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Global Environmental Problems and the Strategic Choice of Technology

von

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September 1992

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GLOBAL ENVIRONMENTAL PROBLEMS AND THE STRATEGIC CHOICE OF TECHNOLOGY

by

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*I thank Helge Berger and Amihai Glazer for helpful discussion.

Abstract

Reductions of environmentally harmful emissions are often a public good in a global context. For strategic reasons, countries may adopt a technology with high per unit costs of emission reduction, even if a technology with lower per unit costs is available at no extra cost. They thereby commit themselves credibly to not reducing emission much in the future. In a game of private voluntary provision of emission reduction, this commitment will make other countries increase their emission reductions. Also, in the case where countries cooperate in the future, such commitment gives a country a strategic advantage, because it shifts the disagreement point in a favorable direction.

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1. Introduction

In recent years scientists and a broader public have become increasingly aware of global environmental problems like the greenhouse effect (Nordhaus 1991), deforestation, the loss of bio–diversity, and the destruction of the ozone layer by emissions of CFC. These effects are the most prominent examples of a class of environmental problems in which only aggregate global emissions or the aggregate activity level are important for determining the damage caused. The damage is non–exclusive and non–rival, and independent of how aggregate emissions are shared among regions or countries. For instance, the radiation protection that is provided by an undamaged ozone layer is a pure public good. Its deterioration hurts globally, and nobody is excluded from a reduction of its quality. Carraro and Siniscalco (1991) point out that this public good property of many global environmental phenomena, combined with the absence of supra–national regulatory government, results in a potential for resource misallocation, and this makes the problem a focus in recent environmental economics. For global problems like the destruction of the ozone layer, countries can be considered to be the relevant economic agents, and their regulatory policy options are their decision variables. Ploeg and Zeeuw (1992) and Hoel (1992a), for instance, concentrate on the intertemporal stock–flow properties of a private provision game for emission reduction. Hoel (1991a, 1991b, 1992b) analyses questions of different measures of international cooperation. Frankhauser and Kverndokk (1992) calculate expected effects of different cooperation regimes.

Hoel (1991a) shows that a country's benevolent unilateral voluntary emission reduction commitment that precedes an environmental convention in which aggregate emission reductions are collectively decided may increase total emissions compared to a situation where all countries act selfishly. This paper is related to Hoel (1991a) from a structural point of view. It, too, is concerned with actions that are taken before a non–cooperative or cooperative game of emission reduction in a multi–country model takes place, where the sum of emissions is a public good for all

countries. Countries first choose their emission reduction technology. When choosing its production technology, a country can decide to apply a technology for which emission reduction is more or less expensive. For instance, when fixed capital is built up by investing in a particular technology, the cost of future emission reduction is irreversibly determined, but not necessarily the quantity of reductions. When some technological commitments are already made, representatives of countries come together in environmental conventions and bargain on emission reductions. They may reach a cooperative agreement. Otherwise they play a non–cooperative game of voluntary emission reduction. It turns out that the technology decision of a country is of strategic importance for the amount of its emission reduction in the non–cooperative as well as in the cooperative equilibrium.

For illustration, suppose that a country chooses between two types of power plants, one with wide pipes that allow for the installation of emission reduction devices at low extra cost, and one with narrow pipes, where the later introduction of an emission reduction device requires the existing pipes to be replaced by appropriately wide ones. Suppose that, in the absence of emission reduction devices, both types of plants are equally expensive. One might naturally assume that a country would prefer to install the plant with the wide pipes, so as not to incur high costs of emission reduction, regardless of whether its own reductions are determined in a non–cooperative or cooperative emission reduction game in the future. Not so. In many circumstances the country will choose the plant with the narrow pipes and high later emission reduction costs. The reason is that, by choosing the technology with high marginal costs of emission reduction, the country can shift some of the burden of emission reduction to other countries. In the non–cooperative solution, higher costs of emission reduction in a country make it more credible for it to be a free rider in a non–cooperative Nash game. In the cooperative solution, the country with high emission reduction costs has an advantage because its technology choice changes the non–cooperative solution, and the non–cooperative solution is the

"disagreement point" in the bargaining game.

