The CO_2 Abatement Game:
Costs, Incentives, and the Stability of a Sub-Global Coalition

by

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Abstract

This paper studies the economic incentives and the institutional issues governing the outcomes of a short-term climate change policy package guided by the United Nations' Framework Convention on Climate Change and the Berlin Mandate initiatives. Game theoretic tools and the global trade-environment interface are explored within a 26-region, 13-commodity computable general equilibrium framework to characterize the incentives of OECD regions to comply with a non-binding agreement in a carbon abatement coalition. The results showed that the achievement of such a coalition as well as its expansion by means of self-financed schemes are possible if suitable trade instruments are designed.

1. Introduction

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Increased concern about the possibility of an irreversible global climate change has resulted in several international initiatives that may ultimately lead to adoption of policies to reduce greenhouse gas emissions. The signing of the United Nations' Framework Convention on Climate Change (FCCC) and the Berlin Declaration are major steps in this direction. In its fourth article, the FCCC calls upon Annex1[1] countries to take early actions to stabilize their greenhouse gas (GHGs) emissions to their 1990 levels by year 2000. The Berlin Mandate, on the other hand, has included a number of proposals each suggesting 10% to 20% reductions in Annex1's GHGs emissions from their 1990 levels by year 2010. Nevertheless, it remains unclear whether and how the policy recommendations of these initiatives may be implemented. Of central importance are two issues: First, will Annex1 voluntarily comply with some non-binding agreement in a coalition to reduce GHGs emissions? And second, what institutional arrangements can be made that would promote cooperation among countries to achieve the emissions-reduction objective?

Both the game theoretic and the empirical literature on global warming seem to fall short of adequately answering these questions[2]. The former, by focusing on general abstract contexts, fails to convey the complexity of the interactions and the heterogeneity among the current international players in the game; unsurprisingly, then, its predictions of

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[1] Annex1 consists of OECD countries, Former Soviet Union and the East European countries. For reasons we explain latter, we treat Annex1 as if it is OECD only.

[2] Examples of the game theoretic literature are Maler (1991), Barrett (1991,1994), Carraro and Siniscalo (1993), and Sandler and Sargent (1995). Most of the empirical literature on global warming has emerged from numerical general equilibrium models e.g. Whalley and Wigle (1991), Manne and Richel (1992), Perroni and Rutherford (1993), Piggott, Whalley and Wigle(1993), Larsen and Shah (1994), OECD (1995), and Harrison and Rutherford (1997).

the likely outcomes appear both vague and conflicting.[3] The latter, on the other hand, by merely focusing on the design and the implementation issues, have neglected to question the feasibility and the self-enforceability of the particular arrangement. The studies by Piggott et al (1993), and Harrison and Rutherford (1997), however, are exceptions in that both of them have, in addition, attempted to accommodate somehow countries' participation incentives. Piggott et al (1993) have extended the regional preferences in their numerical model to include benefits from slowing global warming, and thereby characterize what they call "sub-global maximum consensus carbon-emissions reductions." Harrison and Rutherford (1997) have considered an OECD coalition arrangement in which the welfare costs of abatement are equated across the members. Nevertheless, neither the maximum consensus cutbacks nor the burden sharing arrangements, by themselves, are sufficient to ensure the self-enforceability needed to stabilize the arrangement outcomes.

The primary contribution of this paper is to empirically quantify and assess the incentives of Annex1 countries to voluntarily comply with a non-binding agreement to form a CO_2-abatement coalition. A multi-region, multi-commodity general equilibrium framework is developed to numerically simulate the strategic interactions among member countries in the different coalition structures and to compute payoffs. We show that free riding incentives are so pervasive that a self-enforcing coalition may not be supported as an equilibrium outcome under the current institutional arrangements.

A potentially important dimension in the interplay between global environment and trade issues which has not been fully explored in the current global warming literature is

[3] For example the global warming game in Maler (1991) is a Prisoner's dilemma, in Carraro and Siniscalo (1993) is a supergame with possibly stable partial coalitions, and in Sandler and Sargent (1995) is a coordination game in which both mutual defection and full cooperation are Nash equilibria.

the role of trade measures as enforcement mechanisms. Provided the public aspect of the global environment action, countries would certainly have incentives to free ride unless credible deterrents were designed. As a second contribution of this paper, we motivate and explore a connected trade-environment construct to address the free riding problem and to promote cooperation among the member countries in the abatement coalition. We show that the Annex1 coalition can be supported as a subgame perfect equilibrium if suitable trade rewards and punishment instruments are designed.

Provided that a stable abatement coalition among the member countries can be constructed, the third addition by the paper is to characterize and implement a simple self-financed scheme for expanding such a coalition. With such a scheme, we show that the three largest non-OECD carbon emitters join the abatement coalition and no other region stands to gain by joining it (i.e. the expanded coalition is also stable.)

The rest of the paper is organized as follows. Section 2, the analytical framework, describes our computable general equilibrium model (CGE) and the calibration of the carbon abatement benefit functions. Section 3 provides a numerical assessment of welfare costs, institutions, and quota allocation rules in a 25%-cutback OECD coalition. Section 4 analyses the equilibria of the one-shot abatement game. Section 5 presents the repeated CO_2-game analysis and explores the trade interaction as an enforcement mechanism. Section 6 analyses the expanded CO_2-abatment coalition. Section 7 provides concluding remarks.

2. The Analytical Framework

2.1 General Setup

Consider a group of N countries contemplating an agreement to provide a specified level of a pure public good (CO_2-abatement) through multilateral negotiations. Let W_r be the welfare index for the *rth* country. Since the abatement is a pure public good we assume W_r to have the special form:

$$W_r = U_r(C_r(Y_r, p_r, q)) + B_r(A) \tag{1}$$

Where C_r is a private consumption composite, B_r is region r's abatement benefit function, A is the global CO_2 abatement given by the summation technology:

$$A = \sum_s a_s \tag{2}$$

Where the a_ss are net regional CO_2-abatements over the no-agreement case(i.e. all a_ss are zeros in the status quo).

p_r is the domestic price vector, q is the international price vector, and Y_r is the net output vector (GNP) defined by the transformation:

$$Y_r = Y(p_r, q; a_r) \tag{3}$$

The functions U_r, C_r, B_r, and Y_r are assumed to be well-behaved; in particular, Y_r is non increasing in a_r, and B_r is non decreasing in A.

Provided that W_r is separable in U_r and B_r, the regional abatement benefit functions may be evaluated independently of the private good technology. This is useful because the welfare cost (i.e. the loss in private consumption) of any abatement policy can be assessed with reasonable certainty given the observed regional production, consumption, and bilateral trade flows. In contrast, due to the uncertainties surrounding the benefits side (see Cline 1992, and Nordhaus 1993), it is extremely difficult to model the benefits from reducing global warming within the household choice set. Having made these simplifying assumptions, we may proceed to solve the household optimization problem and measure the welfare costs implied by the given abatement policy. Next, we may use any reasonable exogenous estimates of the regional valuations to compute their total benefits from the resulting global abatement effort. The net regional gains from the given abatement policy would then be obtained by combining their corresponding cost and benefit estimates.

Formally, let $\bar{a}_r$ be the abatement quota of region *r* under the agreement.[4] Complying with the agreement, the representative agent in each country, *r*, solves

$$\max_{C_r} \quad U_r(C_r(Y_r, p_r, q)) \tag{4}$$

$$\text{s.t.} \quad Y_r = Y(p_r, q; a_r)$$

$$a_r \geq \bar{a}_r$$

In a multi-regional equilibrium framework, the solution to such a problem is characterized by the regional equilibrium price vector p^*_r, the regional equilibrium allocations C^*_r and Y^*_r, the regional shadow price vector associated with the CO_2 constraint, and the equilibrium international price vector q^*, such that all domestic and international markets clear and every representative agent maximizes utility on her budget set. Numerically, this multi-regional equilibrium problem is formulated and solved as a CGE model using the GAMS/MPSGE software described in Rutherford (1995,1997).

2.2 An Overview of the CGE Model and its Implementation

[4] In the empirical construct only a subset of the *N* countries is contemplating to form the abatement coalition. In that case for the non colluding countries abatement is unrestricted and their benefits from abatement are assumed to be zeros.

The framework is a static multi-regional general equilibrium model of energy and trade. The model is built on a comprehensive energy-economy dataset that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows. For details on the data set and its construction, see Rutherford and Babiker(1997). The original data set cover 26 regions and 13 sectors, yet for tractability of the later numerical game analyses, the regions are aggregated into 24. Description of the specific regions and commodities included in the model is provided on Table 1.

The sectors in the model have been chosen to identify as many carbon-intensive sectors for which region-specific and industry-specific data can be obtained[5]. The energy goods identified in the model include coal (COL), gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). This disaggregation is essential in order to distinguish energy goods by carbon intensity and by the degree of substitutability. In addition, the model features important carbon-intensive and energy-intensive industries which are potentially those most affected by carbon abatement policies, such as Iron and steel (ORE), chemical products (CRP), non-ferrous metals (NFM), non-metallic minerals (NMM), pulp and paper (PPP), and trade and transportation services (TRN). The rest of the economy is divided into agricultural production (AGR) and other goods (Y).

Primary factors include labor, capital, land and fossil-fuel resources. Labor and capital are treated as perfectly mobile across sectors within each region but internationally immobile. The production functions assumed in each sector allow sufficient levels of

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[5] The primary source for base year (1992) economic statistics is Global Trade Analysis Program (GTAP; see McDougall, 1997), and our primary source for energy demand,

nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy (electricity).

Figure 1 illustrates the nesting structure employed for production sectors other than fossil fuels. Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods, and an energy-primary factor composite. The energy composite is in turn produced with a constant-elasticity-of-substitution (CES) function of a primary-energy composite and electricity. The primary-energy composite is then a function of coal, crude oil, refined oil and natural gas. The value-added composite consists of a Cobb-Douglas aggregation of labor, capital and land.

Fossil fuel production is a nested-CES aggregate of an energy-specific resource and a Leontief composite of labor input and the other goods in the model, where the substitution elasticity between the specific factor and the composite is calibrated to match an exogenous fossil fuel supply elasticity. The supply elasticities used in the model are 2 for crude oil, 0.5 for coal, and 1 for natural gas. (Details on the calibration procedure are provided in Appendix A.)

Table 1. Countries, Regions, and Sectors in the General Equilibrium Model

Country or Region		Commodities	
AUS	Australia	COL	Coal
NZL	New Zealand	CRU	Crude Oil
JPN	Japan	OIL	Refined Oil Products
KOR	Republic of Korea	GAS	Natural Gas
IDN	Indonesia	ELE	Electricity
MYS	Malaysia	ORE*	Iron & Steel

supply and price data is the OECD/IEA publications for 1992.

