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Abstract

In the absence of a comprehensive international agreement, each country unilaterally sets her abatement of greenhouse gas emissions at a level that possibly maximizes her expected net benefit. In addition to a cleaner and healthier domestic environment and a slower global warming, a country's benefit from self emission-abatement may include improved image and, in turn, bilateral economic and political relations. This paper analyses a country's cooperative and non-cooperative emission abatements within a cost-benefit framework that, for equality consideration, is centered on per capita emission and takes international rewards for commitment to be responsive to per capita income and output composition.

JEL Classification: Q56, F51

1. Introduction

Previous studies have considered the effect of international economic relations, particularly trade, on greenhouse gas emissions. For example, Barrett (1997) has study the role of trade sanctions in deterring free riding. Using a general equilibrium model with a game theoretic component, Alpay (2000) has shown under which conditions trade can stimulate environmental protection. Eyckmans and Tulkens (2003) have introduced a world model for simulating cooperative game theoretic aspects of global climate negotiations. Most relevant to our study, Kemfert, Lise and Tol (2004) have focused on the question how international trade changes optimal emission-reduction and incentives to cooperate on emission-reduction. Their modelling of a country's cost of emission-reduction has attempted to capture the domestic costs of self emission-reduction, the effect of international variation in the level of stringency of emission-reduction policy on the country's terms of trade and capital flow, and the negative external effect on the country's export of a slowing international economic growth that is due to foreign emission reduction. The models used in these studies focus on aggregate levels of domestic and foreign emissions and some of their assumptions hold only if the countries were identical.[1]

Countries differ in population size, technology, industrial structure, export of emission-intensive manufactured goods, and consumption level and pattern. Although China, and to a lesser extent India, contributes about thirty percents of the global atmospheric greenhouse gas emissions, the per capita emissions of this major workshop of highly affordable, tradable, manufactured goods are about one fifth of Australia (the world's number one), the United States and Canada. These differences and equity are not captured by models focusing on countries' aggregate levels of emissions.

The cost-benefit model presented in the following sections is centered on per capita emission reduction. The underlying rationale is that per capita income and output composition influence the assessment of, and reaction to, a country's commitment to emission abatement by other countries. This influence is incorporated into the determination of the internationally cooperative and non-cooperative emission reductions. The analysis reveals that when this influence is taken into account the

[1] For instance, in Kemfert, Lise and Tol (2004) there is no external cost effect on a country via the terms of trade and international capital dynamics when all the countries abate the same level of emissions (i.e., $g_i(R_i - R_j) = 0$ when $R_i = R_j$).

non-cooperative emission reduction by some countries may exceed their optimal internationally cooperative abatement.

2. A country's costs and benefits of abatement

The total cost for country *i* of reducing its per capita greenhouse gas emissions from the present periodical level $\hat{e}_i$ to e_i includes the full costs of enforcement of, and adaptation to, the new lower domestic emission level. We assume that these mitigation and adaptation costs (*MAC*) convexly rise with the country's aggregate emission-abatement level:

$$MAC_i = c_i[(\hat{e}_i - e_i)P_i]^2 \tag{1}$$

where P_i denotes country *i*'s population and c_i is a positive scalar indicating the gradient of country *i*'s marginal abatement costs. We further assume that the marginal cost gradient declines from a maximal level $c > 0$ with the country's level of development as some production and consumption activities are less painfully forgone and as technological absorptive and innovative capacities are improved. Taking per capita income ($y \geq 1$) as reflecting level of development, we let c_i be given by:

$$c_i = c / y_i \,. \tag{2}$$

A reduction of domestic emissions increases the health and recreational value of country *i*'s environment for residents and foreign visitors. Due to transboundary externalities, this domestic environment's appreciation (DEA_i) also depends on the emissions abated by other countries. We take DEA_i to be linear (for tractability) in country *i*'s emission-abatement, $(\hat{e}_i - e_i)P_i$, and in each of her *j* ($j \neq i = 1,2,3,...,N$) counterpart's emissions abatement, $(\hat{e}_j - e_j)P_j$. The average external effect of any country *j*'s emission-abatement on DEA_i depends on the directional alignment of *i* and *j* with dominant winds, on the distance between *i* and *j* and on the structure of the surface separating *i* from *j*. Due to these intervening factors, the average *external* effect ($\beta_{ji} \geq 0$) is likely to be smaller than the average *internal* effect ($\alpha_i > 0$) of *i*'s emission abatement. With $e_j^{\exp}$ denoting country *i*'s expectations about any country *j*'s per capita emissions, country *i*'s expected domestic environment's appreciation is:

$$E(DEA_i) = \alpha_i(\hat{e}_i - e_i)P_i + \sum_{j \neq i}^{N} \beta_{ji}(\hat{e}_j - e_j^{\exp})P_j \,. \tag{3}$$

By reducing her emissions, country *i* also contributes to the aggregate international effort of moderating the global accumulation of greenhouse gases and, in turn, global warming. We take country *i*'s expected benefit (in nominal units) from a moderated global warming (*MGW*) to be given by:

$$E(MGW_i) = \gamma_i \left[(\hat{e}_i - e_i)P_i + \sum_{j \neq i}^{N} (\hat{e}_j - e_j^{\exp})P_j \right]. \qquad (4)$$

where γ_i is a positive scalar indicating a fixed (for tractability) marginal benefit to country *i* from the aggregate effort to moderate global warming.

As other countries' environment and terms of trade depend on country *i*'s commitment to emission reduction, there are international benefits to country *i* from impressing her counterparts of being environmentally responsible and non-opportunistic trading partner. Yet country *i* cannot equally impress all her counterparts. A less committed country may regard country *i* as an environmentally responsible and non-opportunistic trading partner, whereas a more committed country may deem country *i* an environmentally irresponsible and opportunistic trading partner. Hence, country *i* may economically and politically be rewarded by the former, but sanctioned by the latter. As a higher degree of tolerance is likely revealed toward a low-income country producing tradable goods, the sanctions and rewards may be responsive to the portion of the per capita income generated by export oriented industries. We therefore assume that country *i* expects her economic and political relations with any other country to change with the relative stringency of their non-export income deflated emission-abatement policies. More specifically, we assume that country *i* expects the loss (in nominal units) of relations with country *j* to diminish from a maximal level $LR_{ji}^{\max} \geq 0$ with her ratio of per capita abatement to per capita non-export income, relative to that of country *j*. The maximal loss depends on the nature of the initial relations, relative size and international influence of *i* and *j*. Consequently, country *i*'s expected aggregate loss of international relations (*ALIR*) is:

$$E(ALIR_i) = \sum_{j \neq i}^{N} \left\{ LR_{ji}^{\max} - r_{ji} \left[\frac{(\hat{e}_i - e_i)/s_i y_i}{(\hat{e}_j - e_j^{\exp})/s_j y_j} \right] \right\}. \qquad (5)$$

The scalar $0 \leq s_i \leq 1$ denotes country *i*'s non-export income share. The scalars $r_{ji} \geq 0$ and $1/[(\hat{e}_j - e_j^{\exp})/s_j y_j] \geq 0$ indicate, respectively, country *i*'s perception of country

j's ability and inclination to reward country i's commitment to per capita domestic emission-reduction with more favorable economic and political relations. A negative (positive) $E(ALIR_i)$ reflects country i's overall expectation to be rewarded (sanctioned) for her relatively strong (weak) commitment to emission abatement with higher (lower) level of economic and political international cooperation.

