The CO₂ abatement game: Costs, incentives, and the enforceability of a sub-global coalition

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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, in the absence of side payments, the achievement of such a coalition might require the design of suitable trade instruments. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

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), the Berlin Mandate, and the Kyoto Accord 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 (GHG) emissions to their 1990 levels by year 2000. The Berlin Mandate has included a number of proposals each suggesting 10–20% reductions in Annex1’s GHG emissions from their 1990 levels by year 2010. Whereas the recent agreement in Kyoto requires the European Union to reduce them by 8%, the US by 7%, and Japan by 6% during the period 2008–2012. 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 GHG emissions? And second, what institutional arrangements can be made that would promote cooperation among countries to achieve the emissions-reduction objective?

A number of recent papers have applied game theory to the problem of climate change, examining the incentives countries have to participate in and comply with international agreement to control GHG emissions.\(^2\) Nonetheless, by focusing on the general context, this theoretical literature fails to convey the complexity of the interactions and the heterogeneity among the current international players in the game. Unsurprisingly, then, its predictions of the likely outcomes appear both vague and conflicting.\(^3\) In contrast, the empirical literature\(^4\), 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 ‘subglobal maximum consensus carbon-emissions reductions’. Harrison and Rutherford (1997) have considered an OECD coalition arrangement

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\(^1\) Annex1 consists of OECD countries, Former Soviet Union and the East European countries. In this paper our focus is on OECD only.


\(^3\) 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. Characterizing it slightly different, Heal (1994) motivates the formation of critical coalitions and establishes the sufficient conditions for their stability; yet these conditions implicitly preclude the presence of strong free rider incentives among the coalition members.

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. In particular, the maximum consensus cutback in Piggott et al is based on beneficarility, i.e. the cutback should be beneficial to the coalition members, which is a necessary but not sufficient condition for the stability of the coalition.

This paper uses a game-theoretic framework and a computable general equilibrium (CGE) model to empirically quantify and assess the incentives of Annex1 countries to voluntarily comply with a non-binding agreement to form a CO\textsubscript{2}-abatement coalition. The multi-region, multi-commodity CGE model is developed to numerically simulate the strategic interactions among member countries in the different coalition structures and to compute payoffs. I show that free riding incentives are so pervasive that a self-enforcing coalition is not supportable as an equilibrium outcome under the current institutional arrangements. I then consider linking climate and trade policy in a combined game to explore the implication of trade measures as enforcement mechanisms. I show that the Annex1 coalition can be supported as a subgame perfect equilibrium if suitable trade rewards and punishment instruments are designed.

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\textsubscript{2}-game analysis and explores the trade interaction as an enforcement mechanism. Section 6 provides concluding remarks.

2. The analytical framework

2.1. General setup

Consider a group of \textit{N} countries contemplating an agreement to provide a specified level of a pure public good (CO\textsubscript{2}-abatement) through multi-lateral negotiations. Let \( W_r \) be the welfare index for the \textit{rth} country. Since the abatement is a pure public good we assume \( W_r \) to have the special form:

\[
W_r = U_r(C_r(Y_r, p_r, q)) + B_r(A),
\]

where \( U_r \) is the indirect utility index defined over income and prices through \( C_r \), \( C_r \) is a private consumption vector, \( B_r \) is region \textit{r}’s abatement benefit function, and \( A \) is the global CO\textsubscript{2} abatement given by the summation technology:

\[
A = \sum_s a_s,
\]
where \( s \) denotes regions and the \( a_s \)'s are net regional CO\(_2\)-abatements over the no-agreement case (i.e. all \( a_s \)'s 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

\[
Y_r = Y(p_r, q; a_r).
\]

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; 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\(^5\). Complying with the agreement, the representative agent in each country, \( r \), solves

\[
\max_{c_r} U_r(C_r(Y_r, p_r, q))
\]

s.t.

\[
Y_r = Y(p_r, q; a_r) \quad a_r \geq \bar{a}_r.
\]

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 \( q^*_I \), such that all domestic and international markets clear and every representative agent maximizes utility on her budget set. Numerically, this multi-regional

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\(^5\)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.
equilibrium problem is formulated and solved as a CGE model using the GAMS/MPSGE software described in Rutherford (1995,1999).

2.2. An overview of the CGE model and its implementation

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 (Rutherford and Babiker, 1997). The analysis covers 26 regions and 13 sectors, the description of which is provided in Table 1.

The sectoral aggregation scheme was chosen to return carbon-intensive industries as separate sectors. 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 nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy (electricity).

Fig. 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

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6 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, supply and price data is the OECD/IEA publications for 1992.
Table 1
Countries, regions, and sectors in the general equilibrium model

<table>
<thead>
<tr>
<th>Country or region</th>
<th>Commodities</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUS Australia</td>
<td>COL Coal</td>
</tr>
<tr>
<td>NZL New Zealand</td>
<td>CRU Crude oil</td>
</tr>
<tr>
<td>JPN Japan</td>
<td>OIL Refined oil products</td>
</tr>
<tr>
<td>KOR Republic of Korea</td>
<td>GAS Natural gas</td>
</tr>
<tr>
<td>IDN Indonesia</td>
<td>ELE Electricity</td>
</tr>
<tr>
<td>MYS Malaysia</td>
<td>ORE* Iron and steel</td>
</tr>
<tr>
<td>PHL Philippines</td>
<td>CRP* Chem, rubber and plastic</td>
</tr>
<tr>
<td>SGP Singapore</td>
<td>NFM* Non-ferrous metals</td>
</tr>
<tr>
<td>THA Thailand</td>
<td>NMM* Non-metallic minerals</td>
</tr>
<tr>
<td>CHN China</td>
<td>PPP* Pulp and paper</td>
</tr>
<tr>
<td>HKG Hong Kong</td>
<td>TRN* Trade and transport</td>
</tr>
<tr>
<td>TWN Taiwan</td>
<td>AGR Agricultural goods</td>
</tr>
<tr>
<td>IDI India</td>
<td>Y Other goods</td>
</tr>
<tr>
<td>CAN Canada</td>
<td></td>
</tr>
<tr>
<td>USA United States</td>
<td></td>
</tr>
<tr>
<td>MEX Mexico</td>
<td></td>
</tr>
<tr>
<td>ARG Argentina</td>
<td></td>
</tr>
<tr>
<td>BRA Brazil</td>
<td></td>
</tr>
<tr>
<td>CHL Chile</td>
<td></td>
</tr>
<tr>
<td>RSM Rest of South America</td>
<td></td>
</tr>
<tr>
<td>E.U European Union 12</td>
<td></td>
</tr>
<tr>
<td>EU3 Austria, Finland, &amp; Sweden</td>
<td></td>
</tr>
<tr>
<td>FSU Former Soviet Union</td>
<td></td>
</tr>
<tr>
<td>MEA Middle East &amp; North Africa</td>
<td></td>
</tr>
<tr>
<td>SSA Sub-Saharan Africa</td>
<td></td>
</tr>
<tr>
<td>ROW Rest of World</td>
<td></td>
</tr>
</tbody>
</table>

*Energy-intensive goods.