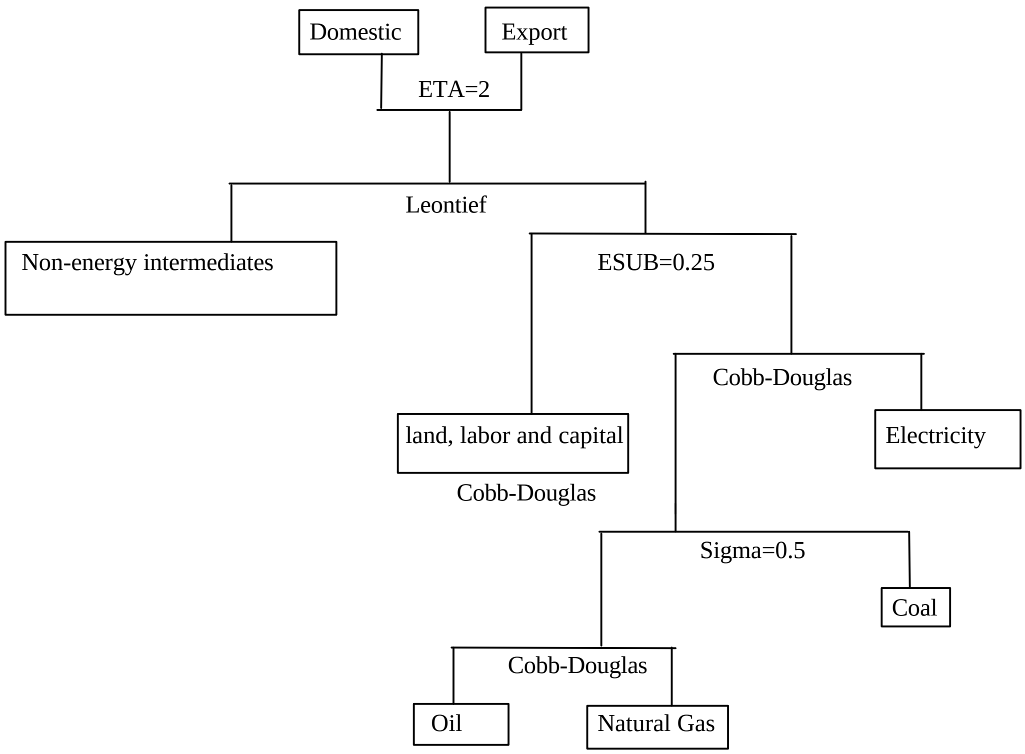
PHL	Philippines	CRP*	Chem, Rubber & Plastic
SGP	Singapore	NFM*	Non-ferrous Metals
THA	Thailand	NMM*	Non-metallic Minerals
CHN	China	PPP*	Pulp & Paper
HKG	Hong Kong	TRN*	Trade and Transport
TWN	Taiwan	AGR	Agricultural Goods
IDI	India	Y	Other Goods
CAN	Canada		
USA	United States		
MEX	Mexico	*Energy-Intensive Goods	
ARG	Argentina		
BRA	Brazil		
CHL	Chile		
RSM	Rest of South America		
E_U	European Union 12		
EU3	Austria, Finland, & Sweden		
FSU	Former Soviet Union		
MEA	Middle East & North Africa		
SSA	Sub-Saharan Africa		
ROW	Rest of World		

Final demand has the structure depicted in Figure 2. Utility in each country is a nested-CES function of an energy consumption composite and a consumption composite of the 12 non-energy goods in the model, where each of the two composites is in turn a Cobb-Douglas aggregate.[6]

CO_2 emissions are associated with fossil fuel consumption in production and final demand. Different fuels have different carbon intensities. The technology producing CO_2, then, is a fixed proportion activity in which each unit of a fuel consumed emits a known amount of carbon, i.e., the only feasible means of abatement, other than reducing consumption, are inter-fuel and fuel-non fuel substitutions.

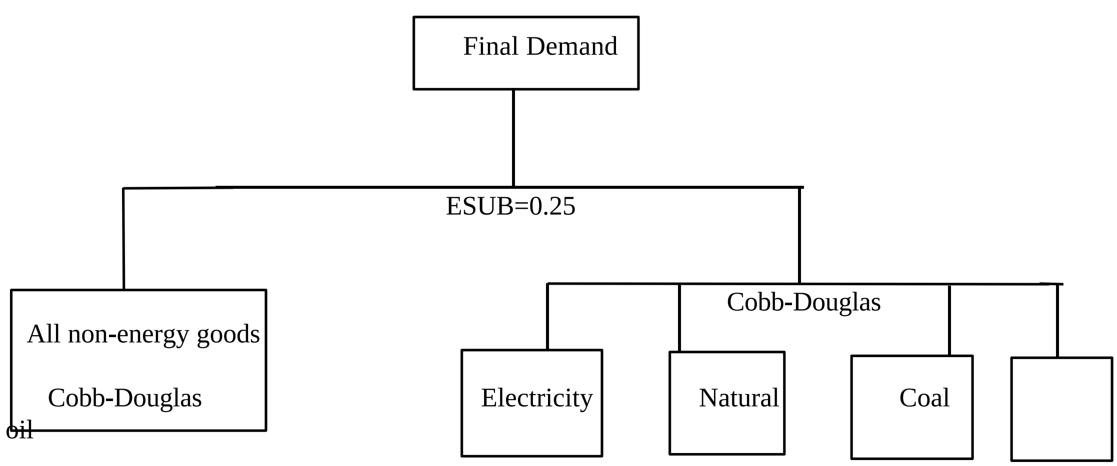
Figure 1. Structure of non-Fossil Fuel Production

[6] The energy demand elasticities used in the model are consistent with those typically used in the literature, and are within the ranges reported in econometric studies (e.g. Pindyck 1979, Nguyen 1986, Nainar 1989.)



ETA is a transformation elasticity,
ESUB and Sigma are substitution elasticities.

Figure 2. Nesting Structure for Final Demand



gas

The model's equilibrium framework is based on final demands for goods and services in each region arising from a representative agent. Final demands are subject to an income balance constraint with fixed investment. Consumption within each region is financed from factor income, taxes and exogenously specified capital flows. Taxes apply to energy demand, factor income and international trade, and these finance a fixed level of public provision. The government budget is balanced through lump-sum taxes.

Energy goods and other commodities are traded in world markets. Crude oil is imported and exported as a homogeneous product, subject to tariffs and export taxes. All other goods, including energy products such as coal, electricity, and natural gas, are characterized by product differentiation with an explicit representation of bilateral trade flows calibrated to trade flows for the reference year, 1992.

Energy products (refined oil, coal, natural gas, and electricity) are sold at different prices to industrial customers and final consumers. The physical quantities of sectoral and final energy demand are calibrated to the OECD/IEA Energy Balances and Statistics. The essential features of the model formulation are provided in Appendix B and the full mixed complemenarity formulation (MCP) in Appendix C.

2.3 The Calibration of CO_2-Abatement Benefit Functions

Given the current state of knowledge on the greenhouse gas effect, there is no obvious way of even characterizing the shape of the damage(benefit) function, B_r. Nevertheless, many in the profession seem to have assumed in their analysis that the marginal abatement benefit is either constant or linear. (see, Hoel (1991), Nordhaus

(1993), and Barrett (1994).) Following these studies, two functional forms of B_r are specified:

(a) $B_r(A) = \beta_r A \quad , \quad \beta_r \geq 0$ (5)

(b) $B_r(A) = \lambda_r A - \gamma_r A^2 \quad , \quad \lambda > 0, \ \gamma > 0$ (6)

Where from (a) the marginal benefit in country r is the constant β_r, and from (b) the marginal benefit is the downward sloped linear function $\lambda_r - 2\gamma_r A$. Given the global abatement level A from the agreement and the solution of the household problem, the evaluation of the benefits from abatement reduces to the determination of the constants β_r, λ_r, and γ_r. The following two methods are used for calibrating these constants in the numerical simulations.

(i) Exogenous calibration of β_r, λ_r, and γ_r. This method is motivated by the retrospective argument that for any CO_2-abatement policy to have been beneficial and therefore acceptable to all participating parties, it should have satisfied the weaker condition that the abatement benefit at least offsets the welfare cost(i.e. the foregone consumption of the private good) of abatement for each party. The empirical literature has generally suggested that the net benefits from slowing global warming are low. On the cost side, the simulations of the OECD GREEN model (OECD 1995) suggest that the world average annual GDP loss from stabilizing CO_2 emissions in Annex1 to their 1990 level is about 1%. On the benefit side, both Cline (1992) and Nordhaus (1993) suggest that for the US, the annual benefit from avoiding the doubling of CO_2 atmospheric concentration is about 1% of 1990 GDP, whereas Fankhauser (1993) suggests the world annual benefit (for the same scenario) to be about 1.4% of the world 1990 GDP. Based on this, two estimates of the regional per-capita marginal benefits (or marginal willingness to pay) are considered. The first estimate assumes the per-capita marginal benefit for each country is 5% higher than the country's corresponding per-capita welfare cost (in dollars). We call this estimate *W0*. The second estimate assumes identical per-capita marginal valuations across all the parties, and calibrates b_r to be 1% higher than the highest regional per-capita welfare cost. On the other hand, l_r and g_r in the linear marginal benefit formulation are calibrated using the estimates of b_r in such a way that the individual marginal willingness to pay declines by $100 for each additional billion tons of CO_2 abated. We call the linearized version of the second estimate *W1*.

(ii) Endogenous calibration of b_r using Lindahl pricing.[7] This approach is similar to the one used in Piggott et al (1993)'s study. In particular, the approach proceeds from the retrospective question: What are the regional individualized prices (or marginal valuations) that would have supported the abatement target specified by the agreement in a Lindahl equilibrium? The global CO_2-abatement is modeled as a public good, the provision of which is the sum of the regional abatements. On the supply side, the abatement of each country contributes in a one-to-one basis to the total provision, and in turn the total provision is available in a non-rival sense for each country. On the demand side, each country, given her income and her marginal valuations, decides on the total provision, *A*, "as if" she is the only consumer of the public good. In equilibrium the sum of the marginal valuations equals the marginal cost of providing the last unit of the good.

Formally, in the context of (4), the representative agent in each country, *r*, chooses her consumption, C_r, and her desired level of the public good, G_r, that solve:

[7] The motivation for this method is the analysis in Chichilnisky and Heal (1993) of the atmosphere as a public good and their argument that Lindahl rather than Walrasian equilibrium is the appropriate concept for addressing the CO_2-abatement issue.

$$\max_{C_r, G_r} \quad W_r = U_r(C_r(Y_r, p_r, q)) + \beta_r G_r \qquad (7)$$

s.t. $Y_r = Y(p_r, q; E_r)$

$$\Gamma(a_1, a_2, \ldots, a_N; \beta_1, \beta_2, \ldots, \beta_N) = a_r$$

$$a_r = \phi(\overline{E}_r)$$

$$E_r + a_r = \overline{E}_r$$

$$G_r = \sum_s a_s$$

Where $\overline{E}_r$ is the initial total fossil fuel CO_2 in country *r*, and E_r is the CO_2 input in the production and consumption activities, Y_r and C_r. $\Gamma(\,)$ is an output transformation technology that translates each unit of abatement in *r* to N units, one for each country *s*. $\phi(\,)$ a constant returns to scale technology (CRTS) that produces one unit of a_r from each unit of $\overline{E}_r$. β_r is country *r*'s marginal valuation for each unit of the public good G_r.

Without calculus, since $E_r + a_r = \overline{E}_r$, in equilibrium the marginal cost (in dollars) of the last unit of $\overline{E}_r$ allocated to production and consumption or to the abatement activity must be equal; in turn, from the abatement technology this marginal cost is given by $\phi'(\overline{E}_r)$. On the other hand, the zero profit condition (i.e. the cost of inputs used should equal the value of output produced) for the CRTS joint outputs abatement activity ensures the Lindahl equilibrium condition:

$$\phi'(\overline{E}_r) = \sum_s \beta_s \qquad (8)$$

i.e. the dollar marginal cost of providing the last abatement unit in each region has to equal the sum of the regional marginal valuations for that unit.

Next, the first order condition for $G_r>0$ implies the usual marginal rate of transformation equals marginal rate of substitution result:

$$-\frac{\partial C^*_r}{\partial G^*_r} = \frac{\beta^*_r}{\frac{\partial U_r}{\partial C^*_r}} \tag{9}$$

Now, the regional marginal valuations, β_rs, consistent with a Lindahl provision of the abatement target specified in the agreement can be recovered by solving (8) and (9) iteratively. Numerically, we extend the regional preferences in our CGE model to include the public provision, and we employ a CRTS abatement technology in each region that produces joint products of the abatement good in fixed proportions. The following iterative algorithm is then used to recover the regional Lindahl prices:

(i) start with initial guesses of the regional Lindahl prices, β_rs, solve the model, and compute the desired G_rs.

(ii) For those whose G_rs are less(greater) than the target specified by the agreement adjust their prices downward(upward) and solve for new G_rs.

(iii) Continue until the desired G_r for each region equals the specified target.

We call the regional benefit estimate corresponding to Lindahl equilibrium *W2*.

3. A 25%-Cutback OECD Carbon Coalition

3.1 Current Policy Climate and Model Scenarios

Article 4 of the FCCC implied that Annex1 countries should take early action to stabilize the atmospheric concentration of the greenhouse gas, and that the developing countries should not be burdened for several decades with abatement responsibilities that may undermine their economic development. Nevertheless, given their current economic situation, neither the Former Soviet Union nor the East European countries are likely to join the rest in Annex1 to meet these responsibilities. Then it is primarily the OECD regions who should honor these obligations. The proposals launched at the Berlin Mandate (1995), on the other hand, call for 10 to 20% reductions in greenhouse gas emissions in the industrialized countries from their 1990 levels by year 2010. Since CO_2 is the major anthropogenic greenhouse gas, any short term abatement action will naturally to focus on fossil fuel use. According to the 1992 projections of the Intergovernmental Panel on Climate Change (IPCC), fossil fuel CO_2-emissions are likely to grow by 2.5-3.5% annually in the business-as-usual trajectories. Given these projections along with the objectives in FCCC and Berlin Mandate, a 10-15% one time reduction in global CO_2-emissions from their 1992 level, seems to be a good approximation of a moderate climate policy within a static framework. From the IEA 1992 Statistics, a 25% reduction in OECD emissions amounts to a 12% reduction in global emissions. Therefore, we adopt a 25% reduction target in the OECD for the analysis in the paper[8].

