Coalition Formation and International Trade in Greenhouse Gas Emission Rights *

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Abstract

The success of any international climate change agreement depends on abatement targets and the incentives for countries to participate. We demonstrate that international emissions trading is effective in making headway on both issues, even if countries choose their permit endowment non-cooperatively. Developing countries are lured into a trading system by the prospective rents from permit sales. Developed countries benefit from the reduced cost of emissions abatement. Using an empirically-based representation of the global economy in seven sectors and six regions, we find that the most effective permit trading coalitions yield abatement at approximately twice the level achieved in a world without permit trading, and these coalitions are often subglobal.

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1 Introduction

The success of any international climate change agreement depends on abatement targets and the incentives for countries to participate. International emissions trading is frequently cited in the policy literature as a means to making headway on both issues. With trading, more stringent targets become less costly, and agreements could be profitable for the developing world, allowing them to capture the rents from permit sales.

The present paper formulates a general equilibrium model of self-enforcing agreements among permit trading countries. In our setting, emissions permit endowments are determined endogenously as equilibrium behavior within a candidate coalition. We embed this strategic behavior in an empirically-based representation of the global economy in seven sectors and six regions and calibrated to a 1998 base year. We use our model to assess the prospects for cooperation over the next twenty years.

There exists by now a substantial literature which uses game theoretic concepts to analyze self-enforcing environmental agreements, whose members are often referred to as 'coalitions'.[1] Our model shares many features with this literature, but differs in important respects. First, international environmental policies are usually modelled as games in emissions. By contrast, we focus on the possibility that countries agree on a system of emissions trading, as in the Kyoto Protocol. The key strategic variable for members of such a trading coalition is the initial endowment with tradable emission rights (or permits). When choosing initial endowments, countries anticipate their later trading on a permit market so that strategic incentives differ substantially from games in emissions (Helm 2003). For example, on top of environmental considerations, we find that countries have incentives to restrict their endowment choices so as to benefit from a higher equilibrium permit price and from terms of trade effects in energy markets.

Second, it is commonly assumed that coalition members behave cooperatively, maximizing their joint payoff. In the case of heterogeneous countries, this involves agreement on a particular sharing rule such as the Shapley value (e.g., Barrett (1997), Botteon and Carraro (1997)). On the other hand, countries act selfishly in that they leave (or do not join) a cooperating coalition if this increases their payoff.[2] The contrasting assumptions of cooperative emission choices and non-cooperative participation decisions in these models strike us as inconsistent. We assume instead that members of a trading coalition choose their permit endowments non-cooperatively, just as coalition outsiders choose their emissions non-cooperatively. Hence, the only bits of cooperation that enter our framework are that (i) countries agree on a tradable permit system if each of them prefers participation to staying outside, and (ii) property rights traded in permit markets are enforced.

The third dimension in which our work differs from the existing literature is empirical foundation. Previously published studies on self-enforcing environmental agreements are restricted to analytical reasoning or are based on simple numerical examples. To remain solvable, the

[1]Early contributions were Carraro and Siniscalco (1993) and Barrett (1994). For surveys of this literature see Barrett (2003), Finus and Rundshagen (2002), as well as Missfeldt (1999).

[2]Obviously, whether this will be the case depends on the reaction of the other countries. If they also cease to cooperate, this provides a strong threat to defecting countries, and global cooperation turns out to be (core) stable (Chander and Tulkens 1997, Helm 2001). However, most of the literature uses the weaker threat that the remaining coalition members continue to cooperate among themselves, and so do we. The result is less cooperation, meaning small coalitions and/or low emission reductions beyond the Nash solution (e.g., Carraro and Siniscalco (1993), Barrett (1994, 2001)).

models used allow for limited heterogeneity across countries. Often, symmetric countries are considered, and even those studies that focus on asymmetries do so in a very stylized way. For example Barrett (2001) considers only two types of countries, each of which faces binary choices between abating and polluting. Obviously, this leaves little scope for an analysis of emissions trading, which exploits the heterogeneity in countries' abatement cost functions. By contrast, we use a computable general equilibrium model which explicitly represents six regions and seven sectors of the economy, with the modeling detail weighted toward the all-important energy sectors. The GTAP5 database (Dimaranan and McDougall (2002), Rutherford and Paltsev (2000)) lends us a micro-consistent, 1998 calibration point on which to base our calculations.

Several models exist that calculate the economic cost of carbon abatement policies (see Rutherford (1993), Bernstein, Montgomery, Rutherford and Yang (1999) and other papers in the associated volumes), and some applications aim to constructively synthesizes the strategic and economic aspects of the problem (e.g., Nordhaus and Yang (1996), Yang (2003), Eyckmans and Tulkens (2003), Tol (2001)). However, none of these papers has analyzed emissions trading, which is the focus of our paper, and none of them has used a framework that allows for a detailed modelling of general equilibrium effects.

The value of doing so lies in the model's description of both regional energy supply and the international trade of energy and energy-intensive goods. Reduced emissions lead to both lower demand for fossil fuels and an increased cost of producing energy-intensive goods in emission-constrained regions. Decreased fuel demand depresses international fuel prices and stimulates emissions increases abroad, an effect known as carbon leakage (Felder and Rutherford 1993). Increases in the cost of producing energy-intensive goods at home make imported varieties relatively less expensive. By this mechanism, energy policy may induce spillovers through the international trade in goods. The partial equilibrium analysis typical of the game-theoretic literature on climate change fails to address either of these dimensions of policy.

Our analysis yields a number of interesting insights. Permit trading assures a minimum cost abatement policy for a given emissions target. However, it does not assure that the number of permit allowances is adequate as they are chosen by self-interested countries which have an incentive to free-ride. We find that the most effective equilibrium coalitions of permit trading countries yield abatement at approximately twice the level achieved in a Nash equilibrium without trading. These coalitions are sub-global and involve high income/high abatement cost countries buying large volumes of emissions permits from their developing world partners. Accordingly, an international permit system successfully induces the participation of developing countries in a climate change agreement. In the most effective coalition, China, as the main developing country participant, is by far the largest seller of emission rights. Therefore, the permit market functions as a natural burden-sharing device, compensating developing countries for their emissions reductions, while supplying environmental goods that are valued by the developed world.

Interestingly, the grand coalition is stable, but is typically suboptimal. Abatement frequently improves when certain countries are excluded from the agreement, because these countries would choose a relatively large permit allocation. When environmental effectiveness is measured by global emissions, hence the optimal agreement may not involve the greatest number of signatory countries. This finding has important implications for how we think about the success of international climate negotiations.

General equilibrium effects work in favor of adopting more stringent targets, as coalition members restrict their permit allocation in order to exploit terms of trade in energy markets.

Nevertheless, equilibrium abatement levels amount to just over half of the first-best emission cut-back. We also ask how much of this gap can be attributed to our 'pessimistic' assumption that members of a trading coalition choose permit endowments non-cooperatively. To answer this question, we compare our results to a scenario where coalition members maximize their joint payoff and allocate the cooperation gains according to the Shapley value. Surprisingly, the additional abatement as compared to our non-cooperative framework is modest. Accordingly, the main problem seems to be countries' incentives to defect from an agreement, rather than the failure to negotiate efficient allocations within a coalition.

Our conclusions are stable over the time horizon and with respect to a variety of baseline growth assumptions. Surprisingly, the model indicates that the usefulness of permit trading coalitions declines as willingness to pay for climate improvement rises in developing countries. The reason is that with reduced divergence in countries' environmental valuation, the Nash equilibrium in emissions exhibits lower differences in marginal abatement cost. Hence there are less benefits from trading. It follows that the prospects for an effective trading agreement do not improve over time. A strategy of delayed negotiations could thus be both costly and ineffective.

The remainder of the paper is organized as follows. Section 2 describes the model, with a schematic overview of both the economic general equilibrium model and the game-theoretic framework through which the model determines regional emissions levels, permit allocations, and coalition formation. Section 3 explains numerical solution methods, and Section 4 the data on which we calibrate model parameters. Section 5 presents central results along with a sensitivity analysis with respect to some key model parameters. Concluding remarks are in Section 6.