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.

Final demand has the structure depicted in Fig. 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.7

7 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).
CO₂ emissions are associated with fossil fuel consumption in production and final demand. Different fuels have different carbon intensities. The technology producing CO₂, 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.

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 A and the full mixed complemenarity formulation (MCP) in Appendix B.

2.3. The calibration of CO₂-abatement benefit functions

Following Hoel (1991), Nordhaus (1993), and Barrett (1994), two functional forms of $B_r$ are specified:

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

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

Where from (5) the marginal benefit in country $r$ is the constant $\beta_r$, and from (6) 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 $\beta_r$, $\lambda_r$, and $\gamma_r$.

Damage estimates of potential greenhouse warming and accordingly the benefits from eliminating such a risk are highly uncertain (Nordhaus, 1994). If benefits are actually less than the cost of mitigation, the problem of forming an abatement coalition is not interesting at all. Thus, I assume that every member of the coalition gets a positive net gain from forming the coalition, i.e. the coalition is beneficial. Much of the empirical evidence, however, has suggested that the net benefits from slowing global warming are low. On the benefit side, both Cline (1992) and Nordhaus (1993) suggest that for the US, the annual
damage from the doubling of CO₂ atmospheric concentration is about 1% of 1990 GDP, whereas Fankhauser (1993) suggests the world annual damage for the same scenario to be about 1.4% of the world 1990 GDP. On the mitigation cost side, the simulations of the GREEN model (OECD, 1995) suggest that the world average annual GDP loss from stabilizing CO₂ emissions in Annex1 to their 1990 level is about 1%.

Based on this, two estimates of the regional per-capita marginal benefits (or marginal willingness to pay) are considered in our numerical simulations. 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) of mitigation. We call this estimate $W_0$. The second estimate assumes identical per-capita marginal valuations across all the parties, and calibrates the marginal benefit coefficient ($\beta_r$) to be 1% higher than the highest regional per-capita welfare cost of mitigation. On the other hand, $\lambda_r$ and $\gamma_r$ in the linear marginal benefit formulation are calibrated using the estimates of $\beta_r$ in such a way that the individual marginal willingness to pay declines by $100 for each additional billion tons of CO₂ abated. We call the linearized version of the second estimate $W_1$.

3. A 25%-cutback OECD carbon coalition

3.1. Current policy climate and model scenarios

According to the 1992 projections of the Intergovernmental Panel on Climate Change (IPCC), fossil fuel CO₂-emissions are likely to grow by 2.5–3.5% annually in the business-as-usual (BaU) trajectories. Since CO₂ is the major anthropogenic greenhouse gas any short-term abatement action will naturally focus on it. Given the GHG reduction targets in Berlin and Kyoto along with the IPCC projections, we find 25% cutback from the 1992 CO₂-emissions level in OECD to be a good approximation of these targets in a static setting. Such an abatement effort, in turn, is equivalent to a global reduction of 12% according to the IEA 1992 statistics.

To simplify the computation of payoffs, the 7 OECD regions in the original dataset are aggregated into 5 regions: AUS Australia and New Zealand, JPN Japan, CAN Canada, USA United States, and E-U European Union as defined in 1990 plus EU3. The observed 1992 fossil fuel CO₂-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

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8 However, some preliminary sensitivity analyses have shown that the main insights of the paper are not affected by the size of the target.
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 allocation rule scenarios. Two types of institutional arrangements are simulated: A uniform OECD permit market and regional permit markets. Four rules for allocating CO\textsubscript{2} emission rights are experimented: The first emphasizes the status quo (Grandfathering) and the other three emphasize equity, carbon 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\textsubscript{2}-emissions (this is equivalent to each OECD region cutting its emissions by 25%); the egalitarian rule, column (3), allocates the members’ quotas in proportion to their 1992 populations; the carbon efficiency rule, column (4), allocates the members’ quotas in proportion to their 1992 CO\textsubscript{2}-intensities per unit of their corresponding per-capita GDPs; and the cost sharing rule, column (5), assigns members’ 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. Along with these, Table 2 also reports trade flows in CO\textsubscript{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\textsubscript{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.

\footnote{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.}

\footnote{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.}
Table 2
Quota allocation rules, institutions, and the welfare impacts of an OECD CO$_2$ Coalition

<table>
<thead>
<tr>
<th>Region</th>
<th>(1)$^a$ Grandfathering, no permit market</th>
<th>(2)$^b$ Grandfathering, with permit market</th>
<th>(3)$^e$ Egalitarian, with permit market</th>
<th>(4)$^f$ Carbon-efficiency with permit market</th>
<th>(5)$^f$ Cost-sharing, with permit market</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Welfare costs</td>
<td>Welfare costs</td>
<td>Welfare costs</td>
<td>Welfare costs</td>
<td>Welfare costs</td>
</tr>
<tr>
<td></td>
<td>EV% $</td>
<td>$ percap $</td>
<td>$ % gdp</td>
<td>Quota % Ev% $</td>
<td>$ percap $</td>
</tr>
<tr>
<td>AUS</td>
<td>1.5 $</td>
<td>$ 150 $</td>
<td>$ 0.9</td>
<td>2.9 $</td>
<td>$ 0.7</td>
</tr>
<tr>
<td>JPN</td>
<td>0.7 $</td>
<td>$ 115 $</td>
<td>$ 0.4</td>
<td>11.5 $</td>
<td>$ 0.7</td>
</tr>
<tr>
<td>CAN</td>
<td>1.4 $</td>
<td>$ 168 $</td>
<td>$ 0.8</td>
<td>4.3 $</td>
<td>$ 1.3</td>
</tr>
<tr>
<td>USA</td>
<td>1.1 $</td>
<td>$ 161 $</td>
<td>$ 0.7</td>
<td>48.0 $</td>
<td>$ 0.9</td>
</tr>
<tr>
<td>E.U</td>
<td>1.1 $</td>
<td>$ 172 $</td>
<td>$ 0.7</td>
<td>33.3 $</td>
<td>$ 1.0</td>
</tr>
<tr>
<td>OECD</td>
<td>1.0 $</td>
<td>$ 157 $</td>
<td>$ 0.6</td>
<td>100 $</td>
<td>$ 0.9</td>
</tr>
<tr>
<td></td>
<td>Quota % EV% $</td>
<td>$ percap $</td>
<td>$ % gdp</td>
<td>CO$_2^d$ Trade BS</td>
<td>Quota % EV% $</td>
</tr>
<tr>
<td>AUS</td>
<td>1.7 $</td>
<td>$ 5.3</td>
<td>527 $</td>
<td>$ 3.3</td>
<td>-4.6 $</td>
</tr>
<tr>
<td>JPN</td>
<td>27.6 $</td>
<td>$ -5.6</td>
<td>-935 $</td>
<td>$ -3.2</td>
<td>108.2 $</td>
</tr>
<tr>
<td>CAN</td>
<td>2.6 $</td>
<td>$ 5.7</td>
<td>674 $</td>
<td>$ 3.4</td>
<td>-10.3 $</td>
</tr>
<tr>
<td>USA</td>
<td>22.1 $</td>
<td>$ 6.5</td>
<td>1000 $</td>
<td>$ 4.3</td>
<td>-165.8 $</td>
</tr>
<tr>
<td>E.U</td>
<td>46.0 $</td>
<td>$ -1.2</td>
<td>-186 $</td>
<td>$ -0.7</td>
<td>72.5 $</td>
</tr>
<tr>
<td>OECD</td>
<td>100 $</td>
<td>$ 1.1</td>
<td>162 $</td>
<td>$ 0.65</td>
<td>0 $</td>
</tr>
</tbody>
</table>

