International Emission Trade and Voluntary Global Warming Agreements *

Jared C. Carbone[†] Carsten Helm[‡] Thomas F. Rutherford[§]

Revised: October 3, 2006

Abstract

We evaluate the prospect of forming voluntary global warming agreements in which membership entitles a country to trade emission permits with other member states. To do so, we construct a calibrated general equilibrium model that jointly describes the world economy and the strategic incentives that guide the design of national abatement policies. Countries choose their initial permit endowments noncooperatively, so a priori it is not clear that permit trade will induce participation in international abatement agreements or that participation will result in significant environmental gains. Despite this, we find that emission trade agreements can be effective; that smaller groupings of two or three countries pairing developing and developed-world partners often perform better than agreements with larger rosters; and that general equilibrium responses play an important role in shaping these outcomes.

Keywords: global warming, coalitions, general equilibrium, tradable permits.
JEL classification: F18, F42, Q58, R13.

*Research supported by the Electric Power Research Institute. Carlo Perroni originally suggested the numerical technique we have employed in these calculations. We also wish to thank Yongmin Chen, Charles Kolstad, Glenn Harrison, Nick Flores, Snorre Kverndokk, Alexander Haupt and V. Kerry Smith for comments and suggestions.

[†]Department of Economics, Morey House, Williams College, Williamstown, MA 01267, USA, jcarbone@williams.edu.

[‡]**Corresponding author.** Technical University Darmstadt, Department of Law and Economics, Marktplatz 15, D-64283 Darmstadt, Germany, ph.: +49 6151 16-2095, fax: +49 6151 16-6043, helm@vwl.tu-darmstadt.de

[§]Ann Arbor, MI, tom@mpsge.org

International Emission Trade and
Voluntary Global Warming Agreements

1 Introduction

Trade in emission rights makes meeting a given abatement target less costly. Many policymakers express hope that it will produce more effective international global warming agreements, inducing fast-growing, pollution-intensive economies, such as China, to join by allowing them to capture the rents from emission permit sales. This hope rests on the belief that: (*i*) permit trading is sufficiently profitable to induce participation by these countries and (*ii*) the aggregate abatement targets agreed upon by participating countries will result in meaningful environmental gains. When decisions regarding abatement targets and participation in international environmental agreements (IEAs) are the result of national policy agendas, however, it is not obvious that either of these conditions will be met.

We evaluate the prospect of forming voluntary global warming agreements in which membership entitles a country to trade emission permits with other member states. By enumerating the possible agreement memberships we are able to characterize the pairings of countries that are likely to produce effective agreements and the incentives that drive equilibrium outcomes.

To do this we construct a numerical model which embeds strategic behavior in the design of national abatement policies within a computable general equilibrium (CGE) description of the world economy. The CGE model provides a basis for describing the profiles of the different world regions which are players in our permit-trade game. Beyond this, it allows us to describe how trade linkages that have long been acknowledged to be an important determinant of abatement costs impact permit-trade agreements.

In the model, agreements are equilibria in which both a country's decision to join an agreement and its decision regarding the size of its permit endowment are best responses to the actions of the other countries. A proposal which specifies the potential members of an agreement is put forward. The proposal is taken as given. In stage 1, potential agreement members simultaneously decide whether they agree to participate in the proposed trading regime. In stage 2, all countries simultaneously choose their allocation of emission rights. Firms located in member countries trade permits with firms in other member countries. Firms in non-member countries trade permits only on domestic markets. Markets clear and payoffs accrue. In the subgame perfect Nash equilibrium of this game, no country wants to unilaterally change its choice of emission rights nor its decision about participation in the trading system.

There is a substantial literature that uses game-theoretic concepts to analyze self-enforcing IEAs (often called "coalitions").[1] While there are similarities between the models presented in these studies and the one here, there are important conceptual differences. Broadly speaking, authors in the self-enforcing IEA literature seek to provide a general description of the degree to which countries will voluntarily internalize pollution externalities. In keeping with this focus, they abstract from the specific instruments used to affect emission reductions and the process that determines how the surplus produced by the agreement is distributed across members. Our focus is on analyzing a specific institutional structure — trade in emission rights — and how a country's key strategic variable in our model — in our model, their initial permit holdings — shapes the equilibrium surplus division and abatement level. Furthermore, because we model the emission rights choice noncooperatively, the gains from permit trade that we describe are independent of the ability of countries to internalize the pollution externality caused by greenhouse gas emissions (Helm 2003).

Our work also departs from the existing literature in its use of a general equilibrium model to quantify the strategic aspects of emission trade agreements. A number of studies have established the importance of general equilibrium responses to global warming abatement policies.[2] Reducing home emissions leads to lower domestic demand for fossil fuels. If this decreased fuel demand is sufficiently large, it may depress international fuel prices and stimulate energy and emission demands abroad. This effect, referred to as carbon leakage (Felder and

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

[2]See Bernstein, Montgomery, Rutherford and Yang (1999) and other papers in the same volume for examples of studies that calculate the general equilibrium implications of exogenous abatement proposals. There are also some studies that aim to synthesize strategic and economic aspects of the abatement problem (e.g., Nordhaus and Yang (1996), Eyckmans and Tulkens (2003), Tol (2001)). However, none analyzes emission trading and none uses a framework that allows for a detailed modeling of general equilibrium effects.

Rutherford 1993), tends to reduce a country's incentive to restrict its own emissions because it can expect that its abatement effort will be partially offset by the increased emission demand elsewhere. Domestic abatement also produces trade spillovers through its effect on world prices. Specifically, net importers of energy-intensive goods are made worse off by this change because the cost of imports increase while net exporters reap the benefits of a higher return on their output. Hence, trade spillovers may either increase or decrease a country's incentive to reduce emissions depending on that country's orientation in international markets. An important objective of the paper is to explore how these channels — carbon leakage and trade spillovers — influence equilibrium outcomes.

Our simulations suggest that permit trade agreements can be effective abatement devices and that the mechanisms that explain this result are quite different from those highlighted in the existing literature on IEAs. The most effective agreements are sub-global and involve countries with high environmental benefit and high abatement cost buying large volumes of emission permits from their developing-world partners (either China or members of the former Soviet Union).

While agreements with global membership are equilibria in our simulations, smaller agreements often perform better. This is because permit-selling countries are motivated by their ability to capture surplus from permit sales. In doing so they face a trade-off since choosing more permits reduces the equilibrium permit price. Agreements with smaller numbers of sellers are better able to capture the monopoly markup by restricting the size of their permit endowment. This causes the agreement as a whole to produce fewer emissions and shifts the share of the surplus created by permit trade to developing-world sellers, increasing the likelihood of their participation.

In much the same way that member states try to manage their effect on the permit market, they also try to influence prices and quantities in the markets for energy and energy-intensive goods. An important determinant of whether equilibria lead to significant environmental benefits is whether the dominant influence of international trade is via quantities (carbon leakage) or prices (terms of trade spillovers). The relative strength of these two effects depends on the degree to which foreign and domestic varieties of energy-intensive goods are substitutes. Carbon leakage *increases* global emissions when traded goods from different regions are close substitutes. Trade spillovers *decrease* global emissions when traded goods are imperfect substitutes.

A final point on experimental design is in order before we move on. The research strategy we have described uses the quantitative content of the general equilibrium model to inform the game-theoretic analysis. This allows us to examine complex issues such as general equilibrium effects and coalition formation with heterogenous countries, which are difficult to analyze in a purely analytical model. The experiment is not, however, intended to be a forecasting exercise. We do not, for example, attempt to model how an agreement proposal comes to the table, mainly because there is no widely agreed upon model of this process to our knowledge. Furthermore, all studies of global warming policy confront sizeable uncertainties regarding growth paths, technological change and, in particular, the regional willingness to pay for climate protection. Hence, interpreting our results on the magnitude of permit trade flows or abatement rates as precise quantitative estimates would be misleading. Rather, we are interested in their general pattern and in understanding the mechanisms and strategic motives that lead to these patterns. In a nutshell, the purpose of the paper is to develop an intuition for the behavior of permit trade agreements in a model that characterizes the environment in which global warming policy operates.

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 emission levels and permit allocations. Section 3 describes the data on which we calibrate model parameters. Results are presented in Section 4 followed by concluding remarks in Section 5. The appendix contains a sensitivity analysis and describes the methods we use to solve the numerical model.

2 The Model

This section describes the elements of the model that are the basis of our analysis. Broadly, the model consists of two components — the competitive general equilibrium system which determines regional abatement costs and international trade flows, and a submodel of strategic interactions between regional governments that determines the membership and emission targets of equilibrium permit trade agreements. While it is conceptually useful to think about these components separately, it is important to note that they are part of a jointly determined system in our analysis.

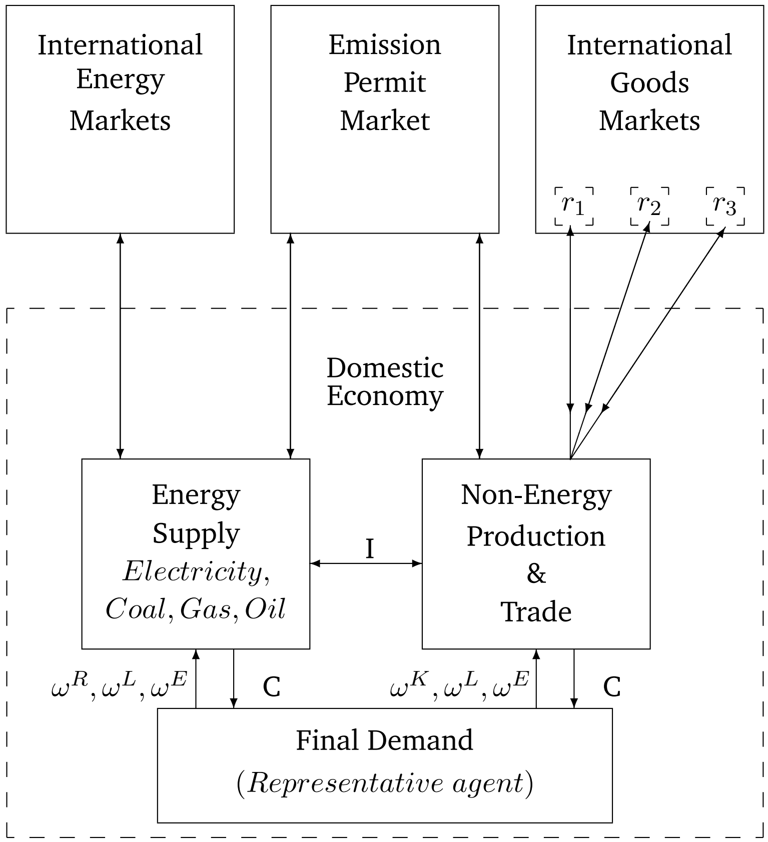
2.1 Competitive Equilibrium in the World Economy

We model the economic impacts of regional abatement choices with a static Shoven-Whalley general equilibrium trade model (see 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 effects of emission policies 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 (ω^L), capital (ω^K), fossil-fuel specific resources (ω^R) and emission permits (ω^E). Emission permits must be used in fixed proportion to fossil fuel consumption. Perfectly competitive firms produce goods for export to other regions, for intermediate input to the production of other goods (I), for final consumption and for investment. Factor revenue finances the purchase of final consumption goods and capital stock investment.