The 7 OECD regions in the original data set are aggregated into 5 regions: AUS Australia and New Zealand, JPN Japan, CAN Canada, USA United States, and E_U European Union(12) plus EU3. The observed 1992 fossil fuel CO_2-emissions in OECD are assumed to characterize a Nash equilibrium, i.e., all feasible no regret energy savings have been exhausted. Regarding implementation and coordination issues, both the FCCC and Berlin Mandate seem to have endorsed economic efficiency, equity, gradual action, and wider coalition as appropriate climate policy responses. Efficiency, equity, and cost sharing issues among the OECD regions are addressed through institution and quota

[8] However some preliminary sensitivity analyses have shown that the main insights of the paper are not

allocation rule scenarios. Two types of institutional arrangements are simulated: A uniform OECD permit market and regional permit markets.[9] Four rules for allocating CO_2 emission rights are experimented: The first emphasizes the status quo (Grandfathering) and the other three emphasize equity, efficiency, and per-capita cost sharing.

3.2 Institutions, Quota Rules, and Welfare Impacts in a Unilateral OECD Abatement Coalition: Simulation Results

Table 2 presents a summary of the simulation results on institutions and quota allocation rules. The grandfathering rule, columns (1) and (2), allocates members' quotas in proportion to their 1992 CO_2-emissions (this is equivalent to each OECD region

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affected by the size of the target.

[9] Following the arguments in Schelling (1992) of the political implausibility of an international carbon tax, a uniform OECD carbon tax is not considered in the analysis.

cutting its emissions by 25%); the equity rule, column (3), allocates the members' quotas in proportion to their 1992 populations; the efficiency rule, column (4), allocates the members' quotas in proportion to their 1992 CO_2-intensities per unit of their corresponding per-capita GDPs; and the cost sharing rule, column (5), assigns members'

Table 2. Quota Allocation Rules, Institutions, and the Welfare Impacts of an OECD CO2 Coalition

Region	(1)[a] Grandfathering with No permit market: Welfare Costs			(2)[b] Grandfathering with Permit market					(3)[c] Per-Capita Allocation with Permit market				
				Quota %	Welfare Costs			CO2 Trade B$	Quota %	Welfare Costs			CO2 Trade B$
	EV%	$ per-cap	% gdp		EV%	$ per-cap	% gdp			EV%	$ per-cap	% gdp	
AUS	-1.5	150	0.9	2.9	-0.7	72	0.5	2.9	2.9	-0.5	50	0.3	3.4
JPN	-0.7	115	0.4	11.5	-0.7	112	0.4	-3.5	17.3	1.7	-278	-0.9	38.0
CAN	-1.4	168	0.8	4.3	-1.3	156	0.8	1.8	4.0	-2.3	276	1.4	-0.5
USA	-1.1	161	0.7	48.0	-0.9	142	0.6	15.1	35.6	-3.6	554	2.4	-74.5
E_U	-1.1	172	0.7	33.3	-1.0	163	0.6	-16.3	40.2	0.2	-29	-0.1	33.6
OECD	-1.0	157	0.6	100	-0.9	144	0.57	0	100	-1.0	150	0.6	0

a leakage 12.5%, net global CO2 abatement 10.4%
b leakage 11.5%, net global CO2 abatement 10.6%
c leakage 11.7%, net global CO2 abatement 10.5%

Table 2. continued.

Region	(4)[d] Per-Capita-gdp carbon-intensity Allocation with Permit market					(5)[e] Per-Capita Cost-sharing Allocation with Permit market				
	Quota %	Welfare Costs			CO2 Trade B$	Quota %	Welfare Costs			CO2 Trade B$
		EV%	$ per-cap	% gdp			EV%	$ per-cap	% gdp	
AUS	1.7	-5.3	527	3.3	-4.6	2.7	-1.5	144	0.8	2.4
JPN	27.6	5.6	-935	-3.2	108.2	11.1	-0.9	144	0.5	-6.8
CAN	2.6	-5.7	674	3.4	-10.3	4.4	-1.2	144	0.7	2.3
USA	22.1	-6.5	1000	4.3	-165.8	47.9	-0.9	144	0.6	13.7
E_U	46.0	1.2	-186	-0.7	72.5	33.9	-0.9	144	0.5	-11.6
OECD	100	-1.1	162	0.65	0	100	-0.9	144	0.57	0

d leakage 11.8%, net global CO2 abatement 10.5%
e leakage 11.5%, net global CO2 abatement 10.6%

quotas in such a way that per-capita welfare costs (in dollars) are equated across the coalition members. The welfare costs are expressed in three forms: the percentage change in the Hicksian index, EV%, the per-capita consumption reduction in dollars, and the regional forgone consumption as a percent of the 1992 regional GDP[10]. Along with these, Table 2 also reports trade flows in CO_2-permit market for the different allocation rules. In terms of institution design, the results in columns (1) and (2) suggest that the movement into a uniform permit market is a Pareto-improvement for every member (assuming away transaction costs.) This improvement is a result of both the lower abatement cost and the lower leakage rate (the increase in CO_2-emissions by non-abating countries as a percentage of the coalition abatement) associated with the uniform permit arrangement. However, even though every member benefits from the coordination provided by the uniform market, some regions (e.g. AUS) appear to benefit more than others because of their lower abatement costs.

With respect to quota rules, both the equity and the efficiency criteria result in higher emission quotas for JPN and E_U, and lower ones for AUS, CAN, and USA compared to those assigned by the grandfathering rule. This is because both JPN and E_U are relatively more energy efficient and relatively more populated than their other OECD partners. The welfare impacts for these two rules are shown respectively in columns (3) and (4). It is clear from the statistics that JPN and E_U are net gainers, whereas AUS,

[10] To check how close our 25% OECD cut approximates the effect of the FCCC and Berlin Mandate: for a grandfathering scenario in which the FCCC global target is wholly met by OECD through a uniform tax, the simulations of the OECD GREEN model suggest that the OECD average real income loss over the period 1990-2050 is 0.76% relative to the business as usual baseline. In contrast, the results on Table 2 (for the grandfathering with uniform permit) indicate an OECD loss of 0.57% of the 1992 GDP.

CAN, and USA appear to experience huge welfare losses. Not only that, but the overall OECD welfare, measured by a base- year-consumption weighted Hicksian index, is lower and the leakage rate is higher for either of these two rules when compared to the corresponding results from the grandfathering rule. Based on these results, an OECD CO_2-coalition with quotas allocated according to either a pure equity criterion or a pure efficiency criterion is unlikely. The last rule simulated in the analysis is the per-capita cost-sharing allocation. The simulation results for this allocation are displayed on column (5). The corresponding quotas implied by this rule suggest a minor reallocation of the grandfathering quotas from the relatively low welfare cost members (AUS,JPN, and USA) to the relatively high welfare cost ones (CAN and E_U). In terms of the overall performance (i.e. OECD welfare and leakage rate), the results for this allocation are identical to those of the grandfathering allocation i.e. the two allocations seem to lie on the same OECD Pareto-frontier.

The main insights from the exercises on Table 2 are therefore: (i) A uniform permit market is better than regional permits or tax arrangements; (ii) quota allocation rules that favor efficiency or equity criteria are unlikely; (iii) irrespective of the institution type or the quota rule, there are likely to be sharp differences in the welfare impacts of the abatement policy across the OECD regions.

To provide insights on the curvature of the marginal abatement costs and to motivate the game analyses in the following sections, we have computed the uniform permit price and the regional per-capita welfare costs for several reduction targets in the range 0 to 40%. The implied elasticities suggest that the marginal abatement cost curves are quite steep. The CO_2-abatement elasticity with respect to the coalition permit price is found to range between 0.04 and 0.13, and that with respect to the regional per-capita welfare costs is found to range between 0.01 and 0.15. The presence of such steep marginal abatement costs implies free riding incentives are likely to be huge and consequently the chances for a self-enforcing OECD abatement coalition are small.

4 The One-Shot Game Analysis and the Stability of an OECD Carbon Coalition

4.1 Benefit Estimates and Payoffs

Following the discussion in section 2, the marginal benefit estimates corresponding to *W0*, *W1*, and *W2* are used for calibrating the OECD payoffs. For the grandfathering with uniform permit scenario, *W0* corresponds to a 5% markup on the regional per-capita welfare costs shown for the scenario on Table 2, whereas *W1* corresponds to the linearized version of a 1% markup on the highest regional per-capita welfare cost shown for the scenario on the same table (namely that of E_U). The regional total benefits from the cutback implied by these estimates lie in the range 0.4%-0.9% of the corresponding 1992 regional GDPs. On the other hand, the per-capita marginal valuations corresponding to the simulated Lindahl equilibrium (*W2*) are computed to be $352 for AUS, $279 for JPN, $327 for CAN, $463 for USA, and $271 for E_U. In 1992 GDP terms, the corresponding regional benefits in the Lindahl provision of the 25% cutback are 2.2% for AUS, 0.9% for JPN, 1.7% for CAN, 2.0% for USA, and 1.0% for E_U.[11] To express the

[11] An interesting insight from the simulated Lindahl equilibrium is the equality of the relative marginal valuations of the abatement provision and the private consumption composite across OECD regions. This imply that the marginal welfare costs in the no-public good case are equated across the coalition members, which in a sense a reinterpretation of the burden sharing arrangement in Harrison and Rutherford (1997).

per-capita benefit estimates in per-billion tons of CO_2 terms, we divide by the coalition net abatement (i.e. abatement - leakage).

4.2 Equilibria in the One-Shot OECD-Coalition Game

The one-shot OECD interaction is a complete-information simultaneous move game in which each region has two strategies: C cooperate (i.e. comply with the abatement agreement), and N not-cooperate (i.e. not comply with the agreement). All players (i.e. OECD regions) are rational (i.e. welfare maximizers), and for every player: both the other players' strategies and the game payoffs are known. The simulated payoffs for the game constructs with grandfathering+permit scenario are reported on Table 3, where players are labeled A for AUS, J for JPN, D for CAN, U for USA, and E for E_U, payoffs correspond to players on the column, and where W0, W1, and W2 correspond to the benefit estimates used in calibrating the payoffs.

