GAMES OF CLIMATE CHANGE WITH INTERNATIONAL TRADE

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Abstract

We analyse games of greenhouse gas emission reduction in which the emissions and the emission reduction costs of one country depend on other countries' emission abatement. In an analytically tractable model, we show that international trade effects on costs and emissions can either increase or decrease incentives to reduce emissions and to cooperate on emission abatement; in some specifications, optimal emission reduction is unaffected by trade. We therefore specify the model further, calibrating it to larger models that estimate the costs of emission reduction, trade effects, and impacts of climate change. If trade affect the total emission reduction costs, but not the marginal emission reduction costs, cooperation is more difficult than in the case without trade effects. If trade affects both marginal and total emission reduction costs, cooperation becomes easier. Carbon leakage does not affect our qualitative insights, although it does change the numbers.

Key words

Climate change, greenhouse gas emission reduction, international trade, carbon leakage, optimal emission control, coalition formation

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1. Introduction

Climate change is a complex problem with many interactions between countries. The main interactions take place, of course, via the atmosphere. However, national emission reduction policies also influence each other via international trade and investment. Other interactions include those between climate policy and technology, development, nature conservation, environmental protection, and transport. Climate change research only slowly comes to grips with this complexity. This paper explores the interactions between emission reduction strategies and trade effects.

Most game theoretic analyses of international climate policy allow for one interaction only: the climate. In those analyses, greenhouse gas emission reduction is a private good while the atmosphere is a public good. However, this is a distorted representation of reality. Greenhouse gas emission reduction in one country affects other countries in more ways than just via climatic change, particularly via international trade and investment, carbon leakage, and technological development and diffusion.

Obviously, other authors have realised this as well. The impacts of international trade on the distribution of the costs of climate change are analysed by, amongst others, Bernstein *et al.* (1997) and Kemfert (2000). The literature on international cooperation and trade is thin; Ioannidis *et al.* (2000) for a recent review of the international environmental agreement literature. Copeland and Taylor (2000) look the demand for unilateral emission reduction in a CGE model with international trade in goods as well as emission permits. Le Breton and Soubayran (1997) investigate second-best environmental policies in the presence of international trade. Feenstra (1999) looks at international trade and environmental dumping. Barrett (1997) looks at trade sanctions as a deterrent to free-riding. We focus on the question how international trade (a) changes optimal emission reduction and (b) incentives to cooperate on emission reduction.

Whether an agreement can be reached depends on the opportunities to reduce conflicts of interests; a bargaining situation contains opportunities to collaborate for mutual benefits (Barrett, 1994). As real negotiation processes demonstrate, an agreement between all players is unlikely. It is more realistic that some players act unilaterally in order to maximise their own welfare and self interests, while other players form small coalitions. The conclusion that stable coalitions are small has been established for single-issue international environmental negotiations (Barrett, 1994; Botteon and Carraro, 1997a,b, 1998; Carraro and Siniscalo, 1992, 1993; Hoel 1994). Carraro and Siniscalco (1997), Katsoulacos (1996) and Tol *et al.* (2000, 2001) investigate whether linking international greenhouse gas emission reduction policy and technology policy would enlarge incentives for cooperation. This paper does not link issues, but analyses the case with dual interactions between players, only one of which (greenhouse gas emissions) is actively managed. Here, the second interaction is trade. In Tol *et al.* (2000, 2001), the second interaction is technology. Barrett (1994) confines himself to *trade sanctions* as a deterrent to free riding. Botteon and Carraro (1997a,b, 1998) confine themselves to carbon leakage.

This paper looks at the effects of international trade and carbon leakage on incentives to abate greenhouse gas emissions and incentives to cooperate on emission reduction. Because of international trade effects, the cost of one country's emission reduction depends on other countries' abatement costs. Because of carbon leakage, one country's emissions depend on other countries' abatement effort. Section 2 takes an analytical viewpoint. We demonstrate that most relationships of interest are ambiguous. Therefore, we introduce a numerical model in Section 3. This is an intertemporal computable general equilibrium (CGE) model of the world economy, designed to answer empirical questions about greenhouse gas emission reduction, international trade and carbon leakage. A simplified version of the model of Section 2 is calibrated to the outcomes of the CGE model. The simple model is used in Section 4. It is analytically tractable and, fully parameterised, used to shed light on the ambiguities of Section 2. Section 5 concludes.

2. Analytical structure

For convenience, we consider only two countries, labelled as $\{i,j\}$, with $i \neq j$. The case with more countries will be introduced below. Let C_i denote the costs of greenhouse gas emission reduction in country *i*. Suppose

(1) $$C_i = C_i(R_i, R_j, C_j) = f_i(R_i) + g_i(R_i - R_j) + h_i(C_j)$$

where *R* denotes emission reduction. The cost function consists of three components: the costs of domestic emission reduction, costs associated with the difference between domestic and foreign emission reduction, and costs associated with foreign emission reduction costs. Additivity is assumed for notational convenience.

Let

(2) $$f_i(0) = 0, f_i(x) > 0 \text{ if } x > 0, \frac{\partial f_i}{\partial x} > 0, \frac{\partial^2 f_i}{\partial x^2} > 0$$

That is, the costs of domestic emission reduction are positive, increasing and concave. The baseline (R=0) is optimal. These are standard assumptions for the costs of greenhouse gas emission reduction.

Let

(3) $$g_i(0) = 0, g_i(x) > 0 \text{ if } x > 0, g_i(x) < 0 \text{ if } x < 0, \frac{\partial g_i}{\partial x} > 0$$

That is, if country *i* and *j* abate the same amount, there are no additional costs or benefits to country *i*. If country *i* abates more than does country *j*, country *i* suffers additional costs. If country *i* abates less, its domestic costs are lower. The additional costs or benefits grow with the difference in abatement effort.

Let

(4) $$h_i(0) = 0, h_i(x) > 0 \text{ if } x > 0, \frac{\partial h_i}{\partial x} > 0$$

That is, if country *j* faces positive emission reduction costs, some of those costs trickle down to country *i*. The larger the costs to country *j*, the larger the effect on country *i*.

Although the model (1)-(4) is fairly simple, it covers the relevant effects. Let us reiterate the basic properties. Emission reduction is costly. If a country has a more stringent emission reduction policy than others, that country faces additional costs because of loss of competitiveness. *Vice versa*, if a country's policy is less stringent, it gains in competitiveness. If a country reduces emissions, it imports less, inflicting losses on other countries.

The model (1)-(4) displays a wide range of behaviour. The costs of emission reduction depend on the emission reduction in other countries. This effect can be positive or negative, depending on the relative sizes of the above mechanisms and the relative sizes of emission reduction. Even in the absence of domestic action, a country can be affected (positively or negatively) by other countries' emission reduction.