Labor, capital and emission permits 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 conventional goods 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 of substitution (CES) production function which aggregates all import varieties to an import bundle. International trade in emission permits, which is the

Figure 1: Regional Flows of Goods and Factors



basis for the global warming agreements in our model, takes place on a single, undifferentiated market between agreement members.

Regional welfare depends on the current economic utility (U_r) from consuming the produce of the traditional (non-environmental) sectors of the economy and on environmental damages of global carbon emissions. These two components of welfare are assumed to be separable. We also assume that the marginal utility of reductions in global emissions (ν_r) is constant. Accordingly, welfare in region r is defined as

$$W_r = U_r(\pi, \omega_r) - \nu_r e^G, \tag{1}$$

where r indexes the set of regions in the model, π is the vector of prices for goods and factors, $\omega_r = (\omega_r^K, \omega_r^L, \omega_r^R, \omega_r^E)$ is the vector of region r's primary factor endowments, and $e^G = \sum_r \omega_r^E$ is the global emission level.

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

$$F(z; \omega^E) = 0, \tag{2}$$

in which $z \in \mathbb{R}^N$ is the vector of equilibrium prices and quantities, $\omega^E \in \mathbb{R}^n$ is a vector of exogenous factor endowments representing regional emission rights for 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. Following Mathiesen (1985), we formulate the general equilibrium model as a system of equations in which the model variables include good and factor prices (π) that are associated with market-clearance conditions, and activity levels (Y) for producers that 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 $z = (\pi, Y)$.

A detailed description of the model and its empirical implementation is provided in the appendices, but a few final points on its implementation are worth noting here. While the model is essentially static, the simulation results that we report span a twenty-year time horizon with the numerical model recalibrated to reflect projected changes in the world economy at each point in time. Because the underlying logic of the model remains constant across these simulations, however, we have supressed time subscripts throughout the paper except where explicitly required to communicate a concept. A discussion of the calibration procedure is contained in section 3.

For parsimony and to keep the paper focused on permit trading agreements, we neglect some important dynamic aspects of global warming. For example, we model willingness to pay for instantaneous emission reductions instead of willingness to pay for actual climate improvements which is known to be a function of the stock of greenhouse gases in the atmosphere. Similarly, the full cost of abatement activity today would be most naturally viewed as the discounted stream of future costs imposed on the economy, including the effects of discouraged capital formation that it implies. Agents in our model respond only to current costs. Thus, regional GDP and investment are assumed to grow exogenously and in fixed proportions. A comprehensive forecast of the welfare effects of global warming policy would need to take these considerations into account, but we view them as separable from the insights on the role of permit trade in global warming policy that we develop in the paper.

2.2 Strategic Interaction

We now turn to the game-theoretic model. As discussed in the introduction, we assume that regions are confronted with a proposal specifying the potential members of a trading coalition. We do not model how this proposal arises but simply take it as a given outcome of the international negotiation process. In particular, let $\mathcal{R}$ be the set of regions. In stage 0, "nature" proposes a coalition $\mathcal{C} \subseteq \mathcal{R} : |\mathcal{C}| \geq 2$ of permit trading regions. The strategic interaction is modeled as an extensive game involving the successive play of two simultaneous move games.

In stage 1 of the game, regions $r \in \mathcal{C}$ decide about their membership in the proposed trading regime. Regions $r \notin \mathcal{C}$ reach no decision node at stage 1. In stage 2, all regions non-cooperatively choose their emission rights. However, interregional trading of these rights takes place only among coalition members $r \in \mathcal{C}$, and only if all $r \in \mathcal{C}$ have agreed to their membership at stage 1.[3]

In a Nash equilibrium of the stage 2 game, all regions choose emission rights as individual best replies to the choices of tradable and non-tradable emission rights of the other regions, thereby anticipating the trading of permits and of the other (non-strategic) goods in our economy. Accordingly, a coalition proposal $\mathcal{C}$ can be established as a subgame perfect Nash equilibrium (SPNE) if — based on the Nash equilibrium of the stage 2 game — the outcome where each potential coalition member accepts participation constitutes a Nash equilibrium of the stage 1 game. Repeating this game for all coalitions that can be formed allows us to characterize all

[3]Accordingly, we assume here that a subset of $\mathcal{C}$ cannot form a permit trading coalition. This is without loss of generality, since in the numerical simulations we solve the above game for all coalitions $\mathcal{C}$ that can be formed.

trading coalitions C that can be established as a SPNE.[4]

The above game differs from nearly all of the literature that uses non-cooperative game theory to analyze self-enforcing environmental agreements in two fundamental respects.[5] First, the standard assumption in this literature is that coalition members cooperatively choose their emissions at a level that is efficient from the coalitional perspective. Consequently, there is no role for trading in emission rights. In our model, coalition members non-cooperatively choose their endowment of tradable permits. Consequently, trading is crucial — without it the outcome would collapse to the standard non-cooperative Nash equilibrium in emissions. As the later simulations show, this leads to substantially different levels of welfare and emissions.

The second difference concerns the equilibrium concept. It is common to use the stability criteria of (i) internal stability (no coalition member wants to leave a coalition), and (ii) external stability (no region wants to join a coalition) (e.g., Carraro and Siniscalco (1993), Barrett (1994)). By contrast, we can apply the standard equilibrium concept of subgame perfection because we consistently assume non-cooperative behavior when players choose their action.

While the membership decision in our game is equivalent to the criterion of internal stability, there is no substitute for external stability. However, in section 4.1 we also consider an equilibrium refinement of the SPNE, which requires that for any SPNE coalition there exists no "larger" SPNE coalition which is a proper superset and which makes all member states better off. Accordingly, regions are admitted to join a coalition, but only if this is to the benefit of both current and joining members. We call this condition "weak external stability" to make clear that it resembles the standard external stability criterion but is less strict.

The latter would imply that a region can force access to a coalition, even if existing members anticipate that this region would choose a very high number of emission rights and, thereby, lead to the breakdown of the coalition. It strikes us as more realistic that coalition members can restrict the access of such regions. This contrasts with the 'standard' model, where joining

[4] We take international negotiations about proposals for trading coalitions as a black box and simply ask which outcomes can be established as SPNEs. Nevertheless, we would hope, of course, that knowledge about the most effective equilibrium coalitions — either in environmental or welfare terms — will feed-back into the negotiation process and provide some guidance.

[5] See Finus (2003) for a survey and Murdoch, Sandler and Vijverberg (2003) for an exception.

regions choose their emissions cooperatively so that the external stability criterion constitutes less of an obstacle for cooperation.

The game is solved by backwards induction, and we first determine regional choices of emission rights. Before doing so, we should mention that the "Rest of World" (ROW) region is not modeled as a (strategic) player of the game. (ROW) is composed of a large number of heterogeneous nations. Modeling them as a unitary actor would misrepresent their individual strategic influence. Furthermore, ROW includes many developing countries which are unlikely to pursue strategic climate change policies. For parsimony, we assume that emissions in this region simply reflect regional demand for fossil fuels at the prevailing market prices.

2.2.1 Regional Choice of Emission Rights

From the perspective of consumers and firms in the regional economy, emission rights endowments are like any other exogenous factor endowment, just as the notation in (2) suggests. Unlike other endowments, however, governments choose the regional level of emission rights strategically to maximize regional welfare. For non-members of the permit trading agreement this welfare is given by (1), for members it also includes their net income from transactions on the permit market. Abstracting from the latter for the moment, a strategic region r chooses its level of emission rights by equating the marginal economic cost of abatement with the marginal environmental benefit, hence

$$\frac{dW_r}{d\omega_r^E} = \frac{dU_r}{d\omega_r^E} - \nu_r \frac{de^G}{d\omega_r^E} = 0 \tag{3}$$

When economic preferences are homothetic, as we assume in our model, economic welfare (U_r) can be expressed in terms of the ratio of regional income to the unit expenditure function (the price index) for a unit of consumption.[6] For the purpose of decomposing the marginal economic cost of abatement ($\frac{dU_r}{d\omega_r^E}$ from (3)) by sector, it is useful to write regional income in

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

terms of the value of net output.[7] Thus, U_r becomes

$$U_r = \frac{\sum_i \left(Y_{ir}\pi_{ir} - \sum_s I_{isr}\pi_{is}\right)}{p_r^c(\pi)} \tag{4}$$

where i indexes the joint set of factors and goods, and r and s index the set of regions. Y_{ir} is the aggregate supply of good (or factor) i in region r, π_{ir} is the price of commoditity i produced by region r, and I_{isr} is aggregate intermediate demand for i imported from s to r. $p_r^c(\pi)$ is the representative agent's unit expenditure function. In the numerical model, this is defined by the solution to the maximization of a nested CES utility function subject to the limitations of region r's factor endowment income.

Differentiating (4) with respect to region r's endowment of emission permits, ω_r^E, gives us

$$\frac{dU_r}{d\omega_r^E} = \frac{1}{p_r^c}\sum_i \left[Y_{ir}\frac{d\pi_{ir}}{d\omega_r^E} + \frac{dY_{ir}}{d\omega_r^E}\pi_{ir} - \sum_s \left(I_{isr}\frac{d\pi_{is}}{d\omega_r^E} + \frac{dI_{isr}}{d\omega_r^E}\pi_{is} + U_r\frac{\partial p_r^c}{\partial \pi_{is}}\frac{d\pi_{is}}{d\omega_r^E}\right)\right] \tag{5}$$

Shepard's lemma and homotheticity of the preference function together imply that the final term on the right-hand side of (5) can be written in terms of final consumption demands (C_{isr}):

$$\frac{dU_r}{d\omega_r^E} = \frac{1}{p_r^c}\sum_i \left[Y_{ir}\frac{d\pi_{ir}}{d\omega_r^E} + \frac{dY_{ir}}{d\omega_r^E}\pi_{ir} - \sum_s \left(I_{isr}\frac{d\pi_{is}}{d\omega_r^E} + \frac{dI_{isr}}{d\omega_r^E}\pi_{is} + C_{isr}\frac{d\pi_{is}}{d\omega_r^E}\right)\right] \tag{6}$$

In the absence of taxes, the regional value of net output must equal the regional value of factor endowments.

$$\sum_i \left(Y_{ir}\pi_{ir} - \sum_s I_{isr}\pi_{is}\right) = \sum_k \omega_r^k \pi_{kr} \tag{7}$$

where k indexes the set of primary factors (K, L, R, E). Hence,

$$\sum_i \left[\frac{dY_{ir}}{d\omega_r^E}\pi_{ir} - \sum_s \frac{dI_{isr}}{d\omega_r^E}\pi_{is}\right] = \sum_k \frac{d\omega_r^k}{d\omega_r^E}\pi_{kr} = \pi_{Er}, \tag{8}$$

where π_{Er} is the price of emission permits in region r. Using (8) and rearranging terms we can

[7] The identity between regional factor income and the value of net output that we use to obtain (4) requires an economy with no taxes and balanced trade.

re-write the full optimality condition from (3) as:

$$\frac{1}{p_r^c}\left[\pi_{Er}+\underbrace{\sum_i\left((Y_{ir}-C_{irr}-I_{irr})\,\frac{d\pi_{ir}}{d\omega_r^E}-\sum_{s\neq r}(C_{isr}+I_{isr})\frac{d\pi_{is}}{d\omega_r^E}\right)}_{Trade\ Spillovers}\right]=\nu_r\left(1\quad\underbrace{+\frac{de_{row}}{d\omega_r^E}}_{Carbon\ Leakage}\right) \tag{9}$$

The left-hand side of (9) describes the marginal economic costs of abatement and the right-hand side describes the marginal environmental benefits. π_{Er} represents the direct cost of a marginal reduction in the size of region r's permit endowment, and in a partial equilibrium model with no international permit trade, equilibrium would be given by

$$\frac{1}{p_r^c}\pi_{Er}=\nu_r. \tag{10}$$

The terms labeled *Trade Spillovers* capture the effects of permit choice on regional income through the induced general equilibrium price changes. The right-hand side of the expression describes the marginal environmental benefits of a marginal change in emissions. This includes a direct effect due to the change in emissions from region r's permit choice and an indirect, carbon leakage effect.

