The Case for International Emission Trade in the Absence of Cooperative Climate Policy*

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Abstract

We evaluate the efficacy of international trade in carbon emission permits when countries are guided strictly by their national self-interest. 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' decisions about their participation in a trading system and about their initial permit endowment are made 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 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: D7, F18, F42, Q58.

1 Introduction

The Kyoto Protocol has achieved little in terms of global emission reductions. Current negotiations of a Post-Kyoto agreement suggest that for most countries national self-interest constitutes a dominant guiding principle. This perception is confirmed by a poll among climate policy experts, who anticipate only modest reductions in global emissions for the year 2020 (Böhringer and Löschel 2005). In a nutshell, there is little hope at the moment that countries adopt cooperative strategies and make substantial voluntary contributions to the global public good of climate protection. In this paper we argue that even in a world where countries only pursue their national self-interest, an international system of tradable emission permits can achieve substantial emission reductions.

A well known effect of permit trading is that it makes meeting a given abatement target less costly. This should reduce emissions. It is less obvious that permit trade will produce emission reductions when countries are free to choose their endowment of emission rights. Countries face a number of different incentives in making this choice. First, countries with a low willingness to pay (WTP) for emission reductions have an incentive to choose more emission rights when these are tradable because they can sell them with little concern for the associated increase in global emissions. In contrast, high WTP countries benefit from the possibility to buy cheap abatement opportunities in other countries, giving them the incentive to choose less emission rights. Second, countries may strategically alter the size of their endowments to affect the permit price. This gives permit exporters an incentive to increase their scarcity and importers an incentive to increase their abundance. Finally, countries also have an incentive to use their choice of emission rights as a substitute for trade policy — to impact markets for other tradable goods, such as energy-intensive goods and fossil fuels. The net effect of these choices on global emissions depends on the profiles of regional economies and the roster of countries that are included in permit trade. We find that certain groupings of countries that exploit these incentives can be quite effective in producing emission reductions.

Determining what characteristics of permit-trade agreements make them effective and what magnitude of emission reductions they are capable of producing are fundamentally empirical issues. To address them, 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 and allows us to describe how trade linkages impact permit-trade agreements.

In the model, agreements are equilibria in which both a country's decision to participate in an agreement and its decision regarding the size of its permit endowment are best responses to the actions of other countries. A proposal which specifies the potential members of a permit trade 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 emission rights with firms in other member countries. Firms in non-member countries trade emission rights only on domestic markets. Markets, which are assumed to be competitive, 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. By enumerating the possible agreement memberships we are able to illustrate which pairings of countries might be most effective in reducing emissions.

There is a substantial literature that uses game-theoretic concepts to analyze self-enforcing international environmental agreements (often called "IEAs" or "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, its initial permit allocation — shapes the equilibrium surplus division and abatement level. Furthermore,

[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).

because we model the choice of emission rights 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.

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 a country's domestic emissions also reduces its demand for fossil fuels. If this decreased fuel demand is sufficiently large, it may depress international fuel prices. Emission reductions also increase the price of energy-intensive goods. These changes in world prices have two effects. First, they may stimulate increased demand for fossil energy in unregulated countries, increasing their emission levels. This effect, referred to as carbon leakage (Felder and 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. Second, they cause changes in the terms of trade. Countries that are net importers of energy-intensive goods, for example, are made worse off because the cost of imports increase while net exporters reap the benefits of a higher return on their output. Hence, terms of trade effects may either increase or decrease a country's incentive to reduce emissions depending on that country's orientation in international markets.

We assume that governments realize their effect on prices in world markets when they set the size of their initial permit endowments (as in Helm (2003)). Permits are costless for the government to print so they can, in theory, scale their endowments up or down without bound. An immediate consequence of this is that countries have leverage in the permit market. Similarly, if the availability of permits affects the demand or supply for other traded goods, it may give them leverage in these markets as well. For some countries in our simulations, the ability to affect terms of trade (rather than concern for the environment) is the primary motive for choosing the

[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.

size of their initial permit allocation.

In contrast we assume that once permit endowments have been established, international markets for permits and other goods are competitive. An implication of this is that, in our model, governments are unable to use trade policy to affect the terms of trade in markets for emission permits or other goods — as if they are bound by the rules of a free-trade agreement — but are able to use environmental policy toward this end. Similarly, it implies that permit-holding firms do not exercise market power and that governments do not intervene after they have set the total number of permits available to firms. The latter assumption is not entirely innocuous as there are several countries where the government still has a strong influence on the energy sector. However, we see the assumption that markets are competitive as the natural one to make in our analysis because the direct manipulation of international markets is increasingly limited by the rise of free-trade agreements and the broadening coverage of the WTO. We assume that the rules governing trade in emission permits would be subject to the same trend.[3]

Our simulations suggest that permit trade agreements can be effective abatement devices even in a world of non-cooperative countries. We find that equilibrium permit-trade agreements can achieve almost twice the emission reductions implied by the Nash equilibrium with no permit trade and more than half of the reductions that would be prescribed by following a global first-best emission policy. Furthermore, 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 benefits and high abatement costs buying large volumes of emission permits from their developing-world partners (either China or members of the former Soviet Union). 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

[3]There is a substantial literature in trade theory that anticipates the use environmental policy as a substitute for trade policy as free-trade agreements become more commonplace. See Copeland and Taylor (2004) for a recent survey of this literature.

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 effects). The relative strength of these two effects depends on the degree to which foreign and domestic varieties of energy-intensive goods are substitutes. The carbon leakage effect dominates when traded goods from different regions are close substitutes. This tends to increase global emissions. Terms of trade effects dominate when traded goods are imperfect substitutes. This tends to decrease global emissions.

