative difference between no cooperation and full cooperation is large, stable coalitions (partial cooperation) achieve only little. For all scenarios, the global payoff in the All Singletons Coalition Structure is roughly one third of that in the Grand Coalition Structure – a large difference – and a stable coalition closes this gap only by a very small amount. Interestingly, the ratio between the All Singletons Coalition Structure and the Grand Coalition Structure in terms of the global payoff rises slightly from 30.6% in the 50% benefit scenario to 32.9% in the 120% benefit scenario, reaching 35.9% in the 300% benefit scenario. Thus, when the difference between no and full cooperation is particular large, no stable (non-trivial) coalition exists. Only when this difference becomes small enough may partial cooperation be stable. Fourth, we can expect stable coalitions only if benefits from emission reduction receive sufficient weight – a result that conforms with intuition. Fifth, membership in stable coalition structures is very robust with respect to the level of global benefits, and hence also with respect to the discount rate.

4.2. Second set of sensitivity analyses (Calibration II)

Here we assume the level of global benefits at 100% as in the base case but consider different regional shares of benefits, as listed in Table 1 under Calibration II. For this run, we find the results displayed in Table 7.

Table 7 largely confirms our previous findings. Whereas the previous sensitivity analysis showed that, in our model, stability of coalition structures is very robust to changes in the level of *global benefits* from abatement, it is now shown that it is sensitive to *regional shares*

Table 7 Sensitivity analysis for Calibration II

Coalitions	Total emission reduction	Annual emission reduction	Total abatement costs	Total benefits from abatement	Payoff
	Gton (over 100 years)	percentage of emissions in 2010	billion US$ 100 over years	billion US$ 100 over years	billion US$ 100 over years
All Singletons	54	4.5	93	2,013	1,920
Coalition JPN, BRA, ROW	58	4.9	141	2,178	2,037
Industrialized countries coalition	89	7.5	346	3,345	2,999
Grand Coalition	256	21.4	3,553	9,584	6,031

The All Singletons Coalition Structure is stable by definition (see section 2); the Grand Coalition and Industrialized Countries Coalition Structures are not stable; a coalition of JPN, BRA and ROW is the only stable non-trivial coalition structure.

Table 8 Results for the model with transfers

Coalitions	Total emission reduction Gton (over 100 years)	Annual emission reduction % of emissions in 2010	Payoff billion US$ over 100 years
All Singletons[a]	55	4.6	1,960
Coalition EET, BRA[b]	56	4.7	1,981
Coalition CHN, BRA[b]	58	4.8	2,059
Coalition USA, EET, EEX, CHN[c]	103	8.6	3,418
Grand Coalition[d]	256	21.4	6,031

a All Singletons Coalition Structure is stable by definition (see section 2)
b Stable coalitions under transfer rule 2
c Stable coalitions under transfer rule 1
d The Grand Coalition Structure is not stable under any rule

of benefits. Even though numerical estimates of regional damages due to climate change are still scarce, especially for non-OECD countries, these regional estimates play an important role in the incentive structure of regions in the negotiations of an IEA.

4.3. Extension of the model to include monetary transfers

In this subsection, we consider the impact of transfers for the success of coalition formation. The analysis assumes the base case, i.e., Calibration I and $\gamma_D = 0.027$ (100% benefits). Transfers are implemented such that every coalition member in the coalition receives the payoff in the All-Singletons Coalition Structure plus a share of the surplus from cooperation. Since the surplus is always positive in our global emission game, this scheme ensures profitability to all coalition members. Hence, a necessary condition for stability is always satisfied. Recall this condition may be violated without transfers as was demonstrated for the Grand Coalition Structure in subsection 3.3 and for the Industrialized Countries Coalition Structure in subsection 3.4. However, since profitability is not a sufficient condition for stability, stability will depend on the shares of the surplus. Obviously, there are many possibilities how the regional shares for the distribution of the surplus can be chosen. We restrict attention to only two assumptions that are sufficient to make the following three points: (a) Transfers can improve upon the success of coalition formation, (b) Success crucially depends on regional surplus shares, (c) Choosing regional shares based on moral motives may not always be a good guide for effective treaty-making.