The model is completed with carbon emissions and carbon leakage. Let

(5) $$E_i^R = (1-R_i)E_i + k_i(R_j - R_i)E_i$$

That is, actual emissions E_i^R depend on the emissions without climate policy E_i and emission reductions in both countries. Let

(6) $$k_i(0) = 0, k_i(x) > 0 \text{ if } x > 0, k_i(x) < 0 \text{ if } k < 0, \frac{\partial k_i}{\partial x} > 0$$

Thus, emissions increase in country i if country j abates more than does country i. That is, there is leakage from j to i. *Vice versa*, if country i abates more than does country j, its emissions leak from i to j. Leakage only replaces emissions, so that

(7) $$k_1(x) + k_2(-x) = 0$$

The benefits of avoided climate change B_i are given by

(8) $$B_i = l_i(E_i + E_j) - l_i(E_i^R + E_j^R)$$

We only assume that B is strictly increasing in total emissions.

There are two possibilities to –logically– extend this framework to n players. The first is as follows.

(1') $$C_i = f_i(R_i) + g_i\left(R_i - \sum_{\substack{j=1\\j\neq i}}^{n} R_j\right) + h_i\left(\sum_{\substack{j=1\\j\neq i}}^{n} C_j\right)$$

(5') $$E_i^R = \left[1 - R_i + k_i\left(\frac{1}{n-1}\sum_{\substack{j=1\\j\neq i}}^{n} R_j - R_i\right)\right]E_i$$

The second and functional simpler possibility has the following shape:

(1'') $$C_i = f_i(R_i) + \sum_{\substack{j=1\\j\neq i}}^{n} g_i^j(R_i - R_j) + \sum_{\substack{j=1\\j\neq i}}^{n} h_i^j(C_j)$$

(5'') $$E_i^R = \left[1 - R_i + \sum_{\substack{j=1\\j\neq i}}^{n} k_i^j(R_j - R_i)\right]E_i$$

In both cases, (8) would be replaced by

(8') $$B_i = l_i\left(\sum_{r=1}^{n} E_r\right) - l_i\left(\sum_{r=1}^{n} E_r^R\right)$$

The two possible functional specifications of the model can be solved by considering the first order conditions (FOC). The expressions which result can be represented by matrices and we need to use matrix inversion or Cramer's rule to get an explicit expression. We do this for the three dimensional case in section 4.

The effect of spillover and leakage effects on optimal emission reduction is ambiguous, as can be seen from the FOC for the case with two players. For player 1,

(9) $$\left(\frac{\partial f_1}{\partial R_1}+\frac{\partial g_1}{\partial R_1}-\frac{\partial h_1}{\partial C_2}\frac{\partial g_2}{\partial R_1}\right)\Big/\left(1-\frac{\partial h_1}{\partial C_2}\frac{\partial h_2}{\partial C_1}\right)=E_1\frac{\partial l_1}{\partial R_1}+\frac{\partial l_1}{\partial R_1}\left(E_1\frac{\partial k_1}{\partial R_1}-E_2\frac{\partial k_2}{\partial R_1}\right)$$

and similar for player 2; in (9), the marginal costs are at the left hand side and the marginal benefits at the right hand side. Recall that leakage is just replacement, that is, the emissions of player 1 (2) go up by the same amount as the emissions of player 2 (1) go down. Then the benefits and the marginal benefits are unaffected, that is, the rightmost term of (9) cancels.

Let us first consider the competitiveness spillover only, that is, h=0. Even though this spillover effect can be either positive or negative, the costs at the margin are always positive, that is, $\partial g_1/\partial R_1 > 0$, so that optimal emission reduction is lower with competitiveness effects than without.

Now consider the case with cost spillovers but without competitiveness effects, that is, g=0. In this case, the marginal costs are the same with and without the spillover effects and optimal emission reduction is unaltered.

Finally, consider the case with both cost and competitiveness spillovers. The competitive spillovers still work towards lowering of optimal emission reduction. The cost spillovers are no longer neutral. The third term of the left-hand-side of (9) has an effect opposite to the effect of the second term. The combined effect is ambiguous. If we assume that the countries are similar – g_1=g_2 – what matters is whether $\partial h_1/\partial C_2$ is greater or smaller than unity. If it is smaller, cost and competitiveness spillover work towards lower emission reduction, albeit it to a lesser extent than without the cost spillovers. If it is smaller, cost and competitiveness spillovers lead to a greater optimal emission reduction. The size of the marginal cost spillover effect depends, obviously, on emission reduction. Therefore, for small emission reduction, spillover effects lower emission reduction even further; for large emission reduction, spillover effects have the opposite effect.

3. CGE

The pay-offs of international emission reduction policies are estimated using WAGEM (Kemfert 2000). WAGEM is an intertemporal computable general equilibrium and multi regional trade model for the global economy. It considers 11 world regions (Table 1) that are linked through bilateral sectoral trade flows based on GTAP data of 1995. For each region, a representative agent maximises lifetime utility from consumption. This determines the level of savings. Firms choose investment in order to make the most of the present value of their companies.

Table 1. Regions in WAGEM.

ASIA	India and other Asia (Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Hong Kong, Taiwan)
CHN	China
CNA	Canada, New Zealand and Australia
EU15	European Union
JPN	Japan
LSA	Latin America (Mexico, Argentina, Brazil, Chile, Rest of Latin America)
MIDE	Middle East and North Africa
REC	Russia , Eastern and Central European Countries
ROW	Other countries
SSA	Sub Saharan Africa
USA	United States of America

In each region, production of the non-energy macro good is captured by an aggregate production function. The production function characterises technology through transformation possibilities on the output side and substitution possibilities on the input side. In each region, a representative household chooses to allocate lifetime income across consumption in different time periods in order to maximise lifetime utility. In each period, households face the choice between current consumption and future consumption, which can be purchased via savings. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalised within and across countries. Domestic and imported varieties for the non-energy good for all buyers in the domestic market are treated as imperfect substitutes by a CES Armington aggregation function, constrained to constant elasticities of substitution. Emission limits can be reached by domestic action or by trading emission permits within Annex B countries allocated initially due to regional commitment targets. Those countries meeting the Kyoto emissions reduction target stabilise their mitigated emissions at 2010 level.