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 coalition formation with heterogenous countries and general equilibrium effects, which are difficult to analyze in a purely analytical model. However, all studies of global warming policy confront sizeable uncertainties regarding growth paths, technological change and the regional demand for climate protection. Thus interpreting our results as precise quantitative estimates would be a mistake. Our goal is to conduct thought-experiments with representative parameter values and look for general insights that may help to guide the design of post-Kyoto climate policy.

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. A detailed analysis of the first-order conditions illustrates how participation in permit trade and other world markets influence a country's decision regarding the size of its initial permit endowment. Section 3 describes the data used to calibrate model parameters. Results are presented in Section 4 followed by concluding remarks in Section 5. The appendix contains sensitivity analysis and describes the methods we use to solve the numerical model. [Note: The appendix material (submitted for review in a separate file) is included for the benefit of reviewers. This material could be included in the JEEM online archive.]

2 The Model

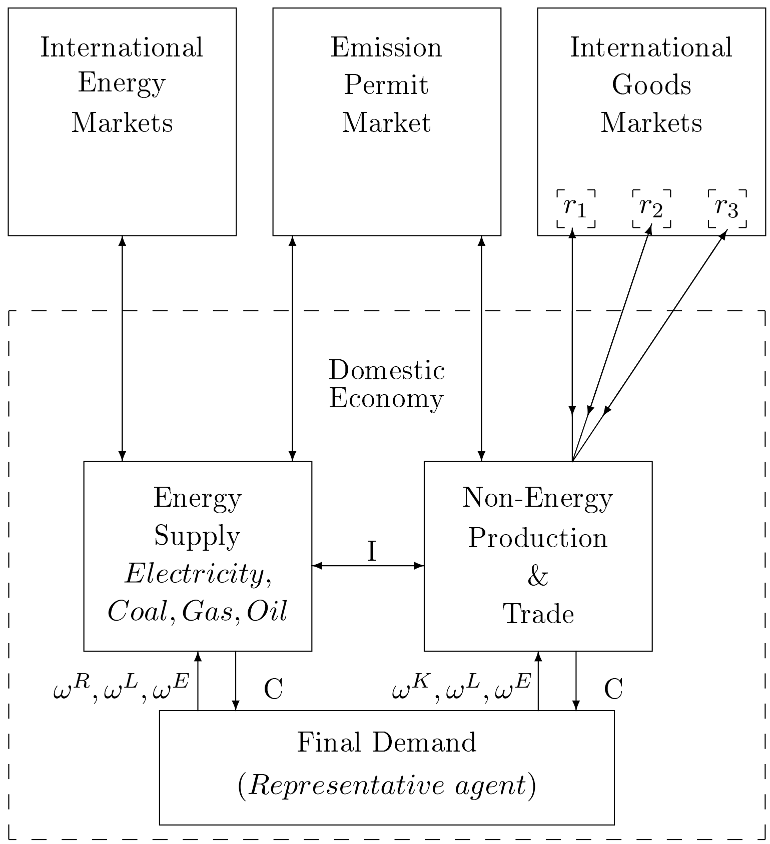
The model consists of two components — the competitive general equilibrium system which determines regional abatement costs and international trade flows, and a submodel of strategic interactions between regional governments that determines the membership and emission levels of permit-trade agreements. 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. We consider six regions (USA, Japan, Western Europe, China, Former Soviet Union, and "Rest of World"). Within each regional economy, goods are produced in seven sectors (Coal, Crude Oil, Electricity, Natural Gas, Refined Oil, Energy-Intensive Goods, and Other Manufactures and Services). All goods can be used to satisfy intermediate or final demands except for crude oil which is only used as an intermediate good. All goods may be traded internationally. 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 based on the carbon content of the different fuels. There is no abatement technology in the model that allows countries to reduce emissions without reducing the use of fossil fuels. 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.

Figure 1: Regional Flows of Goods and Factors



Labor, capital and emission permits are intersectorally mobile within regions but cannot move between regions. The production of crude oil, coal and gas each makes use of its own resource-specific 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. The international trade in emission permits takes place on a single, undifferentiated market between agreement members.

Regional welfare depends on the current economic utility 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 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. $U_r(\pi, \omega_r)$ is the indirect utility function that is implied by solving the representative agent's constrained optimization problem over conventional goods.

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 of other factors, $\omega^E \in \mathbb{R}^n$ 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. The simulation results are based on a calibration point projected forward to the year 2015, but the model is essentially static. Thus we have suppressed time subscripts throughout the paper. A discussion of the calibration procedure is contained in section 3.

We have chosen to work with a static model to highlight the aspects of permit trading agreements that are the focus of the study. The cost of this approach is that we cannot address the question of how strategic permit trade interacts with some of the 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 here.

2.2 Strategic Interaction

We now turn to the game-theoretic model. 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-form 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 permit trading regime. In a Nash equilibrium of this subgame, no region wants to change its participation or non-participation decision, given the decisions of the other regions. Regions $r \notin \mathcal{C}$ reach no decision node at stage 1.

In stage 2, all regions choose emission rights as individual best replies to the choices of the other regions. In doing so, they anticipate the interregional trading of emission rights — which is restricted to coalition members — and of the other (non-strategic) goods in our economy. In the numerical simulations, we solve the above game for all possible coalition proposals $\mathcal{C}$. Thereby, we identify all permit trading coalitions that can be established as a subgame perfect Nash equilibrium (SPNE).