The first transfer scheme assumes regional surplus shares in relation to historical emissions. That is, the higher historical emissions are, the higher the regional share of a region will be. This is a version of the grandfathering rule; shares represent the status quo which may be seen as a pragmatic allocation rule. The second transfer scheme assumes shares in relation to historical responsibility for emissions. This is a version of a morally motivated transfer scheme which allocates the surplus inversely to historical emissions. Thus, transfer scheme 1 favors high current emitters and for transfer scheme 2 just the opposite holds. For simplicity, we use emission levels in 2010 as given in Table 1 in order to compute surplus shares. From Table 1, it is evident that USA but also CHN and EEX have relative high current emissions whereas BRA, DAE, JPN and ROW have low emissions. Table 8 presents the results when computing stable coalition structures for the extended model with transfers.

From Table 8, it is evident that the two transfer schemes lead to very different stable coalition structures in terms of membership and in terms of overall success. The two transfer schemes represent two “corners of the playing field”. Transfers scheme 1 leads to a stable coalition of USA, EET, EEX and CHN, which is among the stable coalitions the one with the highest global payoff and emission reduction, whereas transfer scheme 2 leads to a stable coalition of EET and BRA and a stable coalition of CHN and BRA, but these coalitions achieve only very little emission reduction and a low global payoff. Both transfer schemes improve upon the All Singleton Coalition Structure. However, in the case of transfer scheme 2, the improvement is only marginal. In contrast, in the case of transfer scheme 1, the improvement is substantial though far from first best. Thus, transfers can partially mitigate free-riding but cannot fully overcome stability problems. The morally motivated transfer scheme 2 implies large transfers from the industrialized countries to countries in transition and developing countries. Because these transfers are so pronounced, they make participation for industrialized countries unattractive. This is different for the pragmatic transfer scheme 1 which leads to a less asymmetric allocation of the gains from cooperation. This implies a stable coalition with four members. This coalition is relatively successful because not only CHN as a producer of cheap abatement finds it attractive to participate in cooperation but also the USA as a second key player.

Thus, the results clearly indicate the importance of transfers in general and the design of transfers in particular for the success of climate agreements. Moreover, they provide some rational for the grandfathering rule that is frequently mentioned in the policy debate. Though this rule may not satisfy the criteria of a "fair" surplus sharing rule, it addresses the main free-rider incentives in climate change. It implies moderate transfers from the main beneficiaries to the main contributors in the context of an efficient climate policy, thereby balancing different interests.

5. Summary and conclusions

In this paper, we studied stability of climate change coalitions in a cartel formation game, applying the concept of internally and externally stable coalition structures. Although substantial improvements can be made with respect to the empirical calibration of the model, the approach presented in this paper provides many relevant results and interpretations of which we would like to mention six.

First, the gains from cooperation that are at stake in the case of global warming are large according to our model. This is not only true for the absolute amount of global net benefits in the global optimum (Grand Coalition Structure) but also when this number is put in perspective to net benefits in the Nash equilibrium (All Singleton Coalition Structure). *Second*, neither the grand coalition nor the coalition of industrialized countries that we labeled "Industrialized Countries Coalition" are stable for all parameter scenarios that we considered. Moreover, it turned out that the USA conducts a considerable amount of abatement already as a singleton and has an incentive to leave the Grand Coalition and the Industrialized Countries Coalition. This result provided some rationale for the general difficulties of ratifying the Kyoto Protocol, the withdrawal of the USA and the reluctance of developing countries to participate in a climate agreement. However, we found that the coalition of industrialized countries would imply a non-negligible improvement compared to a situation without cooperation, though it is clearly inferior to full cooperation. *Third*, stable non-trivial coalitions emerge only if benefits from global abatement reach a sufficiently high level, or if appropriate transfers are introduced. This suggests that stable cooperation can only be expected if the impact of greenhouse gases receives sufficient attention by governments, or if transfers are part of an international agreement. The regions that are expected to form a stable coalition are JPN and the EEC, or under transfers USA, CHN, EET and EEX. *Fourth*, if there are stable coalitions, then they are small and only marginally improve upon the Nash equilibrium in terms of global welfare, global emissions and concentrations. But if transfer schemes are introduced, larger coalitions can become stable that may contribute substantially to emission reduction. *Fifth*, membership in stable coalitions can be rationalized by investigating free-rider incentives. It turned out that only regions with similar free-rider incentives form stable coalitions. Those coalitions are stable because members have a sufficiently homogenous cost-benefit structure. This result could help to explain why developing countries have not agreed upon reduction targets in the Kyoto Protocol so far and that without transfer payments this will most likely not change. *Sixth*, our results are very robust in terms of the level of benefits from global abatement but are sensitive in terms of the regional distribution of benefits and the transfer schemes applied.