2 The Model

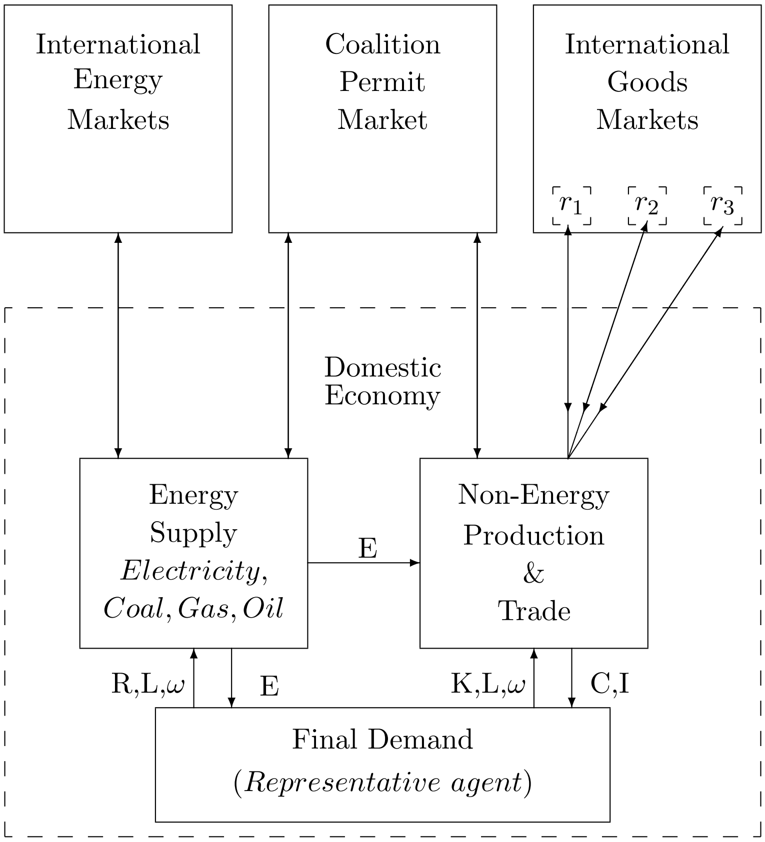
Our model is made up of two conceptually separate components. First, there is a game-theoretic model of strategic interaction across regions in abatement policies. Second, we have a general equilibrium module which determines the myriad economic impacts of policy measures. While it is convenient to think of these submodels separately, our computation algorithm accounts for the jointly-consistent equilibrium outcomes as a single simultaneous system.

2.1 Economic Impacts

We model the economic impacts of regional abatement choices with a static Shoven-Whalley general equilibrium trade model (see Rutherford (1997) and Rutherford and Paltsev (2000)). We consider six regions (USA, Japan, Western Europe, China, Former Soviet Union, and "Rest of World") and seven goods (Coal, Crude Oil, Electricity, Natural Gas, Refined Oil, Energy-Intensive Goods, and Other Manufactures and Services). Naturally, the weight of the modeling detail falls on the energy sectors, as this is where the direct effect of emissions policy will be felt.

Figure 1 provides a diagrammatic sketch of the model. Final consumption (C) follows from the budget-constrained utility maximization of a representative agent in each region. The agent supplies primary factors labor (L), capital (K), and fossil-fuel specific resources (R) to the economy. The perfectly competitive sectors of the economy produce goods for export to other regions, for intermediate input to the production of other goods, for final consumption and for investment. Factor revenue finances the purchase of energy goods (E), other final consumption

Figure 1: Regional Flows of Goods and Factors



goods, and capital stock investment.[3] The representative agent also supplies the economy with emissions permits (ω) which must be used in fixed proportion to fossil fuel consumption. Note that only coalition members can trade these permits across regions.

Labor and capital are intersectorally mobile within regions but cannot move between regions. The production of crude oil, coal and gas makes use of a specific resource factor, resulting in upward sloping supply schedules for fossil fuels. Bilateral trade in all goods (save emissions permits) takes the form of Armington demand functions in which goods are distinguished by region of origin (indicated by r_1, r_2, and r_3 in the figure), so that a region's consumers view imports of different origins as imperfect substitutes. This substitution pattern follows a nested constant elasticity (CES) of substitution production function which aggregates all import varieties to an import bundle.[4]

The numerical simulations are computed over a twenty year time horizon, updating the economic and environmental profiles of the model regions based on predicted changes in GDP,

[3]Because it is a static model, we fix regional investment (I) at benchmark levels in the simulations.

[4]Appendices A - D provide more detailed descriptions of the model's technologies, preferences and equilibrium structure of the economic model.

population and energy technology. This allows us to look at the prospects of cooperation into the future. We do not, however, model any forward-looking behavior with respect to either the game theoretic choices or capital stock development.

For purposes of setting out the game-theoretic model, we can represent the general equilibrium model as a system of equations:

$$F(z; e) = 0 \tag{1}$$

in which $z \in \mathbb{R}^N$ is the vector of equilibrium prices and quantities, $e \in \mathbb{R}^n$ is a vector of exogenous input to the general equilibrium model representing regional emissions of carbon dioxide, and $F : \mathbb{R}^N \Rightarrow \mathbb{R}^N$ is the set of equations which define the economic equilibrium. N is the dimension of the equilibrium model (roughly 400) and n is the number of regions, indexed $i = 1, \ldots, n$. Following Mathiesen (1985), we formulate the general equilibrium model as a system of equations/inequalities paired in complementary slackness relationships with model variables: good and factor prices (π) are associated with market clearance conditions, and activity levels (y) for producers are associated with the zero profit conditions that typically characterize firms in perfectly competitive markets. We therefore partition z into price and quantity variables as $z = (\pi, y)$.

Welfare depends on the current economic utility (U_i) from consuming the produce of the traditional (non-environmental) sectors of the economy and on environmental damages of global carbon emissions. We assume that the marginal willingness to pay for reductions in global emissions (ν_i) is constant. This reflects that no single year's emission is sufficiently large to have a significant impact on the marginal rate of climate damage associated with current emissions. Accordingly, welfare in region i is defined as

$$W_i = U_i(\pi, \Omega_i) - \nu_i e^G, \tag{2}$$

where $\Omega_i = \sum_k \Omega_{ik}$, Ω_{ik} is region i's primary endowment of commodity k, and $e^G = \sum_i e_i$ are global emissions.

When economic preferences are homothetic, as we have assumed in our calibrated model, economic welfare can be expressed in terms of the ratio of regional income to the unit expenditure function (the price index) for a unit of consumption.[5] If we do this, then we can write:

$$W_i = \frac{\sum_k \Omega_{ik} \pi_k}{p_i^c(\pi)} - \nu_i e^G \tag{3}$$

where $p_i^c(\pi)$ is the representative agent's unit expenditure function. In the numerical analysis, this is defined by the solution to the maximization of a nested CES utility function (illustrated graphically in Figure 7 of the Appendix) subject to the limitations of region i's factor endowment income.

2.2 Emissions Choice

We first derive the Nash equilibrium in emissions, which arises in the absence of an international carbon abatement coalition, in order to better differentiate this case from permit trading coalitions. Simply differentiating (3) with respect to e_i yields the first-order condition, which can be

[5] In order for this representation to be sensible, we use a linearly-homogeneous cardinalization of utility so that marginal changes in U_i can be interpreted as equivalent variations in income at benchmark prices.

written as

$$\frac{\sum_k \Omega_{ik}\pi_k}{p_i^c(\pi)}\left[\left(\sum_k \Omega_{ik}\frac{\partial \pi_k}{\partial e_i}\right)\frac{e_i}{\sum_k \Omega_{ik}\pi_k} - \frac{\partial p_i^c(\pi)}{\partial e_i}\frac{e_i}{p_i^c}\right] = \nu_i e_i. \tag{4}$$

The first term in square brackets is the emissions-elasticity of region i factor earnings. The second term is the emissions-elasticity of the region i price level, i.e. of the cost of living in region i. If, for example, a region is a net energy importer, then carbon abatement may not have a substantial impact on income, even though it may increase the cost of living. Alternatively, if a region is dependent on coal-fired electricity, then carbon abatement could simultaneously decrease income and increase the relative price of goods. This distinction between energy importing versus exporting regions and income versus cost of living effects turns out to be important when we come to the simulation analysis. In particular, our framework allows for the possibility that a coalition of energy importing regions chooses the coalitional abatement level in such a way as to manipulate the income effect in outsider regions and shift cost of living effects in their favor.

An alternative representation of the emissions optimality condition follows from applying the chain rule to $\partial p_i^c(\pi)/\partial e_i$ and noting that, by Shepard's lemma, the derivative of p_i^c with respect to π_k equals the compensated demand for good k. Multiplying the compensated demand by the utility level yields the final consumption of good k by region i, denoted C_{ik}. Using this, (4) can be written as a weighted sum of commodity endowments and consumption, i.e.

$$\sum_k (\Omega_{ik} - C_{ik})\frac{\partial \pi_k}{\partial e_i} = \nu_i. \tag{5}$$

The left-hand-side of the equation is the marginal economic benefit of an increase in region i emissions, which is equated to marginal environmental cost.