Table 3. OECD-Coalition Game Payoffs (b$)
Scenario: Grandfathering+ OECD Permit Market

column player	A						J					
row players	JDUE						ADUE					
strat-egy	C			N			C			N		
	W0	W1	W2	W0	W1	W2	W0	W1	W2	W0	W1	W2
CCCC	0.1	2.3	5.0	-0.0	2.2	4.8	0.7	8.9	17.0	20.2	27.6	34.3
NCCC	0.3	2.3	4.6	0.4	2.3	4.5	-0.2	7.8	15.5	19.2	26.4	32.8
CNCC	0.1	2.2	4.8	-0.1	2.0	4.5	-0.4	7.5	15.1	19.0	26.1	32.3
CCNC	0.3	1.4	2.6	-0.9	0.2	1.2	-8.9	-4.6	-1.5	11.5	14.8	17.1
CCCN	-0.2	1.4	3.1	0.3	1.8	3.5	-7.1	-1.2	3.6	10.5	15.6	19.5
NNCC	0.3	2.2	4.3	0.3	2.1	4.2	-1.4	6.4	13.6	18.0	24.9	30.8
NCNC	0.6	1.5	2.3	-0.5	0.3	1.1	-9.8	-5.7	-2.9	10.7	13.8	15.8
NCCN	-0.0	1.3	2.7	0.7	1.9	3.3	-7.9	-2.1	2.5	9.5	14.4	18.0
CNNC	0.6	1.6	2.7	-1.0	-0.1	0.9	-9.8	-5.7	-2.8	10.8	13.8	15.8
CNCN	-0.2	1.3	2.9	0.3	1.7	3.2	-7.9	-2.3	2.2	9.4	14.1	17.6
CCNN	-0.5	-0.0	0.4	-0.4	-0.0	0.3	-16.1	-14.5	-13.4	1.7	2.4	2.8
NNNC	1.0	1.8	2.5	-0.5	0.2	0.8	-10.8	-7.2	-4.7	10.0	12.8	14.6
NNCN	-0.1	1.2	2.5	0.6	1.8	3.0	-9.0	-3.6	0.6	8.6	13.2	16.6
NCNN	-1.0	-0.8	-0.7	0.0	0.1	0.2	-17.8	-16.5	-15.7	0.8	1.2	1.3
CNNN	-0.1	0.2	0.5	-0.4	-0.2	0.0	-17.5	-16.2	-15.4	0.9	1.2	1.4
NNNN	-1.2	-1.0	-1.1	0	0	0	-19.5	-18.5	-17.9	0	0	0

key:
players: A AUS, J JPN, D CAN, U USA, and E E_U.
Strategies: C cooperate, N not-cooperate; payoffs correspond to column players

Table 3. continued..

column player	D						U					
row players	AJUE						AJDE					
strat-egy	C			N			C			N		
	W0	W1	W2	W0	W1	W2	W0	W1	W2	W0	W1	W2
CCCC	0.2	0.8	3.8	2.8	3.3	6.2	1.8	10.6	69.1	13.5	18.7	44.3
NCCC	0.1	0.7	3.6	2.6	3.1	5.9	1.0	9.7	66.1	11.9	16.8	40.6
CNCC	-0.2	0.4	3.0	2.4	2.9	5.3	-3.5	4.7	54.9	9.1	13.2	32.3
CCNC	0.5	0.9	2.2	1.8	2.1	3.3	1.0	9.6	65.0	12.8	17.7	41.4
CCCN	-1.4	-0.9	1.0	1.3	1.7	3.5	-10.0	-3.2	34.1	5.7	7.8	16.7
NNCC	-0.3	0.3	2.8	2.2	2.7	5.0	-4.3	3.7	52.0	7.6	11.3	28.5
NCNC	0.7	1.1	2.3	1.5	1.9	2.9	0.3	8.7	62.1	10.6	15.0	36.0
NCCN	-1.4	-1.0	0.9	1.1	1.5	3.2	-10.4	-3.7	32.6	4.3	6.0	13.2
CNNC	0.2	0.5	1.5	1.5	1.8	2.6	-4.4	3.5	50.8	8.4	12.1	29.3
CNCN	-1.6	-1.2	0.4	1.0	1.4	2.8	-14.0	-7.9	23.5	2.1	2.9	6.5
CCNN	-1.6	-1.5	-1.1	0.4	0.5	0.8	-10.4	-3.8	31.5	5.0	6.7	13.9
NNNC	0.5	0.8	1.7	1.3	1.6	2.3	-5.1	2.6	47.9	6.8	10.2	25.5
NNCN	-1.7	-1.3	0.2	0.9	1.3	2.7	-15.1	-9.3	20.2	0.7	1.2	2.9
NCNN	-1.4	-1.3	-0.9	0.2	0.3	0.5	-11.4	-5.0	28.3	3.7	5.0	10.3
CNNN	-2.3	-2.2	-2.0	0.1	0.2	0.3	-15.1	-9.5	19.1	1.3	1.7	3.5
NNNN	-2.4	-2.3	-2.2	0	0	0	-15.6	-10.1	17.5	0	0	0

Table 3. Continued.

column player	E					
row players	AJDU					
strat-egy	C			N		
	W0	W1	W2	W0	W1	W2
CCCC	2.3	5.8	22.3	35.4	38.9	48.5
NCCC	0.1	3.6	19.4	34.2	37.6	47.0
CNCC	-4.9	-1.3	12.5	28.6	31.9	39.8
CCNC	0.1	3.7	19.1	33.6	37.0	46.0
CCCN	-25.5	-22.6	-16.3	10.4	11.7	13.6
NNCC	-7.2	-3.6	9.5	26.6	29.8	37.1
NCNC	-2.1	1.5	16.2	31.5	34.9	43.3
NCCN	-27.7	-24.9	-19.2	8.4	9.5	11.0
CNNC	-7.1	-3.5	9.3	26.0	29.1	36.2
CNCN	-32.2	-29.8	-25.4	3.7	4.2	5.0
CCNN	-26.7	-23.9	-18.2	8.8	9.8	11.4
NNNC	-9.4	-5.8	6.3	24.8	27.9	34.7
NNCN	-34.6	-32.4	-28.4	1.7	2.0	2.4
NCNN	-29.5	-26.9	-21.9	6.9	7.7	8.9
CNNN	-33.6	-31.3	-27.3	1.9	2.2	2.6
NNNN	-35.5	-33.5	-29.9	0	0	0

Note that the strategies for the row players are ordered in accordance with the ordering of the players, e.g., strategies NCNC and row players JDUE means J plays N, D plays C, U plays N, and E plays C.

Since by construction the values of W0 and W1 that correspond to the full-cooperation entries are predetermined, one can infer nothing about the actual benefit from full-cooperation on their basis. On the other hand, if one is willing to accept the optimality of 25% OECD abatement and the separability assumption employed in simulating the Lindahl equilibrium, one can infer from the entries corresponding to W2 that the benefits from full-cooperation to OECD regions are considerable. Nevertheless, relative to whatever benchmarking is used for the full-cooperation configuration, the rest of the entries are valid payoffs for assessing the regional incentives for cooperation and defection.

For the W0 and W1 games, except for AUS, the net benefit from not-cooperating for each of the OECD regions, given that the other four regions cooperate, is greater than the corresponding net benefit from cooperating. This also true for JPN, CAN, and E_U in the game corresponding to W2. Hence, by the definition of Nash equilibrium, full-cooperation is certainly not an equilibrium in either of the three games, and accordingly none of these games is a coordination one. Next, by looking at the individual region payoff columns that correspond to its strategies C and N, we see in the W0 and W1 games that the payoffs from N strictly exceed those from C for all regions except AUS. But by the concept of iterative dominance, the relevant payoffs facing AUS would then be -1.2,-1.1 for C, and 0,0 for N. Then the only equilibria for the W0 and the W1 games are the iteratively dominant non-cooperation outcomes. In other words, technically, the games corresponding to W0 and W1 belong to the Prisoner's dilemma class. By applying similar analysis to the W2 game, we see that cooperation is a dominant strategy for USA, whereas non-cooperation is the dominant strategy for JPN, CAN, and E_U. Yet, by the concept of iterative dominance AUS would then be facing the payoff of 2.5 from her C strategy and 3 from her N strategy. Therefore, the unique equilibrium of this game is the iterative dominance outcomes of cooperation for USA and defection for all others, i.e., according to this game, we should expect a unilateral USA leadership.[12] To rank this outcome relative to the full-cooperation one, the payoffs indicate that each region, except E_U, strictly prefers the full-cooperation outcome. Nevertheless, by invoking the Kaldor criterion, the sum of the net benefits from the move to full-cooperation for the benefiting regions exceeds the E_U's loss from the move by 42.7 billion dollars.

With respect to the feasibility of a stable (or a self-enforcing) sub-coalition, the preceding analysis suggests the prompt answer that the maximum size of such a sub-coalition is zero for the W0 and W1 games and 1 for W2 game. Alternatively, one may ask the weaker version: Whether smaller beneficial sub-coalitions are feasible, and what is the size of the smallest such sub-coalition?[13] By verifying that the sub-coalition must be beneficial for every member, the smallest size that support such a sub-coalition is 5 for the W0-game (i.e. the minimum beneficial size is full cooperation), 3 for the W1-game (namely JPN, USA, and E_U), and 1 for the W2-game. Ignoring the W2 case, this suggests that a beneficial OECD sub-coalition must include at least JPN, USA, and E_U.

A final piece of inference on the payoffs in Table 3 is the observation that defection incentives among the big OECD members (i.e. JPN, USA, and E_U) appear to be pairwise uncorrelated. This is important for the later repeated game analysis, because it precludes the possibility of effective coalitions among defectors.

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[12] For the 50%-cutback benefit calibration in Piggott et al, their results suggest that both of E_U and North America have incentive to lead a 25% cutback (nevertheless, in their context, such a leadership may not be supported in an equilibrium i.e. may not be a best response.)
[13] In Piggott et al's language, these are the smallest coalitions for which the 25%-cut is *a consensus emission reduction.*

Given the discussed outcomes of the games corresponding to the grandfathering + permit scenario, the natural question is whether these outcomes depend on the assumed institution type and the quota allocation rule. Of particular interest is whether the Prisoner's dilemma outcomes of W0 and the W1 games would be modified by changing the institution type and/or the quota allocation rule. In pursuing answers to these questions, payoffs were simulated for the equal per-capita cost allocation with uniform permit market and for the grandfathering allocation with regional permit markets. Furthermore, to allow for the effect of the benefit method, W0 is used for the former and W1 for the latter. The resulting payoff matrices are shown on Table D1 and Table D2 in Appendix D. Not surprisingly, by the same iterative dominance method, the unique equilibria of these two games are also the mutual non-cooperation strategies.

The other question is whether the mutual defection outcomes are in fact the by-product of the low abatement benefits assumed in calibrating *W0* and *W1*. To show that these outcomes are robust with respect to the size of the regional benefits from abatement, we have simulated payoffs and computed the one-shot game equilibria for per-capita benefit estimates that correspond to 50% and 100% markups on the regional per-capita welfare costs. The benefit estimates and the equilibrium strategies in these two games, along with those in the W0-game, are shown on Table 4.

The results on Table(4) are self-explanatory and clearly underscore the robustness of the mutual defection equilibrium in the one-shot OECD coalition game.

To sum up, the likely equilibrium of the OECD one shot coalition game seems to be the unavoidable Prisoner's dilemma mutual defection outcome. Under the current

Table 4. The OECD One-Shot Game: Sensitivity to the Benefit Estimates

	5% Net-benefit(i.e.W0)			50% Net-benefit			100% Net-benefit		
	Gross Benefit		Equ. Stra tegy	Gross Benefit		Equ. Stra tegy	Gross Benefit		Equ Stra tegy
region	per-capita ($)	gdp (%)		per-capita ($)	gdp (%)		per-capita ($)	gdp (%)	
AUS	75.6	0.53	N	108.0	0.75	N	144.0	1.0	N
JPN	117.6	0.42	N	168.0	0.60	N	244.0	0.8	N
CAN	163.8	0.84	N	234.0	1.20	N	302.0	1.6	N
USA	149.1	0.63	N	213.0	0.90	N	284.0	1.2	C
E_U	171.2	0.63	N	244.5	0.90	N	326.0	1.2	N

Key:
Strategy: C Cooperate, N Not-cooperate; Scenario: Grandfathering+permit

institutional arrangements and in the absence of a regional sovereign institution that enforces commitments, a stable and beneficial carbon coalition among OECD regions is, therefore, unlikely. In the next section we motivate and present a repeated trade-environment framework, within which we show that a stable OECD coalition may be achieved.

5. Repeated Game Analysis: Trade-Environment Interface and Subgame-Perfection of the OECD CO_2-Coalition

In this section we first present the infinitely repeated OECD coalition game and show that full-cooperation in such context is unlikely to be a subgame-perfect equilibrium outcome. Next, we motivate the connected trade-environment framework and present two constructs: The first is an infinitely repeated trade-CO_2 interconnected game and the second is a finitely repeated one. In the first construct, we show that cooperation in the full OECD coalition can be an equilibrium outcome if trade is included in the game. In the second, we show that cooperation in the full OECD coalition can also be supported as an equilibrium outcome in the finite horizon and for relatively impatient players if suitable trade instruments are designed.

Note that for the remaining analysis in the paper, the focus shall be confined to the W0 with grandfathering +permit case.

5.1 The Infinitely Repeated OECD CO_2-Game

Suppose the W0-game on Table 3 is to be repeated infinitely with outcomes from the previous t-1 periods, $\{t\}_0^{\infty}$, being observed before the start of period t. Consider, for each OECD region, the following trigger strategy:

Play C in the first period. In period t, play C if every OECD region has played C in each of the t-1 previous periods; otherwise, play N.

