Self-Enforcing Agreements and International Trade in Greenhouse Gas Emission Rights

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Background

There are two branches of literature on the role of international permit markets in climate policy:

1. Empirical analyses of the costs of abatement measures and the role of international permit markets in minimizing abatement costs (Manne and Richels, Oliviera-Martins et al., Jacoby eta al., etc.)

- Explicit representation of the sectors of economic sectors which are the sources of the pollution (fossil fuel markets, energy-intensive goods).

- Recognition of the importance of international trade – regional policies induce changes in the prices of a number of internationally traded goods (steel, cement, petrochemical products, etc.).

- Subglobal abatement policies affect energy prices, inducing increases in emissions abroad (carbon leakage).

- Abatement targets and permit markets are exogenous to the model.

2. Strategic analyses studying the determinants of effective international policy (Barrett, Carraro, Helm, Hoel, Chander & Tulkens)

- Environmental policies are usually modeled as games in national emission levels.

- In the absence of international institutions which can enforce a globally efficient policy, coalitions are needed to address global policy. Coalition members behave cooperatively once they have decided to particpate, but their decision to participate is selfish.

- Most analysis is based on stylized, partial equilibrium, game-theoretic models.

Helm (2003) proposes a theoretical model in which *burden sharing within an abatement coalitions is endogenous*.

Stage 1. Potential coalition members simultaneously decide whether they agree to participate in the proposed trading regime

Stage 2 Members of a trading coalition choose permits. Countries which refuse to participate or are not invited to participate choose emissions. All choices are made as individual best replies to the permit and emission choices of the other countries.

Trading of permits and of the other (non-strategic) goods in our economy takes place and payoffs accrue.

Contribution of this Paper

We analyze Helm's game in an empirical framework, evaluating different candidate coalitions and identifying all self-enforcing agreements. We evaluate these outcomes on the basis of environmental and welfare impacts.

Our operational game theoretic model provides a complete description of the economic costs of abatement in a GE framework.

Our model has sufficient empirical detail to permit us to characterize the qualitative properties of *optimal* coalition structures within this context. We enumerate all possible coalitions and evaluate equilibria based on welfare and emissions characteristics.

Our analysis underscores the importance of terms of trade effects in the determination of carbon abatement coalitions.

Calibrating the model to projected changes in regional economies over time (environmental Kuznets curve effects) allows us to look at the prospects for cooperation into the future.

Key Insights

While it is widely recognized that permit trading minimizes abatement cost for a given emissions target, nothing assures that global emissions are adequately constrained.

Free-rider incentives and the prospect of selling permits tends to motivate countries to allocate themselves more permits, which reduces permit trade's effectiveness as an abatement device.

In our calibrated numerical model the most effective permit trade coalitions yield abatement at approximately twice the level achieved in a Nash equilibrium without trading.

Permit trade levels are typically heavy in these equilibria. China must sell lots of permits to make it worthwhile for them to be a member.

The grand coalition is an equilibrium outcome, but abatement and welfare may improve when fewer countries are involved. In our simulated scenarios "*good*" equilibria tend to be subglobal and involve high income/high abatement cost countries buying large volumes of emission permits from their developing-world partners.

In the general equilibrium framework, coalitions are more effective in abatement and welfare terms but part of the burden is shifted to energy exporters.

Burden-sharing through non-cooperative agreements is fairly successful. The best equilibrium outcomes produce 1/2 of first-best abatement.

Prospects for cooperation do not change much over the next twenty years based on assumed changes in the profiles of regional economies.

Convergence in willingness to pay for greenhouse gas abatement *reduces* the effectiveness of permit trading coalitions. As valuations become more similar, the Nash equilibrium in emissions supports smaller differences in abatement cost, and hence there are fewer gains from trade. *The prospects for an effective emission trading agreement (involving China) do not improve over time.*

The Economic Model

Economic equilibrium (for exogenously-specified emissions targets):