A complication arises from the fact that the "Rest of World" region (ROW) aggregates a wide collection of countries into a single entity. Using (5) to derive the Nash equilibrium would misrepresent their individual strategic influence. Furthermore, ROW includes many developing countries which are unlikely to become signatories to a climate treaty over the next twenty years. We therefore assume that ROW is *non-strategic*, meaning that governments within ROW impose no emissions restrictions on their constituents. Accordingly, emissions will be determined solely by market forces in the supply and demand for fossil fuels.[6] For example, if international oil prices decline, ROW's consumption of oil may increase and its consumption of coal may decrease. Therefore, the "leakage-compensated" individual optimality conditions become

$$\sum_k (\Omega_{ik} - C_{ik})\frac{\partial \pi_k}{\partial e_i} = \nu_i\left(1 + \frac{\partial e_{row}(\pi)}{\partial e_i}\right), \quad i \neq \text{ROW}, \tag{6}$$

where the derivative on the right-hand side represents the effect that region i takes account of carbon leakage in the ROW region. The Nash equilibrium in emissions is derived by adding these conditions to the system of equations $F(\cdot)$ defining the general equilibrium model. The

[6]Nordhaus and Yang (1996) approach the problem differently, assuming that countries within ROW would only capture fractional environmental benefits from abatement. These fractional benefits are then calibrated to mimic the outcome of a Nash equilibrium in which all ROW members are disaggregated into individual players. The impact on the results is negligible given the "smallness" of most of the countries that define ROW. The assumption that ROW is non-strategic is *not* equivalent to the assumption that $\nu_{row} = 0$. It implies only that these countries do not use carbon policy based on environmental concerns or the strategic manipulation of terms of trade.

complication involved in computing equilibria is that the added equations involve not only the equilibrium values (π and e), but also *partial derivatives* of equilibrium prices with respect to emissions, $\frac{\partial \pi_k}{\partial e_i}$. Numerical methods for simultaneous solution of (1) and (6) are addressed in Section 3.

2.3 Permit Endowment Choice & Coalition Formation

The Nash equilibrium in emission choices represents a worst-case scenario, which is unlikely to provide any significant abatement effort (Whalley and Wigle 1991). While retaining the assumption that countries adopt best-reply strategies, we now extend the model by allowing countries to introduce a system of tradable emission permits. The interaction between countries may then be thought of as a three-stage game. In stage 1, countries decide about the composition of a trading coalition. In stage 2, coalition members choose their permit allocation and non-members their (non-tradable) emissions. In stage 3, coalition members trade their permits. Accordingly, our setup is similar to Helm (2003), but with one important extension. A permit trading system does not require the unanimous approval of all countries, but it can also be introduced by a sub-group.

By the principle of backward induction, we start analyzing the interaction on the permit market. Assuming that this market is competitive, permits are traded among firms and consumers of coalition members as any other good.[7] The general equilibrium model (1) therefore becomes

$$F(z;\omega) = 0, \tag{7}$$

in which $z = (\pi, y, p)$, p is the permit price, and ω is the vector specifying tradable permit endowments for members of a trading coalition, denoted $\mathcal{C}$, and (non-tradable) emissions for non-members. The dimensionality of (7) is $N+1$, as z includes p and $F(\cdot)$ includes the permit market clearance condition $\sum_{i\in\mathcal{C}} e_i = \sum_{i\in\mathcal{C}} \omega_i$.

We now turn to the second stage of the game. Each non-member of a trading coalition chooses its emissions according to (6) as a best-reply to the behavior of the other non-members, of the coalition $\mathcal{C}$ and of the non-strategic (ROW) region. Similarly, each individual coalition member chooses its tradable permit endowment as a best-reply to the permit respectively emission choices of the other regions. In particular, for coalition members welfare as given in (3) is supplemented by the income or expenditure on the permit market, $p(\omega_i - e_i)$. Hence, welfare maximizing choices of permits ω_i satisfy the first-order condition

$$\sum_k (\Omega_{ik} - C_{ik}) \frac{\partial \pi_k}{\partial \omega_i} + (\omega_i - e_i)\frac{\partial p}{\partial \omega_i} + p = \nu_i \left(1 + \frac{\partial e_{row}(\pi)}{\partial \omega_i}\right) \tag{8}$$

for all $i \in \mathcal{C}$. The first term on the left-hand-side represents the economic effect of changes in terms of trade induced by permit choices.[8] The second term describes the indirect economic benefit due to changes in the coalition permit price induced by permit choices. Finally, the third

[7]Implicitly, we thereby assume that the market for permits will be comprised of sufficiently many participants – such as power producers, petroleum refineries and natural gas distributors – so that no buyer or seller can exert market power.

[8]One obvious consequence of this general equilibrium effect is that countries with marginal damages above (below) the permit price are not necessarily permit buyers (sellers), as in the partial equilibrium analysis of Helm (2003).

term, p, represents the direct economic benefit associated with an increase in region i's permit allocation, viz. an increase in the value of permit revenues equal to the permit price. Conditions (6) and (8) define a Nash equilibrium over ω_i and e_i for a given set of trading and non-trading countries.

The partition of the set of regions into coalition and non-coalition members is determined in the first-stage of the game. Countries decide to remain a member of a trading coalition based on the relative welfare benefits of unilateral departure from the coalition. A coalition is self-enforcing (or stable) when none of its members would prefer to be a non-member, given the participation choices of other regions. (A member state contemplating defection takes into account resulting equilibrium adjustments in permit allocations which would emerge in the residual coalition following its departure.)

The literature on coalition formation often uses the additional criterion that no non-member should want to join a coalition (d'Aspremont, Jacquemin, Gabszeweiz and Weymark 1983, Carraro and Siniscalco 1993). However, coalition members in these studies choose coalition-efficient levels of abatement. This fact, combined with a partial equilibrium style of analysis, ensures that having more agreement participants always brings the world closer to first-best emissions levels. In our model of non-cooperative permit choices this is not the case. Furthermore, it is easy to prevent outsiders from joining a coalition by simply not trading with them. Therefore, we employ the 'external stability' requirement only where explicitly noted.

3 Solution

This section provides an overview of the numerical methods which we have developed to solve our hybrid game-theory / market equilibrium model. This material is, to our knowledge, novel and of interest on in its own right, as it provides a clean and general approach to solving hybrid models. However, the section is self-contained and may be skipped by readers who are interested primarily in the model results and policy implications.

The key challenge in computing game-theoretic equilibria is to represent the first-order conditions formulated in terms of local sensitivity of prices to strategic instruments, e.g. $\partial\pi_k/\partial e_i$ in (5) and $\partial e_{row}(\pi)/\partial e_i$ in (6). The implicit function theorem is the standard tool for computing the local sensitivity of the endogenous variables of a model to changes in exogenous variables. In the present context, this implies the following matrix equation:

$$\left[\frac{\partial z}{\partial \omega}\right] = -\left[\frac{\partial F}{\partial z}\right]^{-1}\left[\frac{\partial F}{\partial \omega}\right]. \tag{9}$$

The literal implementation of this system of equations creates considerable modeling overhead, as it would require explicit programming of the Jacobian matrices $\left[\frac{\partial F}{\partial z}\right]$ and $\left[\frac{\partial F}{\partial \omega}\right]$.

The local dependence of endogenous variables on exogenous variables can alternatively be approximated by solving a set of additional equilibria with small perturbations of the permit allocations. That is:

$$\frac{\partial z_k}{\partial \omega_i} \approx \frac{z_k(\omega+\delta^i) - z_k(\omega)}{\delta},$$

where

$$\delta^i = \begin{pmatrix} \delta^i_1 \\ \vdots \\ \delta^i_N \end{pmatrix} \qquad \text{with} \quad \delta^i_j = \begin{cases} \delta & i = j \\ 0 & i \neq j. \end{cases}$$

While numerical differentiation is typically an inferior numerical technique due to the resulting poor precision and efficiency, in the present application it offers significant savings in implementational cost.[9]

At first glance it would appear that the calculation of local sensitivity of prices π_k with respect to permit allocations ω_i would not by itself solve the model. The first order conditions for the permit allocations of strategic countries are indeed *functions* of the local derivatives. The trick is to *simultaneously* solve the model and approximate the partial derivatives, $\partial\pi_k/\partial\omega_i$. We do this by solving an $N \times n + n - 1$ equation system for a model with $n - 1$ strategic states. The central equations which characterize the economic equilibrium and its local sensitivity analysis are:

$$F(z;\omega) = 0,$$
$$F(z^i;\omega + \delta^i) = 0, \quad i \neq \text{ROW}.$$

We compute z and the adjacent perturbed solutions z^i simultaneously, together with permit allocations as endogenous variables. The permits are made endogenous through the introduction of difference approximations of the first order conditions which characterize the Nash equilibrium permit allocation:

$$\sum_k (\Omega_{ik} - C_{ik}) \frac{\pi_k^i - \pi_k}{\delta} + (\omega_i - e_i)\frac{p^i - p}{\delta} + p = \nu_i \left(1 - \frac{e_{row}^i - e_{row}}{\delta}\right), \quad i \in \mathcal{C}$$

and

$$\sum_k (\Omega_{ik} - C_{ik}) \frac{\pi_k^i - \pi_k}{\delta} = \nu_i \left(1 - \frac{e_{row}^i - e_{row}}{\delta}\right), \quad i \neq \text{ROW}, i \notin \mathcal{C}.$$

4 Data

The GTAP5 trade and production database provides the base year data with which we calibrate the production and utility functions that describe the general equilibrium model. These data provide a consistent representation of energy markets in physical units together with economic accounts of regional production, consumption, and bilateral trade flows for 1998. We also employ growth projections in order to calibrate our simulation over a time horizon from 2000 to 2020. These are based on the IEO 2002 dataset (US 2002) which provides baseline estimates of regional GDP, population and carbon dioxide emissions levels through the year 2020. These function as Business as Usual (BaU) levels from which we base our individual Nash and coalitional equilibrium calculations.