The regional minimum discount factors for which this trigger strategy constitutes a subgame-perfect Nash equilibrium of the infinitely repeated game, together with the regional payoffs from full cooperation, unilateral defection, and mutual defections are reported on Table 5.[14]

It is evident from the table results that (especially for JPN, CAN, and E_U) the minimum discount factors needed to support an OECD full compliance are higher than those to be expected for the current OECD policy makers. Therefore, the threat that every one defects does not hold a strong enough punishment to deter OECD regions from free riding. Then an agreement that had solely hinged on this solution concept might not have codified more than the status quo of no action.

Table 5. Subgame-Perfection in the Infinitely Repeated OECD CO_2-Game

Region	Payoffs(b$) Full Cooperation	Unilateral Defection	Mutual Defections	Minimum Discount Factor [δ_r]

[14] The regional discount factor δ_r is computed from the subgame-perfection condition:

$$\frac{1}{1-\delta_r}\left[Full-cooperation\ payoff\right] \geq \left[unilateral-defection\ \ payoff\right] + \frac{\delta_r}{1-\delta_r}\left[mutual-defection\ \ payoff\right]$$

AUS	0.1	0.0	0	SE
JPN	0.7	20.2	0	0.97
CAN	0.2	2.8	0	0.93
USA	1.8	13.5	0	0.87
E_U	2.3	35.4	0	0.94

Key:
SE: cooperation is self-enforcing(best response).
Scenario: W0 with grandfathering+permit.

5.2 The Repeated Trade-Environment Connected Framework

5.2.1 Motivation

The presence of global trade interaction and the subtleties of the global trade-environment interface[15] avail the players additional incentives to coordinate their actions as well as instruments to commit themselves to cooperation. The sub-optimality of the present global trading system[16], the additional distortions injected by the presence of CO_2 taxes, and their associated repercussions on competitiveness of energy-based industries and international trade flows reinforce the need for further coordination of trade policies among the colluding parties. On the other hand, to set a "level playing field", players may be willing to take countervailing trade measures against defectors to limit the scope for environment trade-leakage and to punish free riding.

Motivated by the need of OECD regions to jointly coordinate their environmental actions with their trade policies, we think of a trade-CO_2 interconnected setup in which OECD regions negotiate a 25% reduction of tariffs on energy intensive imports along with the 25% CO_2-cutback. Within this setup, by pooling the players' environment and trade

[15] A detailed exposition on global warming - trade interface and the scope for an environment-based countervailing trade measures is provided in Whalley(1991) and Babiker, Maskus, and Rutherford(1997).
[16] The recent Uruguay reforms are primarily meant to address this issue; nonetheless, they do not exhaust the room for further beneficial trade coordination.

incentives in one game, outcomes better than those in the isolated environment game may be achievable (see Bernheim and Whinston, 1990.)

Alternatively, we may think of a double-instruments trade strategy being added to the original CO_2-game in such a way that during the punishment regime cooperation is rewarded by reduction of trade barriers and defection is punished by countervailing trade measures. Within such a context, our objective would be to characterize the extent of rewards and punishments needed to subgame-perfect the coalition in a finite number of trade-environment repeated interactions.

We consider these two constructs in turn:

5.2.2 The Infinitely Repeated OECD Trade-CO_2 Interconnected Game

Suppose OECD regions agree to play the W0-game on Table 3, in which each region has the strategies {C,N}, jointly with a simultaneous move trade game, in which each OECD region has the strategies {L,H}. L says lower tariffs on energy intensive imports by 25% and H says not lower them. The one-shot trade-CO_2 inter-connected game is then a simultaneous move game in which each OECD region has the strategies {CL, CH, NL, NH}, where in the status quo NH is being played by all regions.

Now, suppose this static interconnected game is to be repeated infinitely with outcomes from all previous t-1 periods observed before the beginning of period t. Next, for each OECD region, consider the trigger strategy:

Play CL in the first period. In period t, play CL if every OECD region has played CL in each of the t-1 previous periods; otherwise, play NH.

The regional minimum discount factors for which this trigger strategy constitutes a subgame-perfect Nash equilibrium of the infinitely repeated trade-CO_2 game together with the regional payoffs from full-cooperation, unilateral defection, and mutual defection are reported on Table 6. Where full cooperation means every region playing CL, mutual defection means every region playing NH, and where the payoffs for unilateral defection are the maximum payoffs from unilaterally defecting in either or both the trade and the environment.

Table 6. Subgame-Perfection in the Infinitely Repeated OECD Trade-CO_2Game

Region	Payoffs(b$) Full Cooperation	Unilateral Defection	Mutual Defections	Minimum Discount Factor [δ_r]
AUS	1.2	1.1	0	SE
JPN	24.7	20.0	0	SE
CAN	0.5	2.3	0	0.78
USA	6.0	17.4	0	0.66
E_U	7.9	35.3	0	0.78

Key:
SE: cooperation is self-enforcing(best response).
Scenario: W0 with grandfathering+permit.

It is obvious that the minimum regional discount factors on Table 6 are on average 20% lower than those on Table 5. In particular, with the presence of trade coordination, Table 6 shows that environmental compliance is a best response for both AUS and JPN. Hence, this suggests that stronger subgame-perfection of the OECD carbon abatement coalition is achievable if trade coordination is invoked within the game.

5.2.3 The Finitely Repeated OECD Trade-CO_2 Connected Game

Suppose the OECD regions agree to condition the play of the original W0-game on a simultaneous move trade game, in which each region has the strategies {R,S,P}; where R says reduce tariffs on energy intensive imports by a given %, S says play the status quo tariffs, and P says play a given hard (punishment) tariff. We interpret the punishment tariff to be a countervailing tariff on the CO_2 content of the defecting region exports to the given region.

Define the finitely repeated trade-CO_2 game construct as one in which the W0-game and the trade game are played simultaneously in each stage with the outcomes of the previous stage being observed before the beginning of the current stage. Let T be the number of stages in the repeated game. Within this construct, our interest is to characterize a subgame-perfect outcome in which cooperation on the CO_2-abatement is played by every OECD region in each stage of the game.

Assume T is sufficiently large, and consider each OECD region adopting the following "3-instruments" strategy:

Play C and S in the first stage. From the second stage on, play C and S if every region has played C and S in all the previous stages; otherwise, in addition to playing C, play R with those who have played C and S in all previous stages and play P with those who haven't.

Notice the two special properties of this strategy: (i) The trade instruments R and P are to be played only when environmental defection is observed, i.e. they are essentially enforcement mechanisms. (ii) The mutual environmental defection is not invoked during the punishment regime, i.e., it avoids the implausible threat that every one defects.

Depending on our earlier observation that an effective coalition among the defectors is unlikely, only the cases of unilateral defections are considered. Our objective is, then, to determine for each OECD region the size of the trade instruments associated with R and P, and the horizon length such that playing the preceding strategy by every region constitutes a subgame-perfect Nash equilibrium of the finitely repeated game.

The countervailing tariff used in the numerical simulations is an endogenous tax on the CO_2-content of the defecting region exports to the remaining regions in the coalition. In turn, the carbon content is measured by the per-dollar CO_2 coefficients from the inverse input-output carbon computation, the details of which are described in Rutherford and

Babiker (1997). We use a 10% discount rate for computing the regional horizon length. The simulation results for this exercise are summarized on Table 7.

Column (1) displays the percentage change in the defecting region's energy intensive exports (relative to their full-cooperation level) to the colluding regions. These are essentially the trade-leakage gains from free riding. As is apparent from "Def" entry, in the absence of punishment, these gains are considerable. In contrast, with the countervailing carbon tariff, these free rider gains are turned into losses (entry "Pun"). Nevertheless, for a large region such as E_U, the credibility of the punishment may call for a complete ban on its EIS exports to the coalition regions.

Table 7. Subgame-Perfection of OECD Coalition in the repeated Trade-CO_2 Game

Def region	(1) %change in EIS exports		(2) Defector's Payoff (b$)			(3) Punishment regime		
	Def	Pun	Def	Cop	Pun	btax	tariff red(%)	yr
AUS	75	-70	0.0	0.1	-0.9	1	10	1
JPN	7	-66	20.2	0.7	-2.9	2	50	11
CAN	33	-31	2.8	0.2	-7.8	1	25	2
USA	34	-65	13.5	1.8	-15.9	1	75	2
E_U	12	-99	35.4	2.3	-2.1	6	90	20

key:
- EIS Energy intensive goods,
- Def Unilateral defection regime,
- Cop Cooperation regime,
- Pun Cooperating and punishing the defector regime,
- btax Border CO2 tax as a multiple of the coalition permit price,
- tariff red % removal of tariff on EIS imports among colluding members,
- yr the required length of the region horizon

Scenario: Grandfathering+permit, Benefit method W0

Column (2) reports for each region the payoffs from unilateral defection without punishment, full-cooperation, and unilateral defection with punishment. For full-cooperation to be subgame-perfect, the present value of the payoffs from cooperation for each member must be at least as high as that from unilateral defection followed by the punishment. For a 10% discount rate, entry "yr" of column (3) shows the region's minimum horizon needed to satisfy subgame-perfection of full-cooperation. As evident from the table, these horizons range from as low as 1 year for AUS to as high as 20 years for E_U, suggesting that, given the punishment terms, a typical OECD decision maker, with a 20-years planning horizon and who uses a 10% discount rate, would have no incentive to free ride. The "btax" entry in column (3) reports the per-ton border carbon tax expressed as a multiple of the corresponding coalition permit price. With exception to JPN and E_U, the results imply that an equal-foot treatment on trans-boundary carbon is a sufficient deterrent to free riding. The needed tariff reductions among the remaining parties in the coalition such that continuing cooperation and punishing the defector are best responses for each one, are in turn shown under entry "tariff red(%)" on column (3). The reported figures suggest that tariff reductions in the range 10-90% could be called for if defection were to occur.

Summing up, the results on Table 7 suggest that full cooperation among OECD regions can be fostered within the finite horizon for relatively impatient policy makers if suitable trade reward and punishment instruments are designed, yet, the required reward and punishment patterns may prove to be quite stringent as they might amount to a complete ban on the imports from the defecting region[17]. Nevertheless, as we shall see in the following section, by expanding the coalition to include some of the non OECD regions, these requirements can be reduced significantly.

6. The Expanded CO_2-Abatement Coalition

[17] Note that if we were to disaggregate the E_U region, these requirements could be quite reduced. Yet it is more plausible that the European countries will jointly coordinate their actions, and therefore it is more defensible to treat them as one player in the carbon abatement game.

The analysis in this section follows Carraro and Siniscalo(1993) analysis of coalition expansion through self-financed transfers. Specifically, we portray a scenario in which OECD approaches other regions through take-or-leave offers to join the OECD CO_2-abatement coalition. The offer specifies a given level of CO_2-abatement in return for a full access to the coalition permit market. The additional CO_2-abatement provided by the new members is netted off against the OECD abatement obligation so that the global reduction target remains the same. The simulated offers are restricted to meet the conditions in Carraro and Siniscalo study, namely:

(i) each OECD region must be at least as better off as without the entry of the last new member. This is made even more stronger by imposing the requirement that the welfare cost (EV%) of each OECD region is not greater than without the additional member.

(ii) with a zero marginal valuation for the environment provision, each new member must be at least as well off as without joining the coalition.

(iii) in the case of sequential offers, each of the old non OECD members in the coalition must be at least as well off by remaining in the coalition after the last entry as by withdrawing from it.

To reduce the transaction costs associated with the expansion and to make the coalition size manageable, a 5% minimum abatement rule is added to the preceding requirements. The simulation results of such an environment have revealed that simultaneous or sequential offers of 10% for the Former Soviet Union (FSU) and 5% for each of China (CHN) and India (IDI) exhaust the mutual benefits from a further expansion of the coalition. With such an expanded coalition the required OECD abatement to meet the global target falls from 25% to 20%. In addition, the leakage rate is found to fall from 11.5% to 2.9%, implying an increase in the actual (net) global abatement from 10.6% to

11.3%. A summary of the simulation results for the original and the expanded coalition is provided on Table 8.