In view of these costs and expected benefits, country i's expected net benefit (ENB_i) from reducing her greenhouse-gas emissions is:

$$\begin{aligned} ENB_i &= E(DEA_i) + E(MGW_i) - E(ALIR_i) - MAC_i \\ &= (\alpha_i + \gamma_i)(\hat{e}_i - e_i)P_i + \sum_{j \neq i}^{N} (\beta_{ji} + \gamma_i)(\hat{e}_j - e_j^{\exp})P_j \\ &\quad - \sum_{j \neq i}^{N} LR_{ji}^{\max} + \sum_{j \neq 1}^{N} r_{ji}(s_j y_j / s_i y_i) \left[\frac{\hat{e}_i - e_i}{\hat{e}_j - e_j^{\exp}} \right] - (c / y_i)(\hat{e}_i - e_i)^2 P_i^2. \end{aligned} \quad (6)$$

3. Optimal emission abatement: cooperative vis-à-vis non-cooperative

The cooperatively optimal abatement of per capita emissions by country i is $\hat{e}_i - e_i^o = \arg\max \sum_{j=1}^{N} ENB_j$. As long as $(c / y_i)P_i^2 > 1/[\sum_{j \neq 1}^{N} r_{ij}(s_i y_i / s_j y_j)(\hat{e}_j - e_j)/(\hat{e}_i - e_i)^3$, $\sum_{j=1}^{N} ENB_j$ is concave in $\hat{e}_i - e_i$ and the marginal expected *global* benefit from country i's optimal per capita emission reduction is equal to this country's marginal cost of the optimal per capita emission abatement:

$$\begin{aligned} &(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^{N} \frac{r_{ji}(s_j y_j / s_i y_i)}{(\hat{e}_j - e_j^o)} + P_i \sum_{j \neq i}^{N} (\beta_{ij} + \gamma_j) \\ &\qquad - \frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i}^{N} r_{ij}(s_i y_i / s_j y_j)(\hat{e}_j - e_j^o) = 2(c / y_i)(\hat{e}_i - e_i^o)P_i^2 \end{aligned} \quad .(7)$$

Country i's cooperatively optimal abatement rises with her own and counterparts' marginal benefits from improved domestic environments and moderated global warming and with her improved international relations, but diminishes with the erosion of her counterparts' relative abatement and subsequent bilateral relations with her. It also decreases with the gradient of country i's marginal costs of abatement.

Though not a close-form solution of equation (7), it is useful for a comparison with the non-cooperative emission abatement to express country *i*'s cooperatively optimal per capita emission abatement as:

$$(\hat{e}_i - e_i^o) = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^{N} \frac{r_{ji}(s_j y_j / s_i y_i)}{(\hat{e}_j - e_j^o)} + P_i \sum_{j \neq i}^{N} (\beta_{ij} + \gamma_j) - \frac{\sum_{j \neq i}^{N} r_{ij}(s_i y_i / s_j y_j)(\hat{e}_j - e_j^o)}{(\hat{e}_i - e_i^o)^2}}{2(c / y_i)P_i^2} \quad .(8)$$

In the absence of cooperation, each country maximizes her individual expected net benefit from emission abatement. As ENB_i is concave in $\hat{e}_i - e_i$, there exists an interior $\hat{e}_i - e_i^* = \arg\max ENB_i$. It equates country *i*'s marginal expected self benefit from abatement to her marginal cost of abatement:

$$(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^{N} \frac{r_{ji}(s_j y_j / s_i y_i)}{(\hat{e}_j - e_j^{\exp})} = 2(c / y_i)(\hat{e}_i - e_i^*)P_i^2 \,. \quad (9)$$

Consequently, for every country $i = 1, 2, 3, ..., N$ the non-cooperative expected net benefit maximizing abatement of per capita emissions is equal to the ratio of the sum of her own marginal benefits from the improvements in her domestic environment, global environment and international relations to the gradient of her marginal costs of abatement:

$$\hat{e}_i - e_i^* = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^{N} \frac{r_{ji}(s_j y_j / s_i y_i)}{(\hat{e}_j - e_j^{\exp})}}{2(c / y_i)P_i^2} \,. \quad (10)$$