Fourteen scenarios are run with WAGEM to get an idea of the costs of carbon dioxide emission reduction. We consider only emission reduction by the European Union, Japan and the USA. In one scenario, all three countries reduce emissions by 10% in comparison to the base year emissions (1990). In three scenarios, two countries reduce their emissions by 10% while the other countries do not reduce at all. In three further scenarios, one country reduces its emissions by 10% while the other countries do not abate emissions. This is repeated for a 20% emission reduction. This makes 14 scenarios:

All:	All Annex B countries reduce emissions by 20% (10%)
EUuni:	EU reduces emissions unilaterally by 20% (10%)
Japuni:	Japan reduces emissions unilaterally by 20% (10%)
Usuni:	USA reduces emissions unilaterally by 20% (10%)
EUJap:	EU and Japan reduce emissions bilaterally by 20% (10%)
EUUS:	EU and USA reduce emissions bilaterally by 20% (10%)
JapUS:	Japan and USA reduce emissions bilaterally by 20% (10%)

Table 2 summarises the results. More detail can be found in the appendix.

Table 2. Emission reduction in 2010 (relative to 1990) and income loss in 2010 (relative to business as usual).

Emission reduction (percent)			Loss of income (percent)		
USA	EU	Japan	USA	EU	Japan
10	10	10	0.00	-0.72	-0.15
0	10	0	0.72	-0.21	0.00
0	0	10	0.57	-0.02	-0.23
10	0	0	-0.35	-0.14	0.00
0	10	10	0.45	-0.18	-0.19
10	10	0	-0.54	-0.22	0.00
10	0	10	-0.19	-0.02	-0.19
20	20	20	-1.01	-0.75	-0.54
0	20	0	0.58	-0.73	0.00
0	0	20	0.47	-0.04	-0.61
20	0	0	-0.93	-0.54	0.04
0	20	20	0.51	-0.70	-0.58
20	20	0	-0.97	-0.73	0.08
20	0	20	-0.95	-0.07	-0.50

4. Simple model

The CGE has 11 regions, but only 3 reduce their emissions: the European Union, Japan and the USA. So, we consider a game with 3 players. The other 8 regions are dummy players, playing a default strategy of zero emission reduction.

4.1. No leakage: model

There are two specifications that fit the outcomes of the CGE. Both simplify (1), because of the strong correlation between emission reduction and emission reduction costs abroad. The first formulation is as follows. The costs of emission reduction are given by, for player 1,

$$\frac{C_1}{Y_1} = \alpha_1 R_1^2 + \chi_1\left(R_1 - .5R_2 - .5R_3\right) \tag{10}$$

and similar for players 2 and 3. The benefits of emission reduction are given by

$$B_1 = \gamma_1\left(R_1E_1 + R_2E_2 + R_3E_3\right) \tag{11}$$

That is, benefits of emission reduction depend linearly on the avoided emissions in all three regions.

The first order condition for non-cooperative behaviour is, for player 1

$$2\alpha_1 Y_1 R_1 + \chi_1 Y_1 - \gamma_1 E_1 = 0 \Leftrightarrow R_1 = \frac{\gamma_1 E_1 - \chi_1 Y_1}{2\alpha_1 Y_1} \tag{12}$$

In this formulation, the marginal costs of emission reduction are not affected by emission reduction in other regions.

The first order condition for cooperative behaviour is, for player 1

$$\begin{aligned} &2\alpha_1 Y_1 R_1 + \chi_1 Y_1 - .5\chi_2 Y_2 - .5\chi_3 Y_3 - (\gamma_1+\gamma_2+\gamma_3)E_1 = 0 \Leftrightarrow \\ &R_1 = \frac{(\gamma_1+\gamma_2+\gamma_3)E_1 - \chi_1 Y_1 + .5\chi_2 Y_2 + .5\chi_3 Y_3}{2\alpha_1 Y_1} \end{aligned} \tag{13}$$

The marginal costs of emission reduction are independent of the spillover effects, but the regions do take the welfare effect in other regions into account.

In the second formulation, the costs of emission reduction are given by

(14) $$\frac{C_1}{Y_1} = \alpha_1 R_1^2 + \beta_1 \left(\frac{C_2 + C_3}{Y_2 + Y_3} \right)$$

That is, costs of emission reduction depend on domestic emission reduction and the costs of emission reduction in the other regions.

Variable, index or parameter	Interpretation
C_i	Costs of emission reduction as a fraction of income
R_i	Emission reduction as a fraction of emissions
Y_i	Income
E_i	Emissions
B_i	Benefits of emission reduction
I	Region

(13) has to be rewritten:

(15) $$\begin{pmatrix} 1 & -\frac{\beta_1 Y_1}{Y_2 + Y_3} & -\frac{\beta_1 Y_1}{Y_2 + Y_3} \\ -\frac{\beta_2 Y_2}{Y_1 + Y_3} & 1 & -\frac{\beta_2 Y_2}{Y_1 + Y_3} \\ -\frac{\beta_3 Y_3}{Y_1 + Y_2} & -\frac{\beta_3 Y_3}{Y_1 + Y_2} & 1 \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} \alpha_1 R_1^2 Y_1 \\ \alpha_2 R_2^2 Y_2 \\ \alpha_3 R_3^2 Y_3 \end{pmatrix}$$

or, in matrix form,

(16) $C = A^{-1} D$

Subtracting the benefits – equation (8) – the objective function becomes:

(17) $W = C - B = A^{-1} D - B$

Without cooperation, optimal emission control follows from solving:

(18) $$\max_{R_1} \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \left(A^{-1} D - B \right)$$
$$\max_{R_2} \begin{pmatrix} 0 & 1 & 0 \end{pmatrix} \left(A^{-1} D - B \right)$$
$$\max_{R_3} \begin{pmatrix} 0 & 0 & 1 \end{pmatrix} \left(A^{-1} D - B \right)$$

With cooperation, optimal emission control follows from solving

(19) $$\max_{R_1, R_2, R_3} \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \left(A^{-1} D - B \right)$$

The first order conditions of(18) are, for player 1

(20) $$\begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & -\frac{\beta_1 Y_1}{Y_2 + Y_3} & -\frac{\beta_1 Y_1}{Y_2 + Y_3} \\ -\frac{\beta_2 Y_2}{Y_1 + Y_3} & 1 & -\frac{\beta_2 Y_2}{Y_1 + Y_3} \\ -\frac{\beta_3 Y_3}{Y_1 + Y_2} & -\frac{\beta_3 Y_3}{Y_1 + Y_2} & 1 \end{pmatrix}^{-1} \begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \gamma_1 E_1 \\ \gamma_2 E_2 \\ \gamma_3 E_3 \end{pmatrix} = 0$$

and similar for players 2 and 3. So, the spillover effects do affect non-cooperative optimal emission reduction, because the solution (18) would be very different if the βs were zero. Spillover effects also affect welfare in the optimum.