$^a$Leakage 12.5%, net global CO$_2$ abatement 10.4%.
$^b$Leakage 11.5%, net global CO$_2$ abatement 10.6%.
$^c$Leakage 11.7%, net global CO$_2$ abatement 10.5%.
$^d$Indicates permit purchase.
$^e$Leakage 11.8%, net global CO$_2$ abatement 10.5%.
$^f$Leakage 11.5%, net global CO$_2$ abatement 10.6%.
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, 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 egalitarian 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 in Table 2 are therefore: (i) a uniform permit market is better than having separate regional permit markets or tax arrangements; (ii) quota allocation rules that favor efficiency or egalitarian criteria are unlikely; and (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 0–40%. 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 $W_0$ and $W_1$ are used for calibrating the OECD payoffs. For the
grandfathering with uniform permit scenario, $W_0$ corresponds to a 5% markup on the regional per-capita welfare costs shown for the scenario in Table 2, whereas $W_1$ 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. To express the 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 in Table 3, where players are labeled A for AUS, J for JPN, D for CAN, U for USA, and E for $E-U$, and where payoffs correspond to players on the column.

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 $W_0$ and $W_1$ that correspond to the full-cooperation entries are predetermined, one can infer nothing about the actual benefit from full-cooperation on their basis. 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 both the $W_0$ and $W_1$ 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. Hence, by the definition of Nash equilibrium, full-cooperation is certainly not an equilibrium in either of the two 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 both $W_0$ and $W_1$ 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 in the two games would, respectively, then be $-1.2$, $-1.1$ for C, and 0.0 for N. Then the only equilibria for the $W_0$ and the $W_1$ games are the iteratively dominant non-cooperation outcomes. In other words, technically,
Table 3
OECD-coalition game payoffs (b$) scenario: grandfathering + OECD permit market

(a) The game based on W0 benefit estimate

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Column player</th>
<th>Row players</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC</td>
<td>0.1</td>
<td>0.0</td>
<td>0.7</td>
<td>20.2</td>
<td>0.2</td>
<td>2.8</td>
<td>18</td>
</tr>
<tr>
<td>NCC</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td>19.2</td>
<td>0.1</td>
<td>2.6</td>
<td>1.0</td>
</tr>
<tr>
<td>CNC</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>19.0</td>
<td>0.2</td>
<td>2.4</td>
<td>3.5</td>
</tr>
<tr>
<td>CCN</td>
<td>0.3</td>
<td>0.9</td>
<td>0.8</td>
<td>11.5</td>
<td>0.5</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>CCC</td>
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<td>0.3</td>
<td>0.7</td>
<td>10.5</td>
<td>1.4</td>
<td>1.3</td>
<td>10.0</td>
</tr>
<tr>
<td>NNCC</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>18.0</td>
<td>0.3</td>
<td>2.2</td>
<td>4.3</td>
</tr>
<tr>
<td>NCN</td>
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<td>10.7</td>
<td>0.7</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>NCN</td>
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<td>0.7</td>
<td>0.7</td>
<td>9.5</td>
<td>1.4</td>
<td>1.1</td>
<td>10.4</td>
</tr>
<tr>
<td>CCN</td>
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<td>1.0</td>
<td>0.9</td>
<td>10.8</td>
<td>0.2</td>
<td>1.5</td>
<td>4.4</td>
</tr>
<tr>
<td>CKN</td>
<td>0.2</td>
<td>0.3</td>
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<td>9.4</td>
<td>1.6</td>
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<td>9.4</td>
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<td>0.4</td>
<td>10.4</td>
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<td>NNN</td>
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<td>10.0</td>
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<tr>
<td>NNC</td>
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<td>8.6</td>
<td>2.7</td>
<td>9.9</td>
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</tr>
<tr>
<td>NNN</td>
<td>1.0</td>
<td>0.0</td>
<td>0.7</td>
<td>17.8</td>
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<td>11.4</td>
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<td>NNN</td>
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<td>0.4</td>
<td>0.9</td>
<td>17.5</td>
<td>1.1</td>
<td>0.1</td>
<td>15.1</td>
</tr>
<tr>
<td>NNN</td>
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<td>0.0</td>
<td>19.5</td>
<td>2.4</td>
<td>0</td>
<td>15.6</td>
</tr>
</tbody>
</table>