The above game differs in two fundamental respects from nearly all of the literature that uses non-cooperative game theory to analyze self-enforcing environmental agreements (see Finus (2003) for a survey). 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.[4] Consequently, trade in emission rights has no effect on the overall emission level. 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)). This is closely related to the Nash equilibrium of our membership game in stage 1, where no regions wants to change its participation or non-participation decision, given the decisions of the other countries.

However, by assuming that coalition proposals arise as an outcome of international negotiations, we introduce a mechanism by which coalition members can block the access of others into the trading regime. Such a mechanism is common in many international treaties such as WTO, EU and NATO. It also seems realistic in our case that existing members want to regulate entry to prevent those regions from joining which would choose a very high number of permits and, thereby, lead to the breakdown of the coalition. This contrasts with the 'standard' model, where joining regions choose their emissions cooperatively so that the external stability criterion

[4]Exceptions are Murdoch, Sandler and Vijverberg (2003) as well as Finus (2004).

constitutes less of an obstacle for cooperation.

For example, in the following numerical simulations the USA-CHN coalition does not satisfy external stability because FSU would want to join (see Table 2, p. 21). However, given the permit choices of FSU the extended coalition is unattractive for USA, which would then decide not to participate. By contrast, if international negotiations result in the coalition proposal USA-CHN, then the two can form a stable trading coalition because the Nash equilibrium of the membership game in stage 1 considers only the participation decisions of USA and CHN.[5]

However, in section 4.1 we also consider an equilibrium refinement of the SPNE that requires that for any SPNE coalition there exists no "larger" SPNE coalition which is a proper superset and in which all members are better off. Consequently, regions are admitted to join a coalition, but only if this is individually beneficial to 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 "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.[6]

2.2.1 Regional Choice of Emission Rights

The game is solved by backwards induction and we first determine regional choices 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.

[5]Nevertheless, the "best" coalition in our later numerical simulations also satisfies the traditional internal and external stability criterion. Accordingly, it would constitute a SPNE if there were no proposal of coalition members by nature, but in stage 1 regions would simply decide whether they want to be a member of a permit trading regime or not.

[6]The "Former Soviet Union" (FSU) is also a region composed of more than one autonomous state but we assume that it acts as a single strategic entity. This reflects that Russia is the dominant player in this region — both in terms of emissions and in terms of the political influence that it wields in the FSU region. Furthermore, our dataset does not allow us to separate Russia from the other countries contained in FSU.

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, $\left(\omega_r^E - e_r\right)\pi_E$, where e_r is aggregate demand for emissions in region r and π_E is the equilibrium permit price.

In the following, we first abstract from the latter, i.e. we discuss the strategic behavior of non-members. Later on, we analyze the additional effects that arise for participants of the international permit market. Accordingly, a strategic region r that is a coalition outsider maximizes (1) and 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.[7] 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 terms of the value of net output.[8] 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 derived from the solution to the maximization of a nested CES utility function subject to the limitations of region r's factor endowment income.

[7] We use a linearly-homogeneous cardinalization of economic preferences so that marginal changes in U_r can be interpreted as equivalent variations in income at benchmark prices.

[8] 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.

Differentiating (4) with respect to region r's endowment of emission rights, 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 rights in region r. Using (8) and rearranging terms we can re-write the full optimality condition from (3) as:

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

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 emission rights, 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 *ToT Effects* in (9) capture the effects of emission rights choices on regional income through changes in the terms of trade that region r faces, where the first term in the large rounded brackets describes the effects of changes in the prices of goods produced in region r and the second term describes the effects of changes in the prices of foreign goods. The right-hand side of (9) 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 and an indirect, carbon leakage effect.

Domestic abatement implies reduced energy demand for region r. This causes energy prices to fall and the prices of energy-intensive goods to rise, inducing increased demand for fuel 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 emission rights, 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 terms of trade effect 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 endowment with emission rights causes the price of good i to rise or fall. For example, an increased supply of emission rights 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 emission rights 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 terms of trade 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 terms of trade effect (within the i-sum in (9)) for each commodity that region r trades internationally. Because of their relationship to the level of region r's permit endowment, however, we would expect the largest effects experienced by a region that is a coalition outsider to occur in the markets for energy-intensive goods and fossil fuels.

When r is a coalition member, they will also account for the impact of their emission rights choices on terms of trade in the international permit market itself. These are given by $\left(\omega_r^E - e_r\right) \frac{d\pi_E}{d\omega_r^E}$, where $\frac{d\pi_E}{d\omega_r^E} < 0$ because a larger supply of permits reduces their equilibrium price. This gives permit exporters an incentive to increase their scarcity and importers an incentive to increase their abundance.

To sum up, terms of trade effects in markets for conventional goods that are tied to the production of emissions and in markets for internationally tradable emission permits are important for countries' choices of emission rights. They give net exporters (importers) of permits or energy-intensive goods the incentive to lower (raise) the level of their emission cap. They give net exporters (importers) of fossil fuels the incentive to lower (raise) the level of their emission cap.

For a given coalition membership, whether or not the coalition achieves emission reductions will depend on how elastic the responses of net importers and exporters are. 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. Similarly, adding potential permit buyers will tend to decrease aggregate supply. We use the numerical model to determine what magnitude of emission reduction results from each coalition and which coalitions represent equilibria.

2.2.2 Equilibrium Outcomes

In a subgame perfect Nash equilibrium, no potential coalition member wants to change its decision whether 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 Δ_r describes the terms of trade effects associated with trade in all conventional goods:

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

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. [9]

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.