Table 8. Self-Financed Expansion of the Carbon Coalition

Region	(1) OECD Coalition			(2) The Expanded Coalition			(3) EV% for Further Expansion by 5% Abatement Rule
	EV%	W0 (b$)	Ctrade (b$)	EV%	W0 (b$)	Ctrade (b$)	
AUS	-0.7	0.1	2.9	-0.7	0.3	-0.3	
JPN	-0.7	0.7	-3.5	-0.1	13.4	-2.9	
CAN	-1.3	0.2	1.8	-0.5	3.2	-0.9	
USA	-0.9	1.8	15.1	-0.4	26.5	-9.3	
E_U	-1.0	2.3	-16.3	-0.3	40.8	-8.8	
CHN	-0.5				0.1		9.4
IDI	-0.4				0.5		1.3
FSU	-0.1				1.0		11.5
KOR	0.4				0.4		0.1
IDN	-0.9				-0.4		-0.4
MYS	1.3				0.2		-0.6
PHL	-0.4				-0.1		-0.3
SGP	-2.2				-0.4		-0.4
THA	-0.9				-0.3		-0.4
HKG	-1.1				-0.2		-0.3
TWN	0.4				0.2		0.0
MEX	-0.6				-0.2		-0.3
ARG	-0.3				-0.1		-0.1
BRA	-0.0				0.1		0.0
CHL	0.7				0.2		0.2
RSM	-1.5				-0.5		-0.4
MEA	-3.3				-1.3		-1.3
SSA	-1.2				-0.5		-0.7
ROW	-0.4				-0.2		

key:
Ctrade CO2 trade,
EV% % change in Hecksian welfare index
Scenario Grandfathering(OECD)+permit

Column (1) displays the original OECD coalition results, column (2) displays the expanded coalition results, and column (3) reports the welfare gains for each of the other regions from joining the expanded coalition. A comparison of the entries on columns (1) and (2) suggest the feasibility of huge welfare gains for the OECD regions from expanding the coalition. These welfare gains are essentially the result of the cheaper off shore abatement option, the smaller cut backs needed to meet the target, and the lower leakage rate associated with the expanded coalition. On the other hand, the new coalition members (CHN, IDI, and FSU) are clearly better off with the self-financed scheme and the opportunity to trade in the coalition permit market. In effect, Table 8 marks a shift in the CO_2-trade from within the OECD to these new members, and indicates a total of 22 billion dollars for the latter from this trade. In addition, all other regions, with exception to those who benefit from the trade leakage, seem to realize considerable gains from the coalition expansion. In particular, the welfare costs in the oil exporting countries appear to fall by more than 100% following the expansion of the coalition. This later result is mainly due to the restoration of the international oil market following the weakening of the constraint on fossil fuel demand in OECD regions. Accordingly, this may suggest a willingness on the part of OPEC countries to finance even a further expansion of the coalition. Finally, column (3) shows that no other region stands to gain from joining the coalition, which in turn completes the stability of the expanded coalition.

Thus, the analysis so far suggests that a beneficial, stable, and manageable self-financed expansion of the CO_2-coalition is feasible. Nevertheless, the stability of such an expanded coalition implicitly hinged upon the punishment and reward scheme that gave the subgame-perfection attribute for the initial OECD coalition. Therefore, we need to characterize, in a similar way, a trade scheme of punishment and reward that supports the subgame-perfection of the expanded coalition. The analyses of such a scheme are provided on Table 9, which shows the same entries on table 7 with the addition of 3 rows and a column to accommodate the new coalition members.

Table 9. Subgame-Perfection of the Expanded Coalition in the repeated Trade-CO_2 Game

Def region	(1) Defector's Payoff (b$)			(2) Non OECD Payoffs (b$)			(3) Punishment regime		
	Def	Cop	Pun	FSU	CHN	IDI	btax	tariff red(%)	yr
AUS	1.6	0.3	-0.5	3.4	1.0	1.6	1	10	2
JPN	14.1	13.4	12.7	3.4	0.5	1.8	1	20	2
CAN	4.8	3.2	1.0	3.4	1.0	1.6	1	10	2
USA	24.3	26.5	NA						
E_U	37.9	40.8	NA						
FSU	-0.3	3.4	NA						
CHN	-1.0	0.2	NA						
IDI	-0.5	0.8	NA						

key: Def Unilateral defection regime,
Cop Cooperation regime,
Pun Cooperating and punishing the defector regime,
btax Border CO2 tax as a multiple of the coalition permit price,
tariff red % removal of tariff on EIS imports among colluding members,
yr. The required length of the region horizon,

NA Not applicable.
Scenario: Grandfathering(OECD)+permit, Benefit method is W0

Note that for FSU, CHN, and IDI the computation of W0 assumes the marginal benefit from abatement is zero.

Provided that all OECD regions have the same old marginal valuations, column (1) suggests that the gaps between the full-cooperation outcomes and the unilateral defection outcomes are now very much narrowed for almost all OECD regions. In particular, for both USA and E_U, cooperation is now a self-enforcing strategy, i.e., a best response. Furthermore, by the definition of the expanded coalition, cooperation is a best response for each of the new coalition members and therefore is also self-enforcing for them.

On the other hand, for a 10% discount rate, column (3) indicates that a threat of a border carbon tax at a rate equivalent to the coalition permit price is sufficient to elevate full cooperation to a subgame perfect outcome within a horizon of only two years. Column (2) ensures that each of the new members is not worse off in the punishment phase. Finally, column (3) indicates that a 20% reduction in tariffs among the regions remaining in the coalition is sufficient to make cooperating and punishing the defector best responses for them. Thus, compared to the exclusively OECD coalition, the requirements to foster full-cooperation in the expanded coalition appear to be quite trivial.

7. Concluding Remarks

This paper has discussed some of the hot issues in the current global warming policy debate such as the design of institutions, the allocation of the abatement responsibilities, and the formation and the expansion of CO_2-abatement coalitions. Specifically, the paper attempted to place the game theoretic analysis on global warming within an empirical context.

The empirical framework used in the paper is a static multi-region, multi-commodity Computable General Equilibrium (CGE) model of the world economy. With respect to institutions design, the simulation results have endorsed the superiority of the uniform permit arrangement, whereas with respect to allocation rules, grandfathering appeared to be the most likely. Nevertheless, irrespective of the institution type or the quota rule and for different benefit estimates, the analysis of the simulated payoffs have indicated that the unique outcome of the one-shot OECD abatement game is the status quo of no action. However, with repetition of the game, the simulation results showed that full-cooperation among OECD regions can be supported as subgame-perfect equilibrium outcome and without invoking the implausible threat of mutual defections provided that appropriate trade punishment and reward instruments are included in the game. Yet, the punishment in some extreme cases might call for a complete ban of energy intensive imports from the defecting region.

The last part of the paper considered a self-financed scheme for expanding the initial OECD coalition in which OECD makes take-or-leave offers to other regions to join the coalition. The simulation results suggested that a beneficial, stable, and manageable self-financed expanded coalition is feasible. In particular, with a 5% minimum abatement offer, the results indicated that the three largest non-OECD emitters will join the coalition, but no other region stands to gain from joining it. Further more, within the context of the expanded coalition, the required trade instruments to support full-cooperation as subgame-perfect outcome within a two years horizon are found to be quite minimal.

APPENDIX A: Fossil Fuel Supply Elasticity

Fossil fuel production levels are determined by the relative price of fuel and domestic output. The production of fuel *f* requires inputs of domestic supply (e.g. labor and intermediate inputs) and a fuel-specific factor which can thought of as a sector-specific resource. The calibrated production function has the form:

$$S_{rf} = \bar{S}_{rf}\left[\gamma_{rf}\left(\frac{R_{rf}}{\bar{R}_{rf}}\right)^{\rho_{rf}} + (1-\gamma_{rf})\left(\frac{X_{rf}}{\bar{X}_{rf}}\right)^{\rho_{rf}}\right]^{1/\rho_{rf}}$$

, where the variables with the

"bar" represent the benchmark flows.

Due to the existence of a specific factor, energy supplies are effectively determined by the domestic prices. The value of the elasticity of substitution between inputs *X* and the resource (σ_{rf}) determines the price elasticity of supply (η_{rf}) at the reference point, according to the relation:

$$\eta_{rf} = \sigma_{rf} \frac{1-\gamma_{rf}}{\gamma_{rf}}$$

Where, $$\sigma_{rf} = \frac{1}{1-\rho_{rf}}$$

APPENDIX B: The Algebraic Structure of the CGE Model

The model includes two types of production functions: Those for fossil fuels (crude oil, coal, and natural gas), and those for other goods. An index, Y_{ir}, characterizes the level of production for good *i* in region *r*, which (except for crude oil) is allocated to export and domestic markets according to a constant elasticity of transformation function:

$$Y_{ir} = \left[\theta_{ir} \left(\frac{D_{ir}}{\overline{\overline{D}}_{ir}} \right)^{\eta} + (1-\theta_{ir}) \left(\frac{X_{ir}}{\overline{\overline{X}}_{ir}} \right)^{\eta} \right]^{1/\eta} \qquad \text{(B1)}$$

Production of goods requires inputs of non-energy goods, energy-goods (oil, coal, gas, and electricity), and primary factors (labor, capital, and land). At the top level, non-energy goods and a constant-elasticity composite of primary factors and energy enter in fixed proportions:

$$Y_{ir} = \min\left[\min_j \left\{ \frac{x_{jir}}{\bar{x}_{jir}} \right\}, \left(\alpha_{ir} E_{ir}^{\rho_E} + (1-\alpha_{ir}) V_{ir}^{\rho_E} \right)^{1/\rho_E} \right] \qquad \text{(B2)}$$

in which the exponent determines the elasticity of substitution between primary factors and energy, $\sigma_E = 1/(1-\rho_E)$. Within this function, composite energy E_{ir} is in turn a nested constant-elasticity composite of electric and non-electric energy inputs, and V_{ir} is a Cobb-Douglas composite of capital, labor, and land. Each fossil fuel input in the non-electric energy aggregate, is in turn a Leontief composite of an energy component and an associated CO_2 component.

The representative consumer in region *r* allocates income across alternative goods to solve:

$$\max \ U_r(c) = \left(\delta \prod_{i \in E} C_{ir}^{(\theta_i \rho_c)} + (1-\delta) \prod_{i \notin E} C_{ir}^{(\theta_i \rho_c)} \right)^{1/\rho_c}$$

$$s.t. \ \sum_i p_{ir} C_{ir} = M_r - p_r^G \overline{G}_r - p_r^I \overline{I}_r \qquad \text{(B3)}$$

in which *E* is the set of energy goods entering final demand (oil, coal, gas, and electricity). Each fossil fuel in *E* is in turn, a fixed proportion composite of an energy and a CO_2 component. δ is the share of the consumption composite, θ_is are the expenditure shares in the corresponding composites, and M_r is region r factor earnings and tax revenue. Final demands for goods and services exhaust income net of expenditures on public goods and final investment, both of which are held constant in model.

Final and intermediate demands are nested CES composites of domestic and imported varieties:

$$C_{ir} = \overline{C}_{ir} \left(\alpha_D \left(\frac{C^D_{ir}}{\overline{C}^D_{ir}} \right)^{\rho_D} + (1-\alpha_D) \left[\sum_{s\_r} \theta_s \left(\frac{C^M_{isr}}{\overline{C}^M_{isr}} \right)^{\gamma} \right]^{\rho_D/\gamma} \right)^{1/\rho_D} \qquad \text{(B4)}$$

Here, the specific choices over domestic and imported demands are made to minimize unit cost (gross of applicable taxes):

$$\min \; p^D_{ir} \; c^D{}_{ir} \; + \; \sum_s \left(\; p^X_{is} \; (1 \; + \; t^X_{isr}) \; + \; \mathsf{f}_{\;isr} \;\; p^T \; \right) (1 + t^M_{isr}) \; c^M{}_{isr}$$

$$s.t. \quad f(c^D{}_{ir} , c^M{}_{isr}) = C_{ir} \qquad \text{(B5)}$$

In this equation, t^X and t^M are export and import taxes, and p^T is the cost of international transportation services.