(b) The game based on the W1 benefit estimate

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Column player</th>
<th>Row players</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC</td>
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<td>2.2</td>
<td>8.9</td>
<td>27.6</td>
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<td>3.3</td>
<td>10.6</td>
</tr>
<tr>
<td>NCC</td>
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<td>2.3</td>
<td>7.8</td>
<td>26.4</td>
<td>0.7</td>
<td>3.1</td>
<td>9.7</td>
</tr>
<tr>
<td>CNC</td>
<td>2.2</td>
<td>2.0</td>
<td>7.5</td>
<td>26.1</td>
<td>0.4</td>
<td>2.9</td>
<td>4.7</td>
</tr>
<tr>
<td>CCN</td>
<td>1.4</td>
<td>0.2</td>
<td>4.6</td>
<td>14.8</td>
<td>0.9</td>
<td>2.1</td>
<td>9.6</td>
</tr>
<tr>
<td>CCC</td>
<td>1.4</td>
<td>1.8</td>
<td>1.2</td>
<td>15.6</td>
<td>0.9</td>
<td>1.7</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>AUS</td>
<td>JPN</td>
<td>CAN</td>
<td>USA</td>
<td>E.U.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
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<td>-----</td>
<td>-----</td>
<td>------</td>
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<td></td>
</tr>
<tr>
<td><strong>NNCC</strong></td>
<td>2.2</td>
<td>2.1</td>
<td>6.4</td>
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<td>3.7</td>
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<tr>
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<td>0.3</td>
<td>-5.7</td>
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<td>1.1</td>
<td>1.9</td>
<td>8.7</td>
</tr>
<tr>
<td><strong>NCCN</strong></td>
<td>1.3</td>
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<td>14.4</td>
<td>-1.0</td>
<td>1.5</td>
<td>-3.7</td>
</tr>
<tr>
<td><strong>CNNC</strong></td>
<td>1.6</td>
<td>-0.1</td>
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<td>0.5</td>
<td>1.8</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>CNCC</strong></td>
<td>1.3</td>
<td>1.7</td>
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<td>14.1</td>
<td>-1.2</td>
<td>1.4</td>
<td>-7.9</td>
</tr>
<tr>
<td><strong>CCNN</strong></td>
<td>-0.0</td>
<td>-0.0</td>
<td>-14.5</td>
<td>2.4</td>
<td>-1.5</td>
<td>0.5</td>
<td>-3.8</td>
</tr>
<tr>
<td><strong>NNNC</strong></td>
<td>1.8</td>
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<td>-7.2</td>
<td>12.8</td>
<td>0.8</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>NNCN</strong></td>
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<td>1.8</td>
<td>-3.6</td>
<td>13.2</td>
<td>-1.3</td>
<td>1.3</td>
<td>-9.3</td>
</tr>
<tr>
<td><strong>NCNN</strong></td>
<td>-0.8</td>
<td>0.1</td>
<td>-16.5</td>
<td>1.2</td>
<td>-1.3</td>
<td>0.3</td>
<td>-5.0</td>
</tr>
<tr>
<td><strong>CNNN</strong></td>
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<td>-0.2</td>
<td>-16.2</td>
<td>1.2</td>
<td>-2.2</td>
<td>0.2</td>
<td>-9.5</td>
</tr>
<tr>
<td><strong>NNNN</strong></td>
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<td>-18.5</td>
<td>0</td>
<td>-2.3</td>
<td>0</td>
<td>-10.1</td>
</tr>
</tbody>
</table>

*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.
the games corresponding to \( W0 \) and \( W1 \) belong to the Prisoner’s dilemma class.\(^{11}\)

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 both the \( W0 \) and \( W1 \) games. 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?\(^{12}\) By verifying that the sub-coalition must be beneficial for every member, the smallest size that support such a principle is 5 for the \( W0 \)-game (i.e. the minimum beneficial size is full cooperation) and 3 for the \( W1 \)-game (namely JPN, USA, and E\(_{-U}\)). 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.

Recognizing that these numerical outcomes are surrounded by uncertainties about the true elasticities governing the solution of the CGE model as well as uncertainties about the magnitudes of benefit from slowing down global warming, it is essential to carry out some sensitivity analysis to test the robustness of these outcomes. The critical elasticities in the CGE model include the crude oil supply elasticity, energy demand elasticities, and the Armington trade elasticities. We have simulated the \( W0 \) game for the low and high values of each of these elasticities and have found for the different configurations that the mutual defection outcomes are the only supported equilibria. This, however, does not suggest that these elasticities are not important but rather that the incentive to free ride is so strong. The pervasiveness of these free rider incentives are best demonstrated by Table 4, which reports the gains from unilateral defection for each level of these elasticities. To test the sensitivity of the mutual defection outcomes to the magnitudes of benefit estimates, 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 in Table 5. The results of Table 5 are

\(^{11}\) This outcome is found to be largely insensitive to both the type of institution and the quota allocation rule. In particular we have simulated the \( W0 \) and the \( W1 \) games for the case of regional permit markets and the case of per-capita cost sharing quota allocation rule and found that the mutual defection outcomes is the unique equilibrium in both cases.

\(^{12}\) In the Piggott et al. language, these are the smallest coalitions for which the 25%-cut is a consensus emission reduction.
Table 4
Sensitivity of free rider incentive to model elasticities (gains from unilateral defection $b$)*

<table>
<thead>
<tr>
<th></th>
<th>Oil supply</th>
<th>Armington</th>
<th>Energy demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>AUS</td>
<td>− 0.1</td>
<td>− 0.1</td>
<td>− 0.4</td>
</tr>
<tr>
<td>JPN</td>
<td>21.5</td>
<td>19.2</td>
<td>17.8</td>
</tr>
<tr>
<td>CAN</td>
<td>3.0</td>
<td>2.4</td>
<td>1.3</td>
</tr>
<tr>
<td>USA</td>
<td>13.8</td>
<td>11.3</td>
<td>8.7</td>
</tr>
<tr>
<td>E.U</td>
<td>36.5</td>
<td>32.8</td>
<td>32.9</td>
</tr>
</tbody>
</table>

*Scenario: W0 Game with Grandfathering + permit.

Table 5
The OECD one-shot game: sensitivity to the benefit estimates*

<table>
<thead>
<tr>
<th>Region</th>
<th>5% Net-benefit (i.e. W0)</th>
<th>50% Net-benefit</th>
<th>100% Net-benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross benefit</td>
<td>Gross benefit</td>
<td>Gross benefit</td>
</tr>
<tr>
<td></td>
<td>Per-capita gdp ($)</td>
<td>Per-capita gdp ($)</td>
<td>Per-capita gdp ($)</td>
</tr>
<tr>
<td></td>
<td>Eq. strategy (%)</td>
<td>Eq. strategy (%)</td>
<td>Eq. strategy (%)</td>
</tr>
<tr>
<td>AUS</td>
<td>75.6 0.53 N</td>
<td>108.0 0.75 N</td>
<td>144.0 1.0 N</td>
</tr>
<tr>
<td>JPN</td>
<td>117.6 0.42 N</td>
<td>168.0 0.60 N</td>
<td>244.0 0.8 N</td>
</tr>
<tr>
<td>CAN</td>
<td>163.8 0.84 N</td>
<td>234.0 1.20 N</td>
<td>302.0 1.6 N</td>
</tr>
<tr>
<td>USA</td>
<td>149.1 0.63 N</td>
<td>213.0 0.90 N</td>
<td>284.0 1.2 C</td>
</tr>
<tr>
<td>E.U</td>
<td>171.2 0.63 N</td>
<td>244.5 0.90 N</td>
<td>326.0 1.2 N</td>
</tr>
</tbody>
</table>

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

self-explanatory and clearly underscore the robustness of the mutual defection outcomes 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 defections outcome. Under the current 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 I 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, I 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 two-phase super-game.$^{13}$ In the first construct, I show that cooperation in the full OECD coalition can be an equilibrium outcome if trade is included in the game. In the second, I characterize a trade regime to support cooperation in the full OECD coalition during the first phase for relatively impatient players.