$$F(z; e) = 0$$

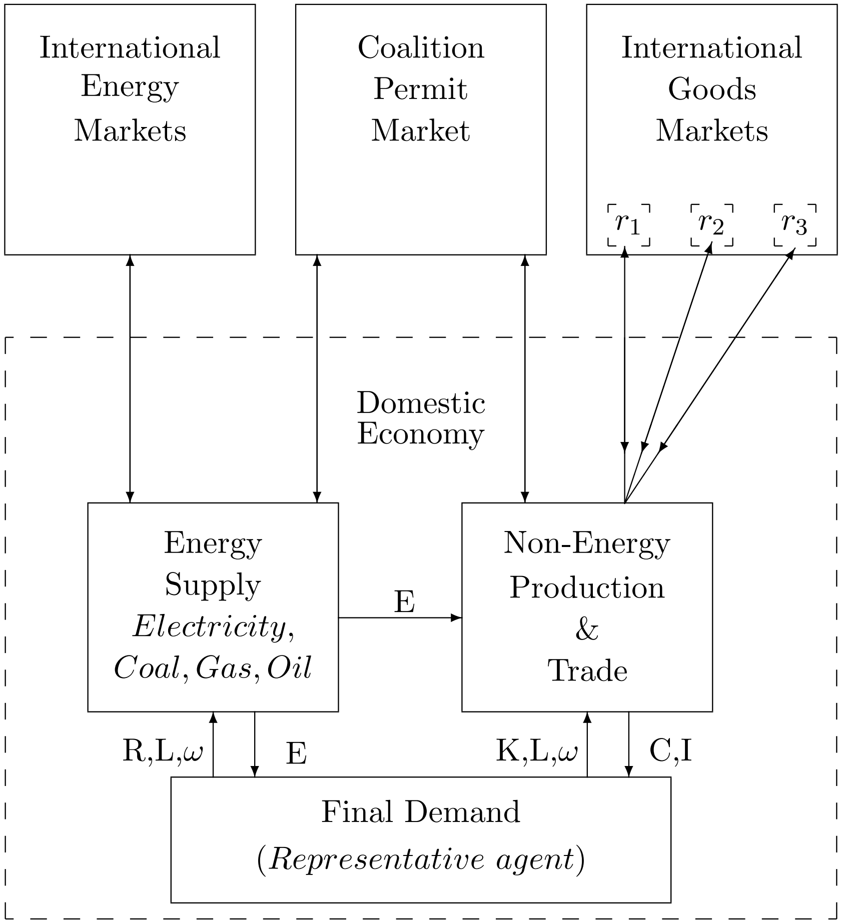
where:

$z = \begin{pmatrix} \pi \\ y \end{pmatrix}$	is the vector of equilibrium prices and quantities
e	is the vector of regional emissions

Global emissions:

$$e^G = \sum_{i=1}^{n} e_i$$

Figure 1: Regional Flows of Goods and Factors



Regional welfare incorporates both economic well-being and environmental impact:

$$W_i = U_i(\pi, \Omega_i) - \nu_i e^G$$

For simplicity we assume linearly homogeneous welfare:

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

Individual Nash equilibrium emissions:

$$\frac{U_i}{e_i}\left[\epsilon_i^M - \epsilon_i^p\right] = \nu_i$$

where ϵ_i^M is the emissions-elasticity of region i income, i.e.

$$\epsilon_i^M = \left(\sum_k \Omega_{ik}\frac{\partial \pi_k}{\partial e_i}\right)\frac{e_i}{\sum_k \Omega_{ik}\pi_k}$$

and ϵ_i^p is the emissions-elasticity of the region i price level, i.e.

$$\epsilon_i^p = \frac{\partial p_i^c(\pi)}{\partial e_i}\frac{e_i}{p_i^c} = \sum_k \frac{\partial p_i^c}{\partial \pi_k}\frac{\partial \pi_k}{\partial e_i}\frac{e_i}{p_i^c}$$

Alternatively:

$$\sum_k \left(\Omega_{ik} - C_{ik}\right)\frac{\partial \pi_k}{\partial e_i} = \nu_i$$

When “Rest of World” region (row) is non-strategic, we adopt a *leakage-adjusted* first order condition:

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

Computational challenge: calculation of $\frac{\partial \pi_k}{\partial e_i}$. Equivalent to incorporating factor market impacts (the “Ford Effect”) in general equilibrium models with imperfectly competitive firms.

Equilibrium with an abatement coalition determines ω_i, the region i permit allocation

$$e_i = \omega_i \quad \forall i \notin \mathcal{C}$$

and

$$\sum_{i \in \mathcal{C}} e_i = \sum_{i \in \mathcal{C}} \omega_i$$

(There is a competitive market for permits among firms within the coalition.)

New equilibrium condition: $F(z;\omega) = 0$ in which

$$z = \begin{pmatrix} \pi \\ y \\ p \end{pmatrix}$$

where p is the equilibrium permit price within the coalition.