Tables 1 reports baseline growth trajectories for GDP and carbon emissions. There is significant GDP growth in all model regions over the twenty year horizon, but the fastest growth occurs in the developing world. China quadruples its output; the Former Soviet Union and the Rest of World region both more than double output. Regional differences in per capita GDP growth are less pronounced but roughly mirror the changes in total output. Growth in total carbon emissions generally reflects the economic growth patterns, and the developing world is the most important source of new emissions. Note that it also achieves the largest improvements

[9] Calculation of $\nabla_z F$ is sufficiently tedious to warrant the cost of conducting computational tests to determine an appropriate difference interval, δ (see Gill, Murray and Wright (1981, section 8.6.)).

in the carbon intensity of output because of the more rapid retirement of old, inefficient capital for newer technologies.

Table 1: GDP and Carbon Statistics

	GDP			*GDP per capita*			*Carbon per capita*			*Carbon per GDP*		
	2000	2020	%Δ	2000	2020	%Δ	2000	2020	%Δ	2000	2020	%Δ
USA	9,219	16,832	3.1	33,437	51,791	2.2	5.6	6.4	0.7	167	124	-1.5
JPN	4,270	6,542	2.2	33,526	51,923	2.2	2.4	2.9	1.0	72	56	-1.3
EUR	9,168	14,786	2.4	23,482	38,104	2.5	2.4	3.0	1.1	104	76	-1.6
CHN	1,095	4,314	7.1	860	2,984	6.4	0.5	1.1	4.0	625	392	-2.3
FSU	610	1,501	4.6	2,101	5,401	4.8	2.1	3.1	2.0	1,021	589	-2.7
ROW	6,843	15,746	4.3	1,854	3,144	2.7	0.5	0.7	1.7	308	234	-1.4

GDP – Value of total output in billions \$1998

Carbon per capita in tons per person

Carbon per GDP in grams per \$1998

%Δ – Equivalent constant annual growth rate

Modelling the demand for reductions in greenhouse gas emissions also requires an assumption about the value that regions place on emission reductions. Some studies have used estimates of economic costs of predicted physical impacts of climate change (Nordhaus and Yang 1996, Botteon and Carraro 1997). However, these attempts are highly conjectural given the current state of climate science (Tol 2002). Our calibration is no less conjectural, but it is anchored more in the observed political behavior. It is based on the idea that countries reveal something about their willingness to pay for environmental improvements through their position in climate change negotiations (Mäler 1989).

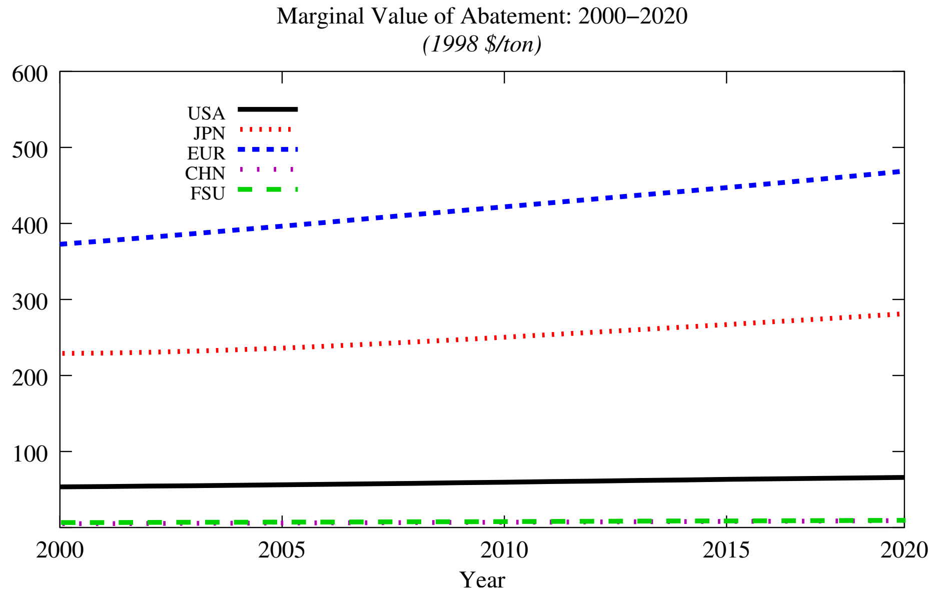
The European Union and Japan have already ratified the Kyoto Protocol that commits them to approximately 20-30% reductions in BaU emissions by 2012. Based on this we calibrate Western Europe (EUR) and Japan (JPN) with a willingness to pursue a 20% reduction target in the Nash equilibrium in emissions in model year 2000. The United States (USA) has shown less interest, and we peg them at a 15% reduction. The remaining model regions appear to be even less willing to pay for carbon abatement. Accordingly, we peg China (CHN) at a 5% reduction and the countries that make up the Former Soviet Union (FSU) at a 5% increase in emissions. This calibration to an increase above BaU may seem inconsistent with the notion of positive value for abatement. However, the terms of trade effects induced by abatement in other regions imply that (FSU) benefits from expanding its energy use beyond BaU levels. This procedure turns out to suggest marginal values of similar magnitude for China and the Former Soviet Union, as shown in Figure 2.

Having tied down the base year marginal values of abatement ($\bar{\nu}_i$), it remains to define the paths that ν_{it} follow over the time horizon. We assume that

$$\nu_{it} = \bar{\nu}_i \Gamma_{it}^{\eta} \tag{10}$$

where Γ_{it} is the mean per capita GDP in region i at time t, and η is the exogenously chosen income elasticity of demand for abatement. We choose a benchmark value of $\eta = 0.5$ so that a marginal increase in per capita income translates into smaller increases in abatement demand in wealthier countries, reflecting the idea of the environmental Kuznets curve (Grossman and Krueger 1995). Figure 2 shows the ν_{it} trajectories under benchmark assumptions.

Figure 2:



In the sensitivity analysis, we also look at one instance which shows more convergence in valuations over the time horizon. In particular, we assume

$$\nu_{it} = \bar{\nu}_i (1 + \gamma_i)^{(t-2000)} \Gamma_{it}^{\eta}$$

and fix values for γ_i such that environmental valuations increase more rapidly in regions with low current valuations ($\gamma_{jpn} = 0, \gamma_{eur} = 0, \gamma_{usa} = 0.05, \gamma_{fsu} = 0.15, \gamma_{chn} = 0.15$). Given these parameter values, marginal valuations of abatement are the same as in the original scenario for EUR and JPN, while they converge to approximately 170, 120 and 110 (in 1998 \$/ton) for USA, CHN, and FSU, respectively.

5 Results

In what follows, we employ the numerical model to discuss (i) the strategic considerations of countries within and outside of a trading coalition, (ii) the composition of self-enforcing trading coalitions as well as (iii) environmental and welfare effects.

The first column in Table 2 lists all stable coalitions of permit trading regions for model year 2010. The following columns display welfare differences from the Nash outcome without permit trading as well the global emissions reductions from BaU that correspond to each coalition. Equilibria are sorted by the level of emissions reduction, which run the gamut from almost no improvement over the no-trade Nash equilibrium to reductions of more than twice that level.

All of the more successful outcomes (both in welfare and abatement terms) involve CHN – a developing country with low abatement cost – paired with EUR and/or JPN – regions characterized by high abatement cost and high valuations for abatement. This shows that a coalition of permit traders is most successful when it can exploit such asymmetries across its members.

Table 2: Equilibrium Coalitions by Welfare and Abatement, 2010

	% Equivalent Variation						*Emissions*	*Average*
	USA	JPN	EUR	CHN	FSU	ROW	*Reduction*	*%EV*
USA-EUR-CHN	0.6	4.1	1.7	2.5	0.4	-4.7E-3	13.6	0.7
EUR-CHN-FSU*	0.3	3.6	1.8	1.0	5.1	2.0E-2	12.9	0.6
EUR-CHN	0.3	3.2	1.8	0.9	0.2	1.9E-2	12.1	0.4
USA-JPN-EUR-CHN-FSU*	0.3	2.5	1.5	1.4	6.1	4.8E-2	11.9	0.7
JPN-CHN	0.2	2.4	2.0	0.2	0.2	2.8E-2	11.6	0.2
USA-EUR-FSU	0.4	1.8	0.3	5.2E-2	8.4	-1.1E-2	9.7	0.4
USA-EUR	0.4	1.5	0.4	7.8E-2	0.2	-3.3E-2	9.1	7.5E-2
USA-JPN	0.2	0.4	0.7	6.4E-2	0.1	-2.0E-2	8.3	5.8E-2
EUR-FSU	7.8E-2	0.9	0.4	-	3.4	1.2E-2	8.1	0.2
JPN-FSU	7.0E-2	0.5	0.5	3.1E-2	0.8	4.8E-3	7.7	8.5E-2
USA-CHN	6.6E-3	0.7	0.5	0.3	-3.8E-2	2.5E-2	7.7	0.1
JPN-CHN-FSU	4.8E-3	6.9E-2	6.6E-2	3.6E-2	0.6	2.3E-2	6.6	5.1E-2
Nash without trading	-	-	-	-	-	-	6.5	-

% Equivalent Variation: % change in money-metric utility from Nash without trading
Emissions Reduction: % reduction in global emissions from BaU
Average %EV: Population-weighted average of regional % changes in EV from Nash without trading
*: Equilibria which survive external stability requirement.