APPENDIX C: The Mixed Complimentarity Formulation (MCP)

Data Definition and Model Parameters:

a) Sets:

I,i,j	Commodity set (13 commodities)
N,n	Non-energy goods (8 commodities)
E,e	Energy goods (5 commodities)
R,r,s	Regions (26 regions)
F,f	Factor inputs (Land, Labor, Capital)

b) Benchmark Commodity Taxes and Prices:

$ty_{i,r}$	Output tax
$ti_{j,i,r}$	Intermediate input tax
$tx_{i,s,r}$	Export tax rate
$tm_{i,s,r}$	Import tariff rate
$tg_{i,r}$	Tax rate on government consumption
$tc_{i,r}$	Tax rate on private consumption
t_r^{OM}	Tax rate on Crude oil imports
t_r^{OX}	Tax rate on Crude oil exports
$PA0_{j,i,r}$	Reference price of intermediates [=1+$ti_{j,i,r}$]
$PMX0_{i,s,r}$	Reference price of imports [=(1+$tx_{i,s,r}$) (1+$tm_{i,s,r}$)]
$PMT0_{i,s,r}$	Reference price of transport services [=1+$tm_{i,s,r}$]
$PG0_{i,r}$	Reference price of government demand [=1+$tg_{i,r}$]
$PC0_{i,r}$	Reference price of private demand [=1+$tc_{i,r}$]

c) Benchmark value shares:

$\delta^D{}_{i,r}$	Domestic market share of output
$\delta^I{}_{j,i,r}$	Intermediate input share
$\delta^V{}_{N,r}$	Value-added share in non-energy production
$\delta^{SR}{}_{E,r}$	Fossil fuel resource share

$\delta^{OM}{}_{r}$	Merchandise share in Crude oil imports
$\delta^{G}{}_{r}$	Non-energy share in government demand
$\delta^{C}{}_{r}$	Non-energy share in private demand
$\theta^{V}{}_{f,i,r}$	Factor demand share in non-energy production
$\theta^{G}{}_{i,r}$	Government consumption share
$\theta^{C}{}_{i,r}$	Private consumption share
$\theta^{T}{}_{i,r}$	Intermediate demand share in transport
$\gamma_{f,E,r}$	Factor demand shares in energy production
$\gamma_{j,E,r}$	Intermediate demand shares in energy production
$\alpha_{i,r}$	Domestic production share in Armington aggregation
$\beta^{M}{}_{i,s,r}$	Import shares across regions
$\beta^{x}{}_{i,s,r}$	Merchandise component of imports

d) Elasticities and other parameters:

σ_t	Domestic-Export transformation elasticity
σ_V	Value-added -Energy substitution elasticity
$\sigma_{e,r}$	Elasticity of substitution in energy production
σ_D	Armington substitution elasticity
σ_M	Substitution elasticity across imports origin
σ_G	Government Energy-Non-energy substitution elasticity
σ_C	Private Energy-Non-energy substitution elasticity
$G0_r$	Benchmark government provision
$FS0_{f,r}$	Benchmark factor supplies
$RS0_{e,r}$	Benchmark supply of energy resource
$Invest_{i,r}$	Benchmark investment
$Bopdef_r$	Benchmark balance of payment deficit
$CO_{e,r}$	Carbon coefficient (kilogram/$)
$Carblim_r$	Carbon emissions quota

Model Declarations:

Variables

C_r	Private consumption
G_r	Government consumption
$Y_{i,r}$	Aggregate production
$M_{i,r}$	Import aggregation
$A_{i,r}$	Armington supply
$Oilm_{,r}$	Crude oil imports
$Oilx_{,r}$	Crude oil exports
YT	International transport service
$CARB_r$	Regional carbon emissions (billion tons)
$PY_{i,r}$	Price index of aggregate production
$PD_{i,r}$	Price index of production for domestic market

$PX_{i,r}$	Price index of production for exports
$PM_{i,r}$	Price index of aggregate imports
$PEV_{i,r}$	Price index of value added - energy aggregate
$PA_{i,r}$	Price index of Armington supply
$PF_{f,r}$	Price index of factor inputs
$PR_{e,r}$	Rent from energy-specific resource
PC_r	Price index of aggregate private consumption
PG_r	Price index of aggregate public provision
PT	Price index of international transport services
Pcrude	International price of crude oil
Pcarb	Carbon permit price
$Income_r$	Regional income

Equations

PRF_C(R)	Private consumption zero-profit
PRF_G(R)	Public provision zero-profit
PRF_Y(I,R)	Aggregate Output zero-profit
PRF_M(I,R)	Import aggregation zero-profit
PRF_A(I,R)	Armington aggregation zero-profit
PRF_YT	Transport zero-profit
PRF_OM(R)	Import of Crude oil zero-profit
PRF_OX(R)	Export of Crude oil zero-profit
DEF_PY(I,R)	Definition of aggregate production cost
DEF_PEV(I,R)	Definition of energy-nonenergy price index
MKT_PC(R)	Private consumption income-expenditure balance
MKT_PG(R)	Public provision
MKT_PD(I,R)	Clearance of Domestic market
MKT_PX(I,R)	Clearance of Exports market
MKT_PM(I,R)	Clearance of Imports market
MKT_PA(I,R)	Clearance for Armington supply
MKT_PF(F,R)	Clearance of Factor market
MKT_PR(E,R)	Clearance of Energy resource market
MKT_PT	Clearance of international transport market
MKT_CRUDE	Clearance of international Crude oil market
MKT_PCRB	Constraint on carbon emissions
CARB_DEF(R)	Regional carbon emissions
INC_RA(R)	Definition of regional income

Model Equations:

* Zero-Profit conditions and definitions of unit cost functions:

DEF_PY(i,r)..

$$PY_{i,r} = \left[\delta^{D}_{i,r}\, PD_{i,r}^{1+\sigma_t} + (1-\delta^{D}_{i,r})\, PX_{i,r}^{1+\sigma_t}\right]^{1/(1+\sigma_t)}$$

DEF_PEV(N,r)..

$$PEV_{N,r} = \left[\delta^{V}_{N,r} \left(\prod_f PF_{f,r}^{\theta^{V}_{f,N,r}} \right)^{1-\sigma_V} + (1-\delta^{V}_{N,r}) \left(\sum_e \delta^{I}_{e,N,r} \frac{PA_{e,r}(1+ti_{e,N,r}) + CO_{e,r}\, Pcarb}{PA0_{e,r}} \right)^{1-\sigma_V} \right]^{1/(1-\sigma_V)}$$

DEF_PEV(E,r)..

$$PEV_{E,r} = \left[\sum_f \gamma_{f,E,r} PF_{f,r} + \sum_j \gamma_{j,E,r} \frac{PA_{j,r}(1+ti_{j,E,r}) + CO_{j,r}\, Pcarb}{PA0_{j,r}} \right]$$

PRF_Y(N,r)..

$$\sum_n \delta^{I}_{n,N,r} \frac{PA_{n,r}(1+ti_{n,N,r})}{PA0_{n,r}} + (1-\sum_n \delta^{I}_{n,N,r})\, PEV_{N,r} = (1-ty_{N,r})\, PY_{N,r}$$

PRF_Y(E,r)..

$$\left[\delta^{SR}_{E,r} PR_{E,r}^{1-\sigma_{E,r}} + (1-\delta^{SR}_{E,r})\, PEV_{E,r}^{1-\sigma_{E,r}} \right]^{1/(1-\sigma_{E,r})} = (1-ty_{E,r})\, PY_{E,r}$$

PRF_OM(r)..

$$(\delta^{OM}_{r}\, Pcrude + (1-\delta^{OM}_{r}) PT)(1+t^{OM}_{r}) = PD_{CRU,r}$$

PRF_OX(r)..

$$PD_{CRU,r}(1+t^{OX}_{r}) = Pcrude$$

PRF_A(i,r)..

$$\left[\alpha_{i,r} PD_{i,r}^{1-\sigma_D} + (1-\alpha_{i,r})\, PM_{i,r}^{1-\sigma_D} \right]^{1/(1-\sigma_D)} = PA_{i,r}$$

PRF_M(i,r)..

$$\left[\sum_s \beta^{M}_{i,s,r} \left\{ \beta^{X}_{i,s,r} \frac{PX_{i,s}(1+tx_{i,s,r})(1+tm_{i,s,r})}{PMX0_{i,s,r}} + (1-\beta^{X}_{i,s,r}) \frac{PT(1+tm_{i,s,r})}{PMT0_{i,s,r}} \right\}^{1-\sigma_M} \right]^{1/(1-\sigma_M)} = PM_{i,r}$$

PRF_G(r)..

$$\left[\delta^{G}_{r} \left(\prod_n \left(\frac{PA_{n,r}(1+tg_{n,r})}{PG0_{n,r}} \right)^{\theta^{G}_{n,r}} \right)^{1-\sigma_G} + (1-\delta^{G}_{r}) \left(\prod_e \left(\frac{PA_{e,r}(1+tg_{e,r}) + CO_{e,r}\, Pcarb}{PG0_{e,r}} \right)^{\theta^{G}_{e,r}} \right)^{1-\sigma_G} \right]^{1/(1-\sigma_G)} = PG_r$$

PRF_C(r)..

$$\left[\delta_r^C\left(\prod_n\left(\frac{PA_{n,r}(1+tc_{n,r})}{PC0_{n,r}}\right)^{\theta^C_{n,r}}\right)^{1-\sigma_C} + (1-\delta_r^C)\left(\prod_e\left(\frac{PA_{e,r}(1+tc_{e,r})+CO_{e,r}\,Pcarb}{PC0_{e,r}}\right)^{\theta^C_{e,r}}\right)^{1-\sigma_C}\right]^{1/(1-\sigma_C)} = PC_r$$

PRF_YT..

$$\prod_{i,r} PD_{i,r}^{\theta^T_{i,r}} = PT$$

* Market clearing and income-expenditure balance:

MKT_PD(i,r)..

$$\delta^D_{i,r} Y_{i,r}\left(\frac{PD_{i,r}}{PY_{i,r}}\right)^{\sigma_t} = \alpha_{i,r} A_{i,r}\left(\frac{PA_{i,r}}{PD_{i,r}}\right)^{\sigma_D} + \theta^T_{i,r}\, YT \frac{PT}{PD_{i,r}} + Invest_{i,r}$$

MKT_PX(i,r)..

$$(1-\delta^D_{i,r})Y_{i,r}\left(\frac{PX_{i,r}}{PY_{i,r}}\right)^{\sigma_t} = \sum_s M_{i,s}\,\beta^M_{i,r,s}\frac{\beta^X_{i,r,s}}{PMX0_{i,r,s}}\, PM_{i,s}^{\sigma_M}\left[\beta^X_{i,r,s}PX_{i,r} + (1-\beta^X_{i,r,s})PT\right]^{-\sigma_M}$$

MKT_PM(i,r)..

$$M_{i,r} = (1-\alpha_{i,r})\, A_{i,r}\left[\frac{PA_{i,r}}{PM_{i,r}}\right]^{\sigma_D}$$

MKT_PT..

$$YT = \sum_i\sum_r \sum_s M_{i,s}\,\beta^M_{i,r,s}\frac{(1-\beta^X_{i,r,s})}{PMT0_{i,r,s}}\, PM_{i,s}^{\sigma_M}\left[\beta^X_{i,r,s}PX_{i,r}+(1-\beta^X_{i,r,s})PT\right]^{-\sigma_M} + \sum_r(1-\delta^{OM}_r)Oilm_r$$

MKT_PA(N,r)..

$$A_{N,r} = \sum_n \delta^I_{N,n,r}Y_{n,r} + \sum_e(1-\delta^{SR}_{e,r})\frac{\gamma_{N,e,r}}{PA0_{N,r}}\left[\frac{(1-ty_{e,r})PY_{e,r}}{PEV_{e,r}}\right]^{\sigma_{e,r}} Y_{e,r} +$$

$$\delta^G_r\,\theta^G_{N,r}\left[\prod_n PA_{n,r}^{\theta^G_{n,r}}\right]^{1-\sigma_G}\frac{PG_r^{\sigma_G}}{PA_{N,r}(1+tg_{N,r})}G_r + \delta^C_r\,\theta^C_{N,r}\left[\prod_n PA_{n,r}^{\theta^C_{n,r}}\right]^{1-\sigma_C}\frac{PC_r^{\sigma_C}}{PA_{N,r}(1+tc_{N,r})}C_r$$

MKT_PA(E,r)..