First order condition for a coalition member:

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

Compare with the partial equilibrium formulation:

$$(\omega_i - e_i)\frac{\partial p}{\partial \omega_i} + p = \nu_i$$

In the partial equilibrium model, the marginal valuation of the environment (ν_i) alone determines whether a member state is a permit seller or a buyer. In the general equilibrium framework, a much wider range of impacts are possible.

Solving the Model

Key challenge: computing sensitivity of prices to strategic instruments, e.g. $\frac{\partial \pi_k}{\partial \omega_i}$ and $\frac{\partial e_{row}(\pi)}{\partial \omega_i}$.

N.B. These partial derivatives are *functions* of the equilibrium values.

Calibration of Willingness to Pay Parameters

Regional valuations of emissions, represented in the model through the willingness to pay parameters, ν_{it}, are *calibrated* to match an exogenously-specified Nash equilibrium abatement target in 2010:

$$\bar{\nu}_i = \sum_k \left(\Omega_{ik} - C_{ik}\right) \left.\frac{\partial \pi_k}{\partial e_i}\right|_{e_i = \bar{e}_i}$$

where $\bar{e}_i$ is based on region i abatement targets tended in the Kyoto round of climate negotiations. (Europe and Japan are assumed to abate by 20%, the United States 15%, 5% in China and -5% in the FSU.)

The evolution over time of willingness to pay is assumed to increase with per-capita GDP ($\mathcal{G}_{it}$):

$$\nu_{it} = \bar{\nu}\mathcal{G}_{it}^{\eta}$$

GDP Statistics

	*Total (Billion $)**			*$ per Capita**		
	GDP			*GDP per capita*		
	2000	2020	%Δ	2000	2020	%Δ
usa	9,219	16,832	3.1	33,437	51,791	2.2
jpn	4,270	6,542	2.2	33,526	51,923	2.2
eur	9,168	14,786	2.4	23,482	38,104	2.5
chn	1,095	4,314	7.1	860	2,984	6.4
fsu	610	1,501	4.6	2,101	5,401	4.8
row	6,843	15,746	4.3	1,854	3,144	2.7

GDP – Value of total output in billions $1998

%Δ – Equivalent constant annual growth rate

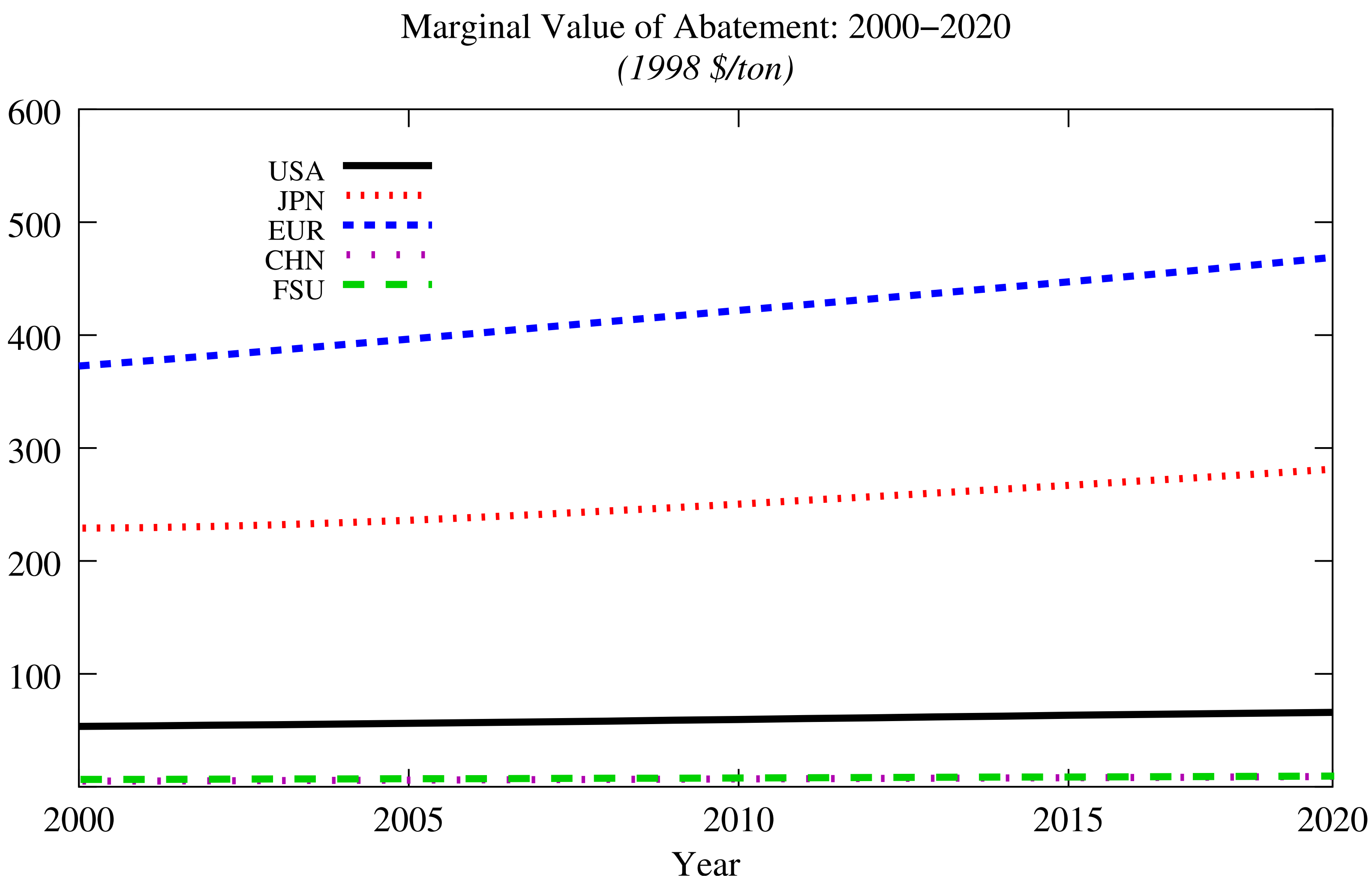
Data sources:

- GTAP5 trade and production database provides, in addition to economic values, a consistent representation of energy markets in physical units
- The US DOE International Energy Outlook (2002) provides growth projections from for emissions by fuel and GDP are used to calibrate our simulation over a time horizon from 2000 to 2020.

Carbon Statistics

	*Carbon per capita $)**			*Carbon per $ GDP*		
	2000	2020	%Δ	2000	2020	%Δ
usa	5.6	6.4	0.7	167	124	-1.5
jpn	2.4	2.9	1.0	72	56	-1.3
eur	2.4	3.0	1.1	104	76	-1.6
chn	0.5	1.1	4.0	625	392	-2.3
fsu	2.1	3.1	2.0	1,021	589	-2.7
row	0.5	0.7	1.7	308	234	-1.4

Carbon per capita in tons per person
Carbon per GDP in grams per $1998
%Δ – Equivalent constant annual growth rate



Marginal Value of Abatement: 2000–2020

(1998 $/ton)

Results

1. Evolution of Emission Trading Coalitions
2. Incentives for Participation
3. Terms of Trade Effects
4. Sensitivity Analysis: Convergence in Environmental Values

Table 2: Equilibrium Coalitions by Welfare and Abatement, 2010

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

% Equivalent Variation: % change in money-metric utility from Nash without trading