Domestic abatement implies reduced energy demand for region r. This causes world energy prices to fall, inducing increased demand and emissions abroad. This is the source of the carbon leakage effect. Because the contribution of strategic regions to world emissions are capped by the availability of permits, the only source of leakage in the model comes from the response of the non-strategic ROW countries, hence $\frac{de^G}{d\omega_r^E}$ from (3) becomes $\left(1+\frac{de_{row}}{d\omega_r^E}\right)$. The carbon leakage effect will tend to diminish the incentive for domestic abatement by region r because $\frac{de_{row}}{d\omega_r^E}<0$.

Now consider the trade spillover terms on the left-hand side of (9). The individual terms in the sum over i may take on either a positive or negative sign depending on the whether region r is a net exporter or importer of good i and whether an incremental change in the permit endowment causes the price of good i to rise or fall. For example, an increased supply of emission permits will tend to lower the price of energy-intensive goods $\left(\frac{d\pi_{ir}}{d\omega_r^E},\ \frac{d\pi_{is}}{d\omega_r^E}<0\right)$ because permits are an input to the production processes of these goods. If region r is a net exporter of these goods ($Y_{ir} - \sum_s (C_{isr} + I_{isr}) > 0$), then higher emission rights levels will tend to make region r worse off through the trade spillover effect. This is because lowering the price reduces the revenue the region collects on their exports of energy-intensive goods and, therefore, lowers region r income. In contrast, price reductions on goods for which the region is a net importer are beneficial because they lower the regional cost of living.

In principle, there will be a trade spillover effect (within the i-sum in (9)) for each commodity which is not separable from the supply of emission permits and which region r trades internationally. Based on this characterization, however, we would expect energy-intensive goods to be most likely to exhibit significant spillovers among the conventional commodities in the model. We would also expect spillovers associated with the permit market itself when a country is a member of an emission trade agreement. This type of spillover is, in fact, the mechanism by which member countries manipulate the size of their permit endowment in order to capture the surplus generated by permit trade. It gives the incentive for exporters to increase the scarcity of permits and for importers to increase their abundance.

Alternatively, trade spillovers can be thought of as describing general equilibrium implications of the imperfect competition models from first principles. Net importers of embodied emissions (either emission-intensive goods or emission permits themselves) with strategic influence behave like monopsonists, using their emission rights choice to manage the cost of purchasing these goods from abroad. Net exporters with strategic influence behave like monopolists acting to restrict supply of these goods to achieve a markup.

Pushing the analogy a step further, the effect of adding new members to a permit trade agreement will depend on whether the role they will play in the agreement will be as a net importer or exporter of permits. Adding permit exporters will tend to raise the aggregate supply of permits as suppliers compete for surplus, analogous to the quantity competition that takes place in the Cournot model of imperfect competition. Similarly, adding potential permit buyers will tend to decrease aggregate supply. It is less clear, however, what the equilibrium implications of this competition are for emission levels and regional welfare because of the general equilibrium context and the fact that the emission market exhibits a negative externality.

2.2.2 Equilibrium Outcomes

In a subgame perfect Nash equilibrium, each potential coalition member accepts to participate in the proposed permit trading regime, and the Nash equilibrium of the stage 2 game is defined as

$$
\begin{aligned}
\frac{1}{p_r^c}\left[\pi_E + \left(\omega_r^E - e_r\right)\frac{d\pi_E}{d\omega_r^E} + \Delta_r\right] - \nu_r\left(1 + \frac{de_{row}}{d\omega_r^E}\right) &= 0 \quad , \quad \forall r \in \mathcal{C} \\
\frac{1}{p_r^c}\left[\pi_{Er} + \Delta_r\right] - \nu_r\left(1 + \frac{de_{row}}{d\omega_r^E}\right) &= 0 \quad , \quad \forall r \notin \{\mathcal{C}, row\} \\
F(z;\omega^E) &= 0
\end{aligned}
\tag{11}
$$

where e_r is aggregate demand for emissions in region r and Δ_r describes the spillover effects associated with trade in all conventional goods, i.e.

$$
\Delta_r = \sum_{i \neq E}\left(\left(Y_{ir} - C_{irr} - I_{irr}\right)\frac{d\pi_{ir}}{d\omega_r^E} - \sum_{s \neq r}(C_{isr} + I_{isr})\frac{d\pi_{is}}{d\omega_r^E}\right) \tag{12}
$$

The first two lines of (11) describe the emission rights problems faced by coalition members and non-members, respectively, based on the generic expression in (9). Because permits are bought and sold across member countries, their price (π_E) captures the joint abatement possibilities of these countries, whereas the permit price in nonmember countries (π_{Er}) captures only domestic abatement possibilities. Member countries also anticipate how their choice of emission rights affects the price π_E at which they buy or sell permits. [8]

The final line of (11) indicates that the prices and activity levels that enter the emission optimality conditions are determined by the general equilibrium module. This is the sense in which the strategic emission behavior and the general equilibrium module are components of a simultaneous system.

[8] In the discussion of our simulation results (Section 4), we analyze the numerical counterparts to the different marginal effects discussed here: direct costs and benefits (π_E and ν_r), trade spillovers in the permit market ($\left(\omega_r^E - e_r\right)\frac{d\pi_E}{d\omega_r^E}$) and in conventional markets (Δ_r), and carbon leakage ($\nu_r \frac{de_{row}}{d\omega_r^E}$).

We judge the achievements of the SPNE emission trade agreements against two benchmarks. The first benchmark, the no-trade Nash equilibrium, is simply the instance of (11) in which $\mathcal{C}$ is the empty set. The second benchmark is the globally efficient allocation of emission rights. Accordingly, each country sets emission rights to equate its marginal abatement costs with the sum of marginal benefits over all model regions, hence:

$$\frac{1}{p_r^c}\left[\pi_{Er} + \Delta_r\right] - \sum_s \nu_s \left(1 + \frac{de_{row}}{d\omega_r^E}\right) = 0 \quad , \quad \forall r \notin \{row\} \tag{13}$$

$$F(z; \omega^E) = 0$$

3 Data

The GTAP5 trade and production database (Dimaranan and McDougall 2002) 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 International Energy Outlook (IEO) 2002 dataset (US 2002) which provides baseline estimates of regional GDP, population and carbon dioxide emission levels through the year 2020. We express our model results as deviations from these Business as Usual (BaU) levels.

Table 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. It also achieves the largest improvements 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

A few of the assumptions required to match the GTAP database to our application are worth noting. Our model is static, so we do not describe the capital dynamics associated with different abatement policies. We assume that investment is fixed in proportion to regional GDP in any given model year, where GDP is based on the growth projections from the IEO. We assume that tax revenues and current account imbalances are unaffected by abatement policy in any given model year and across model years.[9]

Modeling the demand for reductions in greenhouse gas emissions also requires an assumption about the value that regions place on emission reductions. Our calibration is based on the idea that countries reveal their willingness to pay for environmental improvements through their position in global warming negotiations (Mäler 1989).

The European Union and Japan have already ratified the Kyoto Protocol, an agreement 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 calibrate them at a 15% reduction. The remaining model regions appear to be even less willing to pay for carbon abatement. Accordingly, we calibrate China (CHN) at a 5% reduction and the countries that make up the Former Soviet Union (FSU) at a

[9] We ignore tax interaction effects in the present analysis since such an extension would require a substantial overhaul of the underlying GTAP social accounting data. Sensitivity analysis with respect to pre-existing energy taxes which are part of the GTAP database, indicates that including these taxes has only limited impact on the model results (see Appendix A).

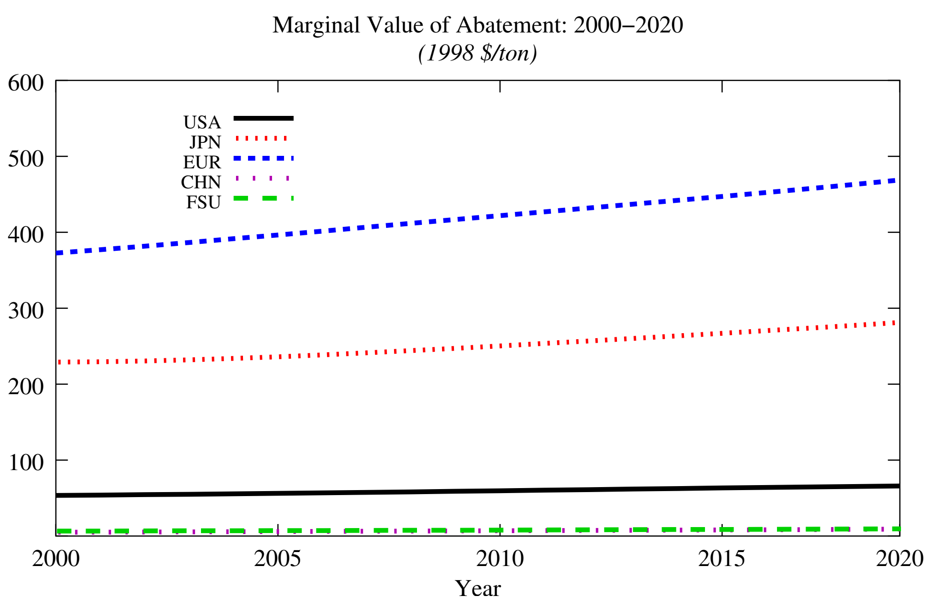
5% increase in emissions above BaU. This last assumption may seem inconsistent with a positive valuation for abatement. However, the general equilibrium effects induced by the benchmark abatement assumptions in other regions imply that FSU benefits from expanding its energy use beyond BaU levels. Our calibration turns out to suggest marginal values (expressed in US-$) of similar magnitude for China and the Former Soviet Union, as shown in Figure 2.