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 in Table 3 is to be repeated infinitely with outcomes from the previous $t - 1$ periods, {$t^t_{t'}$}, 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 in Table 6.$^{14}$

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.

---

$^{13}$ The two-phase construct is meant to capture the likeliness that, within the current climate policy regime, any agreement to be reached will be renegotiated after a decade or two.

$^{14}$ The regional discount factor $\delta_r$ is computed from the subgame-perfection condition:

\[
\frac{1}{1 - \delta_r} \text{[Full-cooperation payoff]} \geq \text{[unilateral-defection payoff]} + \frac{\delta_r}{1 - \delta_r} \text{[mutual-defection payoff]}.
\]
Subgame-perfection in the infinitely repeated OECD CO$_2$-game$^a$

<table>
<thead>
<tr>
<th>Region</th>
<th>Full cooperation</th>
<th>Unilateral defection</th>
<th>Mutual defections</th>
<th>Minimum discount factor $[\delta_r]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUS</td>
<td>0.1</td>
<td>0.0</td>
<td>0</td>
<td>SE</td>
</tr>
<tr>
<td>JPN</td>
<td>0.7</td>
<td>20.2</td>
<td>0</td>
<td>0.97</td>
</tr>
<tr>
<td>CAN</td>
<td>0.2</td>
<td>2.8</td>
<td>0</td>
<td>0.93</td>
</tr>
<tr>
<td>USA</td>
<td>1.8</td>
<td>13.5</td>
<td>0</td>
<td>0.87</td>
</tr>
<tr>
<td>E-U</td>
<td>2.3</td>
<td>35.4</td>
<td>0</td>
<td>0.94</td>
</tr>
</tbody>
</table>

$^a$Key:
SE: cooperation is self-enforcing (best response).
Scenario: W/0 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 incentives in one game, outcomes better than those in the isolated environment game may be achievable (Bernheim and Whinston, 1990).

---

$^{15}$ 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 et al. (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.
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. 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 in 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 in Table 7. 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.

It is obvious that the minimum regional discount factors in Table 7 are on average 20% lower than those in Table 6. In particular, with the presence of trade coordination, Table 7 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 than if not.

5.2.3. The two-phase OECD trade-CO\(_2\) connected super-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
Table 7
Subgame-perfection in the infinitely repeated OECD trade-CO$_2$ game

<table>
<thead>
<tr>
<th>Region</th>
<th>Payoffs (b$)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full cooperation</td>
<td>Unilateral defection</td>
<td>Mutual defections</td>
<td>Minimum discount factor $[\delta_r]$</td>
</tr>
<tr>
<td>AUS</td>
<td>1.2</td>
<td>1.1</td>
<td>0</td>
<td>SE</td>
</tr>
<tr>
<td>JPN</td>
<td>24.7</td>
<td>20.0</td>
<td>0</td>
<td>SE</td>
</tr>
<tr>
<td>CAN</td>
<td>0.5</td>
<td>2.3</td>
<td>0</td>
<td>0.78</td>
</tr>
<tr>
<td>USA</td>
<td>6.0</td>
<td>17.4</td>
<td>0</td>
<td>0.66</td>
</tr>
<tr>
<td>E-U</td>
<td>7.9</td>
<td>35.3</td>
<td>0</td>
<td>0.78</td>
</tr>
</tbody>
</table>

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

tariff on the CO$_2$ content of the defecting region exports to the given region in the coalition.

Define the two-phase repeated trade-CO$_2$ super-game construct as one in which, within each phase, the $W0$-game and the trade game are played simultaneously 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 first phase of the repeated super-game, and consider phase 2 to be infinite. 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 first phase, with the second phase providing the continuation of the punishment and reward regime.

Consider each OECD region adopting the following ‘3-instruments’ strategy:

*Play C and S in the first stage of phase 1. 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. Punishment and rewards are carried over to phase 2.*

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 deflections 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 first phase of the repeated super-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 in Table 8.

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.

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

Table 8
Subgame-perfection of OECD coalition in the two-phase repeated trade-CO\(_2\) game\(^a\)

<table>
<thead>
<tr>
<th>Def region</th>
<th>(1) % change in EIS exports</th>
<th>(2) Defector’s payoff (b$)</th>
<th>(3) Punishment regime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Def</td>
<td>Pun</td>
<td>Def</td>
</tr>
<tr>
<td>AUS</td>
<td>75</td>
<td>- 70</td>
<td>0.0</td>
</tr>
<tr>
<td>JPN</td>
<td>7</td>
<td>- 66</td>
<td>20.2</td>
</tr>
<tr>
<td>CAN</td>
<td>33</td>
<td>- 31</td>
<td>2.8</td>
</tr>
<tr>
<td>USA</td>
<td>34</td>
<td>- 65</td>
<td>13.5</td>
</tr>
<tr>
<td>E..U</td>
<td>12</td>
<td>- 99</td>
<td>35.4</td>
</tr>
</tbody>
</table>

\(^a\)Key:
EIS Energy intensive goods.
Def Unilateral defection regime.
Cop Cooperation regime.
Pun Cooperating and punishing the defector regime.
btax Border CO\(_2\) 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.
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 yr for E-U, suggesting that, given the punishment terms, a typical OECD decision maker, with a 20-yr 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.17

Summing up, the results in Table 7 suggest that full cooperation among OECD regions can be fostered 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.18

6. 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 of CO₂-abatement coalitions. With respect to the latter, the paper attempted to place the game theoretic analysis on global warming within an empirical context.

Estimates of the damage from potential global warming are highly uncertain. Yet, provided that the formation of a coalition in Annex 1 to abate greenhouse gas emissions along the lines in Kyoto is beneficial, the issue of compliance is even more challenging. This paper has used a multi-region, multi-commodity computable general equilibrium (CGE) model of the world economy to simulate payoffs and thereby to analyzes the incentives of OECD regions to comply with

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17 Babiker (1998) shows that these requirements are substantially reduced if the coalition is expanded to include some of the non-OECD regions.

18 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.
an abatement coalition to abate carbon emissions. Our analysis has shown that
the unique outcome of the one-shot OECD abatement game is the status quo of
no action. This outcome is shown to be quite robust with respect to both the
damage and the mitigation cost parameters. In the absence of side payments and
given the difficulty of commitment, some compliance mechanism is needed. Our
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. Nevertheless, the punishment
terms may prove to be quite stringent as they might call for a complete ban of
some trade with the defecting region.