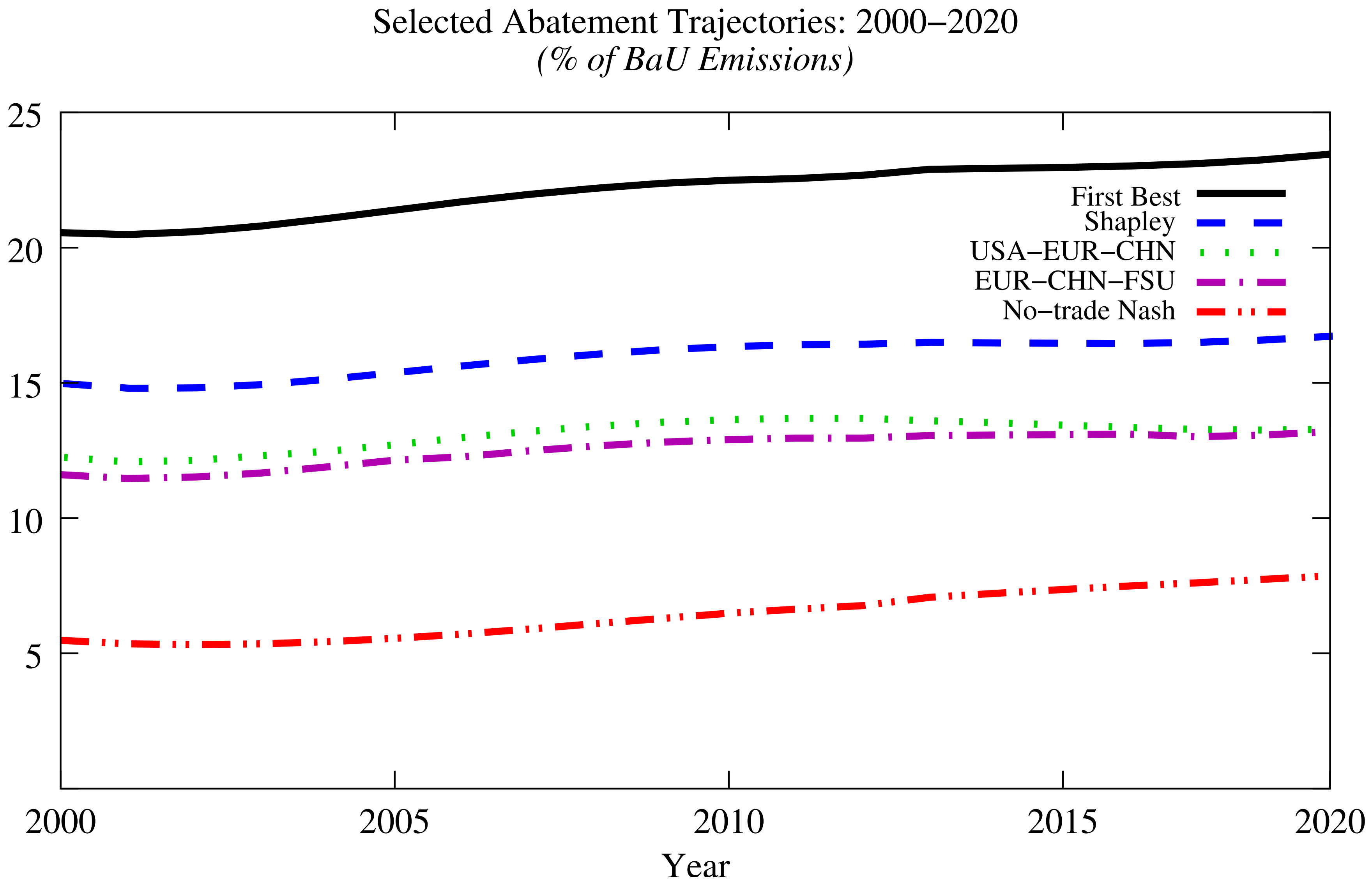
Emissions Reduction: % reduction in global emissions from BaU

Average %EV: Population-weighted average of regional % changes in EV from Nash without trading

*: Equilibria which survive external stability requirement.

External Stability and the USA-EUR-CHN coalition

This equilibrium fails “external stability” because FSU would like to join and sell permits, but if FSU were to join it would weaken the group abatement target, making the coalition less valuable to the USA and cut into CHN’s permit revenues.


Selected Abatement Trajectories: 2000–2020

(% of BaU Emissions)

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

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

e_i^N: No-trade Nash emissions as % of BaU

$e_i^{\mathcal{C}}$: equilibrium emissions with coalition as % of BaU

ω_i: permit allocation of coalition members as % of BaU

ev_i: % change in EV from no-trade Nash equilibrium

p: Permit price resp. marginal abatement cost ($/Tons)

ν_i: Marginal value of emissions reductions ($/Tons)

Marginal Impacts of Permit Allocations

Nash Equilibrium, Armington Elasticities=8,16

	USA	JPN	EUR	CHN	FSU
Y	0.6	4.0	2.5	0.4	0.2
EIS	-1.2	-7.2	-3.1	-0.2	-0.4
COL	0.2	0.0	0.0	0.0	0.2
OIL	0.1	0.2	0.7	0.0	0.0
CRU	-0.5	-0.5	0.4	0.0	0.3
GAS	-0.1	-0.1	0.6	0.0	0.7
ELE	0.0	0.0	0.1	-1.2	-0.3
Misc.	-0.1	0.2	-0.4	0.0	-0.1
dπ	-1.0	-3.4	0.8	-0.8	0.6
p_r	7.0	28.5	41.4	1.5	0.1
ν_r	6.0	25.0	42.2	0.7	0.6

Marginal Impacts of Permit Allocations

Nash Equilibrium, Armington Elasticities=1,2

	USA	JPN	EUR	CHN	FSU
Y	-2.2	-5.4	-5.5	0.0	-0.8
EIS	-2.6	-12.1	-6.5	-0.5	-0.7
COL	0.1	-0.1	0.1	0.0	0.4
OIL	0.2	-0.1	1.4	0.0	0.2
CRU	-0.7	-1.0	1.3	0.0	0.7
GAS	-0.1	-0.4	0.3	0.0	1.2
ELE	0.0	0.0	-0.6	0.0	-0.1
Misc.	-0.2	-2.4	-1.4	-0.1	-0.1
dπ	-5.6	-21.6	-10.7	-0.5	0.6
p_r	11.6	46.6	52.9	1.2	0.0
ν_r	6.0	25.0	42.2	0.7	0.6