The first order conditions of (19) are, for emission reductions by player 1

$$(21)\qquad \begin{pmatrix}1 & 1 & 1\end{pmatrix}\begin{pmatrix} 1 & -\frac{\beta_1 Y_1}{Y_2+Y_3} & -\frac{\beta_1 Y_1}{Y_2+Y_3} \\ -\frac{\beta_2 Y_2}{Y_1+Y_3} & 1 & -\frac{\beta_2 Y_2}{Y_1+Y_3} \\ -\frac{\beta_3 Y_3}{Y_1+Y_2} & -\frac{\beta_3 Y_3}{Y_1+Y_2} & 1 \end{pmatrix}^{-1}\begin{pmatrix}2\alpha_1 R_1 Y_1 \\ 0 \\ 0\end{pmatrix} - \begin{pmatrix}1 & 1 & 1\end{pmatrix}\begin{pmatrix}\gamma_1 E_1 \\ \gamma_2 E_2 \\ \gamma_3 E_3\end{pmatrix} = 0$$

and similar for the emission reduction by players 2 and 3. So, the spillover effects affect the difference between non-cooperative and cooperative optimal emission reduction.

The two alternative formulations thus include different aspects of the spillover effects. In the first formulation, trade effects do not influence the non-cooperative optimum, although the non-cooperative pay-off is affected. In the second formulation, trade effects do influence the non-cooperative optimum, and the non-cooperative pay-off as well. In both formulations, trade effects influence the cooperative optimum, as well as the cooperative pay-off.

Of course, we can combine the two models, but then we lose sight on the different aspects. Besides, the parameter estimates are insignificant in that case (Table 3).

Table 3. Parameter estimates.

	α_i	β_i	χ_i	R^2
Japan	0.142	0	0	0.983
	(0.006)	(-)	(-)	
	0.148	0.076	0	0.991
	(0.005)	(0.023)	(-)	
	0.133	0	0.003	0.990
	(0.005)	(-)	(0.001)	
	0.143	0.052	0.001	0.991
	(0.012)	(0.054)	(0.003)	
USA	0.244	0	0	0.809
	(0.048)	(-)	(-)	
	0.351	0.949	0	0.907
	(0.048)	(0.282)	(-)	
	0.159	0	0.032	0.913
	(0.042)	(-)	(0.009)	
	0.239	0.020	0.430	0.919
	(0.102)	(0.016)	(0.498)	
EU15	0.191	0	0	0.721
	(0.026)	(-)	(-)	
	0.182	-0.169	0	0.758
	(0.026)	(0.136)	(-)	
	0.215	0	-0.009	0.768
	(0.030)	(-)	(0.006)	
	0.207	-0.007	-0.056	0.769
	(0.045)	(0.010)	(0.216)	

4.2. No leakage: Results

Table 4 shows results of the two models presented above. Tables 5 and 6 summarise the findings. The parameters are estimated, using ordinary least squares, from the outcomes of the CGE of the previous section. In addition, we present the results of a model without any international trade interaction, calibrated to the same CGE. See Table 3.

We assume that the marginal costs of carbon dioxide emissions are \$200/tC for all three regions. This is high (cf. Tol, 1999), but we need this to generate substantial emission reductions.

Without trade interactions, except for the coalition between the USA and the EU, the grand coalition nor any of the two other possible coalitions of two players is internally stable. That is, in each coalition, there is one player that is better of in the non-cooperative case and thus has an incentive to leave the coalition. This conclusion holds for the best guess as well as for the sensitivity analyses.

In our first representation of trade interactions, the grand coalition is in the γ-core, that is, all players are better off with full cooperation that with non-cooperation. The grand coalition, however, is internally instable, using the myopic stability criterion of Carraro: The EU is better of if it plays as a singleton, and the USA and Japan form a coalition. The USA and Japan are better off in a coalition than as singletons, so the grand coalition is also internally instable using the far-sighted stability criterion of Chwe. The EU does not want to from a coalition with Japan alone, but it does with the USA. The USA and Japan would like to form a coalition with the EU, either of size 2 or 3. The grand coalition is not stable in all sensitivity analyses. The coalition between the USA and the EU, and the coalition between the USA and EU are internally stable in all sensitivity analyses. The EU never wants to cooperate with Japan alone.

In our second representation of trade interaction, the grand coalition nor any of the three possible coalitions of two players is internally stable. This holds for the best guess as well as for the sensitivity analysis.

Table 4. Optimal emission reduction and pay-off.

	Reduction (percent)			Pay-off (million dollar)		
	USA	EU15	Japan	USA	EU15	Japan
No Cooperation						
NT	7.0	4.9	4.7	25.8	31.3	35.1
	(5.8-8.7)	(4.3-5.7)	(4.5-4.9)	(22.5-30.4)	(26.8-37.7)	(30.0-42.3)
T1	0.6	6.5	3.7	32.9	13.3	18.4
	(0.0-4.6)	(4.4-9.3)	(3.1-4.3)	(27.4-41.5)	(2.3-28.9)	(5.5-38.1)
T2	5.1	5.5	4.5	20.2	27.4	30.2
	(4.6-5.6)	(4.9-6.1)	(4.4-4.6)	(19.4-20.6)	(25.8-28.6)	(27.2-32.9)
Full Cooperation						
NT	20.9	14.7	14.0	11.2	60.3	94.4
	(17.5-26.0)	(13.0-17.1)	(13.5-14.6)	(8.9-12.2)	(51.0-74.3)	(79.7-115.6)
T1	20.4	18.3	19.8	55.5	32.4	91.3
	(15.1-29.6)	(15.5-22.0)	(15.6-23.6)	(36.9-75.8)	(28.8-46.3)	(54.1-139.3)
T2	11.4	9.8	29.6	0.5	81.5	3.9
	(11.0-11.8)	(9.8-9.8)	(23.4-37.3)	(0.6-2.7)	(60.3-115.3)	(-35.8-27.2)
Coalition of USA and EU						
NT	13.9	9.8	4.7	26.0	47.8	68.3