Suppose that *i* is a large manufacturing country of highly affordable, tradable goods. If the rest of the countries are expected, despite being less intensive workshops of affordable and tradable goods, to be weakly committed to emission-abatement, their aggregate ability and inclination to reward country *i* ($\sum_{j \neq i}^{N} r_{ji} / [(\hat{e}_j - e_j^{\exp}) / s_j y_j]$) is perceived by country *i* to be low. Consequently, the per capita emissions abated by country *i* is mainly determined by her domestic and global environmental self interests and is smaller than the cooperatively optimal level. Moreover, selfishness might lead to power abuse. A large producer *i* of highly affordable and exportable goods, who is also capable of inflicting a large punishment $LR_{ij}^{\max}$ on any other country j and who strongly evaluates her own benefit from improved global environment (i.e., has a large γ_i), might coerce other countries into abating greater quantities of emissions than the cooperatively optimal ones by adhering to an inflexible punitive policy (low r_{ij}). The possibility that for some countries the non-cooperative expected net benefit maximizing abatement of per capita emissions is larger than the cooperatively optimal level is indicated in the following proposition.

PROPOSITION: If

$$\left\{P_i\sum_{j\neq i}^{N}(\beta_{ij}+\gamma_j)+\sum_{j\neq i}^{N}\frac{r_{ji}(s_jy_j/s_iy_i)}{(\hat{e}_j-e_j^o)}\right\}$$
$$\overset{>}{\underset{<}{=}}\left\{\sum_{j\neq i}^{N}\frac{r_{ji}(s_jy_j/s_iy_i)}{(\hat{e}_j-e_j^{\exp})}+\frac{1}{(\hat{e}_i-e_i^o)^2}\sum_{j\neq i}^{N}r_{ij}(s_iy_i/s_jy_j)(\hat{e}_j-e_j^o)\right\}$$

then $\left\{\hat{e}_i-e_i^*\right\}\overset{<}{\underset{>}{=}}\left\{\hat{e}_i-e_i^o\right\}$. (Straightforward from equations (8) and (10).)

4. Cournot-Nash equilibrium and concluding remarks

If each country's expectations about the other countries' abatement levels are perfect ($e_j^{\exp}=e_j^*$), the solution of the N equation-system (10) is the Cournot-Nash equilibrium of the N countries' emission-abatement levels. In order to shed light on the properties of the Cournot-Nash equilibrium levels of abatement, the analytically tractable case of a world divided into two alliances is considered (e.g., an alliance of poor workshop countries of tradable primary and manufactured goods versus the rest of the world). In this case, the expected-net-benefit maximizing per capita emissions are

$$e_1^*=\hat{e}_1-\frac{(\alpha_1+\gamma_1)P_1+\dfrac{r_{21}(s_2y_2/s_1y_1)}{(\hat{e}_2-e_2^{\exp})}}{2(c/y_1)P_1^2} \tag{11}$$

for alliance 1, and by symmetry,

$$e_2^*=\hat{e}_2-\frac{(\alpha_2+\gamma_2)P_2+\dfrac{r_{12}(s_1y_1/s_2y_2)}{(\hat{e}_1-e_1^{\exp})}}{2(c/y_2)P_2^2}. \tag{12}$$

for alliance 2. The solution to this system of reaction equations yields the Cournot-Nash equilibrium per capita emission-abatement for alliance 1:

$$\hat{e}_1 - e_1^* = 0.5\frac{[0.5(\alpha_1+\gamma_1)(\alpha_2+\gamma_2)P_1P_2 + (c/y_2)r_{21}(s_s y_2/s_1y_1)P_2{}^2 - (c/y_1)r_{12}(s_1y_1/s_2y_2)P_1{}^2]}{(c/y_1)(\alpha_2+\gamma_2)P_2P_1^2}$$
$$+0.5\sqrt{\left[\frac{0.5(\alpha_1+\gamma_1)(\alpha_2+\gamma_2)P_1P_2 + (c/y_2)r_{21}(s_2y_2/s_1y_1)P_2{}^2 - (c/y_1)r_{12}(s_1y_1/s_2y_2)P_1^2}{(c/y_1)(\alpha_2+\gamma_2)P_2P_1^2}\right]^2 + 2\frac{(\alpha_1+\gamma_1)P_1r_{12}(s_1y_1/s_2y_2)}{(c/y_1)(\alpha_2+\gamma_2)P_2P_1^2}} \quad .(13)$$

The quantity and properties of $(\hat{e}_2 - e_2^*)$ are obtained by symmetry.