Marginal Impacts of Permit Allocations

USA-EUR-CHN Coalition, Armington Elasticities=8,16

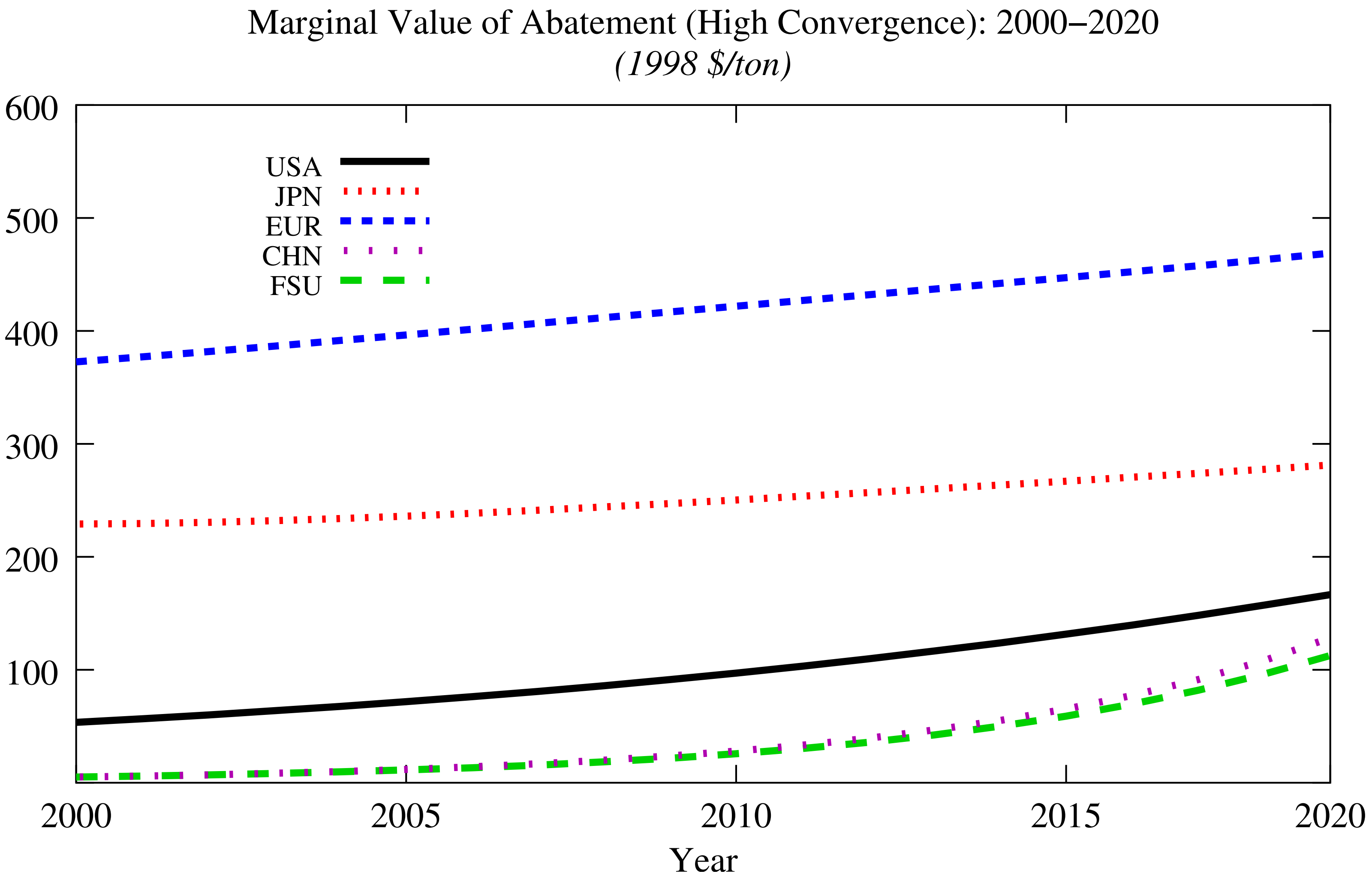
	USA	JPN	EUR	CHN	FSU
Y	0.3	4.1	0.9	0.3	0.2
EIS	-0.7	-7.4	-0.1	-0.3	-0.4
COL	0.1	0.0	0.0	0.0	0.1
OIL	0.2	0.3	0.1	0.1	0.0
CRU	-0.6	-0.5	-0.1	0.0	0.3
GAS	-0.1	-0.1	-0.1	0.0	0.8
ELE	0.0	0.0	-0.4	0.0	-0.4
Misc.	0.0	0.2	0.0	0.0	-0.1
dπ	-0.8	-3.5	0.3	0.0	0.6
p_r	14.0	28.6	13.8	14.3	0.0
dp_r	-7.2		20.4	-13.6	
ν_r	6.0	25.0	42.2	0.7	0.6