	(11.6-17.3)	(8.7-11.4)	(4.6-4.9)	(23.1-29.6)	(40.4-58.7)	(58.3-82.7)
T1	9.4	13.7	3.7	48.7	22.7	64.4
	(6.4-14.8)	(11.4-16.8)	(3.1-4.3)	(44.8-55.3)	(11.7-39.0)	(49.0-88.6)
T2	10.2	8.8	4.5	14.8	44.6	52.9
	(9.9-10.5)	(8.7-8.8)	(4.4-4.6)	11.9-16.5)	(41.4-48.7)	(51.7-53.9)
Coalition of USA and Japan						
NT	13.9	4.9	9.4	18.4	57.0	55.3
	(11.6-17.3)	(4.3-5.7)	(9.0-9.7)	(16.8-20.5)	(48.8-69.0)	(46.8-67.9)
T1	9.4	6.5	18.5	54.8	39.5	30.5
	(6.3-14.8)	(4.4-9.3)	(16.8-19.9)	(53.4-60.3)	(36.6-49.3)	(9.5-59.5)
T2	6.3	5.5	16.3	20.5	44.7	21.6
	(5.7-6.8)	(4.9-6.1)	(14.4-17.9)	(18.2-23.0)	(40.7-48.6)	(14.3-28.3)
Coalition of EU and Japan						
NT	7.0	9.8	9.4	40.6	29.3	44.4
	(5.8-8.7)	(8.7-11.4)	(9.0-9.7)	(35.8-47.1)	(25.4-35.0)	(38.1-53.4)
T1	0.6	11.0	5.1	53.3	8.1	29.1
	(0.0-4.6)	(8.4-14.5)	(6.9-3.1)	(54.4-56.8)	(-0.2-23.0)	(14.1-50.2)
T2	6.3	7.2	21.7	19.0	51.7	11.6
	(5.5-7.2)	(6.3-8.4)	(21.1-22.4)	(9.6-24.8)	(48.5-53.3)	(8.3-15.8)

Table 5. Ranking of priorities based on the payoffs (N= not in coalition, C=in coalition):

	NT			T1			T2		
	US	EU	JAP	US	EU	JAP	US	EU	JAP
NNN	3	2	1	1	2	1	4	1	4
CCN	4	3	4	2	3	4	2	2	5
CNC	2	4	3	4	5	3	5	3	3
NCC	5	1	2	3	1	2	3	4	2
CCC	1	5	5	5	4	5	1	5	1

Table 6. Stable coalitions[a]

	NT	T1	T2
Internally stable coalitions	{US,EU}	{US,EU},{US,JAP}	Ø
Externally stable coalitions[b]	{EU,JAP}	{US,JAP}	{US,EU},{EU,JAP}
Stable coalitions	Ø	{US,JAP}	Ø

[a] Stability based on the theory of cartel stability (Carraro et al., 1997):
Notation:
$P_i(s)$ is the value of player i –who is not a member of s– for joining coalition s.
$Q_i(s)$ is the value of player i –who is not a member of s– for not joining coalition s.
Definition:
A coalition is internally stable iff: $P_i(s) > Q_i(s\backslash i)$ for all $i \notin s$.
A coalition is externally stable iff: $P_i(s \cup i) < Q_i(s)$ for all $i \in s$.
A coalition is stable iff it is both internally and externally stable.
[b] The grand coalition is externally stable by default.

In sum, without trade effects, cooperation is hard to achieve. If we extend the model to include the welfare effects of trade, cooperation is easier. If we further extend the model to also include the marginal cost effects of trade, cooperation is harder.

4.3. Leakage: Model

With leakage, equation (8) has to be replaced with:

$$(22)\quad \begin{aligned} B_1 = \gamma_1 \{ & R_1 \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] + \\ & R_2 \left[(1+k_2) E_2 - 0.5k_1 E_1 - 0.5k_3 E_3 \right] + \\ & R_3 \left[(1+k_3) E_3 - 0.5k_1 E_1 - 0.5k_2 E_2 \right] \} \end{aligned}$$

The first order condition for non-cooperative behaviour is, for player 1

$$(23)\quad \begin{aligned} & 2\alpha_1 Y_1 R_1 + \chi_1 Y_1 - \gamma_1 \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] = 0 \Leftrightarrow \\ & R_1 = \frac{\gamma_1 \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] - \chi_1 Y_1}{2\alpha_1 Y_1} \end{aligned}$$

Compared to the case without leakage (k_i=0), optimal emission reduction goes up or down depending on the relative sizes of k and E. If economy 1 is relatively sensitive to the other regions' emission reduction (k is large) or if the emissions E of economy 1 are relatively large, optimal emission reduction of region 1 would increase compared to the case without leakage.

The first order condition for cooperative behaviour is, for player 1

$$(24)\quad \begin{aligned} & 2\alpha_1 Y_1 R_1 + \chi_1 Y_1 - .5\chi_2 Y_2 - .5\chi_3 Y_3 - (\gamma_1 + \gamma_2 + \gamma_3) \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] = 0 \Leftrightarrow \\ & R_1 = \frac{(\gamma_1 + \gamma_2 + \gamma_3) \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] - \chi_1 Y_1 + .5\chi_2 Y_2 + .5\chi_3 Y_3}{2\alpha_1 Y_1} \end{aligned}$$

In the second formulation, the first order conditions for non-cooperative behaviour are, for player 1

$$(25)\quad \begin{aligned} & \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & -\frac{\beta_1 Y_1}{Y_2 + Y_3} & -\frac{\beta_1 Y_1}{Y_2 + Y_3} \\ -\frac{\beta_2 Y_2}{Y_1 + Y_3} & 1 & -\frac{\beta_2 Y_2}{Y_1 + Y_3} \\ -\frac{\beta_3 Y_3}{Y_1 + Y_2} & -\frac{\beta_3 Y_3}{Y_1 + Y_2} & 1 \end{pmatrix}^{-1} \begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} - \\ & \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \gamma_1 \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] \\ \gamma_2 \left[(1+k_2) E_2 - 0.5k_1 E_1 - 0.5k_3 E_3 \right] \\ \gamma_3 \left[(1+k_3) E_3 - 0.5k_1 E_1 - 0.5k_2 E_2 \right] \end{pmatrix} = 0 \end{aligned}$$

The first order conditions for cooperative behaviour are, for emission reductions by player 1

$$(26)\quad \begin{aligned} & \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & -\frac{\beta_1 Y_1}{Y_2 + Y_3} & -\frac{\beta_1 Y_1}{Y_2 + Y_3} \\ -\frac{\beta_2 Y_2}{Y_1 + Y_3} & 1 & -\frac{\beta_2 Y_2}{Y_1 + Y_3} \\ -\frac{\beta_3 Y_3}{Y_1 + Y_2} & -\frac{\beta_3 Y_3}{Y_1 + Y_2} & 1 \end{pmatrix}^{-1} \begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} - \\ & \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \gamma_1 \left[(1+k_1) E_1 - 0.5k_2 E_2 - 0.5k_3 E_3 \right] \\ \gamma_2 \left[(1+k_2) E_2 - 0.5k_1 E_1 - 0.5k_3 E_3 \right] \\ \gamma_3 \left[(1+k_3) E_3 - 0.5k_1 E_1 - 0.5k_2 E_2 \right] \end{pmatrix} = 0 \end{aligned}$$

4.4. Leakage: Results

Table 7 shows results of the two models presented above. The parameters are the same as above (central estimates only). We assume a leakage of 10%, with 5% and 15% as sensitivity analysis.