Overall, we conclude that the prospects for stable and effective IEAs are not very positive from the perspective of game theory. However, the paper demonstrated two main possibilities that may help to improve upon the current situation. First, we showed that a stronger recognition of the benefits from a joint environmental policy fosters the incentive for stable cooperation. For this it is important that more research on the negative impacts of global warming is conducted and that this information disseminates not only to the scientific community but also to a broader public. This will raise the consciousness for the global warming problem and will initiate a stronger pressure by environmental groups on governments to strive for stricter regulation and for more cooperation. Second, it became apparent that transfer payments can lead to more stable and successful cooperation. We demonstrated that the success of a transfers scheme crucially depends on its design. For an "optimal design", we showed that three issues are important. (a) Defining and capturing the interests of the different players at stake. (b) Identifying the key players in climate change, i.e., the main potential beneficiaries and the main potential contributors to a climate agreement. (c) Designing a transfer scheme that sufficiently balances the heterogeneous interests between various groups without favoring one group too much. As we have shown, it is not sufficient to implement a transfer scheme that appears to be fair if this violates the interest of key players. The global nature of the climate problem and the heterogeneous interests world wide clearly suggests that future research should give much attention to the design of transfers schemes in order to mitigate the free-rider problem. This applies not only to direct transfers as modeled in this paper, but also to indirect transfers as for instance implied by the policy instruments of the Kyoto Protocol which includes permit trading, clean development mechanism and joint implementation. For these activities, it will important to strengthen the role of international organizations like the United Nations with its Environmental Program (UNEP) or the scientific committee IPCC (International Panel of Climate Change), not only to gain more insights and to develop policy measures but also to achieve more consensus about these insights and measures. We believe this will be an important step in broadening the current climate coalition and to induce the participants to accept higher abatement targets.

Appendix: details on the calibration of the STACO model

A.1. Concentrations of greenhouse gases

For the development of the stock of carbon dioxide in the BAU-scenario, we base our calibration on the market scenario in the DICE model (Nordhaus 1994). This scenario assumes no emission reduction, though there is a feedback between the environment and the economy.

In our analysis, we focus on carbon dioxide, but the exogenous level of other greenhouse gases is included in the calibration of the damage cost function.

The stock of carbon dioxide in the atmosphere at time t is expressed by the following equation (following DICE):

$$M_t(q_{2011},\dots,q_t) = M_{\text{pre-ind}} + (1-\delta)^{(t-2010)} \cdot \left(M_{2010} - M_{\text{pre-ind}}\right) + \sum_{s=2011}^{t} \left((1-\delta)^{t-s} \cdot \omega \cdot (e_s - q_s)\right) \tag{2}$$

That is, the stock, M_t, at time t depends on global abatement from time $t = 2011$ onwards, $q_{2011}, q_{2012}, \dots, q_t$ where $q_t = \sum_{i=1}^{N} q_{it}$. More specifically, the stock depends on three terms. The first term is the pre-industrial stock, $M_{\text{pre-ind}}$, which is 590 Gton CO_2 according to DICE. This stock remains constant over time and may be interpreted as the "natural equilibrium". The second term is the stock in 2010 in excess of the pre-industrial stock that decays with a rate δ per annum. The "natural removal or decay rate" as well as the stock in 2010 are taken from DICE and are $\delta = 0.00866$ and $M_{2010} = 835$ Gton CO_2, respectively. The third term describes how global (BAU) emissions e_s, minus global abatement after 2010, q_s contribute to the stock in year t. The BAU-emissions are calibrated such that the stock of carbon dioxide without abatement mirrors the development of the stock in the market scenario of DICE. The airborne fraction of total net emissions (BAU-emissions minus abatement) that remains in the atmosphere is 64% ($\omega = 0.64$) according to DICE.

In the game-theoretical setting of the model we assume stationary abatement strategies, which implies that annual emission reduction, $q_t = q/100$, is constant once the emission reduction strategy has been chosen.

A.2. Calibration of the benefits from abatement

In DICE, damages are linked to concentrations in a climate module, such that global damages depend on world temperature increase. However, in order to establish a direct link between concentrations and damages, we follow Germain and van Steenberghe (2001), who approximate the full climate module by linking temperature increases to the stock of carbon dioxide. Thus, we can write[14]

$$D_t = \left(\frac{\gamma_D}{9}\right) \cdot \left[\eta \cdot \ln\left(\frac{M_t}{M_{\text{pre-ind}}}\right)\right]^2 \cdot Y_t \tag{3}$$

where parameter γ_D measures the impact on GDP due to an increase in temperature of 3 degrees Celsius compared to the pre-industrial level, η is a scaling parameter used in the approximation of the full climate module[15] and Y_t denotes global GDP in year t.