Note: The net marginal benefit of an extra unit of emissions by EUR is negative because the equilibrium permit allocation is zero.

Marginal Impacts of Permit Allocations

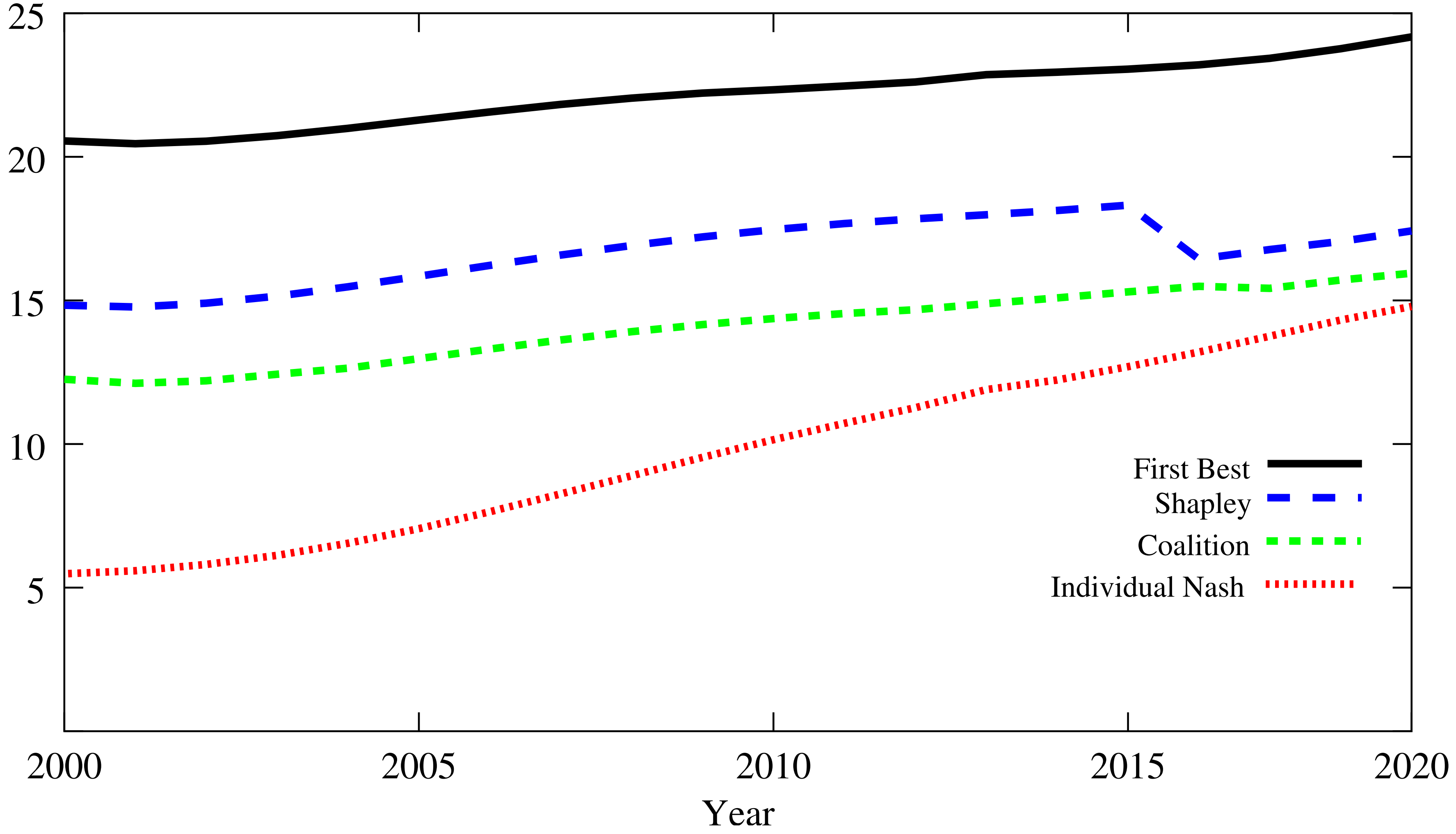
USA-EUR-CHN Coalition, Armington Elasticities=1,2