7. For further reading
Cline, 1993; Farrell and Maskin, 1989; Swanson, 1991.

Appendix A. 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

\[
Y_{ir} = \theta_{ir} \left( \frac{D_{ir}}{D_{ir}} \right)^{\eta} + (1 - \theta_{ir}) \left( \frac{X_{ir}}{X_{ir}} \right)^{\eta}_{1/\eta}.
\]  

(A.1)

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:

\[
Y_{ir} = \min \left\{ \min_j \left( \frac{X_{jir}}{X_{jir}} \right), (\alpha_{ir} E_{ir}^{\rho_e} + (1 - \alpha_{ir}) V_{ir}^{\rho_e})^{1/\rho_e} \right\}
\]  

(A.2)

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
\[
\max U_r(c) = \left( \delta \prod_{i \in E} c_{ir}^{\theta_1 \rho_1} + (1 - \delta) \prod_{i \in E} c_{ir}^{\theta_2 \rho_2} \right)^{1/\rho_1},
\]
\[\text{s.t. } \sum_i p_{ir} C_i = M_r - p_r^E G_r - p_r^I I_r\] \hspace{1cm} (A.3)

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. $\delta$ is the share of the consumption composite, $\theta_i$'s 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:
\[
C_{ir} = C_{ir}^{D} \left( \alpha_D \left( \frac{c_{ir}^{D}}{c_{ir}^{P}} \right)^{\rho_0} + (1 - \alpha_D) \left[ \sum_{s \neq r} \theta_s \left( \frac{c_{isr}^{M}}{c_{isr}^{P}} \right)^{\gamma} \right]^{\rho_0/\gamma} \right)^{1/\rho_0}.
\]
\hspace{1cm} (A.4)

Here, the specific choices over domestic and imported demands are made to minimize unit cost (gross of applicable taxes):
\[
\min p_{ir}^{D} C_{ir}^{D} + \sum_s (p_{is}^{X} (1 + t_{isr}^{X}) + \phi_{isr}^{P}) (1 + t_{isr}^{M}) C_{isr}^{M}
\]
\[\text{s.t. } f(c_{ir}^{D}, c_{isr}^{M}) = C_{ir}.\] \hspace{1cm} (A.5)

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

**Appendix B. 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} \quad \text{tax rate on government consumption}

tc_{i,r} \quad \text{tax rate on private consumption}

t_{OM}^{r} \quad \text{tax rate on crude oil imports}

t_{OX}^{r} \quad \text{tax rate on crude oil exports}

PA0_{j,i,r} \quad \text{reference price of intermediates} \ [ = 1 + ti_{j,i,r} ]

PMX0_{i,s,r} \quad \text{reference price of imports} \ [ = (1 + t_{X,s,r})(1 + tm_{i,s,r}) ]

PMT0_{i,s,r} \quad \text{Reference price of transport services} \ [ = 1 + tm_{i,s,r} ]

PG0_{i,r} \quad \text{Reference price of government demand} \ [ = 1 + tg_{i,r} ]

PC0_{i,r} \quad \text{Reference price of private demand} \ [ = 1 + tc_{i,r} ]

(c) Benchmark value shares

\delta_{D}^{i,r} \quad \text{domestic market share of output}

\delta_{I}^{i,r} \quad \text{intermediate input share}

\delta_{N}^{i,r} \quad \text{value-added share in non-energy production}

\delta_{E}^{SR} \quad \text{fossil fuel resource share}

\delta_{E}^{OM} \quad \text{merchandise share in crude oil imports}

\delta_{G}^{i} \quad \text{non-energy share in government demand}

\delta_{C}^{i} \quad \text{non-energy share in private demand}

\phi_{y}^{i} \quad \text{factor demand share in non-energy production}

\phi_{G}^{i} \quad \text{government consumption share}

\phi_{C}^{i} \quad \text{private consumption share}

\phi_{I}^{i} \quad \text{intermediate demand share in transport}

\gamma_{f,E}^{i} \quad \text{factor demand shares in energy production}

\gamma_{j,E}^{i} \quad \text{intermediate demand shares in energy production}

\zeta_{i,r} \quad \text{domestic production share in Armington aggregation}

\beta_{M}^{i} \quad \text{import shares across regions}

\beta_{I}^{i,s,r} \quad \text{merchandise component of imports}

(d) Elasticities and other parameters

\sigma_{t} \quad \text{domestic-export transformation elasticity}

\sigma_{V} \quad \text{value-added-energy substitution elasticity}

\sigma_{e,r} \quad \text{elasticity of substitution in energy production}

\sigma_{D} \quad \text{Armington substitution elasticity}

\sigma_{M} \quad \text{substitution elasticity across imports origin}

\sigma_{G} \quad \text{government energy-non-energy substitution elasticity}

\sigma_{C} \quad \text{private energy-non-energy substitution elasticity}

G_{0} \quad \text{benchmark government provision}

FS0_{i,r} \quad \text{benchmark factor supplies}

RS0_{e,r} \quad \text{benchmark supply of energy resource}

Invest_{i,r} \quad \text{benchmark investment}

Bopdef_{r} \quad \text{benchmark balance of payment deficit}

CO_{e,r} \quad \text{carbon coefficient (kg/$)}

Carblim_{r} \quad \text{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
- \( Oil_{m,r} \): crude oil imports
- \( Oil_{x,r} \): 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
- \( PF_{i,r} \): price index of factor inputs
- \( PR_{i,r} \): 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
- \( P_{crude} \): international price of crude oil
- \( P_{carb} \): 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
- \( MKT_{-PC}(I, R) \): 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_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

\[ DEF\_PY(i, r) = \] 
\[ PY_i = \left[ P_{D,i} (1+\sigma_i) + (1 - \delta_{i,r}^P) P_{X,i} (1+\sigma_i) \right]^{1/(1+\sigma_i)} \]

\[ DEF\_PEV(N, r) = \] 
\[ PEV_{N,r} = \left[ \delta_{N,r}^V \left( \prod_f P_{f,r}^{-\gamma_{f,N,r}} \right) \right]^{1-\sigma_v} + (1 - \delta_{N,r}^V) \left( \sum_e \delta_{e,N,r}^V \frac{P_{A,e,r}(1 + t_{e,N,r}) + CO_{e,r} P_{carb}}{PA_{0,e,r}} \right) \]

\[ DEF\_PEV(E, r) = \] 
\[ PEV_{E,r} = \left[ \sum_f \gamma_{f,E,r} P_{f,r} + \sum_j \gamma_{j,E,r} \frac{P_{A,j,r}(1 + t_{j,E,r}) + CO_{j,r} P_{carb}}{PA_{0,j,r}} \right] \]

\[ PRF\_Y(N, r) = \] 
\[ \sum_n \delta_{n,N,r}^i \frac{P_{A,n,r}(1 + t_{n,N,r})}{PA_{0,n,r}} + \left( 1 - \sum_n \delta_{n,N,r}^i \right) PEV_{N,r} = (1 - t_{y,N,r}) PY_{N,r} \]