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

$$\nu_{rt} = \bar{\nu}_r \Gamma_{rt}^{\eta}, \tag{14}$$

where Γ_{rt} is the mean per capita GDP in region r at time t, and η is the exogenously chosen income elasticity of demand for abatement. We choose a benchmark value of $\eta = 0.5$. Figure 2 shows the ν_{rt} trajectories under benchmark assumptions.

Figure 2:



We are well aware that this calibration is highly conjectural. Other studies have adopted an alternative approach, using estimates of economic costs of predicted physical impacts of global warming (Nordhaus 1991, Nordhaus and Yang 1996, Botteon and Carraro 1997). However, we believe that these attempts are no less conjectural, given the current state of climate science (Tol 2002). Nevertheless, it is interesting to note some differences. Our estimates imply that Europe and Japan have marginal willingness to pay (MWTP) values that are orders of magnitude larger than developing countries such as China or the former Soviet republics. In Nordhaus and Yang (1996), developing countries like China have the highest values for climate protections because their economies are disproportionately tied to agriculture and their populations disproportionately exposed to the elements (such as floods, droughts, and vector-born diseases). As these countries also have the lowest abatement costs, no permit trade would take place in our model. China would simply undertake all of the abatement it demands at home as this is the least costly method (see section 4).

A second interesting feature of our calibration results is how little convergence in regional MWTP values takes place over the time horizon we consider. Despite the fact that income per capita in China is growing at approximately 6.5% annually during this period there is no noticeable convergence in values described by figure 2. In Section 4.3, we also look at one instance which shows more convergence in valuations over the time horizon. In particular, we assume

$$\nu_{rt} = \bar{\nu}_r(1+\gamma_r)^{(t-2000)}\Gamma_{rt}^{\eta} \tag{15}$$

and fix values for γ_r 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.

4 Results

This section discusses the results of several illustrative numerical simulations. Section 4.1 describes the equilibrium emission trade agreements and the incentive structures that typify the more successful agreements under baseline calibration of the model. Section 4.2 explores the effects of international trade — via trade spillovers and carbon leakage — in more detail. Section 4.3 considers how changes in the distribution of marginal willingness to pay for environmental improvements affects future prospects for effective emission trade agreements.

4.1 Analysis of Emission Trading Coalitions

The first column in Table 2 lists all coalitions that can be formed. For each of them we solved equation system (11) for model year 2010. The results are summarized in the following columns, which display welfare differences from the no-trade Nash equilibrium as well as the global emission reductions from BaU. Coalitions that are SPNEs are indicated with a "*". Coalitions that also satisfy the "weak external stability" condition that there exists no larger SPNE coalition which improves the welfare of all its members are indicated with a "**".[10] Observe that the equilibrium refinement excludes those SPNE coalitions that have the worst performance.

The rows of the table are sorted by the level of the global emission reduction that each coalition produces. The simulations were performed under the assumption that varieties of the same good produced by different countries are relatively close substitutes (i.e. homogenous trade). We discuss the significance of this assumption in Section 4.2.

The abatement achievements of the different coalitions run the gamut from coalitions that actually lead to higher emission levels than 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.

Given that permit endowments are chosen noncooperatively by self-interested countries, these asymmetries lead to substantial differences in endowment choices. This can be seen from Table 3, which compares regional permit and emission choices for the USA-EUR-CHN coalition

[10] For example, USA-EUR does not satisfy weak external stability since USA-EUR-CHN is a SPNE in which the welfare of all members is higher.

Table 2: Coalitions by Emission Reduction and Welfare Change, 2010

Homogenous Trade $(\sigma_{DM}, \sigma_{MM}) = (8, 16)$

	% Equivalent Variation						*Average*	*Emission*
	USA	JPN	EUR	CHN	FSU	ROW	*%EV*	*Reduction*
USA,JPN,EUR,CHN	0.75	7.57	2.81	3.04	0.40	0.00	0.96	13.95
USA,EUR,CHN**	0.66	8.62	2.57	2.52	0.42	0.00	0.86	13.64
JPN,EUR,CHN,FSU	0.35	6.88	2.93	1.35	6.67	0.02	0.87	13.14
EUR,CHN,FSU**	0.33	7.71	2.77	0.98	5.45	0.02	0.75	12.90
EUR,CHN**	0.29	6.75	2.82	0.89	0.26	0.02	0.50	12.10
JPN,EUR,CHN	0.29	6.60	2.76	1.16	0.25	0.02	0.55	12.07
USA,JPN,EUR,CHN,FSU**	0.36	5.36	2.27	1.39	6.54	0.05	0.83	11.88
JPN,CHN**	0.26	5.03	3.13	0.22	0.17	0.03	0.35	11.56
USA,EUR,CHN,FSU	0.21	5.02	1.85	0.86	4.78	0.05	0.61	10.72
USA,JPN,EUR,FSU	0.47	2.85	0.58	0.07	10.79	-0.01	0.56	10.01
USA,EUR,FSU**	0.38	3.92	0.42	0.05	8.98	-0.01	0.49	9.74
USA,JPN,CHN	0.13	2.61	1.73	0.64	0.03	0.04	0.31	9.27
USA,EUR*	0.43	3.21	0.68	0.08	0.23	-0.03	0.12	9.13
USA,JPN,EUR	0.47	3.21	0.57	0.08	0.24	-0.03	0.12	9.06
USA,JPN*	0.18	0.83	1.06	0.07	0.12	-0.02	0.09	8.26
EUR,FSU*	0.08	1.93	0.60	0.00	3.60	0.01	0.23	8.10
JPN,EUR,FSU	0.08	1.73	0.51	0.01	4.64	0.02	0.27	8.07
JPN,FSU*	0.07	0.99	0.78	0.03	0.91	0.00	0.11	7.75
USA,CHN*	0.01	1.47	0.79	0.33	-0.04	0.03	0.15	7.74
USA,JPN,CHN,FSU	-0.05	0.49	0.44	0.31	1.80	0.05	0.20	7.16
USA,JPN,FSU	0.04	-0.16	0.37	0.02	2.39	0.01	0.13	7.07
JPN,CHN,FSU*	0.01	0.15	0.10	0.04	0.60	0.02	0.06	6.65
No-trade Nash*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.48
JPN,EUR	-0.01	0.50	-0.11	-0.01	0.05	0.01	0.01	6.44
USA,CHN,FSU	-0.09	-0.13	-0.03	0.16	1.21	0.03	0.09	6.39
USA,FSU	-0.05	-0.96	-0.46	-0.03	0.66	0.02	-0.01	5.69
CHN,FSU	-0.07	-1.63	-0.82	-0.06	0.10	0.00	-0.09	5.12

* indicates that a coalition is a SPNE.
** indicates a SPNE coalition which satisfies the weak external stability condition.
% Equivalent Variation: % change in money-metric utility from Nash without trading.
Emission Reduction: % reduction in global emissions from BaU.
Average %EV: Population-weighted average of regional % changes in EV from no-trade Nash.

(the "best" SPNE outcome from Table 2) to the no-trade Nash outcome in model year 2010. EUR, the coalition member with by far the highest valuation for abatement (see column "$MWTP_r$"), chooses a very low permit allocation ω_r^E. In contrast, the coalition members with lower valuations for abatement, USA and CHN, choose permit endowments that even exceed their emissions in the no-trade Nash equilibrium (e_r^N). Despite this diversity, all regions benefit from agreement on trading (see column "ev_r"), though for different reasons.

For EUR it becomes much cheaper to foster its environmental goals — by choosing a low ω_{EUR}^E

Table 3: USA-EUR-CHN Coalition Profile, 2010
Homogenous Trade $(\sigma_{DM}, \sigma_{MM}) = (8, 16)$

	e_r^N	$e_r^{\mathcal{C}}$	ω_r^E	ev_r	π_{Er}	$MWTP_r$
			Coalition Members			
USA	84.3	74.3	92.2	0.7	117.9	59.7
EUR	77.6	86.9	3.1	2.6	117.9	428.6
CHN	88.1	41.9	89.7	2.5	117.9	6.8
			Outsiders			
JPN	79.5	80.0	80.0	8.6	195.2	253.7
FSU	103.4	103.0	103.0	0.4	1.8	6.3
			Non-strategic			
ROW	106.8	108.7	-	-	-	-

e_r^N: no-trade Nash emissions as % of BaU
$e_r^{\mathcal{C}}$: equilibrium emissions with coalition as % of BaU
ω_r^E: permit endowment as % of BaU emissions
ev_r: EV as % change from no-trade Nash equilibrium
π_{Er}: real permit price ($/Tons)
$MWTP_r = \nu_r p_r^c$: MWTP for emission reductions, ($/Tons)

— because that part of abatement which would be most costly is shifted through the permit market to the other regions. Indeed, after-trade emissions ($e_r^{\mathcal{C}}$) of EUR greatly exceed its permit allocation 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 regions CHN and USA both emit less than in the no-trade Nash equilibrium.[11]

It is worthwhile to consider why coalition members with low valuation for abatement, i.e. CHN and USA, do not choose tradable permits ω_r^E that more substantially exceed their emission choices in the no-trade Nash equilibrium. After all, permits are precious, as indicated by the permit price (π_{Er}) in Table 3, and coalition members are free to choose their initial permit allocation in our noncooperative framework.

[11] Admittedly, such a pattern where permit endowments in USA and Europe differ by such a large extent, and where Europe relies on China for such a large fraction of its emission rights may not be politically acceptable. The reason is that our model neglects political aspects which are important but hard to quantify, e.g. that countries compare their reduction burdens with that of others. As discussed in the introduction, results should not be interpreted as precise quantitative estimates, but as qualitative insights about the general pattern of permit endowment choices and equilibrium coalitions.