Equation (13) reveals that in a Cournot-Nash equilibrium, the per capita emission abated by alliance 1 $(\hat{e}_1 - e_1^*)$ rises with the marginal improvement in its own environment generated by its own abatement (α_1), with its marginal benefit from the combined effort of curbing global warming (γ_1), with alliance 2's ability to reward commitment weighted by its relative non-export per capita income ($r_{21}(s_2y_2/s_1y_1)$) and with alliance 2's marginal abatement costs' gradient ($c_2 = c/y_2$). In the Cournot-Nash equilibrium, alliance 1's per capita emission-abatement declines with its own marginal abatement costs' gradient ($c_1 = c/y_1$) and with the size of its own population (P_1). In order to assess the effect of alliance 1's ability to reward alliance 2 and the effect of alliance 2's population size on alliance 1's emission-abatement level in a Cournot-Nash equilibrium note that

$$\frac{\partial(\hat{e}_1 - e_1^*)}{\partial\{r_{12}[(s_1y_1)/(s_2y_2)]\}} = -0.5[1/((\alpha_2+\gamma_2)P_2)]\{1+[1-2(\alpha_1+\gamma_1)/((c/y_1)P_1)]\Delta^{-0.5}\} \quad (14)$$

and

$$\begin{aligned}\frac{\partial(\hat{e}_1 - e_1^*)}{\partial P_2} &= 0.5[((c/y_2)r_{21}(y_2/y_1)/((c/y_1)(\alpha_2+\gamma_2)P_1{}^2)) + (r_{12}(s_1y_1/s_2y_2)/((\alpha_2+\gamma_2)P_2^2))] \\ &\quad + 0.25\Delta^{-0.5}\{((c/y_2)r_{21}(s_2y_2/s_1y_1)/((c/y_1)(\alpha_2+\gamma_2)P_1{}^2)) \\ &\quad + [1-2(\alpha_1+\gamma_1)/((c/y_1)P_1)][r_{12}(s_1y_1/s_2y_2)/((\alpha_2+\gamma_2)P_2^2)]\}\end{aligned} \quad (15)$$

where $\Delta > 0$ is the discriminant (the square of the second term on the right hand side) of equation (13). As long as the population of alliance 1 (P_1) is not very small, $[1-2(\alpha_1+\gamma_1)/((c/y_1)P_1)] > 0$. In which case, the per capita emissions abated by alliance 1 in a Cournot-Nash equilibrium rise with the population of alliance 2 and decline with alliance 1's ability to reward alliance 2 (r_{12}). The emission-abatement moderating effect of the latter factor is increased by alliance 1's relative non-export per capita income $(s_1 y_1 / s_2 y_2)$. Recalling that $\partial(\hat{e}_1 - e_1^*) / \partial\{r_{21}[(s_2 y_2)/(s_1 y_1)]\} > 0$, the total effect of alliance 1's relative non-export per capita income $(s_1 y_1 / s_2 y_2)$ on alliance 1's emission reduction is negative.