\[ PRF\_Y(E, r) = \] 
\[ \left[ \delta_{E,E,r}^{PR} (1 - \sigma_{E}) + (1 - \delta_{E,E,r}^{SR}) PEV_{E,r} (1 - \sigma_{E}) \right]^{1/(1 - \sigma_{E})} = (1 - t_{y,E,r}) PY_{E,r} \]

\[ PRF\_OM(r) = \] 
\[ (\delta_{r}^{OM} P_{crude} + (1 - \delta_{r}^{OM}) PT)(1 + t_{r}^{OM}) = PD_{CRU,r} \]
Market clearing and income-expenditure balance

\[
PRF_{-OX}(r).
\]

\[
PD_{CRU,i}(1 + t^{OX}_r) = Pr_{crude}.
\]

\[
PRF_{-A(i,r)}.
\]

\[
[\alpha_{i,r}PD_{i,r}^{1-\sigma_0} + (1 - \alpha_{i,r})PM_{i,r}^{1-\sigma_0}]^{1/(1-\sigma_0)} = PA_{i,r}.
\]

\[
PRF_{-M(i,r)}.
\]

\[
\sum_s \beta^{M}_{i,s,r} \left\{ \beta^{X}_{i,s,r} \frac{PX_{i,s}(1 + t_{i,s,r})(1 + tm_{i,s,r})}{PMX_{0i,s,r}} \right. \\
+ (1 - \beta^{X}_{i,s,r}) \frac{PT(1 + tm_{i,s,r})}{PMT_{0i,s,r}} \left[ 1 - \frac{1}{1/(1-\sigma_u)} \right] \\
= PM_{i,r}.
\]

\[
PRF_{-G(r)}.
\]

\[
\left[ \delta^{G}_r \left( \prod_n \left( \frac{PA_{n,r}(1 + t_{g,n,r})}{PG_{0n,r}} \right)^{\theta^{G}_{n,r}} \right) \right]^{1-\sigma_0} \\
+ (1 - \delta^{G}_r) \left( \prod_c \left( \frac{PA_{c,r}(1 + t_{c,r} + CO_{c,r}P_{carb})}{PC_{0c,r}} \right)^{\theta^{G}_{c,r}} \right) \left[ 1 - \frac{1}{1/(1-\sigma_c)} \right] = PG_{r}.
\]

\[
PRF_{-C(r)}.
\]

\[
\left[ \delta^{C}_r \left( \prod_n \left( \frac{PA_{n,r}(1 + t_{c,n,r})}{PC_{0n,r}} \right)^{\theta^{C}_{n,r}} \right) \right]^{1-\sigma_c} \\
+ (1 - \delta^{C}_r) \left( \prod_c \left( \frac{PA_{c,r}(1 + t_{c,r} + CO_{c,r}P_{carb})}{PC_{0c,r}} \right)^{\theta^{C}_{c,r}} \right) \left[ 1 - \frac{1}{1/(1-\sigma_c)} \right] = PC_{r}.
\]

\[
PRF_{-YT}.
\]

\[
\prod_{i,r} PD_{i,r}^{\delta^{Y}_{i,r}} = PT.
\]

Market clearing and income-expenditure balance

\[
MKT_{-PD(i,r)}.
\]

\[
\delta^{D}_{i,r} Y_{i,r} \left( \frac{PD_{i,r}}{PY_{i,r}} \right)^{\sigma_i} = \alpha_{i,r} A_{i,r} \left( \frac{PA_{i,r}}{PD_{i,r}} \right)^{\sigma_o} + \theta^{T}_{i,r} YT \frac{PT}{PD_{i,r}} + Invest_{i,r}.
\]

\[
MKT_{-PX(i,r)}.
\]

\[
(1 - \delta^{D}_{i,r}) Y_{i,r} \left( \frac{PX_{i,r}}{PY_{i,r}} \right)^{\sigma_i} = \sum_s M_{i,s} \beta^{M}_{i,s,r} \frac{\beta^{X}_{i,s,r}}{PMX_{0i,s,r}} \left[ \beta^{X}_{i,s,r} PX_{i,r} + (1 - \beta^{X}_{i,s,r}) PT \right]^{-\sigma_u}.
\]
\[ \text{MKT}_i \cdot \text{PM}(i,r) \cdot \]

\[ M_{i,r} = (1 - \alpha_{i,r}) A_{i,r} \left[ \frac{P A_{i,r}}{P M_{i,r}} \right]^{\sigma_P}. \]

\[ \text{MKT}_i \cdot \text{PT} \cdot \]

\[ Y_T = \sum_i \sum_r \sum_s M_{i,s} \beta_{i,s,r}^{M} \left( 1 + \beta_{i,s,r}^{X} \right) P M_{i,s} \left[ \beta_{i,s,r}^{X} P X_{i,r} + (1 - \beta_{i,s,r}^{X}) P T \right]^{-\sigma_M} \]

\[ + \sum_r (1 - \delta_{r,OM}) \text{Oil}_r. \]

\[ \text{MKT}_i \cdot \text{PA}(N,r) \cdot \]

\[ A_{N,r} = \sum_n \delta_{N,n,r} Y_{n,r} + \sum_e (1 - \delta_{e,SR}^{SR}) \frac{\gamma_{N,e,r}^{SR}}{P A_{0,N,r}} \left[ \frac{(1 - \tau_{y,e,r}) P Y_{e,r}}{P E V_{e,r}} \right]^{\sigma_e} Y_{e,r} \]

\[ + \delta_{G}^{G} \theta_{N,r}^{G} \left[ \prod_n P A_{n,r}^{\theta_{n,r}} \right]^{1 - \sigma_G} \frac{P G_{e,r}^{\sigma_G}}{P A_{N,r}(1 + t g_{N,r})} G_r \]

\[ + \delta_{C}^{C} \theta_{N,r}^{C} \left[ \prod_n P A_{n,r}^{\theta_{n,r}} \right]^{1 - \sigma_C} \frac{P C_{r}^{\sigma_C}}{P A_{N,r}(1 + t c_{N,r})} C_r. \]

\[ \text{MKT}_i \cdot \text{PA}(E,r) \cdot \]

\[ A_{E,r} = \sum_n \left( 1 - \sum_n \delta_{n,N,r} \right) P E V_{N,r}^{\sigma_{N,r}} \delta_{E,N,r}^{V} Y_{N,r} \]

\[ + \sum_e (1 - \delta_{e,SR}^{SR}) \frac{\gamma_{E,e,r}^{SR}}{P A_{0,E,r}} \left[ \frac{(1 - \tau_{y,e,r}) P Y_{e,r}}{P E V_{e,r}} \right]^{\sigma_e} Y_{e,r} \]