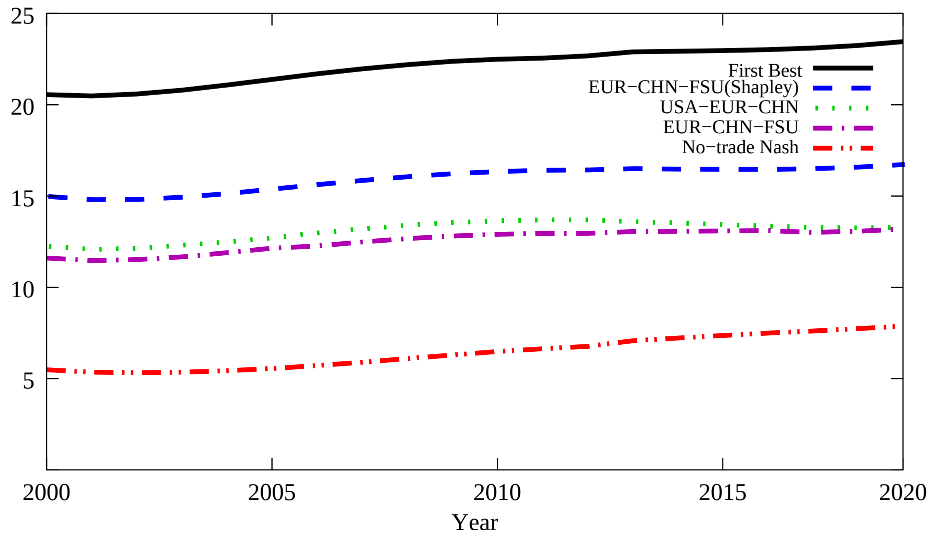
Recalling our discussion of the first-order conditions in Section 2.2, three effects are responsible for this restraint. First, more permits generally lead to more emissions and associated environmental damages (final term from the first-order conditions in (11)). Second, choosing more permits increases supply, thereby generally reducing the equilibrium permit price and lowering revenues from permit sales (negative second term in square brackets from first line of (11)). Third, less emissions and energy use leads to lower energy prices and higher prices for energy-intensive goods (both contributions to a negative Δ_r term from (11)). The USA-EUR-CHN coalition is dominated by countries who are net importers of fossil fuels and net exporters of energy-intensive goods. They find it in their interest to exploit both of these trade spillovers by restricting their permit levels.

Coalition outsiders also have strategic motives. As illustrated in Table 3, JPN benefits from coalitional abatement without contributing itself. Given its high valuation for abatement (ν_r), it can therefore secure the highest welfare gains of all regions (ev_r).

In contrast, FSU has the lowest welfare gains of all (strategic) regions. The additional abatement produced by USA-EUR-CHN yields only modest benefits for this region due to its low valuation for abatement. Therefore, FSU would prefer to join the coalition so as to gain from the right to sell permits, just like CHN. In a USA-EUR-CHN-FSU coalition, FSU would add cheap abatement options but choose a permit allocation that is 59% above its emissions as a coalition outsider. As a consequence, pollution would rise and the permit price would fall. Despite the associated welfare losses, EUR and CHN would stay inside this extended coalition so as not to lose its cheap abatement options (EUR), respectively the income from permit sales (CHN). However, USA would defect since its welfare increases as an outsider (see row 4 and 9 in Table 2). Hence USA-EUR-CHN-FSU is not a SPNE.

Figure 3 depicts abatement trajectories for selected equilibria over the model time horizon (2000-2020). Comparing the best trading coalition (USA-EUR-CHN) with the Nash equilibrium without emission trade (No-trade Nash) again illustrates that the possibility of forming a trade coalition substantially increases emission abatement. However, the figure also shows that emission reductions in the efficient solution (First Best) would be nearly twice as high.

Figure 3:
Selected Abatement Trajectories: 2000−2020
(% of BaU Emissions)



A natural question is to ask how much of this shortfall is due to our assumption that coalition members choose their permit endowments noncooperatively, and how much of it is due to noncooperative decisions to participate in the agreement. In order to address this question, we consider one profile where coalition members choose emissions to maximize group surplus and agree on the Shapley value as the surplus-distribution scheme. Accordingly, only the decision to join an agreement is made noncooperatively.[12]

The highest reductions are achieved by the coalition depicted in "EUR-CHN-FSU (Shapley)". Interestingly, the difference between this series and the outcome for the same coalition but noncooperative choices of permit endowments, labeled "EUR-CHN-FSU", is small relative to the difference from the no-trade Nash equilibrium. This indicates that noncooperative participation decisions are responsible for most of the difference between equilibrium and first-best outcomes.

Finally, we note that the grand coalition (all regions except for the non-strategic ROW region) is an equilibrium outcome (see Table 2) but one that is dominated by coalitions with fewer members. These are both results that are not obtained in studies that assume cooperative allocation schemes. Countries with low environmental valuations are potential free-riders in the

[12]This distribution scheme has been applied, e.g., by Barrett (1997) and Botteon and Carraro (1997).

cooperative framework, yet they tend to be important permit sellers who stand to lose revenues if they defect from the agreement in our model. However, nothing guarantees that emission levels produced by the agreement will be efficient in our model, implying that emissions may actually rise with the number of agreement members.

4.2 International Trade and Equilibrium Abatement

This section looks more closely at the strategic influence of international trade on equilibrium outcomes through carbon leakage and trade spillover effects. Table 4 reports on the realization of the individual marginal effects that enter countries' first-order conditions. While we report on the realization of these effects in the no-trade Nash equilibrium, the intuition gained by studying this benchmark inform our subsequent discussion of the interaction between coalition formation and international trade effects.

To illustrate how these effects function, the Table 4 describes simulations under two different calibrations of the Armington trade elasticities. Armington elasticities determine the responsiveness of bilateral trade flows to changes in relative prices. When these are high, foreign and domestic varieties of trade goods are close substitutes, so import demand is sensitive to changes in relative prices. In contrast, when imports are less perfect substitutes, trade patterns are more rigid and economic shocks tend to be transmitted in prices rather than in quantities.

In a partial equilibrium model, countries would equate direct marginal cost of abatement (π_{Er}) with the direct marginal willingness to pay for abatement ($MWTP_r = \nu_r p_r^c$), as in equation (10). Thus, the difference between π_{Er} and $MWTP_r$ reveals the degree to which a country's permit choice is modified by trade spillovers (Δ_r) and carbon leakage ($MWTP_r \frac{\partial e_{row}}{\partial \omega_{Er}}$).

The trade spillover terms are negative for all regions except FSU, implying that the net effect of this channel is to reduce the cost of abatement for these regions. The sector that makes the single largest contribution to Δ_r for these regions is energy-intensive production (EIS) and the table row with this label reports on the magnitude of this contribution. Abatement causes countries to produce energy-intensive goods and to sell this output at higher prices.

On the left side of Table 4, traded goods are closer substitutes. Therefore, trade spillover

Table 4: Marginal Impacts of Permit Allocations by Trade Regime

No-trade Nash Equilibrium Outcomes

	Homogenous Trade (σ_{DM}, σ_{MM}=8,16)					Differentiated Trade (σ_{DM}, σ_{MM}=1,2)				
	USA	JPN	EUR	CHN	FSU	USA	JPN	EUR	CHN	FSU
EIS	-11	-64	-25	-2	-3	-26	-128	-63	-4	-5
Δ_r	-9	-32	$\boxed{-15}$	-7	5	-56	-238	$\boxed{-118}$	-4	6
π_{Er}	59	191	203	13	0	113	427	433	10	0
$MWTP_r$	60	255	432	7	6	60	295	460	6	6
$MWTP_r \frac{\partial e_{row}}{\partial \omega_{Er}}$	-11	-96	$\boxed{-243}$	-1	-1	-4	-106	$\boxed{-145}$	0	-1
ω_r^E	1557	273	821	1022	768	1412	245	760	967	771
$\ell_r\%$	18	38	$\boxed{56}$	12	17	6	36	$\boxed{32}$	2	8

EIS: marginal value of trade spillover effect in energy-intensive sectors (\$/Tons)
Δ_r: net effect of all marginal trade spillovers for conventional goods (\$/Tons)
π_{Er}: real permit price (\$/Tons)
$MWTP_r = \nu_r p_r^c$: MWTP for emission reductions, (\$/Tons)
$MWTP_r \frac{\partial e_{row}}{\partial \omega_{Er}}$: marginal value of carbon leakage effect (\$/Tons)
ω_r^E: permit endowment (millions of tons of carbon)
$\ell_r\%$: value of carbon leakage as a % of $MWTP_r$

effects are small relative to both the direct costs and benefits of abatement and the carbon leakage effects. The final row calculates the marginal value of carbon leakage as a fraction of the direct marginal benefits. The value of carbon leakage in this version of the model ranges from 12.2% for CHN up to 56% for EUR. This is a strong deterrant against abatement for all of the strategic regions in the model.

When traded goods are less perfect substitutes (the right side of Table 4), the marginal effect of trade spillovers remains negative in sign but grows in magnitude. At the same time, carbon leakage becomes less of a problem. The boxed entries in Table 4 highlight these differences for the EUR region. Trade spillovers are a more important influence on a country's emission decision in a model with highly differentiated goods because domestic production cannot be replaced by close substitutes from other countries when energy prices rise. Hence, countries are more effective at extracting rents from their trade partners in the course of implementing their abatement policies.

Table 5 demonstrates the effect of bilateral goods trade on the formation of emission trade coalitions. It lists the achievements of the different coalitions in the same format as Table 2 but assuming that goods are less perfect substitutes. Equilibrium abatement levels are uniformly higher in these scenarios. Abatement improves from 12.9% (from Table 2) to 16.1% for the best coalition outcome that is a SPNE, EUR-CHN-FSU, and from 6.5% to 10.7% for the no-trade Nash equilibrium. This is a direct result of the stronger emission-reducing trade spillovers and weakened carbon leakage effects.

In spite of this, the incremental improvement delivered by the most effective emission trade agreement on top of no-trade Nash abatement is slightly smaller (5.4 versus 6.1 percentage points). The USA-EUR-CHN coalition that dominates in Table 2 remains an effective agreement when traded goods are less perfect substitutes. This coalition yields the highest average welfare improvement but no longer produces the greates reduction in emissions. Some coalitions also lead to welfare losses — for both members (EUR) and outsiders (CHN) — and the welfare rankings of the coalitions are generally less monotonically related to abatement rankings than in the model with higher Armington elasticities. For example, USA-EUR-FSU is a SPNE in this set of simulations in spite of the fact that EUR would experience a welfare loss (-0.8%) relative to the no-trade Nash outcome. This is because EUR would be even worse off if it defected from this coalition because the remaining coalition members USA-FSU would choose permit endowments so large that they lead to an overall increase in the global emission level.

These results stand in contrast to Copeland and Taylor (1995) in which strategic manipulation of trade spillovers has no effect on the equilibrium global emission level in the Heckscher-Ohlin model. In our Armington model, trade spillovers have an important influence on emissions reductions when goods produced at home and abroad are imperfect substitutes.