$$A_{E,r} = \sum_N\left(1-\sum_n\delta^I_{n,N,r}\right) PEV_{N,r}^{\sigma_V}(1-\delta^V_{N,r})\frac{\delta^I_{E,N,r}}{PA0_{E,r}}Y_{N,r} +$$

$$\sum_e(1-\delta^{SR}_{e,r})\frac{\gamma_{E,e,r}}{PA0_{E,r}}\left[\frac{(1-ty_{e,r})PY_{e,r}}{PEV_{e,r}}\right]^{\sigma_{e,r}}Y_{e,r} +$$

$$(1-\delta_r^G)\theta_{E,r}^G\left[\prod_e\left(\frac{PA_{e,r}(1+tg_{e,r})+CO_{e,r}\,Pcarb}{PG0_{e,r}}\right)^{\theta_{e,r}^G}\right]^{1-\sigma_G}\frac{PG_r^{\sigma_G}}{PA_{E,r}(1+tg_{E,r})}G_r +$$

$$(1-\delta_r^C)\theta_{E,r}^C\left[\prod_e\left(\frac{PA_{e,r}(1+tc_{e,r})+CO_{e,r}\,Pcarb}{PC0_{e,r}}\right)^{\theta_{e,r}^C}\right]^{1-\sigma_C}\frac{PG_r^{\sigma_C}}{PA_{E,r}(1+tc_{E,r})}C_r$$

MKT_PG(r)..

$$G_r = G0_r$$

MKT_Crude..

$$\sum_r\left[Oilx_r - Oilm_r\right] = 0$$

MKT_PF(F,r)..

$$FS0_{F,r} = \sum_N \theta_{F,N,r}^V(1-\sum_n \delta_{n,N,r}^I)\delta_{N,r}^V\left[\prod_f PF_{f,r}^{\theta_{f,N,r}^V}\right]^{1-\sigma_V}\frac{PEV_{N,r}^{\sigma_V}}{PF_{F,r}}Y_{N,r} +$$

$$\sum_E \gamma_{F,E,r}(1-\delta_{E,r}^{SR})\left[\frac{(1-ty_{E,r})PY_{E,r}}{PEV_{E,r}}\right]^{\sigma_{E,r}}Y_{E,r}$$

MKT_PR(e,r)..

$$RS0_{e,r} = \delta_{e,r}^{SR}\left[\frac{(1-ty_{e,r})PY_{e,r}}{PR_{e,r}}\right]^{\sigma_{e,r}}Y_{e,r}$$

MKT_PC(r)..

$$PC_r\, C_r = Income_r$$

INC_RA(r)..

$Income_r = \sum_f PF_{f,r}\, FS0_{f,r} + \sum_e PR_{e,r}\, RS0_{e,r}$ {Factor incomes and resource rents}

$+\, PF_{\text{"lab","USA"}}\, Bopdef_r$ {POB deficit denominated in USA labor price}

$+\sum_i PD_{i,r}\, Invest_{i,r}$ {Investment is fixed exogenously}

$-\, PG_r\, G0_r$ {Lump sum taxes to finance government provision}

$+\, Pcarb\;\; Carb\lim_r$ {Revenues from carbon rights}

* Revenue from output tax:

$$+\sum_i ty_{i,r} Y_{i,r} PY_{i,r}$$

* Revenue from intermediate inputs tax:

$$+\sum_N \sum_n ti_{N,n,r} PA_{N,r} \delta^{I}_{N,n,r} Y_{n,r} + \sum_j \sum_e ti_{j,e,r} PA_{j,r} (1-\delta^{SR}_{e,r}) \frac{\gamma_{j,e,r}}{PA0_{j,r}} \left[\frac{(1-ty_{e,r})PY_{e,r}}{PEV_{e,r}}\right]^{\sigma_{e,r}} Y_{e,r}$$

$$+\sum_E \sum_N ti_{E,N,r} PA_{E,r} (1-\sum_n \delta^{I}_{n,N,r}) PEV^{\sigma_V}_{N,r} (1-\delta^{V}_{N,r}) \frac{\delta^{I}_{E,N,r}}{PA0_{E,r}} Y_{N,r}$$

* Revenue from export tax:

$$+\sum_s \sum_i tx_{i,r,s} PX_{i,r}\ M_{i,s} \beta^{M}_{i,r,s} \frac{\beta^{X}_{i,r,s}}{PMX0_{i,r,s}} PM^{\sigma_M}_{i,s} \left[\beta^{X}_{i,r,s} PX_{i,r} + (1-\beta^{X}_{i,r,s})PT\right]^{-\sigma_M}$$

* Revenue from import tariff:

$$+\sum_s \sum_i (1+tx_{i,s,r}) tm_{i,s,r} PX_{i,s}\ M_{i,r} \beta^{M}_{i,s,r} \frac{\beta^{X}_{i,s,r}}{PMX0_{i,s,r}} PM^{\sigma_M}_{i,r} \left[\beta^{X}_{i,s,r} PX_{i,s} + (1-\beta^{X}_{i,s,r})PT\right]^{-\sigma_M}$$

$$+\sum_s \sum_i tm_{i,s,r} PT\ M_{i,r} \beta^{M}_{i,s,r} \frac{(1-\beta^{X}_{i,s,r})}{PMT0_{i,s,r}} PM^{\sigma_M}_{i,r} \left[\beta^{X}_{i,s,r} PX_{i,s} + (1-\beta^{X}_{i,s,r})PT\right]^{-\sigma_M}$$

* Revenues from taxes on Crude oil trade:

$$+t^{OM} Oilm_r \left[\delta^{OM}_r\ Pcrude + (1-\delta^{OM}_r)PT\right] + t^{OX} Oilx_r PD_{"CRU",r}$$

* Revenue from commodity taxes on government consumption:

$$+\sum_N tg_{N,r} \delta^{G}_r \theta^{G}_{N,r} \left[\prod_n PA_{n,r}^{\theta^{G}_{n,r}}\right]^{1-\sigma_G} \frac{PG_r^{\sigma_G}}{(1+tg_{N,r})} G_r$$

$$+\sum_E tg_{E,r} (1-\delta^{G}_r) \theta^{G}_{E,r} \left[\prod_e \left(\frac{PA_{e,r}(1+tg_{e,r}) + CO_{e,r} Pcarb}{PG0_{e,r}}\right)^{\theta^{G}_{e,r}}\right]^{1-\sigma_G} \frac{PG_r^{\sigma_G}}{(1+tg_{E,r})} G_r$$

* Revenue from commodity taxes on private consumption:

$$+\sum_N tc_{N,r} \delta^{C}_r \theta^{C}_{N,r} \left[\prod_n PA_{n,r}^{\theta^{C}_{n,r}}\right]^{1-\sigma_C} \frac{PC_r^{\sigma_C}}{(1+tc_{N,r})} C_r$$

$$+\sum_E tc_{E,r} (1-\delta^{C}_r) \theta^{C}_{E,r} \left[\prod_e \left(\frac{PA_{e,r}(1+tc_{e,r}) + CO_{e,r} Pcarb}{PC0_{e,r}}\right)^{\theta^{C}_{e,r}}\right]^{1-\sigma_C} \frac{PG_r^{\sigma_C}}{(1+tc_{E,r})} C_r$$

CARB_DEF(r)..

$$CARB_r = \sum_e CO_{e,r} \, A_{e,r}$$

MKT_PCRB..

$$\sum_r Carb\lim_r \geq \sum_r CARB_r$$

Model Definition:

The equilibrium model is defined by associating each zero_profit equation with a dual activity level and each market clearing equation with a dual price level as follows:

Model MCP /PRF_Y.Y, PRF_M.M, PRF_A.A, PRF_YT.YT, PRF_C.C, PRF_G.G, PRF_OM.Oilm, PRF_OX.Oilx, DEF_PY.PY, DEF_PEV.PEV, MKT_PD.PD, MKT_PX.PX, MKT_PA.PA, MKT_PM.PM, MKT_PT.PT, MKT_PF.PF, MKT_PC.PC, MKT_PG.PG, MKT_Crude.Pcrude, MKT_PR.PR, CARB_DEF.CARB, MKT_PCRB.Pcarb, INC_RA.Income/

APPENDIX D: The One-Shot OECD Abatement Coalition Game: Sensitivity to Institution and Quota Rules

Table D1. Payoffs Matrix for the OECD Cost-Sharing Game(b$)

column player	A		J		D		U		E	
row players	JDUE		ADUE		AJUE		AJDE		AJDU	
strategy	C	N	C	N	C	N	C	N	C	N
CCCC	0.2	1.5	0.9	23.8	0.2	2.4	1.8	13.8	2.1	31.6
NCCC	0.2	1.7	-0.4	22.7	0.0	2.2	0.2	12.3	-0.4	30.5
CNCC	0.1	1.3	-0.4	22.4	-0.4	2.1	-5.6	9.3	-6.2	25.4
CCNC	-0.8	-0.2	-11.9	13.0	0.7	1.5	1.1	12.5	0.3	30.0
CCCN	-0.3	1.3	-7.1	12.8	-1.0	1.1	-6.5	5.9	-22.1	9.4
NNCC	0.1	1.5	-1.7	21.3	-0.5	1.9	-7.2	7.7	-8.9	23.6
NCNC	-0.7	0.0	-13.5	12.0	0.8	1.4	-0.4	10.9	-2.2	28.1
NCCN	-0.2	1.5	-8.2	11.7	-1.1	0.9	-7.7	4.5	-25.1	7.6
CNNC	-0.7	-0.4	-13.3	12.1	-0.0	1.4	-6.4	8.6	-8.1	23.1
CNCN	-0.3	1.2	-7.9	11.5	-1.4	0.8	-13.0	2.1	-32.3	3.3
CCNN	-1.1	-0.2	-16.6	2.0	0.1	0.3	-6.4	5.1	-23.2	8.0
NNNC	-0.5	-0.1	-14.9	11.2	0.1	1.2	-8.0	6.9	-10.8	22.0
NNCN	-0.3	1.4	-9.4	10.7	-1.6	0.7	-15.1	0.7	-36.1	1.5
NCNN	-1.6	0.1	-19.2	1.0	0.3	0.1	-8.2	3.7	-26.1	6.3
CNNN	-0.6	-0.3	-16.3	1.0	-1.6	0.1	-13.8	1.3	-33.5	1.7
NNNN	-1.1	0	-19.1	0	-2.4	0	-15.3	0	-37.1	0

key:
players: A AUS, J JPN, D CAN, U USA, and E E_U.
Strategies: C cooperate, N not cooperate.
Scenario: permit market with quota allocated to equate per-capita costs across the participating regions.
Benefit: W0

Table D2. OECD-Coalition Game Payoffs (b$)
Scenario: Grandfathering with Regional Permit Markets.

column player	A		J		D		U		E	
row players	JDUE		ADUE		AJUE		AJDE		AJDU	
strategy	C	N	C	N	C	N	C	N	C	N
CCCC	0.5	1.8	7.4	27.3	0.2	3.2	3.4	16.4	0.5	36.7
NCCC	0.6	1.9	6.4	26.2	0.0	3.0	1.9	14.9	-1.3	35.5
CNCC	0.4	1.6	6.0	25.8	-0.2	2.7	-2.1	11.2	-7.6	29.4
CCNC	-1.2	-0.0	-5.4	14.4	-0.8	1.8	1.9	14.7	-1.7	34.8
CCCN	0.3	1.6	-5.1	14.5	-1.3	1.5	-5.9	6.9	-25.0	10.8
NNCC	0.5	1.8	5.0	25.0	-0.3	2.6	-3.6	9.7	-9.4	27.4
NCNC	-1.1	0.2	-6.3	13.2	-0.9	1.7	0.4	13.2	-3.5	32.8
NCCN	0.6	1.8	-5.7	13.4	-1.4	1.3	-6.6	5.4	-26.8	8.8
CNNC	-1.4	-0.2	-6.7	12.9	-1.0	1.5	-3.6	9.6	-9.7	26.7
CNCN	0.2	1.4	-6.1	13.0	-1.5	1.2	-9.8	2.5	-32.0	3.7
CCNN	-1.3	-0.1	-16.9	2.2	-2.0	0.4	-6.6	5.9	-27.1	9.0
NNNC	-1.2	0.1	-7.7	12.1	-1.2	1.4	-4.3	8.8	-10.7	25.6
NNCN	0.4	1.7	-7.0	12.3	-1.6	1.1	-11.3	1.0	-33.8	1.8
NCNN	-1.0	0.1	-17.8	1.1	-2.2	0.2	-8.1	4.4	-28.9	7.0
CNNN	-1.4	-0.2	-17.8	1.1	-2.2	0.2	-11.4	1.5	-34.1	2.0
NNNN	-1.1	0	-18.8	0	-2.3	0	-12.1	0	-35.1	0

key:
players: A AUS, J JPN, D CAN, U USA, and E E_U.
Strategies: C cooperate, N not cooperate.
Benefit: W1

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