\[ + (1 - \delta_{r}^{G} \theta_{E,r}^{G}) \left[ \prod_e \left( \frac{P A_{e,r}(1 + t g_{e,r}) + C O_{e,r} P carb}{P G_{0,e,r}} \right)^{\theta_{e,r}} \right]^{1 - \sigma_G} \]

\[ \times \frac{P G_{e,r}^{\sigma_G}}{P A_{E,r}(1 + t g_{E,r})} G_r \]

\[ + (1 - \delta_{r}^{C} \theta_{E,r}^{C}) \left[ \prod_e \left( \frac{P A_{e,r}(1 + t c_{e,r}) + C O_{e,r} P carb}{P C_{0,e,r}} \right)^{\theta_{e,r}} \right]^{1 - \sigma_C} \]

\[ \times \frac{P G_{e,r}^{\sigma_C}}{P A_{E,r}(1 + t c_{E,r})} C_r. \]

\[ \text{MKT}_i \cdot \text{PG}(r) \cdot \]

\[ G_r = G_{0,r}. \]
MKT\textsubscript{Crude}.

\[ \sum_r [Oilx_r - Oilm_r] = 0. \]

MKT\textsubscript{PF}(F, r).

\[
FS_{0,F,r} = \sum_N \theta_r^Y \left( 1 - \sum_n \delta_{n,N,r}^Y \right) \delta_{N,r}^Y \left[ \prod_f PF_{f,r}^{\theta_f^{SS_0}} \right]^{1-\sigma} \frac{PEV_{N,r}^{\sigma}}{PF_{F,r}} Y_{N,r} + \sum_E \gamma_{F,E,r} (1 - \delta_{E,r}^{SR}) \left( \frac{(1 - tY_{E,r})PY_{E,r}}{PEV_{E,r}} \right)^{\sigma_{E,r}} Y_{E,r}. \]

MKT\textsubscript{PR}(e, r).

\[
RS_{0,e,r} = \delta_{e,r}^{SR} \left[ \frac{(1 - tY_{e,r})PY_{e,r}}{PR_{e,r}} \right]^{\sigma_{e,r}} Y_{e,r}. \]

MKT\textsubscript{PC}(r).

\[ PC_r C_r = Income_r \]

INC\textsubscript{RA}(r).

\[ Income_r = \sum_f PF_{F,r} FS_{0,F,r} + \sum_e PR_{e,r} RS_{0,e,r} \]

\{Factor incomes and resource rents\}

\[ + PF_{lab,USA} 'Bopdef' \]

\{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\}

\[ + P_{carb} Carblim_r \} \{Revenues from carbon rights\}

Revenue from output tax:

\[ + \sum_i tY_{i,r} Y_{i,r} P Y_{i,r} \]

Revenue from intermediate inputs tax:

\[ + \sum_N \sum_n t_{N,n,r} P A_{N,r} \delta_{N,n,r} Y_{n,r} + \sum_f \sum_t t_{i,j,c,r} P A_{j,r} (1 - \delta_{E,r}^{SR}) \]
\[
\gamma_{j,e,r} \left[ \frac{(1 - t_{j,e,r}) P Y_{j,e,r}}{P E V_{j,e,r}} \right]^{\sigma_r} Y_{j,e,r} \\
+ \sum_{E} \sum_{N} t_{E,N,r} P A_{E,r} \left( 1 - \sum_{n} \delta_{n,N,r} \right) P E V_{N,r}^{\sigma_r} \left( 1 - \delta_{E,N,r}^{V} \right) \frac{P A_{E,r}}{P E V_{N,r}} Y_{N,r}
\]

Revenue from export tax:

\[
+ \sum_{s} \sum_{i} t_{s,i,r} P X_{i,r} M_{i,r} \beta_{i,r,s} \beta_{i,r,s}^{M} \frac{P M_{i,r}^{\sigma_{s}} \beta_{i,r,s}^{X} P X_{i,r} + (1 - \beta_{i,r,s}^{X}) P T}{P M_{i,r}^{\sigma_{s}}} - \sigma_{u}
\]

Revenue from import tariff:

\[
+ \sum_{s} \sum_{i} (1 + t_{s,i,r}) t_{m_{i,s,r}, P X_{i,s}, M_{i,s,r}, \beta_{i,s,r}^{M}} \frac{P M_{i,s,r}^{\sigma_{s}} \beta_{i,s,r}^{X} P X_{i,s} + (1 - \beta_{i,s,r}^{X}) P T}{P M_{i,s,r}^{\sigma_{s}}} - \sigma_{u}
\]

Revenue from taxes on crude oil trade:

\[
+ t^{OM} Oilm_{E} \left[ \delta_{r}^{OM} P_{crude} + (1 - \delta_{r}^{OM}) P T \right] + t^{OX} Oil_{E} P D_{CRU}, r
\]

Revenue from commodity taxes on government consumption:

\[
+ \sum_{N} t_{g_{N,r}, \delta_{r}^{G}, \theta_{N,r}^{G}} \left[ \prod_{n} P A_{n,r}^{\delta_{n}^{G}} \right]^{1 - \sigma_{G}} \frac{P G_{r}^{\sigma_{G}}}{(1 + t g_{N,r})} G_{r}
\]

\[
+ \sum_{E} t_{g_{E,r}, (1 - \delta_{r}^{G}), \theta_{E,r}^{G}} \left[ \prod_{e} \left( P A_{e,r}(1 + t g_{e,r}) + C O_{e,r} P_{carb} \right) \right]^{1 - \sigma_{G}} \frac{P G_{r}^{\sigma_{G}}}{(1 + t g_{E,r})} G_{r}
\]

Revenue from commodity taxes on private consumption:

\[
+ \sum_{N} t_{c_{N,r}, \delta_{r}^{C}, \theta_{N,r}^{C}} \left[ \prod_{n} P A_{n,r}^{\delta_{n}^{C}} \right]^{1 - \sigma_{C}} \frac{P C_{r}^{\sigma_{C}}}{(1 + t c_{N,r})} C_{r}
\]

\[
+ \sum_{E} t_{c_{E,r}, (1 - \delta_{r}^{C}), \theta_{E,r}^{C}} \left[ \prod_{e} \left( P A_{e,r}(1 + t c_{e,r}) + C O_{e,r} P_{carb} \right) \right]^{1 - \sigma_{C}} \frac{P C_{r}^{\sigma_{C}}}{(1 + t c_{E,r})} C_{r}
\]
CARB...DEF(r).

\[ CARB_r = \sum_e CO_{e,r} A_{e,r} \]

MKT...PCRB..

\[ \sum_r Carb \text{ lim}_r \geq \sum_r CARB_r \]

**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/

**References**