Without trade interactions, the grand coalition nor any of the three possible coalitions of two players is internally stable. That is, in each coalition, there is one player that is better of in the non-cooperative case and thus has an incentive to leave the coalition. This conclusion holds for the best guess as well as for the sensitivity analyses. The only qualitative difference with the case without leakage is that the coalition between the USA and EU is no longer internally stable.

In our first representation of trade interactions, the grand coalition is in the γ-core, that is, all players are better off with full cooperation that with non-cooperation. The grand coalition, however, is internally instable, using the myopic stability criterion of Carraro (1997): The EU is better of if it plays as a singleton, and the USA and Japan form a coalition. The USA and Japan are better off in a coalition than as singletons, so the grand coalition is also internally instable using the far-sighted stability criterion of Chwe (1994).

In our second representation of trade interaction, the grand coalition nor any of the three possible coalitions of two players is internally stable. This holds for the best guess as well as for the sensitivity analysis.

In our formulation, leakage alters the strategic interests of the players, even though, in the chosen representation, leakage does not alter relative and marginal abatement costs. However, leakage does alter the effectiveness of emission reduction.

Table 7. Optimal emission reduction and pay-off.

	Reduction (percent)			Pay-off (million dollar)		
	USA	EU15	Japan	USA	EU15	Japan
No Cooperation						
NT	0.3	5.0	3.5	25.0	31.5	36.2
	(7.1-7.5)	(4.9-5.0)	(2.9-4.1)	(24.6-25.4)	(31.4-31.6)	(35.7-36.8)
T1	1.1	6.6	2.4	30.2	14.5	20.3
	(0.9-1.4)	(6.5-6.6)	(1.8-3.1)	(28.9-31.6)	(13.9-15.1)	(19.4-21.1)
T2	5.4	5.6	3.3	19.7	27.4	31.1
	(5.3-5.5)	(5.6-5.6)	(2.8-3.9)	(19.4-20.0)	(27.3-27.4)	(30.2-31.4)
Full Cooperation						
NT	22.0	14.9	10.5	1.8	60.1	102.7
	(21.4-22.5)	(14.8-15.0)	(8.7-12.3)	(-3.1-6.6)	(60.0-60.2)	(98.8-106.1)
T1	22.1	18.5	16.0	37.4	34.9	105.5
	(21.3-22.9)	(18.4-18.5)	(14.1-17.9)	(28.0-46.6)	(33.7-36.1)	(98.7-111.7)
T2	11.4	9.8	29.7	0.5	81.5	3.9
	(11.4-11.4)	(9.8-9.8)	(29.7-29.7)	(0.5-0.5)	(81.5-81.5)	(3.9-3.9)
Coalition of USA and EU						
NT	14.6	10.0	3.5	22.9	48.9	70.8
	(14.3-15.0)	(9.9-10.0)	(2.9-4.1)	(21.3-24.5)	(48.3-49.4)	(69.6-72.0)
T1	10.5	13.8	2.4	43.2	24.9	68.2
	(10.0-11.1)	(13.8-13.9)	(1.8-3.1)	(40.3-46.0)	(23.8-26.0)	(66.3-70.0)

T2	10.2	8.8	3.3	14.2	43.6	52.8
	(10.2-10.2)	(8.8-8.8)	(2.8-3.9)	13.9-14.5)	(43.1-44.1)	(52.6-52.9)
Coalition of USA and Japan						
NT	14.6	5.0	7.0	14.3	57.5	59.2
	(14.3-15.0)	(4.9-5.0)	(5.8-8.2)	(12.2-16.4)	(57.2-57.7)	(57.4-60.7)
T1	10.5	6.6	15.9	46.2	41.9	39.6
	(10.0-11.1)	(6.5-6.6)	(14.6-17.1)	(41.8-50.5)	(40.7-43.1)	(35.2-43.7)
T2	6.3	5.6	16.3	20.5	44.7	21.8
	(6.3-6.3)	(5.6-5.6)	(16.3-16.3)	(20.5-20.6)	(44.7-44.7)	(21.7-21.9)
Coalition of EU and Japan						
NT	7.3	10.0	7.0	39.1	28.3	47.2
	(7.1-7.5)	(9.9-10.0)	(5.8-8.2)	(38.3-39.8)	(27.8-28.8)	(46.0-48.3)
T1	1.1	11.2	2.6	47.9	8.9	31.2
	(0.9-1.4)	(11.1-11.2)	(1.3-3.8)	(45.2-50.6)	(8.6-9.2)	(30.3-31.9)
T2	6.3	7.2	21.7	19.0	51.7	11.6
	(6.3-6.3)	(7.2-7.2)	(21.7-21.7)	(19.0-19.0)	(51.7-51.7)	(11.6-11.6)

Table 8. Ranking of priorities based on the payoffs (N= not in coalition, C=in coalition)

	NT			T1			T2		
	US	EU	JAP	US	EU	JAP	US	EU	JAP
NNN	3	2	1	1	2	1	4	1	4
CCN	4	3	4	2	3	4	2	2	5
CNC	2	4	3	4	5	3	5	3	3
NCC	5	1	2	3	1	2	3	4	2
CCC	1	5	5	5	4	5	1	5	1

Table 9. Stable coalitions[a]

	NT	T1	T2
Internally stable coalitions	Ø	{US,EU},{US,JAP}	Ø
Externally stable coalitions[a]	{EU,JAP}	{US,JAP}	{US,EU},{EU,JAP}
Stable coalitions	Ø	{US,JAP}	Ø

[a] See the footnotes to table 6.

5. Conclusion

A number of conclusions emerge from the analyses in this paper. These conclusions are reached on the basis of admittedly simple representations of complex interactions.

It matters whether trade affects only the total costs of emission reduction or also the marginal costs. If trade affects only the total emission reduction costs, optimal emission reduction and the incentives to cooperate are almost as if there were no trade effects. The first result is trivial, the second is not. Incentives to cooperate depend on total welfare effects, and these depend on trade. As cooperative emission reduction is larger than non-cooperative emission reduction, the trade effect on welfare is larger in case of cooperation than in case of non-cooperation. If trade spillovers of emission reduction affect welfare negatively – the case considered in this paper – the incentives to cooperate fall. However, the incentives to cooperate are already small without these trade effects, which is why we observe in the analyses above only a slight reduction in cooperation.

If trade affects both total and marginal emission reduction costs, we find that cooperation is easier than in the case without trade effects. The intuition behind this result is that the interdependence between countries' emission reduction policies is stronger so that international coordination has a higher pay-off.