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 "First-Best" allocation of emission rights, which is defined as the solution in which each country sets emission rights to equate its marginal

[9] 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), terms of trade effects in the permit market ($(\omega_r^E - e_r)\frac{d\pi_E}{d\omega_r^E}$) and in conventional markets (Δ_r), and carbon leakage ($\nu_r \frac{de_{row}}{d\omega_r^E}$).

abatement costs with the sum of marginal benefits over all model regions:

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

We should note that equation (13) is a first best calculation in very specific sense. It is the program in which all strategic regions in the model fully internalize the environmental impacts of their emissions. This definition excludes two elements that will also impact global economic efficiency. First, it does not allow for the direct regulation of ROW emissions. Second, it does not prohibit strategic regions from taking terms of trade into account in choosing their initial permit levels.

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 project the economy forward to 2015, the year in which all of our policy experiments take place. The growth projections 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. We express our model results as deviations from the Business as Usual (BaU) predictions produced by this dataset. The assumption in the BaU simulations is that countries do not implement any climate policies, so that firms use fossil fuels and produce carbon emissions at levels that are consistent with price-taking, profit-maximizing behavior.

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. 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*		
	1998	2015	%Δ	1998	2015	%Δ	1998	2015	%Δ	1998	2015	%Δ
USA	8,719	14,696	4.0	32,197	46,967	2.7	5.5	6.3	0.8	171	134	-1.4
JPN	4,294	5,828	2.4	33,847	45,557	2.4	2.4	2.8	1.0	70	61	-1.1
EUR	8,729	13,180	2.9	22,470	33,816	2.9	2.4	2.8	0.9	108	82	-1.4
CHN	974	3,148	12.5	776	2,233	10.7	0.6	1.0	5.5	763	439	-2.0
FSU	539	1,233	6.8	1,834	4,405	7.3	2.0	3.0	2.4	1107	666	-2.3
ROW	6,493	12,857	5.9	1,823	2,748	3.2	0.6	1.0	1.4	313	252	-1.2

GDP in billions $1998
GDP per capita in $1998 per person)
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, and GDP is based on the growth projections from the IEO. For simplicity we abstract from issues related to tax revenues and current account imbalances which could be affected by abatement policy.[10]

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 marginal willingness to pay values are calibrated with the aim to reflect the regions' positions in international climate negotiations. Of the three OECD regions in our sample, Europe has shown a considerably higher willingness to reduce its emissions than the United States and Japan. Based on this we assume a marginal

[10]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 (see Gurgel, Metcalf, Osouf and Reilly (2007)). 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).

value of abatement (1998, US-$ per ton of carbon) of 300 for Western Europe (EUR), and of 150 for Japan (JPN) and the United States (USA). The remaining model regions have shown a much lower willingness to pay for carbon abatement. Accordingly, we calibrate the countries that make up the Former Soviet Union (FSU) at 50 and China (CHN) as well as the "Rest of World" region (ROW) at 0. Overall, these assumptions lead to global emission reductions in the no-trade Nash equilibrium of 7.8% as compared to the business as usual scenario. This figure seems to conform with the assessments of climate policy experts (Böhringer and Löschel 2005), as well as with the results of integrated-assessment studies such as RICE (Nordhaus and Yang 1996).

There are no widely accepted estimates of regional willingness to pay for climate improvements, so we have undertaken several model runs with alternative values.[11] The qualitative insights that are discussed in the following appear to be very stable, as long as differences in the willingness to pay across regions are sufficiently large. To illustrate this, in section 4.3 we present one scenario where we raise the marginal value of abatement for FSU to 100 and for CHN to 50.

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 terms of trade effects and carbon leakage — in more detail. Section 4.3 considers how changes in the distribution of marginal willingness to pay for environmental improvements affects the prospects for effective emission trade agreements.

[11] 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). We believe that these attempts are no less conjectural given the current state of climate science (Tol 2002). Nevertheless, it is interesting to note an important difference. In Nordhaus and Yang (1996), for example, 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, little 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).

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 2015. 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 "**".[12]

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 nearly twice that level. The more successful outcomes (both in welfare and abatement terms) involve CHN — a developing country with low abatement cost — paired with EUR — a region with high abatement cost and the highest valuation 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 EUR-CHN-FSU coalition (the "best" SPNE outcome from Table 2) to the no-trade Nash outcome. EUR, the coalition member with the highest valuation for abatement, chooses a permit endowment of only 28% of its BaU emissions. In contrast, CHN and FSU have much lower valuations for abatement and, therefore, choose substantially larger permit endowments. In the case of FSU, these even exceed its BaU-emissions; a result which mirrors the phenomenon of 'hot air' in the Kyoto Protocol (Böhringer and Löschel 2003).

[12]For example, JPN-EUR-CHN-FSU is not a SPNE because JPN can improve its welfare by leaving the coalition. Similarly, CHN-FSU does not satisfy weak external stability since EUR-CHN-FSU is a SPNE in which the welfare of all members is higher.