Given that permit endowments are chosen non-cooperatively by self-interested countries, this is a surprising result because asymmetries tend to accentuate differences in endowment choices, which may thwart agreement on trading. This effect can be seen in Table 3, which compares the USA-EUR-CHN coalition (the "best" outcome) to the BaU scenario in model year 2010. EUR, the coalition member with by far the highest valuation for abatement (see column "v_i"), chooses a very low permit allocation ω_i. By contrast, the coalition members with low valuations for abatement, USA and CHN, choose a permit allocation that even exceeds their emissions in the no-trade Nash equilibrium (e_i^N). Despite this very diverse pattern, all regions benefit from agreement on trading (see column "ev_i"), though for different reasons.

For EUR it becomes much cheaper to foster its environmental goals – by choosing a low ω_{EUR} – because that part of abatement which would be most costly is shifted through the permit market to the other regions. Indeed, after-trade emissions ($e_i^{\mathcal{C}}$) of EUR exceed its permit allocation by a factor of 28 and are even higher than its emissions in the no-trade Nash equilibrium. By contrast, CHN benefits primarily from selling permits to EUR, about half of its initial allocation. This is also the case for USA, but to a lesser extent because abatement is more costly. After trading, the low valuation countries CHN and USA both emit less than in the no-trade Nash equilibrium.

It is worthwhile to take a closer look at why coalition members with low valuation for abatement, i.e. CHN and USA, do not choose tradable permits ω_i that more substantially exceed their emissions choices in the no-trade Nash equilibrium. After all, permits are precious, as indicated by the permit price (p) in Table 3, and coalition members are free to choose their initial permit

Table 3: USA-EUR-CHN Coalition Profile, 2010

	e_i^N	e_i^C	ω_i	ev_i	p	ν_i
USA	84.3	74.3	92.2	0.6	117.9	59.6
EUR	77.6	86.9	3.1	1.7	117.9	415.3
CHN	88.1	41.9	89.7	2.5	117.9	7.1
JPN	79.5	80.0	-	4.1	195.2	247.1
FSU	103.4	103.0	-	0.4	1.7	6.4
ROW	106.8	108.7	-	-	-	-

e_i^N: No-trade Nash emissions as % of BaU
e_i^C: equilibrium emissions with coalition as % of BaU
ω_i: permit allocation of coalition members as % of BaU
ev_i: % change in EV from no-trade Nash equilibrium
p: Permit price resp. marginal abatement cost ($/Tons)
ν_i: Marginal value of emissions reductions ($/Tons)

allocation in our non-cooperative framework. In principle, three effects are responsible for this restraint. Firstly, more permits generally lead to more emissions and associated environmental damages. However, by assuming constant marginal valuations for abatement, this effect is not present in our analysis. Secondly, choosing more permits increases supply, thereby generally reducing the equilibrium permit price. Thirdly, less emissions imply less energy demand which leads to lower energy prices. Energy importing CHN and USA find it in their interest to exploit this terms of trade effect through restricting their permit choices.

To illustrate the last point, we undertake the following experiment. Initially, income in ROW is fixed at its no-trade Nash level, while the other regions choose their permit respectively emissions levels in a manner consistent with the USA-EUR-CHN coalition structure. We then release the income constraint on ROW and look at the full equilibrium. We focus on the income effect in ROW because it is the most prominent single general equilibrium effect.

Table 4 reports some effects of releasing the ROW income constraint. Entries for $\%\Delta\omega_i$ show that the coalition members with low environmental valuations, USA and CHN, contract their permit choices, and overall emissions of the coalition fall. The reduced energy demand leads to less revenue for the energy exporting ROW region, especially for crude oil and natural gas (see the lower half of Table 4). This loss to ROW translates into terms of trade gains for all energy importing regions (all other regions except FSU), which are presented in the first data row as percentage changes of economic utility (U_i) from the restricted equilibrium levels.[10]

Until now we have focused on the strategic considerations of the coalition members USA, EUR and CHN. What about the two (strategic) coalition outsiders? As illustrated in Table 3, JPN is in a classical free-rider position. It benefits from coalitional abatement without contributing itself. Given its high valuation for abatement (v_i), it can therefore secure the highest welfare gains of all regions (ev_i). By contrast, FSU has the lowest welfare gains of all (strategic) regions. Being a free-rider yields only modest benefits due to its low valuation for abatement. Therefore,

[10]Remember that U_i represent benefits or costs associated with changes in emissions policy that have nothing to do with environmental effects (see eq. 2).

Table 4: Income Effects, 2010

	USA	JPN	EUR	CHN	FSU	ROW
	Economic Utility & Permit Endowment Changes					
$\%\Delta U_i$	0.15		0.01	0.04	-0.01	-0.21
$\%\Delta \omega_i$	-1.52		137.68	-0.03		
	Changes in ROW *Exports to Other Regions*					
ROW	-3.4	-0.9	-0.8	-0.6		(Crude Oil)
ROW	-0.8	-0.3	-1.2			(Natural Gas)

ΔU_i and $\Delta \omega_i$ are in % changes from fixed income equilibrium
Export changes are in tens of millions of 1998 US dollars.

FSU would prefer to join the coalition so as to gain from the right to sell permits, just like CHN. However, in a USA-EUR-CHN-FSU coalition, FSU would choose a permit allocation that is 59% above its emissions as a coalition outsider. As a consequence, pollution would rise – to the displeasure of EUR – and the permit price would fall – to the displeasure of CHN. The cheap abatement options that FSU brings into the coalition are not enough as compensation, hence current members block its admission.

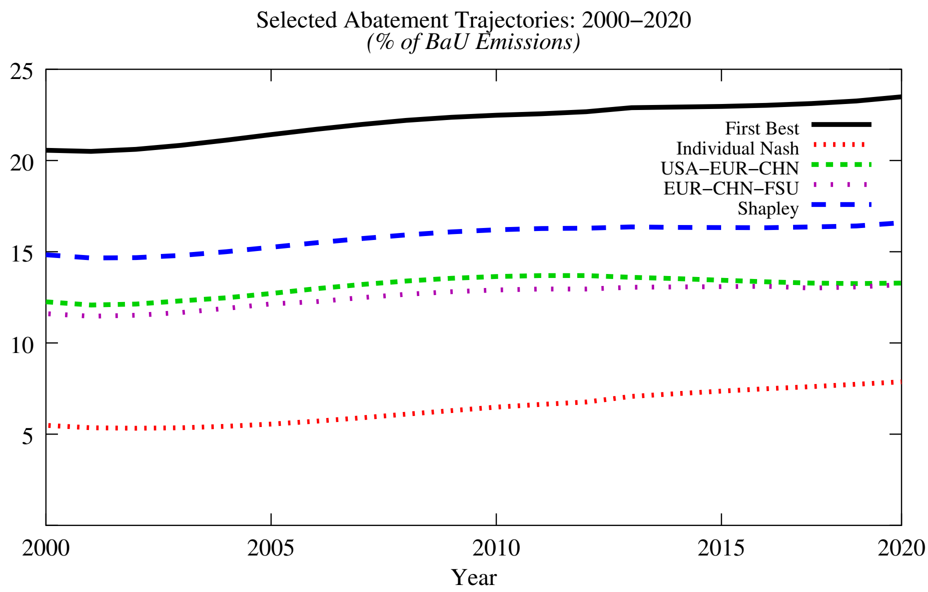
That they can do so is, accordingly, an important assumption for the stability of trading coalitions. Nevertheless, there are two equilibria which also survive the criterion of external stability that outsiders are free to join a coalition regardless of the welfare effect on current members. These are EUR-CHN-FSU and the grand coalition USA-JPN-EUR-CHN-FSU (indicated by superscript * in Table 2), both of them achieving emission reductions and welfare gains of similar magnitude as the best coalition USA-EUR-CHN. The stability of the grand coalition and its relatively good environmental performance are results that have not been obtained by most other studies on climate coalitions. This is due to the different assumptions about the strategies of coalition members. If they maximize the coalitional payoff, i.e. take account of damages that their emission cause in other countries, then particularly countries with low environmental valuation stand to gain a lot from leaving a coalition and free-riding on its abatement. In our framework, however, coalition members do not reduce their permit choices to account for environmental damages in other countries. Furthermore, the above elaborations have demonstrated that countries with low environmental valuations are likely to be the most important permit sellers. They would loose these revenues by leaving a coalition. Accordingly, incentives to defect are substantially lower.

To summarize, the possibility to form trading coalitions may entail substantial environmental and welfare benefits as compared to the Nash-equilibrium without trading. Nevertheless, trading alone while keeping the assumption that countries adopt best-reply strategies falls substantially short of achieving the global welfare maximum. This is illustrated in Figure 3, which shows abatement trajectories for selected equilibria over the model time horizon (2000-2020). In particular, the "First Best" trajectory shows emissions reductions if the world followed a utilitarian first best path.[11] These reductions are nearly twice as high as with the best trading coalition (USA-EUR-CHN), but even about four times as high as equilibrium abatement without

[11] A first-best outcome is obtained when each region chooses a level of emissions which equates *collective* marginal

permits.