Leakage changes the numbers but not the qualitative insights. The intuition is straightforward. On the one hand, leakage means that a country has less control over its own emissions. On the other hand, with leakage, a country has some control over other countries' emissions. Essentially, leakage implies that a country has control over different base emissions. Leakage thus changes the relative importance of countries, but not their incentives to abate or cooperate.

Clearly, the analysis in this paper is only a small step, and our understanding is far away from where we would like it to be. The most obvious shortcoming is that we use a static analysis for a dynamic problem. The functional forms are not a generic as can be, and the number of players is limited. Furthermore, the analysis should be extended to more linkages (e.g., technology) and to other issues (e.g., conventional air pollution). All that is deferred to future research. For the moment, we conclude that international trade and carbon leakage are important considerations in the choice how much greenhouse gas emissions to reduce and whether and with whom to cooperate.

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Appendix

Model results

1. 20 % emissions reduction

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	-8.908	-31.179	0	-35.633	2.227	-33.406	4.454	-28.952
2010.CHN	-3.244	-5.241	-250	998	-1.248	-749	-2.745	-1.747
2010.USA	0	-94.535	54.540	43.632	-87.263	47.268	-90.899	-89.081
2010.SSA	-3.507	-5.846	-1.559	390	-1.559	-2.533	-4.287	-2.533
2010.ROW	-1.810	-1.810	-1.810	0	0	-2.414	-1.810	0
2010.CNA	-8.991	-23.600	0	1.686	-2.248	-562	115.753	-2.810
2010.EU15	-86.653	-90.986	-88.820	-4.333	-64.990	-84.487	-88.820	-8.665
2010.REC	-21.689	-61.625	-1.033	-689	0	-1.721	-689	-344
2010.LSA	-6.245	-10.929	-1.561	781	-3.903	-3.903	-8.587	-5.465
2010.ASIA	-5.004	-12.511	0	0	-12.511	-2.502	-6.255	-1.043
2010.MIDE	-16.523	-27.905	-7.343	1.102	-7.711	-12.484	-20.929	-12.851

Table 1: GDP changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	-10.797	-37.259	0	-43.259	2.728	-41.123	5.603	-35.351
2020.CHN	-4.393	-6.923	-335	1.299	-1.690	-970	-3.550	-2.308
2020.USA	0	-124.881	72.265	58.554	-117.980	62.582	-119.260	-117.587
2020.SSA	-3.591	-5.957	-1.649	402	-1.655	-2.748	-4.510	-2.647
2020.ROW	-1.849	-1.845	-1.854	0	0	-2.540	-1.887	0
2020.CNA	-10.879	-28.084	0	2.014	-2.699	-653	140.293	-3.484
2020.EU15	-117.675	-122.831	-117.242	-5.979	-87.086	-109.411	-116.354	-11.438
2020.REC	-27.046	-76.723	-1.271	-827	0	-2.126	-885	-432
2020.LSA	-6.608	-11.279	-1.649	847	-4.196	-4.235	-9.068	-5.601
2020.ASIA	-7.647	-19.166	0	0	-19.617	-3.938	-9.527	-1.588
2020.MIDE	-30.964	-51.736	-13.181	1.996	-14.311	-22.758	-38.153	-23.851

Table 2: GDP changes in bil. US$92 2020 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	-2669	-5527	29480	-4279	29480	-4700	29480	45310
2010.CHN	24738	25441	38390	23450	38390	24095	38390	5039
2010.USA	835	-5027	8061	5380	-60119	5967	-48048	-24511
2010.SSA	450	796	2411	-44	2411	289	2411	-12242
2010.ROW	128	232	3697	-17	3697	77	3697	-6991
2010.CNA	-710	-1912	95	-59	95	337	95	793
2010.EU15	-19006	-20072	-195788	280	-195788	-116796	-195788	12390
2010.REC	3616	841	3740	17	9044	6089	9044	4036
2010.LSA	687	1201	13183	-38	13183	486	13183	-2098
2010.ASIA	254	406	5955	-82	5955	94	5955	-13848
2010.MIDE	2338	4126	9748	-90	-19589	1679	9748	-5191

Table 3: Export changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	-2935	-6444	41453	-6896	41453	-6790	41453	80005
2020.CHN	985	-17177	8636	-268	8636	397	8636	-29442
2020.USA	2266	-47704	27863	8030	-8572	9563	-1270	24162
2020.SSA	649	1118	1580	-48	1580	442	1580	-20091
2020.ROW	256	434	3494	-22	3494	175	3494	-13809
2020.CNA	-1146	-2973	3972	-129	3763	-16165	4494	13402
2020.EU15	-26606	-24855	-155137	42	-155137	-116236	-155137	121679
2020.REC	-3159	-7283	3835	-14	3835	658	3835	-1863
2020.LSA	1127	2049	9592	-102	9592	-590	9592	-42222
2020.ASIA	1108	2048	-24830	-187	-27218	567	-26544	-42975
2020.MIDE	3115	5441	6584	-169	-26344	2274	6584	-31531

Table 4: Export changes in bil. US$92 2020 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	10278	32787	23204	46149	20109	42723	17014	75896
2010.CHN	38771	40731	40364	19894	44496	27785	50693	12392
2010.USA	2217	161292	-87664	-71248	90957	-77040	109966	131340
2010.SSA	13640	22785	8511	-1509	8511	9812	18733	-4063
2010.ROW	2169	2298	6592	-21	4581	2777	6592	-8664
2010.CNA	24496	85577	94	-6308	8426	2419	3010	11204
2010.EU15	146596	153858	46602	8053	3216	85157	46602	23062
2010.REC	12692	90917	5321	1024	9218	8721	10225	4617
2010.LSA	15045	26328	17527	-1830	22896	9463	33635	10309
2010.ASIA	9911	10064	6019	-83	10846	4922	10846	-9171
2010.MIDE	6748	11233	14386	-6240	20714	71468	127689	65712

Table 5: Import changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	12693	39307	32628	54686	28837	51801	24842	112097
2020.CHN	19189	1776	10233	-5649	15840	4419	23538	-20613
2020.USA	4170	170190	-98214	-94768	198892	-100265	208771	232380
2020.SSA	14177	23558	7929	-1560	7953	10788	18648	-12327
2020.ROW	2371	2587	6390	-27	4330	3038	6426	-17114
2020.CNA	29354	101142	3958	-7596	13756	-13688	8012	26268
2020.EU15	198609	209026	122252	10911	67348	130865	120634	92366
2020.REC	8011	104702	5767	1194	3909	3777	5202	-1267
2020.LSA	16341	28027	13928	-2050	19768	9085	30939	-31828
2020.ASIA	15870	16859	-25099	-189	-19944	8171	-19480	-36089
2020.MIDE	11207	18318	13428	-11313	49819	129393	220072	97089