Table 2: Coalitions by Emission Reduction and Welfare Change, 2015

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

	% Equivalent Variation						*Global*	*Emission*
	USA	JPN	EUR	CHN	FSU	ROW	*%EV*	*Reduction*
First-Best	**1.2**	**6.2**	**4.7**	**-3.0**	**0.1**	**-0.1**	**1.7**	**21.4**
Shapley (EUR,CHN)	**1.0**	**3.6**	**0.5**	**0.5**	**5.6**	**0**	**1.2**	**15.4**
JPN,EUR,CHN,FSU	0.9	2.7	1.6	0.7	9.0	0	1.0	14.1
EUR,CHN,FSU**	**0.8**	**2.9**	**1.5**	**0.6**	**8.2**	**0**	**1.0**	**14.0**
EUR,CHN**	0.8	2.9	1.8	0.4	4.5	0	1.0	13.9
JPN,EUR,CHN	0.8	2.9	1.7	0.6	4.5	0	1.0	13.8
USA,EUR,CHN	0.8	2.7	1.2	1.7	4.3	0	1.0	13.6
USA,JPN,EUR,CHN,FSU	0.7	2.3	0.9	1.8	12.2	0	1.0	13.6
USA,JPN,EUR,CHN	0.8	2.7	1.2	1.8	4.2	0	1.0	13.5
USA,EUR,CHN,FSU	0.7	2.7	0.9	1.6	11.4	0	1.0	13.4
JPN,CHN**	0.7	1.8	1.7	0.2	3.6	0	0.8	12.7
USA,JPN,CHN	0.5	1.4	1.5	1.0	3.1	0	0.8	12.2
JPN,CHN,FSU	0.5	1.4	1.3	0.2	2.8	0	0.6	11.6
USA,JPN,CHN,FSU	0.3	1.1	1.3	0.9	5.5	0	0.7	11.5
USA,CHN**	0.3	1.6	1.2	0.7	2.3	0	0.6	11.2
USA,CHN,FSU	0.2	1.4	1.0	0.7	3.7	0	0.5	10.7
CHN,FSU*	0.3	1.1	0.8	0.1	0.9	0	0.4	10.2
EUR,FSU*	0.1	0.4	0.1	0	3.1	0	0.1	8.5
USA,EUR,FSU	0.1	0.3	-0.4	0	8.9	0	0.1	8.5
JPN,EUR,FSU	0.1	0.4	0	0	3.5	0	0.1	8.5
USA,JPN,EUR,FSU	0.1	0.4	-0.5	0	9.0	0	0.1	8.4
USA,EUR	0.2	0.3	-0.1	0	0.4	0	0.1	8.3
JPN,FSU**	0.1	0.1	0.2	0	0.7	0	0.1	8.3
USA,JPN,EUR	0.1	0.8	-0.3	0	0.2	0	0	8.1
No-Trade Nash	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7.8**
JPN,EUR	0	0.2	-0.1	0	0	0	0	7.8
USA,JPN,FSU	-0.1	-0.4	0	0	3.7	0	0	7.7
USA,JPN	0	0	-0.1	0	-0.1	0	0	7.7
USA,FSU	-0.1	-0.2	-0.2	0	2.2	0	-0.1	7.4

* 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.
Global %EV: global equivalent variation as % change from no-trade Nash

Our simulations suggest that hot air is less of a problem with respect to CHN's participation in a climate treaty. It is interesting to explore this difference in more depth. After all, permits are precious, as indicated by the permit price in Table 3, and coalition members are free to choose their initial permit allocation in our noncooperative framework. Furthermore, CHN's valuation

Table 3: EUR-CHN-FSU Coalition Profile, 2015
Homogenous Trade $(\sigma_{DM}, \sigma_{MM}) = (8, 16)$

	No-Trade Nash Emissions	Coalition Emissions	Coalition Endowments	Permit Prices	Equivalent Variation
			Coalition Members		
EUR	80.6	91.5	27.8	79.7	1.5
CHN	95.6	48.6	77.3	79.7	0.6
FSU	95.1	84.5	120.8	79.7	8.2
			Outsiders		
USA	72.6	73.1	-	126.9	0.8
JPN	84.4	84.6	-	131.6	2.9
			Non-strategic		
ROW	106.7	108.7	-	0	0

No-Trade Nash Emissions: no-trade Nash emissions as % of BaU
Coalition Emissions: equilibrium emissions with coalition as % of BaU
Coalition Endowments: permit endowment as % of BaU emissions
Coalition Permit Prices: real permit price ($/Tons)
Equivalent Variation: EV as % change from no-trade Nash equilibrium

for climate protection is lower than that of FSU which, by itself, should lead to higher permit endowments (see the final term from the first-order conditions in (11)). Strategic considerations in the permit market provide the answer to this puzzle. To understand this point, consider the hypothetical situation where CHN and FSU both have permit endowments equal in size to their BaU emission levels. If CHN has lower abatement costs than FSU (as it does in the model), it would sell more permits. Therefore, CHN has a strong interest in maintaining a high permit price. It achieves this by reducing the size of its permit endowment. FSU sells comparatively few permits in this experiment. Therefore, its losses due to a lower permit price are relatively low, and the incentive to sell more permits by increasing the permit endowment dominates.[13]

General equilibrium effects provide a further explanation for the different endowment choices of CHN and FSU. Less emissions and energy use lead to lower energy prices and higher prices for energy-intensive goods (both contributions to a negative Δ_r term from (11)). CHN is a net importer of fossil fuels and a net exporter of energy-intensive goods. They find it in their interest

[13]In the first-order conditions, the effect that more permits increase supply, thereby generally reducing the equilibrium permit price and lowering revenues from permit sales, is represented by a negative second term in square brackets in the first line of (11)

to exploit both of these terms of trade effects by restricting their permit levels. By contrast, FSU is a net exporter of fossil fuels and net importer of energy-intensive goods so that it faces the opposite incentives.