Though this damage function is non-linear, it can be approximated by a linear function in the relevant range of our study, that is, between the stock in 2010 (1.4 times pre-industrial level) and the estimated uncontrolled level in 2110 (3.5 times pre-industrial level):

$$D_t = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t}{M_{\text{pre-ind}}}\right)\right] \cdot (\gamma_D \cdot Y_t) \tag{4}$$

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[14] All market values are expressed in billion US$ of 1985 using the deflator provided by NASA (2002). This applies to damages, benefits and abatement costs.

[15] This includes an exogenous additional impact of other greenhouse gases on radiative forcing (see Nordhaus (1994).

Table 9 Parameter values

Symbol	Description	Value	Unit	Source
e_{2010}	Global emissions in 2010	11.96	Gton CO_2	Nordhaus (1994)
$e_{i,2010}$	Regional emissions in year 2010	see Table 1 in section 3	Gton CO_2	Own calculation based on Ellerman and Decaux (1998)
d_E	Annual absolute growth in global and regional emissions in BAU-scenario	0.153	Gton CO_2	Own calculation based on Nordhaus (1994)
$M_{\text{pre-ind}}$	Pre-industrial level of CO_2-stock	590	Gton CO_2	Nordhaus (1994)
M_{2010}	Stock of CO_2 in 2010	835	Gton CO_2	Nordhaus (1994)
δ	Natural annual removal or decay rate of CO_2-stock	0.00866	–	Nordhaus (1994)
ω	Airborne fraction of emissions that remain in the atmosphere	0.64		Nordhaus (1994)
r	Annual uniform discount rate	0.02	–	Assumption
s_i	Share of region i in global benefits	see Table 1 in section 3	–	Own calculation based on Fankhauser (1995) and Tol (1997)
α_i, β_i	Abatement cost parameters of region i	see Table 1 in section 3	–	Own calculation based on Ellerman and Decaux (1998)
$M_{\text{no-effect}}$	No-effect level of CO_2 stock for damage function	786	Gton	Own calculation
φ	Slope of damage and benefit function	178.331	Billion US$ per Gton	Own calculation
γ_D	Scale parameter of damage and benefit function	0.027	–	Tol (1997)

where γ_1 and γ_2 are calculated via OLS-regression.[16] As the stock of carbon dioxide (cf. (2)) is linear in abatement under stationary reduction strategies, damages as specified in (4) are also linear in abatement.

A.3. Calibration of the abatement costs

For the specification of the abatement cost function, we rely on estimates of the EPPA model that are reported in Ellerman and Decaux (1998). They assume an annual abatement cost function of the following form:

$$AC_{it}(q_{it}) = \frac{1}{3}\cdot\alpha_i\cdot(q_{it})^3 + \frac{1}{2}\cdot\beta_i\cdot(q_{it})^2 \tag{5}$$

We can use their estimates but have to adjust their figures in three respects. First, we have to account for the fact that their abatement cost estimates are in million US$ per megaton greenhouse gas reduction whereas our unit of measurement is billion US$ per gigaton. Second, we replace q_{it} by $q_i/100$ because we assume stationary strategies ($q_{i,2011} = \cdots = q_{i,2110}$). Third, they estimate a negative value for the parameter α_i for OOE. Since this would cause

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[16] Given our interpretation of γ_D, damages equal to $\gamma_D Y_t$ for doubling of concentrations. Hence, we can impose $\gamma_1 = 1 - 2\cdot\gamma_2$ and estimate γ_2. OLS gives $\gamma_2 = 1.497$ with standard error 0.011 (t value: 136.2) and adjusted $R^2 = 0.998$, indicating an almost perfect fit.

problems for computations, we set $\alpha_i = 0$ in this case and re-estimate β_i for OOE. All estimates are displayed in the last two columns in Table 1.

In order to derive total abatement costs of region i, $TAC_i(q_i)$, we discount and sum discounted abatement costs over time: $\mathrm{TAC}_i(q_i) = \sum_{t=2011}^{2110}(1+r)^{-(t-2010)}\mathrm{AC}_{it}(q_i)$. This implies that we assume the same abatement cost structure throughout, neglecting possible exogenous or endogenous cost efficiency effects.

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