	USA	JPN	EUR	CHN	FSU
Y	-0.2	-5.4	7.4	-0.9	-0.7
EIS	-1.4	-12.1	1.3	-1.0	-0.6
COL	0.0	-0.1	0.0	0.2	0.3
OIL	0.1	-0.1	0.2	0.0	0.1
CRU	-0.8	-1.0	0.1	0.0	0.5
GAS	-0.1	-0.4	-0.1	0.0	1.2
ELE	0.0	0.0	-0.1	0.0	-0.1
Misc.	-0.1	-2.5	1.1	-0.1	-0.1
dπ	-2.5	-21.7	10.0	-1.9	0.6
p_r	14.4	46.7	13.9	16.8	0.0
dp_r	-5.9		18.4	-14.2	
ν_r	6.0	25.0	42.2	0.7	0.6


Marginal Value of Abatement (High Convergence): 2000−2020
(1998 $/ton)
600
500
400
300
200
100
2000
2005
2010
2015
2020
Year
USA
JPN
EUR
CHN
FSU

Selected Abatement Trajectories (High Convergence): 2000–2020

(% of BaU Emissions)



Conclusions

- International carbon abatement policy should be informed no only as to what is efficient, but also as to what is *feasible*.
- Self-enforcing agreements provide about one half of the first-best level of abatement when compared to BaU levels, but they offer considerable improvement over the individual Nash outcome.
- Suboptimal abatement is due more to the free-rider problem than to inefficient negotiations within the coalition.
- Good agreements are often subglobal.
- Terms of trade effects influence equilibrium outcomes.
- Better coalitions may be formed when certain countries are *excluded* from participation. There is a crucial role for international instiutions such as the Framework Convention for Climate Change.
- The convergence in willingness to pay for emissions reductions by developing countries does not increase the likelihood of forming effective global coalitions.
- Future research: simultaneous formation of multiple coalitions, extension to a repeated game framework, assessment of the role of uncertainty.

Supplemental Slides on the Solution Algorithm

A Scalar Model

$$f(z;\omega) = 0$$

in which $z \in R$ is an implicit function of ω.

Assume that z adjusts to satisfy the equilibrium condition as ω varies:

$$\frac{df}{d\omega} = \frac{\partial f(z;\omega)}{\partial z}\frac{\partial z}{\partial \omega} + \frac{\partial f(z;\omega)}{\partial \omega} = 0$$

Hence, the rate of change of the *endogenous* variable z with respect to the *exogenous* variable ω is:

$$\frac{\partial z}{\partial \omega} = -\frac{\partial f/\partial \omega}{\partial f/\partial z}$$

In the multidimension setting, the implicit function theorem generalizes to the following system of $N \times n$ equations when $z \in R^N$ and $\omega \in R^n$:

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

The programming of such a system of equations is nontrivial as it explicit specification of:

$$\left[\frac{\partial F}{\partial z}\right]_{ij} = \left[\frac{\partial F_i(z;\omega)}{\partial z_j}\right]$$

and

$$\left[\frac{\partial F}{\partial \omega}\right]_{ik} = \left[\frac{\partial F_i(z;\omega)}{\partial \omega_k}\right]$$

Define $z(\omega)$ as the solution of the system of equations,

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

and let $z_k(\omega)$ represent the kth element of the solution vector.

The local dependence of endogenous variables on exogenous variables can alternatively be *numerically approximated* as:

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

in which δ^i is the ith perturbation vector:

$$\delta^i_j = \left\{ \begin{array}{ll} \delta & i = j \\ 0 & i \neq j \end{array} \right.$$

Here is the new idea:

Consider then the following $N \times n + n - 1$ equation system for a model with N economic equilibrium variables $n - 1$ strategic regions:

$$\begin{array}{rl} F(z;\omega) = 0 & \\ F(z^i;\omega + \delta^i) = 0 & i \neq \text{row} \end{array}$$

This system of equations computes z and the adjacent perturbed solutions z^i *simultaneously*.

Difference approximations can then be used to characterize Nash optimal permit allocation:

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

and

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