Despite the diversity among the coalition members, all regions benefit from agreement on trading (see column "equivalent variation"), though for different reasons. For EUR it becomes much cheaper to foster its environmental goals — by choosing a low permit endowment — because that part of abatement which would be most costly is shifted through the permit market to the other regions. Indeed, after-trade emissions of EUR greatly exceed its permit allocation and are even higher than its emissions in the no-trade Nash equilibrium. By contrast, the low valuation regions CHN and FSU benefit primarily from selling permits. After trading, they both emit less than in the no-trade Nash equilibrium. These gains are considerably larger for FSU because most of its permit sales result from 'hot air', while CHN's permit sales are associated with actual reductions in emissions. Finally, the coalition outsiders USA and JPN benefit from the favorable terms of trade effects and the reduced emissions generated by the coalition.

We have demonstrated that the best trading coalition, EUR-CHN-FSU, leads to substantial emission reductions, but it is important to note that it still falls short of the optimal level of reductions. Taking the no-trade Nash equilibrium as the reference point, it achieves only half of the emission reductions that would arise in the first-best solution (see Table 2). 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 solution 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.[14]

The highest reductions are achieved by the coalition EUR-CHN (listed as "EUR-CHN (Shapley)" in Table 2). Interestingly, the difference between this solution and the outcome for the agreement with the same membership but using the noncooperative permit-choice assumption ("EUR-CHN"

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

from Table 2) 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.

4.2 The Structure of International Trade

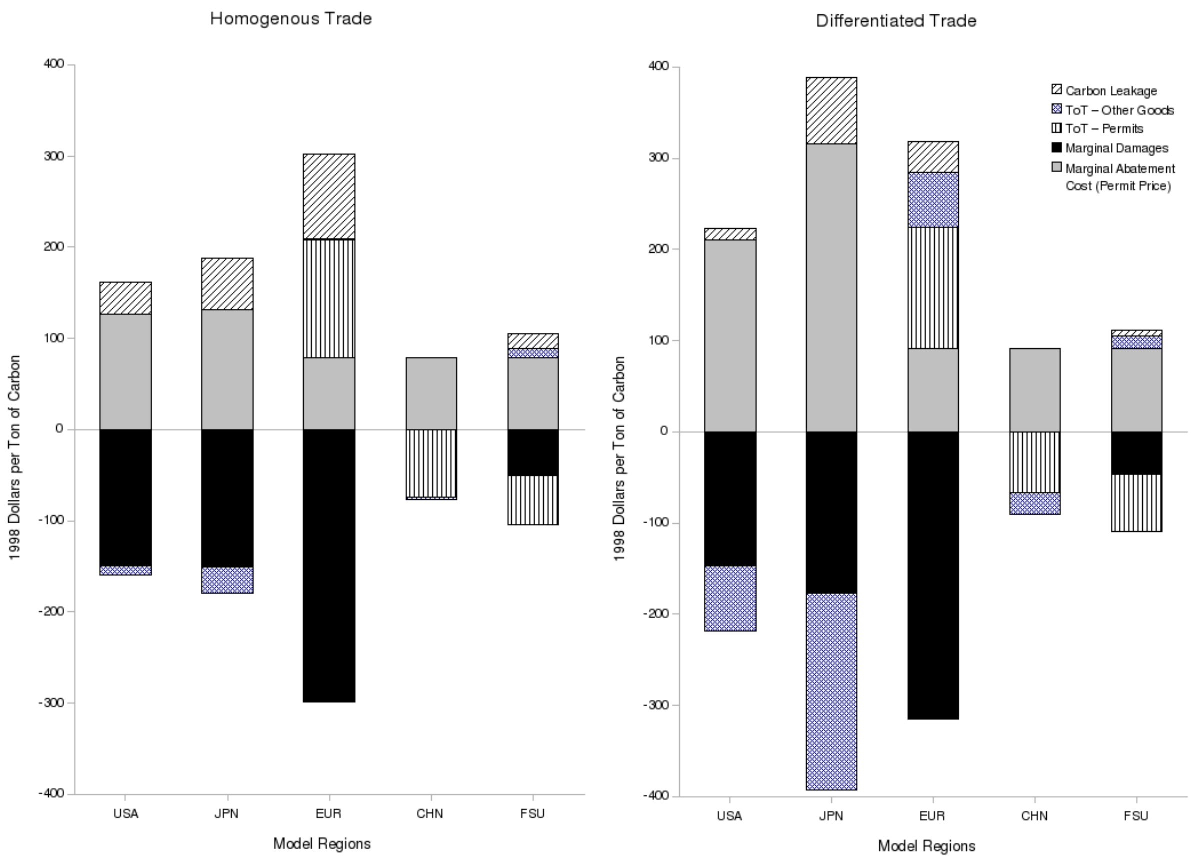
This section looks more closely at the strategic influences of international trade on equilibrium outcomes through carbon leakage and terms of trade effects. Figure 2 reports on the realization of the individual marginal effects that enter countries' first-order conditions in the best coalition equilibrium, the EUR-CHN-FSU coalition. The figure quantifies the individual elements that govern the size of their chosen permit endowment as described in equation (11), allowing us to determine the relative importance of the different channels of influence. For each region, the figure shows the money-metric value of the direct marginal abatement cost (π_{Er}), the marginal damages from carbon emissions ($\nu_r p_r^c$), the marginal value of carbon leakage ($\nu_r \frac{de_{row}}{d\omega_r^E} p_r^c$), the value of terms-of-trade effects in the permit market ($(\omega_r^E - e_r)\frac{d\pi_E}{d\omega_r^E}$) and the value of the net terms-of-trade effect in other markets (Δ_r), where the mappings to the elements in (11) are given in the parentheses.[15]