Figure 3:



The "Shapley" series has been constructed to compare our results to the literature which assumes that coalition members choose efficient reductions and are able to agree on a surplus distribution scheme – in our case the Shapley value (Shapley 1953).[12] The coalition depicted in "Shapley" is the EUR-CHN-FSU outcome, which is also one of the dominant coalitions in the non-cooperative model. Despite the substantially more optimistic assumptions about the strategies followed by coalition members, the difference to the best trading coalition is relatively small. The reason for this has already been discussed: If countries behave cooperatively within a coalition but non-cooperatively as outsiders, then the defection problem is substantial even with well-designed transfer payments.

Figure 3 indicates stability of abatement impacts over the time horizon, implying that the demographic and economic changes have limited impact on the prospects for global policy measures.

Stability of the optimal coalition might be attributed to our assumptions regarding the evolution of willingness to pay for carbon abatement over the model horizon. (See Section 4.) We therefore report on a single sensitivity analysis based on an alternative baseline in which we assume a faster rate of convergence in China's valuation of greenhouse gas emissions. Figure

benefits with marginal cost. In the first-best equilibrium e_i is then associated with the first-order condition:

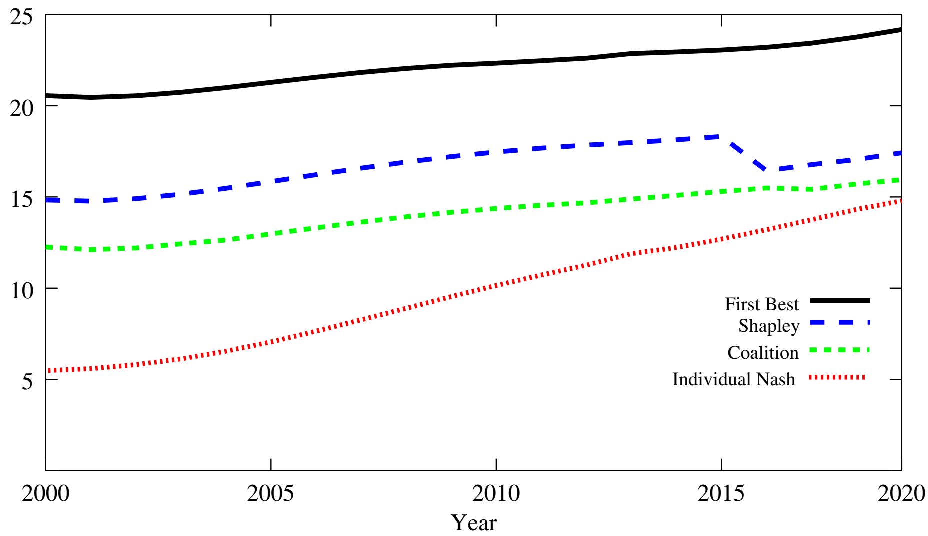
$$\sum_k (\Omega_{ik} - C_{ik}) \frac{\partial \pi_k}{\partial e_i} = \sum_{j \in \mathcal{C}^g} \nu_j \left(1 + \frac{\partial e_{row}(\pi)}{\partial e_j}\right), \quad i \neq \text{ROW}, \tag{11}$$

thereby accounting also for damages in other regions ($\mathcal{C}^g$ represents the grand coalition).

[12]This distribution scheme has been applied, e.g., by Barrett (1997) and Botteon and Carraro (1997). For a discussion of the Shapley value see, e.g., Moulin (1988).

4 summarizes results from this scenario. The best coalition now varies over time, starting with USA-EUR-CHN and ending with EUR-CHN-FSU.[13] Coalition formation and permit trade are, however, less effective under this scenario because there are lower potential gains from trade. Permit coalitions are driven by heterogeneity in environmental values among member states, exploiting the associated differences in marginal abatement cost that would arise without trading. While an evolution towards more effective agreements might arise from enhanced coalitional stability, we find no evidence of any such effects. With convergence in valuation of the climate resource abatement levels increase as a fraction of BaU emissions, reflecting the fact that the global mean value of emissions reductions is increasing. However, with convergence, the difference between the optimal coalitional outcome and the no-trade Nash equilibrium vanishes as we approach 2020.

Figure 4:
Selected Abatement Trajectories (High Convergence): 2000–2020
(% of BaU Emissions)



6 Conclusions

The structure of an international carbon abatement agreement must be informed not only by what is efficient but also by what is feasible. More than a decade of climate negotiations has clearly demonstrated the problems to agree on cooperative emissions target that overcome countries' free rider incentives. In our computations, we have analyzed the extent to which self-enforcing agreements based on a system of internationally tradable permits might enhance abatement. Reflecting the above considerations, we have undertaken this analysis in a framework where members of a trading coalition as well as outsiders adopt non-cooperative best-reply strategies in their choices of permits and emissions.

[13]The "Shapley" series also represents more than one coalition, with EUR-CHN-FSU dominating from 2000-2015, after which point the EUR-CHN takes over.

Even with our pessimistic representation of climate negotiations as a non-cooperative game, we find levels of abatement which are not substantially lower than were scenario coalition members cooperatively maximizing their joint payoff. This provides a strong environmental and welfare argument in favor of international emissions trading. Furthermore, such a system proves to be quite successful in inducing some members of the developing world to participate in carbon abatement.

We find that equilibrium agreements get us about half of the way to the first-best level of abatement. The best coalitions combine China, which serves as the major permit exporter in the agreement, with regions that exhibit both high abatement costs and a high demand for the well-being of the climate. We also find that in the balance between the free-rider problem and the possibility of non-optimal negotiations within a coalition, it is the former problem that accounts for the majority of the difference between equilibrium outcomes and an efficient provision of the environmental good.

In contrast to prior partial equilibrium models of environmental agreements our general equilibrium model provides new strategic insights. In a general equilibrium setting coalitions both reduce emissions and improve terms of trade with energy-exporting countries. The terms of trade motive makes permit coalitions a more effective abatement device but it also indicates a need for careful analysis of burden sharing.

There may be several equilibrium coalitions. We presume that one role of an international body assisting climate negotiations is to assist in the selection of the most effective coalition. Our calculations indicate that coalitions (and global abatement) may benefit from *excluding* certain countries from membership. When countries choose permit allocation non-cooperatively, then the net effect of adding a new country to the coalition may be higher global emissions levels.

Propsective changes in regional wealth and emissions profiles do not have strong implications for the future effectiveness of permit trade agreements. The abatement rates achieved by the most successful coalitions in our model are stable over the twenty year horizon. Higher rates of convergence in the willingness to pay for emissions reductions in the developing world produce higher levels of unilateral abatement but smaller potential benefits from collective action.

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A The Economic Impacts Model

Table 5 lists the dimensions of the economic model. The model describes a general equilibrium in geographical regions, sectors of the economy, and the primary factors each region holds. Most of the sectoral detail centers around the production of energy and energy-intensive goods, as the impact of changes in a region's emissions constraint are focused here.

Table 5: Elements of the Model

Time Horizon	2000-2020
Regions	
EUR	Europe (EU15, EFTA)
JPN	Japan
USA	United States
CHN	China
FSU	Former Soviet Union
ROW	Rest of World
Sectors	
COL	Coal
CRU	Crude oil
GAS	Natural gas
OIL	Refined oil products
ELE	Electricity
EIS	Energy-intensive sectors
Y	Other economic activity
Primary Factors	
L	Labor
K	Capital
R_{ff}	Fossil fuel resources (coal, oil and natural gas)
P	CO_2 emissions permits

Benchmark data on quantities, prices, and elasticities provide the calibration point for the production and utility functions that describe the economy. The underlying data base is GTAP5 for the year 1998 which provides a consistent representation of energy markets in physical units as well as and detailed accounts of regional production, consumption, and bilateral trade flow (see Dimaranan and McDougall (2002), Rutherford and Paltsev (2000)).

Key assumptions and notation:

- Nested separable constant elasticity of substitution (CES) functions characterize the use of inputs in production. All production exhibits non-increasing returns to scale. Goods are produced with capital, labor, energy, and emissions permits (KLE).
- A representative agent (RA) in each region controls these primary factors. The RA maximizes utility from consumption of a CES composite subject to a budget constraint with fixed investment demand (i.e. fixed demand for the savings good). The aggregate consumption bundle combines demands for fossil fuels, electricity and non-energy commodities. Total income of the RA consists of factor income including revenues from permit sales.
- All goods are differentiated by region of origin. Regarding imports, nested CES functions characterize the choice between imported and domestic varieties of the same good (Armington).
- Labor and capital are mobile within domestic borders but cannot move between regions; natural resources are sector specific.

B Algebraic Model Description

Following Mathiesen (1985), two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. Zero profit conditions determine activity levels, while market clearance dictates the price levels. In our algebraic exposition, the notation Π^u_{ik} is used to denote the profit function of region i in sector k where u is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices yields compensated demand and supply coefficients (Shepard's lemma), which appear subsequently in the market clearance conditions.