Appendix: The Cournot-Nash equilibrium

Recall (11), (12) and (2),

$$\hat{e}_1 - e_1^* = \frac{(\alpha_1+\gamma_1)P_1 + \dfrac{r_{21}(s_2y_2/s_1y_1)}{(\hat{e}_2 - e_2^{\exp})}}{2c_1P_1^2} \tag{A1}$$

and

$$\hat{e}_2 - e_2^* = \frac{(\alpha_2+\gamma_2)P_2 + \dfrac{r_{12}(s_1y_1/s_2y_2)}{(\hat{e}_1 - e_1^{\exp})}}{2c_2P_2^2}. \tag{A2}$$

Let $\theta_1 \equiv \alpha_1+\gamma_1$, $\theta_2 \equiv \alpha_2+\gamma_2$, $\tilde{y}_1 = s_1y_1$ and $\tilde{y}_2 = s_2y_2$ and substitute the right hand side of A1 into A2:

$$\hat{e}_1 - e_1^* = \frac{\theta_1P_1 + \dfrac{r_{21}(\tilde{y}_2/\tilde{y}_1)}{\dfrac{\theta_2P_2 + \dfrac{r_{12(\tilde{y}_1/\tilde{y}_2)}}{(\hat{e}_1 - e_1^{\exp})}}{2c_2P_2^2}}}{2c_1P_1^2} \tag{A3}$$

In turn,

$$2c_1P_1^2(\hat{e}_1 - e_1^*) - \theta_1P_1 = \frac{2c_2P_2^2r_{21}(\tilde{y}_2/\tilde{y}_1)(\hat{e}_1 - e_1^*)}{\theta_2P_2(\hat{e}_1 - e_1^*) + r_{12}(\tilde{y}_1/\tilde{y}_2)} \tag{A4}$$

By rearranging terms,

$$2\theta_2P_2c_1P_1^2(\hat{e}_1 - e_1^*)^2 - [\theta_1\theta_2P_1P_2 + 2c_2P_2^2r_{21}(\tilde{y}_2/\tilde{y}_1) - 2c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2](\hat{e}_1 - e_1^*) - \theta_1P_1r_{12}(\tilde{y}_1/\tilde{y}_2) = 0 \tag{A5}$$

and, consequently,

$$(\hat{e}_1 - e_1^*)^2 - \frac{[0.5\theta_1\theta_2P_1P_2 + c_2r_{21}(\tilde{y}_2/\tilde{y}_1)P_2^2 - c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2]}{c_1\theta_2P_2P_1^2}(\hat{e}_1 - e_1^*) = \frac{\theta_1P_1r_{12}(\tilde{y}_1/\tilde{y}_2)}{2c_1\theta_2P_2P_1^2} \tag{A6}$$

The roots of (A6) are:

$$\hat{e}_1 - e_1^* = 0.5\frac{[0.5\theta_1\theta_2P_1P_2 + c_2r_{21}(\tilde{y}_2/\tilde{y}_1)P_2^2 - c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2]}{c_1\theta_2P_2P_1^2} \pm 0.5\sqrt{\left[\frac{0.5\theta_1\theta_2P_1P_2 + c_2r_{21}(\tilde{y}_2/\tilde{y}_1)P_2^2 - c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2}{c_1\theta_2P_2P_1^2}\right]^2 + 4\frac{\theta_1r_{12}(\tilde{y}_1/\tilde{y}_2)}{2c_1\theta_2P_2P_1^2}} \tag{A7}$$

As the discriminant in (A7) is positive and larger than the absolute value of the coefficient of $(\hat{e}_1 - e_1^*)$ in (A6), only the following root is considered to be relevant:

$$\hat{e}_1 - e_1^* = 0.5\frac{[0.5\theta_1\theta_2P_1P_2 + c_2r_{21}(\tilde{y}_2/\tilde{y}_1)P_2^2 - c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2]}{c_1\theta_2P_2P_1^2} + 0.5\sqrt{\left[\frac{0.5\theta_1\theta_2P_1P_2 + c_2r_{21}(\tilde{y}_2/\tilde{y}_1)P_2^2 - c_1r_{12}(\tilde{y}_1/\tilde{y}_2)P_1^2}{c_1\theta_2P_2P_1^2}\right]^2 + 4\frac{\theta_1r_{12}(\tilde{y}_1/\tilde{y}_2)}{2c_1\theta_2P_2P_1^2}} \quad .\text{(A8)}$$

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