The elasticities that govern the structure of international trade, Armington elasticities, are key parameters for determining the value of carbon leakage and terms of trade effects so Figure 2 describes simulations under two different calibrations of the Armington 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. The left side of Figure 2 displays results for the benchmark

[15] N.B. — We measure the marginal value of the different effects driving permit endowment choice at the point of equilibrium in the EUR-CHN-FSU coalition. Figure 2, therefore, tells us what forces are important in governing each country's endowment choice at that point. An alternative would have been to perform a decomposition on the non-marginal policy response moving from, for example, the no-trade Nash equilibrium to the coalition equilibrium. A difficulty with this type of experiment is that the relative importance of the different effects is path dependent. The magnitude of the different marginal effects that enter a country's first-order conditions depend on the order in which we evaluate the adjustments in different countries permit endowments. Theory provides no guidance on the path of adjustment, so one is the position choosing one path arbitrarily or summarizing the results from repeated decompositions based on different paths.

version of the model, in which foreign and domestic varieties are assumed to be close substitutes (Homogenous Trade). The right side of the figure presented the results of the alternative version of the model in which they are imperfect substitutes (Differentiated Trade).

Figure 2: Decomposition of First-Order Conditions: EUR-CHN-FSU Coalition, 2015



In a partial equilibrium model, countries would equate direct marginal abatement cost (Marginal Abatement Cost in the figure) with the marginal willingness to pay for abatement (Marginal Damages), as in equation (10). In our model, the difference between the marginal abatement cost and the marginal damages reflects the degree to which a country's permit choice is modified by terms of trade effects in the permit market (ToT - Permits), in other markets (ToT - Other Goods) and Carbon Leakage. In the figure, the numerical values of these elements are stacked vertically with the columns corresponding to each of the strategic regions in the model. Positive elements, those incentives that tend to drive increases in the size of a region's permit endowment, appear above the x-axis and negative elements, those which give regions the incentive to decrease the size of their endowment, appear below. In equilibrium, where we measure the value of these derivatives, the negative and positive elements must balance for a region to satisfy its first-order conditions.

The results of the Homegenous Trade model show that the partial equilibrium effects, marginal abatement cost and marginal damages, are influential in deciding the level of permit endowment that a region chooses, as we would expect. What is striking, however, is that carbon leakage and terms of trade effects also make sizable contributions. Carbon leakage exerts a strong upward pressure on the endowment choices of USA, JPN and EUR. Terms of trade effects in the permit market are an important determinant of endowment levels for the permit-trading regions, EUR, CHN and FSU. Depending on the region, either carbon leakage or ToT effects in the permit market (or both) are *more* important than a region's marginal damages or marginal abatement cost in shaping the equilibrium.

The marginal effect of terms of trade effects in other goods markets plays a relatively minor role in the benchmark model, but these terms grow in magnitude when we assume that traded goods are less perfect substitutes (the right side of Figure 2). Terms of trade effects have 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. In particular, coalition outsiders USA and JPN experience strong incentives to curb their emissions in order to exploit terms of trade in the export of energy-intensive goods to coalition member states. Terms of trade effects in other markets also play a larger role in shaping the allocation decisions of coalition members. EUR has an incentive to increase its permit endowment to increase the value of its non-energy-intensive exports. CHN gets a gain in energy-intensive markets from restricting the size of its endowment in a fashion similar to the coalition outsiders, and FSU has an incentive to increase its level of permits to stimulate demand for its fossil fuel exports. At the same time, carbon leakage becomes less of a factor because energy-intensive industries are less able to relocate to countries without emission restrictions under the alternative Armington assumption.

Table 4 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 14% (see Table 2) to 17.3% for the EUR-CHN-FSU coalition, and from 7.8% to 11% for the no-trade Nash equilibrium. This is a direct result of the stronger emission-reducing terms of trade effects and weakened carbon leakage effects.

It is also interesting to note that the achievements of the best permit trade coalitions change very little when measured relative to the emission reductions of the no-trade Nash and first-best outcomes. The absolute reduction in emission achieved by the best coalition goes up in the simulations with the low trade elasticities but so do the emission reductions in the benchmarks against which we measure the achievements of the coalition. This suggests that terms of trade effects in markets for conventional goods impart no particular advantage or disadvantage to the formation of effective permit trade coalitions in our model. These effects are important in determining the absolute level of emission reductions, however.

These results stand in contrast to Copeland and Taylor (1995) in which strategic manipulation of terms of trade effects has no effect on the equilibrium global emission level in the Heckscher-Ohlin model. In our Armington model, terms of trade effects 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-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