Tables 6 - 11 explain the notations for variables and parameters employed within our algebraic exposition. Table 7 summarizes the activity variables of vector y, whereas Table 8 summarizes the price variables of vector π. Figures 5 - 8 provide a graphical exposition of the production and final consumption structure.

B.1 Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\begin{aligned}\Pi^Y_{ik} &= \pi^Y_{ik} - \sum_{j \notin FE} \theta_{jik}\pi^A_{ji} \\ &\quad -\theta^{KLE}_{ik}\left[\theta^E_{ik}\left(\pi^E_{ik}\right)^{1-\sigma_{KLE}} + (1-\theta^E_{ik})\left(w_i^{\alpha_{ik}} r_i^{1-\alpha_{ik}}\right)^{1-\sigma_{KLE}}\right]^{1/(1-\sigma_{KLE})} \\ &= 0 \quad \forall\, k \notin FF\end{aligned}$$

2. Production of fossil fuels:

$$\begin{aligned}\Pi^Y_{ik} &= \pi^Y_{ik} - \left[\theta^Q_{ik} {q_{ik}}^{1-\sigma_{Qik}} + (1-\theta^Q_{ik})\left(\theta^{FF}_{Lik} w_i + \theta^{FF}_{Kik} r_i + \sum_j \theta^{FF}_{jik}\pi^A_{jr}\right)^{1-\sigma_{Qik}}\right]^{1/(1-\sigma_{Qik})} \\ &= 0 \quad \forall\, k \in FF\end{aligned}$$

3. Sector-specific energy aggregate:

$$\begin{aligned}\Pi^E_{ik} &= \pi^E_{ik} - \Big\{\theta^{ELE}_{ik}(\pi^A_{ELE,i})^{1-\sigma_{ELE}} \\ &\quad +(1-\theta^{ELE}_{ik})\Big[\theta^{COL}_{ik}\left(\pi^E_{col,i}+p_i\epsilon^{COL}_{ik}\right)^{1-\sigma_{COL}} \\ &\quad +(1-\theta^{COL}_{ik})\left(\sum_{j\in LQ}\theta^j_{ik}\left(\pi^A_{ji}+p_i\epsilon^j_{ik}\right)^{1-\sigma_{LQ}}\right)^{(1-\sigma_{COL})/(1-\sigma_{LQ})}\Big]^{(1-\sigma_{ELE})/(1-\sigma_{COL})}\Big\}^{1/(1-\sigma_{ELE})} \\ &= 0\end{aligned}$$

4. Armington aggregate:

$$\begin{aligned}\Pi^A_{ik} &= \pi^A_{ik} - \left[\theta^D_{ik}\left(\pi^Y_{ik}\right)^{1-\sigma_{DM}} + (1-\theta^D_{ik})\left(\pi^M_{ik}\right)^{1-\sigma_{DM}}\right]^{1/(1-\sigma_{DM})} \\ &= 0\end{aligned}$$

5. Aggregate imports across import regions:

$$\begin{aligned}\Pi^M_{ik} &= \pi^M_{ik} - \left(\sum_s \theta^M_{ksi}\left(\pi^Y_{sk}+\mu_{ksi}\pi^T\right)^{1-\sigma_{MM}}\right)^{1/(1-\sigma_{MM})} \\ &= 0\end{aligned}$$

6. Household consumption demand:

$$\begin{aligned}\Pi^C_i &= p^C_i - \left(\theta^E_{Ci}(\pi^E_{Ci})^{1-\sigma_C} + (1-\theta^E_{Ci})\left[\prod_{j\notin E}\left(\pi^A_{ji}\right)^{\theta^C_{ji}}\right]^{1-\sigma_C}\right)^{1/(1-\sigma_C)} \\ &= 0\end{aligned}$$

7. Household energy demand:

$$\begin{aligned}\Pi^E_{iC} &= \pi^E_{iC} - \prod_{j\in E}\left(\pi^A_{ji}+p_i\epsilon^j_{iC}\right)^{\theta^E_{jiC}} \\ &= 0\end{aligned}$$

B.2 Market Clearance Conditions

8. Labor:

$$\bar{L}_i = \sum_k Y_{ik}\frac{\partial \Pi^Y_{ik}}{\partial w_i}$$

9. Capital:

$$\bar{K}_i = \sum_k Y_{ik}\frac{\partial \Pi^Y_{ik}}{\partial r_i}$$

10. Natural resources:

$$\bar{Q}_{ik} = Y_{ik} \frac{\partial \Pi^Y_{ik}}{\partial q_{ik}} \quad \forall k \in FF$$

11. Sectoral output:

$$Y_{ik} = A_{ik} \frac{\partial \Pi^A_{ik}}{\partial \pi^Y_{ik}} + \sum_{s \neq i} M_{sk} \frac{\partial \Pi^M_{sk}}{\partial \pi^Y_{ik}}$$

12. Sector specific energy demand:

$$E_{ik} = Y_{ik} \frac{\partial \Pi^Y_{ik}}{\partial \pi^E_{ik}}$$

13. Import supply:

$$M_{ik} = A_{ik} \frac{\partial \Pi^A_{ik}}{\partial \pi^M_{ik}}$$

14. Aggregate supply:

$$A_{ik} = \sum_j Y_{ji} \frac{\partial \Pi^Y_{ji}}{\partial \pi^A_{ki}} + C_i \frac{\partial \Pi^C_i}{\partial \pi^A_{ki}}$$

15. Household energy consumption:

$$E_{iC} = C_i \frac{\partial \Pi^C_i}{\partial \pi^E_{iC}}$$

16. Carbon emissions:

$$\omega_i + X_i = E_{iC} \frac{\partial \Pi^E_{iC}}{\partial p_i} + \sum_k E_{ik} \frac{\partial \Pi^E_{ik}}{\partial p_i}$$

17. International permit market:

$$\sum_{i \in CC} X_i = 0$$

B.3 Income balance

$$p^C_i C_i = w_i \bar{L}_i + r_i \bar{K}_i + \sum_{j \in FF} q_{ji} \bar{Q}_{ji} + p_i \bar{E}_i + \bar{B}_i$$

C Notation for the Algebraic Model Description

Table 6: Sets

k	Sectors and goods
j	Aliased with k
i	Regions
s	Aliased with i
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
FE	Final energy goods: Coal, gas and refined oil
LQ	Liquid fuels: Refined oil and gas
CC	Permit trading coalition members

Table 7: Activity Variables

Y_{ik}	Production in region i and sector k
E_{ik}	Aggregate energy input in region i and sector k
M_{ik}	Aggregate imports of region i and sector k
A_{ik}	Armington aggregate for region i in sector k
C_i	Aggregate household consumption in region i
E_{Ci}	Aggregate household energy consumption in region i
X_i	Net exports in carbon permits in region i

Table 8: Price Variables

π_{ik}	Output price of good k produced in region i for domestic market
π_{ik}^X	Output price of good k produced in region i for export market
π_{ik}^E	Price of aggregate energy in region i and sector k
π_{ik}^M	Import price aggregate for good k imported to region i
π_{ik}^A	Price of Armington good k in region i
π^T	Price of international transport
p_i^C	Price of aggregate household consumption in region i
π_{Ci}^E	Price of aggregate household energy consumption in region i
w_i	Wage rate in region i
r_i	Price of capital services in region i
q_{ik}	Rent to natural resources in region i $(k \in FF)$
p_i	Carbon tax in region i

Table 9: Cost Shares

θ_{ik}^X	Share of exports in region i and sector k
θ_{jik}	Share of intermediate good j in region i and sector k $(k \notin FF)$
θ_{ik}^{KLE}	Share of KLE aggregate in region i and sector k $(k \notin FF)$
θ_{ik}^E	Share of energy in the KLE aggregate of region i and sector k $(k \notin FF)$
α_{ik}	Share of labor region i and sector k $(k \notin FF)$
θ_{ik}^Q	Share of natural resources in region i of sector k $(k \in FF)$
θ_{Tik}^{FF}	Share of good j $(T = j)$ or labor $(T = L)$ or capital $(T = K)$ in region i and sector k $(k \in FF)$
θ_{ik}^{COL}	Share of coal in fossil fuel demand by region i in sector k $(k \notin FF)$
θ_{ik}^{ELE}	Share of electricity in energy demand by region i in sector k
β_{jik}	Share of liquid fossil fuel j in energy demand by region i in sector k $(k \notin FF, j \in LQ)$
θ_{sik}^M	Share of imports of good k from region s to region i
θ_{ik}^D	Share of domestic variety in Armington good k of region i
θ_{iC}^E	Share of fossil fuel composite in aggregate household consumption in region i
θ_{ik}^C	Share of non-energy good k in non-energy household consumption demand in region i
θ_{ikC}^E	Share of fossil fuel k in household energy consumption in region i

Table 10: Endowments and Emissions Coefficients

$\bar{L}_i$	Aggregate labor endowment for region i
$\bar{K}_i$	Aggregate capital endowment for region i
$\bar{Q}_{ik}$	Endowment of natural resource k for region i $(k \in FF)$
$\bar{B}_i$	Balance of payment deficit or surplus in region i (note: $\sum_i \bar{B}_i = 0$)
ω_i	Carbon emission permit endowment for region i
ϵ_{ik}^j	Carbon emissions coefficient for fossil fuel j in region i in sector k $(j \in FE)$
ϵ_{iC}^k	Carbon emissions coefficient for household energy demand for fossil fuel k in region i $(k \in FE)$

Table 11: Elasticities

σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.5
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}.	$\mu_{COA} = 1.0$ $\mu_{CRU} = 1.0$ $\mu_{GAS} = 1.0$
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.1
σ_{COL}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_{LQ}	Substitution between liquid fossil fuels in production	2
σ_{DM}	Substitution between the import aggregate and the domestic input	8
σ_{MM}	Substitution between imports from different regions	16
σ_{C}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.5

D Production Structure

The following figures give a graphical description of the various production technologies in the model. The top level in each figure represents the output, while all subsequent levels of the tree structure describe the nesting structure of the inputs in the nested constant elasticity of substitution production functions. The substitution patterns for each nest are listed in italics at each node of the tree. *CES* denotes the general form of the function, while other labels (i.e. *Leontief* or *Cobb-Douglas (C-D)*) correspond to specific elasticity values (0 or 1 respectively). All elasticity values appear in Table 11.