Observed patterns of bilateral trade with cross-hauling cannot be explained in competitive equilibrium models where traded goods are perfectly homogenous. It remains an open research question as to what set of Armington elasticities best characterizes world trade flows. Time-

Table 5: Coalitions by Emission Reduction and Welfare Change, 2010

Differentiated Trade $(\sigma_{DM}, \sigma_{MM}) = (1, 2)$

	% Equivalent Variation						*Emission*	*Average*
	USA	JPN	EUR	CHN	FSU	ROW	*Reduction*	*%EV*
JPN,EUR,CHN,FSU	0.21	4.59	2.01	2.66	9.39	0.29	16.12	1.32
EUR,CHN,FSU**	0.20	5.65	1.96	1.87	7.92	0.19	16.06	1.05
EUR,CHN**	0.20	5.48	2.39	2.21	1.18	0.10	15.84	0.80
JPN,CHN**	0.25	4.44	2.73	0.68	0.36	0.07	15.62	0.45
JPN,EUR,CHN	0.17	5.06	2.11	2.75	1.22	0.20	15.43	0.95
USA,JPN,EUR,CHN	0.71	3.63	1.03	5.74	1.35	0.22	15.35	1.50
USA,EUR,CHN**	0.60	4.79	0.93	4.80	1.38	0.13	15.26	1.27
USA,JPN,EUR,CHN,FSU	0.40	1.73	0.44	3.86	11.15	0.38	14.22	1.56
JPN,CHN,FSU**	0.12	1.86	1.30	0.39	1.35	0.16	13.05	0.35
USA,EUR,CHN,FSU	0.13	1.94	0.06	2.17	7.72	0.33	12.65	1.01
USA,JPN,CHN	0.15	0.67	1.04	1.72	0.17	0.20	12.58	0.56
USA,EUR*	0.52	1.48	0.24	-0.05	0.76	0.00	12.25	0.09
JPN,FSU*	0.07	0.67	0.70	0.12	1.23	0.13	11.93	0.22
USA,EUR,FSU**	0.28	0.97	-0.78	-0.13	11.88	0.18	11.78	0.57
EUR,FSU*	0.01	1.01	0.20	-0.08	6.19	0.19	11.75	0.39
USA,JPN,EUR,FSU	0.37	-0.05	-0.80	-0.02	13.35	0.28	11.75	0.70
USA,JPN,EUR	0.49	1.48	-0.31	-0.04	0.83	0.13	11.52	0.14
USA,JPN**	0.15	0.15	0.39	0.10	0.05	0.05	11.46	0.08
JPN,EUR,FSU	-0.01	0.58	-0.02	-0.01	7.20	0.29	11.42	0.49
No-trade Nash*	0.00	0.00	0.00	0.00	0.00	0.00	10.72	0.00
USA,JPN,FSU	0.01	-2.01	-0.16	0.12	4.62	0.20	10.37	0.30
USA,CHN	-0.09	-0.60	-0.30	0.50	0.00	0.12	10.14	0.15
JPN,EUR	-0.07	0.42	-0.41	-0.04	0.46	0.15	10.09	0.09
CHN,FSU	-0.04	-0.95	-0.50	-0.03	-0.03	0.00	9.84	-0.05
USA,JPN,CHN,FSU	-0.13	-1.72	-0.53	0.69	2.02	0.30	9.72	0.35
USA,CHN,FSU	-0.20	-2.22	-1.13	0.21	0.96	0.16	8.64	0.07
USA,FSU	-0.17	-2.55	-1.30	-0.06	1.11	0.13	8.34	-0.01

* indicates that a coalition is a SPNE.

** indicates a SPNE coalition which satisfies the weak external stability condition.

% Equivalent Variation: % change in money-metric utility from no-trade Nash.

Emission Reduction: % reduction in global emissions from BaU.

Average %EV: Population-weighted average of regional % changes in EV from no-trade Nash.

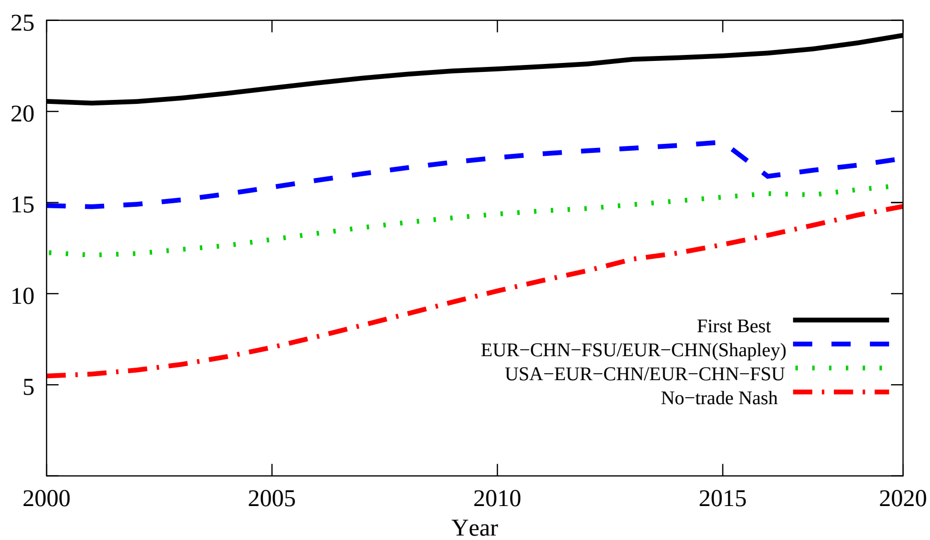
series estimates of these elasticities can be as low as unity, yet evidence from the evaluation of free trade agreements (Kehoe 2005) suggests that these values fail to predict large swings in the composition of trade when barriers to trade are lowered. Cross-section estimates (Hummels (2001) and Hertel, Hummels, Ivanic and Keeney (2003)) lend support to higher values. Recent work which focuses on the role of imperfect competition and firm-level heterogeneity yields even higher underlying implicit Armington elasticities (Rolleigh 2003).

4.3 Economic Development and Incentives for Coalition Formation

The failure of existing international treaties to prescribe binding abatement targets for developing country participants is based broadly on two perceptions. First, there is the commonly held view among observers from these nations that present global warming problems are due to historical OECD emissions. The equitable solution, they reason, is for OECD countries to be responsible for the initial abatement effort. Second, historical evidence suggests that some stages of economic development are more energy intensive (see Nakicenovic (1995)). Developing countries fear that by accepting abatement targets today they may hamper future growth in ways that static models (such as ours) fail to recognize.

Based on this, negotiators often focus on the prospects for involving these countries in the future when the environment becomes a higher social priority. This perspective seems to be based on the idea that economic development acts as a catalyst for environmental protection — as income rises, so does its interest in protecting the environment. This idea is built into our baseline calibration, but the end of Section 3 described an alternative scenario which shows more convergence in valuations for greenhouse gas abatement over time. Figure 4 summarizes the results of this experiment.

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



In comparison to the scenario with less convergence (Figure 3), abatement levels increase as a fraction of BaU emissions. This reflects the fact that the global mean valuation of emission reductions is increasing. However, permit trading coalitions are 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. Therefore, with convergence the difference between the most effective coalitional outcome and the no-trade Nash equilibrium vanishes as we approach 2020. It follows that involvement of developing countries in a permit trading system is more valuable today than it will be in the future.[13]

This result poses something of the dilemma for policy design. We outlined the equity and efficiency arguments for postponing abatement from developing countries, yet our results show that their participation in emission trade is most valuable now. Furthermore, the developing world stands to benefit substantially from the sale of permits in our model, a fact that would tend to nullify any equity concerns. A full description of the tradeoffs involved will clearly require the ability to model the relationship between energy demand and growth in these countries in greater detail, and future research should make this a priority.

5 Concluding Remarks

This study responds to three stylized observations regarding current efforts to establish an international global warming treaty. First, more than a decade of negotiations have demonstrated the difficulty of establishing collective abatement agreements in which member countries are required to substitute their national interests for the global good. The theoretical literature on self-enforcing environmental agreements largely confirms this experience. Second, in the near term, most of the world's reductions in greenhouse gases will come at the cost of curbing demand for fossil fuels. Because of the structure of international energy markets and the role that

[13]While the optimal coalition was stable over time in our core results, both the permit trade ("Coalition") and the cooperative ("Shapley") coalition now vary with time. This is most obvious in the discrete change in the abatement level in the "Shapley" series from Table 4 in model year 2015, where the optimal structure changes from EUR-CHN-FSU to EUR-CHN. The optimal permit trade coalition changes from USA-EUR-CHN to EUR-CHN-FSU.

these inputs play in many basic economic functions, determining the economic costs of abatement is a general equilibrium problem. Third, the currency of policy negotiations is emission rights, and topic of debate is the extent to which international trade in these rights should play a role in the design of global warming treaties.

We explore the extent to which agreements based on a system of internationally tradable emission permits might enhance abatement. We also evaluate the degree to which the structure of the world economy affects these outcomes.

We find that equilibrium agreements are capable of producing emission reductions that are about half of the first-best level. This is a striking result because members of a trading coalition as well as outsiders adopt noncooperative best-reply strategies in their choices of permits and emissions — the only difference between the second stage of our game and the standard Nash equilibrium in emission levels is the extension of the action set to include permit endowments and their subsequent trade on international permit markets.

A permit trading system proves to be quite successful in inducing members of the developing world to participate in carbon abatement. The best coalitions combine China, which serves as the major permit seller in the agreement, with regions that exhibit both high abatement costs and a high valuation for protection of the climate system. This supports the view that the Kyoto Protocol is flawed in its failure to include developing countries in a meaningful way. While this criticism is not new, it is typically focused on the failure to impose binding targets for developing countries. Our analysis shows that the essential point is not the subjection to such targets — developing countries are free to choose them unilaterally in our framework — but the cheap abatement options that they contribute to a trading coalition.

There are several equilibrium coalitions, and we presume that an important role of the negotiation process and of the institutions involved therein is to direct countries towards 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 allocations noncooperatively, then the net effect of adding a new country to the coalition may be higher global emission levels.

Working within a general equilibrium framework also provides new strategic insights. In this setting, countries have the opportunity to use environmental policy to both reduce emissions and improve terms of trade. Carbon leakage discourages abatement while the net effect of trade spillovers is to foster it. Our simulations suggest that both mechanisms may exert significant pressure on equilibrium outcomes.

References

Barrett, Scott, "Self-Enforcing International Environmental Agreements," *Oxford Economic Papers*, 1994, *46*, 878–894.

_____ , "Hetergeneous International Environmental Agreements," in Carlo Carraro, ed., *International Environmental Negotiations*, Cheltenham, UK: Elgar, 1997.

_____ , *Environment and Statecraft*, Oxford: Oxford University Press, 2003.

Bernstein, Paul M., W. David Montgomery, Thomas F. Rutherford, and Gui-Fang Yang, "Effects of restrictions on international permit trading: the MS-MRT model," *The Energy Journal – Kyoto Special Issue*, 1999, pp. 221–256.

Botteon, Michelle and Carlo Carraro, "Burden Sharing and Coalition Stability in Environmental negotiations with Assymetric Countries," in Carlo Carraro, ed., *International Environmental Negotiations*, Cheltenham, UK: Elgar, 1997.

Carraro, Carlo and Dominico Siniscalco, "Strategies for the International Protection of the Environment," *Journal of Public Economics*, 1993, *52*, 309–328.

Copeland, Brian R. and M. Scott Taylor, "Trade and Transboundary Pollution," *American Economics Review*, 1995, *85*, 716–737.

Dimaranan, Betina V. and Robert A. McDougall, "Global Trade, Assistance, and Production: The GTAP 5 Data Base," Technical Report, Center for Global Trade Analysis, Purdue University 2002.

Eyckmans, Johan and Henry Tulkens, "Simulating coalitionally stable burden sharing agreements for the climate change problem," *Resource and Energy Economics*, 2003, *25* (4), 299–327.