Table 6: Import changes in bil. US$92 2020 in comparison to BAU

	Highemired	Lowemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010	0,8648	0,4324	0,1137	0,0386	0,1586	0,1972	0,2723	0,1523
2015	0,934	0,467	0,122	0,0415	0,1699	0,2114	0,2919	0,1635
2020	1,0022	0,5011	0,1304	0,0445	0,1812	0,2257	0,3116	0,1749
2025	1,0692	0,5346	0,1386	0,0474	0,1924	0,2398	0,331	0,186
2030	1,148	0,574	0,1479	0,0507	0,2051	0,2558	0,353	0,1986

Table 7: Carbon leakage in billion tons

1. 10 % emissions reduction

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	-8.908	-31.179	0	-13.363	0	-11.135	0	-11.135
2010.CHN	-3.244	-5.241	749	1.497	-250	250	-998	-250
2010.USA	0	-94.535	67.629	53.085	-32.724	41.814	-50.904	-18.180
2010.SSA	-3.507	-5.846	0	974	-390	-390	-1.169	-390
2010.ROW	-1.810	-1.810	-603	0	0	-603	-603	0
2010.CNA	-8.991	-23.600	1.124	1.686	-1.124	562	-1.124	0
2010.EU15	-86.653	-90.986	-25.996	-2.253	-17.331	-21.663	-26.429	-2.166
2010.REC	-21.689	-61.625	-344	-344	0	-689	-344	0
2010.LSA	-6.245	-10.929	781	1.561	-781	0	-2.342	-781
2010.ASIA	-5.004	-12.511	0	0	-12.511	0	-3.753	-104
2010.MIDE	-16.523	-27.905	0	3.672	-4.406	-2.203	-6.242	-2.570

Table 8: GDP changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	-10.797	-37.259	0	-16.222	0	-13.708	0	-13.596
2020.CHN	-4.393	-6.923	1.005	1.948	-338	323	-1.291	-330
2020.USA	0	-124.881	89.609	71.240	-44.243	55.361	-66.786	-23.997
2020.SSA	-3.591	-5.957	0	1.005	-414	-423	-1.230	-407
2020.ROW	-1.849	-1.845	-618	0	0	-635	-629	0
2020.CNA	-10.879	-28.084	1.360	2.014	-1.350	653	-1.362	0
2020.EU15	-117.675	-122.831	-34.315	-3.109	-23.223	-28.054	-34.622	-2.860
2020.REC	-27.046	-76.723	-424	-413	0	-850	-442	0
2020.LSA	-6.608	-11.279	824	1.694	-839	0	-2.473	-800
2020.ASIA	-7.647	-19.166	0	0	-19.617	0	-5.716	-159
2020.MIDE	-30.964	-51.736	0	6.653	-8.178	-4.016	-11.379	-4.770

Table 9: GDP changes in bil. US$92 2020 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	-2669	-5527	33412	-1821	33412	-2079	33412	47729
2010.CHN	24738	25441	42422	22946	39196	25440	39031	6004
2010.USA	835	-5027	6589	4050	-39047	6675	-45349	-19628
2010.SSA	450	796	3070	286	2906	847	2891	-11684
2010.ROW	128	232	4057	-17	3751	483	4057	-6882
2010.CNA	-710	-1912	95	-59	1140	4517	-801	2883
2010.EU15	-19006	-20072	-186298	64682	-185949	-106819	-186363	22453
2010.REC	3616	841	4069	264	9538	6385	9291	4530
2010.LSA	687	1201	15720	-1729	14536	2177	14413	-19498
2010.ASIA	254	406	6432	-82	6432	4869	10730	-112235
2010.MIDE	2338	4126	11549	4714	-18817	3162	11012	-3750

Table 10: Export changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	-2935	-6444	46172	-4616	49710	-2859	49710	114212
2020.CHN	985	-17177	11156	55	9220	5538	10148	-28565
2020.USA	2266	-47704	27127	4472	-3235	10851	2226	27475
2020.SSA	649	1118	1718	-3147	2068	824	1962	-19933
2020.ROW	256	434	3808	-330	3716	543	3629	-13680
2020.CNA	-1146	-2973	5790	310	4285	-4042	4995	15178
2020.EU15	-26606	-24855	-78659	60419	-54508	-104831	-121594	191448
2020.REC	-3159	-7283	3958	267	6501	1250	5020	-1433
2020.LSA	1127	2049	13652	-9237	10556	3470	10692	-40784
2020.ASIA	1108	2048	-23827	-187	-26740	12027	-14606	-11938
2020.MIDE	3115	5441	10907	-2402	-25372	3084	7755	-30612

Table 11: Export changes in bil. US$92 2020 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2010.JPN	10278	32787	20109	17135	10825	13838	9587	53042
2010.CHN	38771	40731	40261	17312	41190	25031	44120	7184
2010.USA	2217	161292	-112260	-89290	16878	-66693	42325	11532
2010.SSA	13640	22785	3400	-3334	4677	2398	7581	-11477
2010.ROW	2169	2298	5699	-21	3308	1269	5699	-8597
2010.CNA	24496	85577	-4072	-6516	5302	2210	3367	2873
2010.EU15	146596	153858	27645	2689	2592	8815	28986	17145
2010.REC	12692	90917	4650	773	9721	7514	9973	4566
2010.LSA	15045	26328	14842	-5409	17169	2303	20618	-1835
2010.ASIA	9911	10064	5054	-83	10363	4439	-738	-112967
2010.MIDE	6748	11233	15818	-15105	3178	15867	47288	10062

Table 12: Import changes in bil. US$92 2010 in comparison to BAU

	Lowemired	Highemired	Euuni	Japuni	USuni	EUjap	EUUS	JapUS
2020.JPN	12693	39307	18392	18910	14988	16798	22415	108358
2020.CHN	19189	1776	7271	-8006	10845	4336	15739	-27901
2020.USA	4170	170190	-129537	-120833	74563	-86198	119979	70963
2020.SSA	14177	23558	1903	-7252	3840	2497	6781	-20545
2020.ROW	2371	2587	5406	-409	3265	1378	5196	-16953
2020.CNA	29354	101142	729	-7159	9065	-6448	10027	15125
2020.EU15	198609	209026	24001	8052	6331	10557	8453	82268
2020.REC	8011	104702	4654	876	6626	2517	3750	-1461
2020.LSA	16341	28027	12554	-13656	13092	3671	16982	-41314
2020.ASIA	15870	16859	-24085	-189	-19944	2504	-10354	-11332
2020.MIDE	11207	18318	18338	-39801	16749	25881	72214	-8190

Table 13: Import changes in bil. US$92 2020 in comparison to BAU