Figure 5: Nesting in non-fossil fuel production

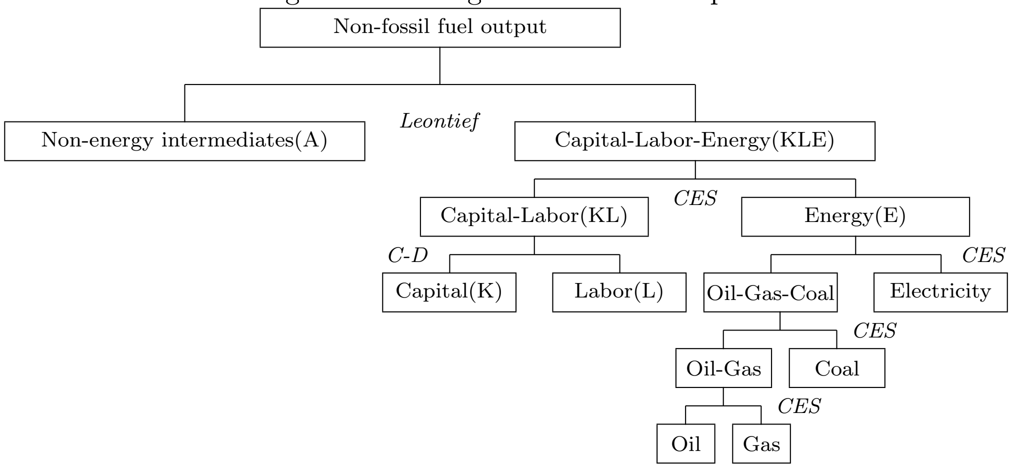


Figure 6: Nesting in fossil fuel production

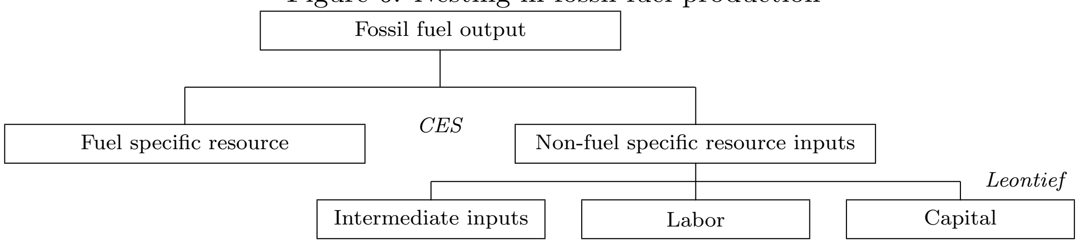


Figure 7: Nesting in household consumption

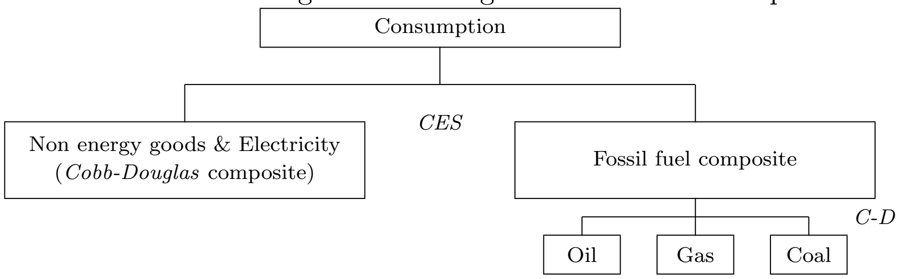
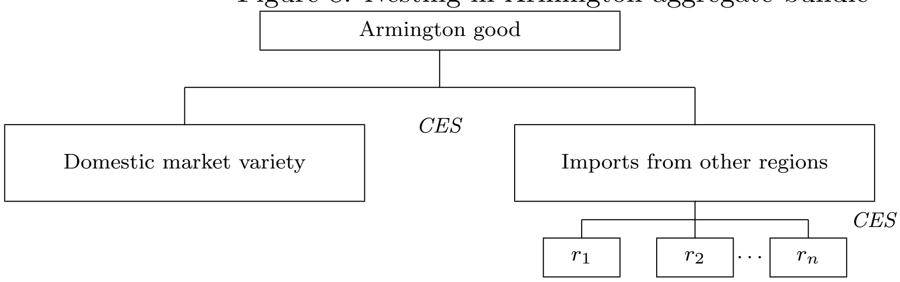


Figure 8: Nesting in Armington aggregate bundle



E Benchmark Data - Regional and Sectoral Aggregation

The model is built on a comprehensive energy-economy data set that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flow. The underlying data base is GTAP-EG which reconciles the GTAP economic production and trade data set for the year 1997 with OECD/IEA energy statistics for 45 regions and 22 sectors (Rutherford and Paltsev 2000). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Sectors and regions of the original GTAP-EG data set are aggregated according to Tables 12 and 13 to yield the model's sectors and regions (see Table 5).

Table 12: Sectoral Aggregation

Sectors in GTAP-EG			
AGR	Agricultural products	NFM	Non-ferrous metals
CNS	Construction	NMM	Non-metallic minerals
COL	Coal	OIL	Refined oil products
CRP	Chemical industry	OME	Other machinery
CRU	Crude oil	OMF	Other manufacturing
DWE	Dwellings	OMN	Mining
ELE	Electricity and heat	PPP	Paper-pulp-print
FPR	Food products	SER	Commercial and public services
GAS	Natural gas works	T_T	Trade margins
I_S	Iron and steel industry	TRN	Transport equipment
LUM	Wood and wood-products	TWL	Textiles-wearing apparel-leather

Mapping from GTAP-EG sectors to model sectors from Table 1		
		Energy
COL	Coal	COL
CRU	Crude oil	CRU
GAS	Natural gas	GAS
OIL	Refined oil products	OIL
ELE	Electricity	ELE
		Non-Energy
EIS	Energy-intensive sectors	CRP, I_S, NFM, NMM, PPP, TRN
Y	Rest of industry	T_T, ATP,AGR, OME, OMN, FPR, LUM, CNS, TWL, OMF, SER, DWE

Table 13: Regional Aggregation

Regions in GTAP-EG

ARG	Argentina	MYS	Malaysia
AUS	Australia	NZL	New Zealand
BRA	Brazil	PHL	Philippines
CAM	Central America and Caribbean	RAP	Rest of Andean Pact
CAN	Canada	RAS	Rest of South Asia
CEA	Central European Associates	REU	Rest of EU
CHL	Chile	RME	Rest of Middle East
CHN	China	RNF	Rest of North Africa
COL	Columbia	ROW	Rest of World
DEU	Germany	RSA	Rest of South Africa
DNK	Denmark	RSM	Rest of South America
EFT	European Free Trade Area	RSS	Rest of South-Saharan Africa
FIN	Finland	SAF	South Africa
FSU	Former Soviet Union	SGP	Singapore
GBR	United Kingdom	SWE	Sweden
HKG	Hong Kong	THA	Thailand
IDN	Indonesia	TUR	Turkey
IND	India	TWN	Taiwan
JPN	Japan	URY	Uruguay
KOR	Republic of Korea	USA	United States of America
LKA	Sri Lanka	VEN	Venezuela
MAR	Morocco	VNM	Vietnam
MEX	Mexico		

Mapping from GTAP-EG regions to model regions from Table 1

EUR	Western Europe	GBR, DEU, ITA, NLD, CEA, DNK, EFT, FIN, REU, SWE
JPN	Japan	JPN
USA	United States	USA
CHN	China	CHN, HKG, TWN
FSU	Former Soviet Union	FSU
ROW	Rest of the World	ARG, AUS, BRA, CAM, CAN, CHL, COL, IDN, IND, KOR, LKA, MAR, MEX, MYS, NZL, PHL, RAP, RAS, RME, RNF, ROW, RSA, RSM, RSS, SAF, SGP, THA, TUR, URY, VEN, VNM