Felder, Stefan and Thomas Rutherford, "Unilateral CO2 reductions and carbon leakage: the effect of international trade in oil and basic materails," *Journal of Environmental Economics and Management*, 1993, *25*, 162–176.

Finus, Michael, "Stability and Design of International Environmental Agreements: The Case of Transboundary Pollution," in H. Folmer and T. Tietenberg, eds., *International Yearbook of Environmental and Resource Economics 2003/4*, Edward Elgar, 2003, chapter 3, pp. 82–158.

Gill, Phillip E., Walter Murray, and Margaret H. Wright, *Practical Optimization*, Academic Press, 1981.

Helm, Carsten, "International Emissions Trading with Endogenous Allowance Choices," *Journal of Public Economics*, 2003, *87* (12), 2737–2747.

Hertel, Thomas, David Hummels, Maros Ivanic, and Roman Keeney, "How Confident Can We Be in CGE-Based Assessments of Free Trade Agreements?," Working Paper, Purdue University 2003.

Hummels, David, "Toward a Geography of Trade Costs," Working Paper, Purdue University 2001.

Kehoe, Timothy J., "An Evaluation of the Performance of Applied General Equilibrium Models on the Impact of NAFTA," in Timothy J. Kehoe, T. N. Srinivasan, and John Whalley, eds., *Frontiers of Applied General Equilibrium Modeling: in Honor of Herbert Scarf*, Cambridge: Cambridge University Press, 2005, pp. 341–377.

Mathiesen, Lars, "Computation of Economic Equilibrium by a Sequence of Linear Complementarity Problems," *Mathematical Programming Study*, 1985, *23*, 144–162.

Missfeldt, Fanny, "Game-Theoretic Modelling of Transboundary Pollution," *Journal of Economic Surveys*, 1999, *13* (3), 287–321.

Mäler, K.-G., "The Acid Rain Game," in H. Folmer and E. v. Ierland, eds., *Valuation Methods and Policy Making in Environmental Economics*, Amsterdam: Elsevier, 1989, pp. 231–252.

Murdoch, James C., Todd Sandler, and Wim P.M. Vijverberg, "The Participation Decision versus the Level of Participation in an Environmental Treaty: A Spatial Probit Analysis," *Journal of Public Economics*, 2003, *87*, 337–362.

Nakicenovic, Nebojsa, *Global Energy Perspectives to 2050 and Beyond*, Cambridge: Cambridge University Press, 1995.

Nordhaus, William D., "To Slow or Not to Slow: The Economics of Greehouse Effect," *The Economic Journal*, July 1991, *101* (407).

____ **and Zili Yang**, "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies," *American Economic Review*, 1996, *86*, 741–765.

Rolleigh, Michael, "Plant Heterogeneity and Applied General Equilibrium Models of Trade: Lessons from the Canada-US Free Trade Agreement," Technical Report, University of Minnesota 2003.

Rutherford, Thomas F. and Sergey Paltsev, "GTAP-Energy in GAMS: The Dataset and Static Model," Working Paper 00-2, University of Colorado, Boulder 2000.

Tol, Richard, "Estimates of the Damage Cost of Climate Change," *Environmental and Resource Economics*, 2002, *21* (2), 135–160.

Tol, Richard S.J., "Climate Coalitions in an Integrated Assessment Model," *Computational Economics*, 2001, *18*, 159–172.

US Department of Energy, Office of Integrated Analysis and Forecasting, *International Energy Outlook 2002* 2002. DOE/EIA-0484(2002).

A Equilibrium Coalition Results with Pre-Existing Taxes

The following Appendix need not be part of the published paper, but can be made available as a download from the internet.

Table 6: Coalitions by Emission Reduction and Welfare Change, 2010, w/ Pre-Existing Taxes
Homogenous Trade $(\sigma_{DM}, \sigma_{MM}) = (8, 16)$

	% Equivalent Variation						*Average*	*Emission*
	USA	JPN	EUR	CHN	FSU	ROW	*%EV*	*Reduction*
USA,JPN,EUR,CHN	0.82	9.54	4.05	2.72	0.13	-0.03	0.98	14.17
JPN,EUR,CHN,FSU	0.48	9.02	4.22	1.23	6.46	-0.02	0.93	13.53
USA,EUR,CHN**	0.69	10.86	3.50	2.13	0.18	-0.01	0.86	13.33
EUR,CHN,FSU**	0.43	10.03	3.73	0.83	4.98	-0.01	0.79	12.71
JPN,EUR,CHN	0.40	8.21	3.87	0.83	0.07	0.00	0.56	12.04
USA,JPN,EUR,CHN,FSU	0.41	7.36	3.39	1.19	5.95	0.01	0.84	11.63
EUR,CHN*	0.37	8.63	3.62	0.53	0.13	0.02	0.51	11.58
JPN,CHN**	0.34	6.39	4.16	0.10	0.27	0.02	0.42	11.10
USA,EUR,CHN,FSU	0.26	6.63	2.73	0.71	4.19	0.03	0.63	10.04
USA,JPN,EUR,FSU	0.50	3.14	0.94	0.15	10.60	-0.08	0.56	9.03
USA,JPN,CHN	0.19	4.30	2.68	0.50	0.15	0.03	0.37	8.82
USA,EUR,FSU**	0.37	4.51	0.50	0.10	8.39	-0.05	0.47	8.24
USA,JPN,EUR	0.45	3.07	0.77	0.15	-0.09	-0.08	0.10	7.77
USA,EUR*	0.38	3.55	0.62	0.13	-0.08	-0.06	0.11	7.43
USA,JPN,CHN,FSU	0.05	2.58	1.54	0.27	1.63	0.03	0.28	7.08
USA,CHN*	0.07	2.84	1.50	0.23	0.07	0.03	0.21	6.99
JPN,EUR,FSU	0.13	1.87	0.82	0.06	4.03	-0.06	0.23	6.92
USA,JPN**	0.17	0.81	1.31	0.09	0.04	-0.05	0.09	6.72
EUR,FSU*	0.10	2.25	0.66	0.04	2.79	-0.03	0.19	6.46
JPN,FSU**	0.09	1.17	1.01	0.04	0.75	-0.03	0.10	6.28
USA,CHN,FSU**	-0.01	1.61	0.85	0.14	1.05	0.03	0.17	6.01
JPN,CHN,FSU	0.07	1.54	0.77	0.04	0.31	0.01	0.10	5.89
USA,JPN,FSU	0.06	0.18	0.63	0.03	2.23	-0.02	0.13	5.68
JPN,EUR**	0.02	0.01	0.04	0.02	-0.07	-0.03	-0.01	4.96
No-trade Nash	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.67
CHN,FSU	-0.02	-0.52	-0.26	-0.01	0.00	0.00	-0.03	4.25
USA,FSU	-0.04	-0.89	-0.45	-0.03	0.61	0.01	-0.02	3.97

* indicates that a coalition is a SPNE.
** indicates a SPNE coalition which satisfies the weak external stability condition.
% Equivalent Variation: % change in money-metric utility from no-trade Nash.
Emission Reduction: % reduction in global emissions from BaU.
Average %EV: Population-weighted average of regional % changes in EV from no-trade Nash.

Table 6 describes the results of a sensitivity analysis in which we calibrate and run counterfactual scenarios in a version of the model which includes the pre-existing tax structure described by the GTAP database. The equilibrium results for these simulations are reported in the same manner as in Tables 2 and 5 in the main text of the paper. They indicate that including these taxes has only limited impact on the model results. In particular, USA,EUR,CHN remains the 'best' SPNE coalition and achieves comparable emission reductions and %EV as without taxes (see Table 2).

B Solution Method

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.

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. $d\pi_{ir}/d\omega_r^E$ and $de_{row}(\pi)/d\omega_r^E$ in (9). 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:

$$\left[\frac{dz}{d\omega}\right] = -\left[\frac{dF}{dz}\right]^{-1}\left[\frac{dF}{d\omega}\right]. \tag{16}$$

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

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:

$$\frac{dz_k}{d\omega_r^E} \approx \frac{z_k(\omega+\delta^r) - z_k(\omega)}{\delta}, \tag{17}$$

where

$$\delta^r = \begin{pmatrix} \delta_1^r \\ \vdots \\ \delta_N^r \end{pmatrix} \qquad \text{with} \quad \delta_j^r = \begin{cases} \delta & r = s \\ 0 & r \neq s. \end{cases} \tag{18}$$

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.[14]

At first glance it would appear that the calculation of local sensitivity of prices π_{ir} with respect to permit allocations ω_r^E 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, $d\pi_{ir}/d\omega_r^E$. 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:

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

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:

$$\frac{1}{p_r^c}\left[\pi_E + \left(\omega_r^E - e_r\right)\frac{\pi_E^{rr} - \pi_E}{\delta} + \Delta_r\right] - \nu_r\left(1 + \frac{e_{row}^{rr} - e_{row}}{\delta}\right) = 0 \quad , \quad \forall r \in \mathcal{C}$$
$$\frac{1}{p_r^c}\left[\pi_{Er} + \Delta_r\right] - \nu_r\left(1 + \frac{e_{row}^{rr} - e_{row}}{\delta}\right) = 0 \quad , \quad \forall r \notin \{\mathcal{C}, row\}$$
$$\Delta_r = \left(\sum_{i \neq E}\left(Y_{ir} - C_{irr} - I_{irr}\right)\frac{\pi_{ir}^{rr} - \pi_{ir}}{\delta} - \sum_{s \neq r}(C_{isr} + I_{isr})\frac{\pi_{is}^{rr} - \pi_{is}}{\delta}\right)$$

[14]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.)).

C The Economic Impacts Model

Table 7 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 emission constraint are focused here.

Table 7: 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)
E	CO_2 emission 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 emission 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.

D 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_{rk} is used to denote the profit function of region r 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 8 - 13 explain the notations for variables and parameters employed within our algebraic exposition. Table 9 summarizes the activity variables of vector y, whereas Table 10 summarizes the price variables of vector π. Figures 5 - 8 provide a graphical exposition of the production and final consumption structure.