Table 4: Coalitions by Emission Reduction and Welfare Change, 2015

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

	% Equivalent Variation						*Global*	*Emission*
	USA	JPN	EUR	CHN	FSU	ROW	*%EV*	*Reduction*
First-Best	**1.3**	**7.6**	**5.3**	**-4.2**	**0.8**	**-0.6**	**1.9**	**28.7**
Shapley (EUR,CHN)	**1.2**	**3.9**	**0.5**	**0.5**	**6.6**	**-0.1**	**1.3**	**19.8**
EUR,CHN*	0.9	3.0	1.9	1.1	5.8	0	1.2	17.7
EUR,CHN,FSU**	**0.8**	**2.8**	**1.5**	**1.2**	**11.0**	**0**	**1.1**	**17.3**
JPN,EUR,CHN	0.8	2.8	1.7	1.4	5.5	0.1	1.1	17.2
JPN,EUR,CHN,FSU	0.8	2.4	1.5	1.5	11.7	0.1	1.2	17.1
JPN,CHN**	0.8	2.3	2.0	0.3	4.6	0.1	1.0	17.0
JPN,CHN,FSU**	0.7	1.8	1.9	0.5	5.9	0.1	1.0	16.6
USA,EUR,CHN	0.7	1.9	0.7	3.6	4.2	0.1	0.9	15.3
USA,JPN,EUR,CHN	0.6	1.8	0.6	3.7	4.0	0.2	0.9	14.9
USA,EUR,CHN,FSU	0.4	1.6	0.2	3.1	13.4	0.2	0.8	14.6
USA,JPN,EUR,CHN,FSU	0.5	1.2	0.2	3.5	14.3	0.3	0.9	14.6
USA,JPN,CHN	0.4	0.9	1.1	2.0	2.6	0.2	0.7	14.3
CHN,FSU*	0.4	1.4	1.1	0.1	1.8	0	0.5	14.2
USA,CHN**	0.2	1.1	0.9	1.3	2.0	0.2	0.5	13.4
USA,JPN,CHN,FSU	0.2	0.3	0.9	1.8	6.5	0.3	0.6	13.4
USA,CHN,FSU	0	0.7	0.5	1.1	3.6	0.2	0.4	12.4
JPN,FSU	0.1	0	0.2	0.1	0.9	0.1	0.1	11.4
EUR,FSU	0	0.1	-0.1	0	4.8	0.1	0.1	11.1
No-Trade Nash	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**11.0**
JPN,EUR,FSU	0	0	-0.2	0	5.2	0.1	0.1	10.9
JPN,EUR	-0.1	0.2	-0.2	0	0	0.1	-0.1	10.3
USA,EUR	0.1	-0.4	-0.3	0	-0.1	0.1	-0.1	10.2
USA,JPN	-0.2	-0.2	-0.5	0	-1.0	0.1	-0.2	9.6
USA,EUR,FSU	-0.1	-0.7	-1.0	-0.1	11.1	0.2	-0.1	9.5
USA,JPN,EUR	-0.1	0.1	-0.8	0	-0.6	0.2	-0.2	9.2
USA,JPN,EUR,FSU	-0.2	-0.6	-1.2	0	10.5	0.3	-0.2	9.0
USA,JPN,FSU	-0.3	-1.2	-0.6	0	4.4	0.2	-0.2	9.0
USA,FSU	-0.4	-0.9	-0.7	0	2.9	0.2	-0.3	8.8

* 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.
Global %EV: global equivalent variation as % change from no-trade Nash

work which focuses on the role of imperfect competition and firm-level heterogeneity yields even higher underlying implicit Armington elasticities (Rolleigh 2003).

4.3 Participation of Developing Countries in Emission Abatement

A commonly held view is that the prospects for involving developing countries in emission abatement will improve in the future when the environment becomes a higher social priority for them. 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. To analyze this, we now consider a scenario in which we have raised the marginal value of abatement (1998, US-$ per ton of carbon) for CHN from 0 to 50, and for FSU from 50 to 100 (values for the other regions remain unchanged).

Table 5 summarizes the results of this experiment. The left side of the table reproduces the outcome for the EUR-CHN-FSU agreement and the no-trade Nash equilibrium from Table 2. The right side of the table presents the same simulations run using the alternative assumption about the distribution of regional marginal willingness to pay.

Table 5: Coalitions by Emission Reduction and Welfare Change, 2015
High Developing-World MWTP (CHN = $50 per ton, FSU = $100 per ton)

	Baseline		*High MWTP*	
	Global % EV	Emission Reduction	Global % EV	Emission Reduction
EUR,CHN,FSU	1.0	14.0	0.4	14.7
No-Trade Nash	0	7.8	0	12.8

Emission Reduction: % reduction in global emissions from BaU.
Global %EV: global equivalent variation as % change from no-trade Nash.

In comparison to the baseline scenario, abatement levels increase as a fraction of BaU emissions. This reflects the fact that the global mean valuation of emission reductions is higher. However, the difference between the most effective coalitional outcome and the no-trade Nash equilibrium is considerably lower under this scenario. Hence there are lower potential gains from a permit trade agreement. The reason is that 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.

It follows that involvement of developing countries in a permit trading system is more valuable today than it will be in the future when their environmental valuation and abatement cost are more similar to those of the other regions. The fact that developing countries stand to benefit substantially from the sale of permits in our model provides some hope that the prospects for a timely involvement are better than it is often perceived.

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 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 a major subject 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 a system of internationally tradable emission permits might enhance abatement, even if states are guided in their behavior by national self-interest. 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.

Furthermore, 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 contributes its low abatement cost, with Europe, which has the highest valuation for abatement and, therefore, acts as its main financier by choosing a low permit endowment. 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.

Our results also highlight how the incentive to use environmental policy as a substitute for trade policy contributes to the performance of environmental policies. This idea has long been acknowledged in the theoretical literature on strategic trade and the environment but has received almost no attention from researchers attempting to quantify the interactions between trade and environmental policy. In some of our simulations, trade channels are more influential in shaping equilibrium outcomes than the impulse to equate marginal abatement cost with marginal damages. The extent to which the insights from our analysis can be applied to other policy settings remains an open question.

A limitation of our analysis that we assume that only governments act strategically. A valuable extension of the model would be to allow for imperfect competition on the permit market (and, consistently, on the energy market). A standard way to do so would be to assume that there is region with market power which is surrounded by a competitive fringe (Hahn 1984). However, implementation of this idea is not trivial because the degree of market power depends on the overall size of the permit market, which differs across coalitions.

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