D.1 Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\begin{aligned}\Pi_{rk}^{Y} &= \pi_{rk}^{Y} - \sum_{j \notin FE} \theta_{jik} \pi_{ji}^{A} \\ &\quad -\theta_{rk}^{KLE} \left[\theta_{rk}^{N} \left(\pi_{rk}^{N}\right)^{1-\sigma_{KLE}} + (1-\theta_{rk}^{N}) \left(w_r^{\alpha_{rk}} r_r^{1-\alpha_{rk}}\right)^{1-\sigma_{KLE}}\right]^{1/(1-\sigma_{KLE})} \\ &= 0 \quad \forall\, k \notin FF\end{aligned}$$

2. Production of fossil fuels:

$$\begin{aligned}\Pi_{rk}^{Y} &= \pi_{rk}^{Y} - \left[\theta_{rk}^{R} q_{rk}^{1-\sigma_{Rik}} + (1-\theta_{rk}^{R}) \left(\theta_{Lik}^{FF} w_r + \theta_{Kik}^{FF} r_r + \sum_j \theta_{jik}^{FF} \pi_{jr}^{A}\right)^{1-\sigma_{Rik}}\right]^{1/(1-\sigma_{Rik})} \\ &= 0 \quad \forall\, k \in FF\end{aligned}$$

3. Sector-specific energy aggregate:

$$\begin{aligned}\Pi_{rk}^{N} &= \pi_{rk}^{N} - \{\theta_{rk}^{ELE} (\pi_{ELE,i}^{A})^{1-\sigma_{ELE}} \\ &\quad +(1-\theta_{rk}^{ELE}) \left[\theta_{rk}^{COL} \left(\pi_{col,i}^{N} + \pi_r^{E} \epsilon_{rk}^{COL}\right)^{1-\sigma_{COL}}\right. \\ &\quad \left.\left. +(1-\theta_{rk}^{COL}) \left(\sum_{j \in LQ} \theta_{rk}^{j} \left(\pi_{ji}^{A} + \pi_r^{E} \epsilon_{rk}^{j}\right)^{1-\sigma_{LQ}}\right)^{(1-\sigma_{COL})/(1-\sigma_{LQ})}\right]^{(1-\sigma_{ELE})/(1-\sigma_{COL})}\right\}^{1/(1-\sigma_{ELE})} \\ &= 0\end{aligned}$$

4. Armington aggregate:

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

5. Aggregate imports across import regions:

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

6. Household consumption demand:

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

7. Household energy demand:

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

D.2 Market Clearance Conditions

8. Labor:

$$\omega^L_r = \sum_k Y_{rk}\frac{\partial \Pi^Y_{rk}}{\partial w_r}$$

9. Capital:

$$\omega^K_r = \sum_k Y_{rk}\frac{\partial \Pi^Y_{rk}}{\partial r_r}$$

10. Natural resources:

$$\omega_{rk}^{R} = Y_{rk}\frac{\partial \Pi_{rk}^{Y}}{\partial q_{rk}} \quad \forall k \in FF$$

11. Sectoral output:

$$Y_{rk} = A_{rk}\frac{\partial \Pi_{rk}^{A}}{\partial \pi_{rk}^{Y}} + \sum_{s \neq i} M_{sk}\frac{\partial \Pi_{sk}^{M}}{\partial \pi_{rk}^{Y}}$$

12. Sector specific energy demand:

$$N_{rk} = Y_{rk}\frac{\partial \Pi_{rk}^{Y}}{\partial \pi_{rk}^{N}}$$

13. Import supply:

$$M_{rk} = A_{rk}\frac{\partial \Pi_{rk}^{A}}{\partial \pi_{rk}^{M}}$$

14. Aggregate supply:

$$A_{rk} = \sum_{j} Y_{ji}\frac{\partial \Pi_{ji}^{Y}}{\partial \pi_{ki}^{A}} + C_{r}\frac{\partial \Pi_{r}^{C}}{\partial \pi_{ki}^{A}}$$

15. Household energy consumption:

$$N_{rC} = C_{r}\frac{\partial \Pi_{r}^{C}}{\partial \pi_{rC}^{N}}$$

16. Carbon emissions:

$$\omega_{r}^{E} + X_{r} = N_{rC}\frac{\partial \Pi_{rC}^{N}}{\partial \pi_{r}^{E}} + \sum_{k} N_{rk}\frac{\partial \Pi_{rk}^{N}}{\partial \pi_{r}^{E}}$$

17. International permit market:

$$\sum_{r \in \mathcal{C}} X_{r} = 0$$

D.3 Income balance

$$p_{r}^{c}(C_{r} - \bar{V}_{r}) = w_{r}\omega_{r}^{L} + r_{r}\omega_{r}^{K} + \sum_{j \in FF} q_{ji}\omega_{ji}^{R} + \pi_{r}^{E}\omega_{r}^{E} + \bar{B}_{r}$$

Table 8: Sets

i, j, k	Sectors and goods
r, s	Regions
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
$\mathcal{C}$	Emission trading coalition members

Table 9: Activity Variables

Y_{rk}	Production in region r and sector k
N_{rk}	Aggregate energy input in region r and sector k
M_{rk}	Aggregate imports of region r and sector k
A_{rk}	Armington aggregate for region r in sector k
C_r	Aggregate household consumption in region r
N_{Ci}	Aggregate household energy consumption in region r
X_r	Net exports in carbon permits in region r

Table 10: Price Variables

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

Table 11: Cost Shares

θ_{rk}^{X}	Share of exports in region r and sector k
θ_{jik}	Share of intermediate good j in region r and sector k $(k \notin FF)$
θ_{rk}^{KLE}	Share of KLE aggregate in region r and sector k $(k \notin FF)$
θ_{rk}^{N}	Share of energy in the KLE aggregate of region r and sector k $(k \notin FF)$
α_{rk}	Share of labor region r and sector k $(k \notin FF)$
θ_{rk}^{R}	Share of natural resources in region r 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 r and sector k $(k \in FF)$
θ_{rk}^{COL}	Share of coal in fossil fuel demand by region r in sector k $(k \notin FF)$
θ_{rk}^{ELE}	Share of electricity in energy demand by region r in sector k
β_{jik}	Share of liquid fossil fuel j in energy demand by region r in sector k $(k \notin FF, j \in LQ)$
θ_{sik}^{M}	Share of imports of good k from region s to region r
θ_{rk}^{D}	Share of domestic variety in Armington good k of region r
θ_{rC}^{N}	Share of fossil fuel composite in aggregate household consumption in region r
θ_{rk}^{C}	Share of non-energy good k in non-energy household consumption demand in region r
θ_{rkC}^{N}	Share of fossil fuel k in household energy consumption in region r

Table 12: Endowments and Emission Coefficients

ω_{r}^{L}	Aggregate labor endowment for region r
ω_{r}^{K}	Aggregate capital endowment for region r
ω_{rk}^{R}	Endowment of natural resource k for region r $(k \in FF)$
$\bar{B}_r$	Balance of payment deficit or surplus in region r (note: $\sum_r \bar{B}_r = 0$)
$\bar{V}_r$	Capital investment in region r
ω_{r}^{E}	Carbon emission permit endowment for region r
ϵ_{rk}^{j}	Carbon emission coefficient for fossil fuel j in region r in sector k $(j \in FE)$
ϵ_{rC}^{k}	Carbon emission coefficient for household energy demand for fossil fuel k in region r $(k \in FE)$

Table 13: Elasticities

σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.5
$\sigma_{R,i}$	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

E 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 13.

Figure 5: Nesting in non-fossil fuel production

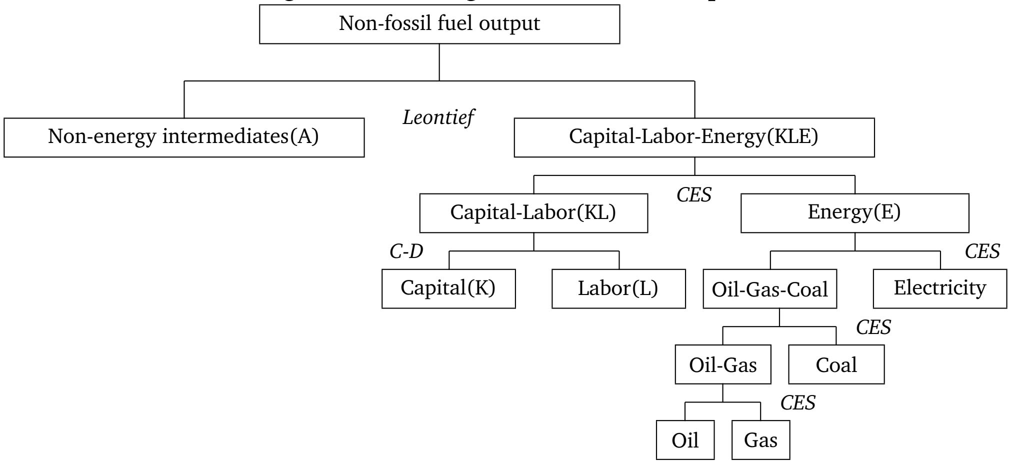


Figure 6: Nesting in fossil fuel production

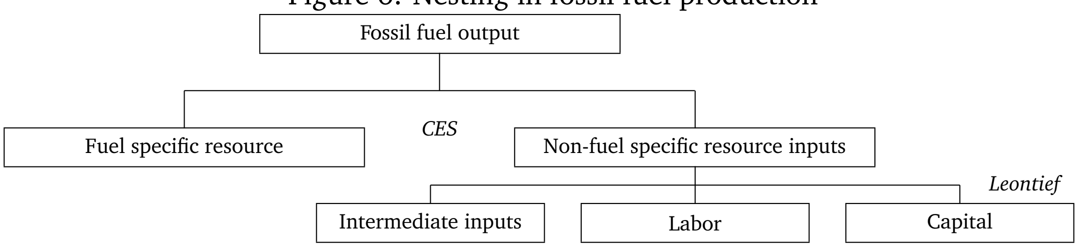


Figure 7: Nesting in household consumption

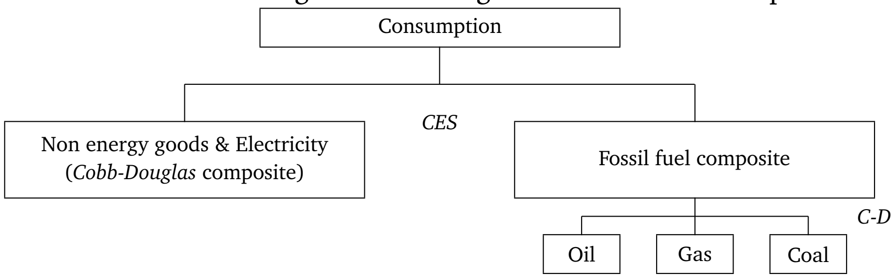
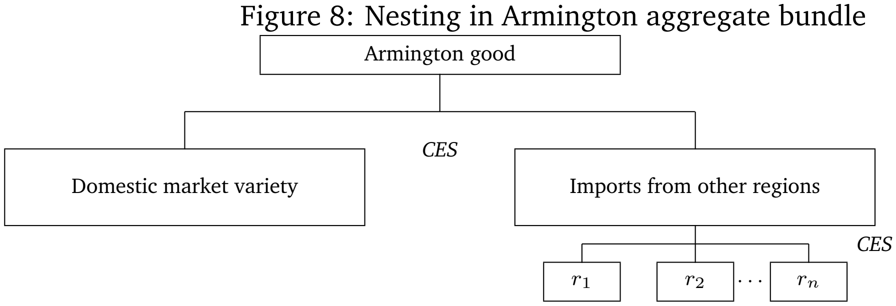


Figure 8: Nesting in Armington aggregate bundle



F 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 14 and 15 to yield the model's sectors and regions (see Table 7).

Table 14: 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 15: 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