The problem is studied in a two–stage setting. At stage 1 countries choose their technology; they make irreversible investments that determine their future unit costs of emission reduction. At stage 2 countries play non–cooperatively or cooperatively. If they play non–cooperatively, emission reduction of each country is like voluntary provision of a public good. The standard model of private provision of a public good (e.g., Bergstrom, Blume and Varian 1986) will be adequate to describe the stage–2 equilibrium outcome. Alternatively, they may agree on a cooperative Nash bargaining solution with side payments. In any case, the choice of emission reduction technology will determine each country's utility in the stage–2 equilibrium; and this will make them choose strategically in stage–1.

2. Voluntary emission reductions

Consider countries $i = 1,...n$. Each country has utility

$$u(y_i,G), \tag{1}$$

where y_i is the amount of an universal good consumed in country i, and $G = \Sigma_i g_i$ are aggregate reductions of environmentally harmful emissions, with $g_i \geq 0$ the emission reduction in country i. This supposes that, without emission reduction, the emission level of country i is exogenously given to be some $\overline{E}_i > 0$, and actual emissions of a country are $\overline{E}_i - g_i$. The utility function (1) suggests that utility of a country depends on *aggregate* emissions $\Sigma_i \overline{E}_i - g_i$ only, or, what is equivalent for exogenous $\overline{E}_i$ for $i = 1,...n$, on aggregate reductions G, but not on how these reductions are shared among countries. Utility (1) is twice continuously differentiable with positive marginal utilities u_y and u_G of consumption of the

universal good and of aggregate emission reductions, and strictly concave. Output of the universal good is a function

$$y_i = m - \lambda_i g_i, \tag{2}$$

where m is an exogenous output level, and λ_i is the cost to country i of reducing a unit of emission. For simplicity only, marginal costs λ_i are independent of the quantity of reductions, and are measured in units of the universal good. Each country can choose λ_i by its choice of technology. All technologies yield the same output m that can be considered as net of all capital cost, installation cost etc. However, the technologies differ with regard to unit reduction costs $\lambda_i \in [\lambda_{min}, \lambda_{max}]$ with $\lambda_{min} > 0$.

Note that this implies that a country incurs no extra cost for choosing a technology with lower unit costs of emission reduction. This assumption could be replaced by assuming that a technology with lower unit costs of emission reduction has different installation costs. The cost associated with installing a particular reduction technology would enter like set up costs and would be sunk in the stage–2 game when only emission reduction quantities are determined. If set up costs were different for technologies with different unit costs of emission reduction, this model complication would not offset the basic incentive mechanism that is derived in this paper, but would distract attention from it. What makes the result in this paper surprising is that the strategic incentive to choose an expensive technology occurs *despite* the assumption that the technology with lower cost of emission reduction is available at no extra cost.

The technology choice occurs before the production and emission reduction activity. Therefore, the following two games with two stages are considered:

NON-COOPERATIVE GAME

Stage 1: All countries choose simultaneously their λ_i. This choice then becomes public knowledge.

Stage 2: All countries choose simultaneously their emission reduction g_i, $i = 1,...n$, assuming that their own decision on emission reduction does not affect the choices of emission reduction of other countries.

and

COOPERATIVE GAME

Stage 1: As in the non–cooperative game.

Stage 2: Countries ($n = 2$) participate in a Nash–bargaining solution with side–payments. The "disagreement point" is the non–cooperative stage 2 equilibrium of the non–cooperative game.

In both games, the non–cooperative stage–2 Nash game of choosing $(g_1,...,g_n)$ for given technology choices of others plays a crucial role. This goes without saying for the non–cooperative game. In the cooperative game, the stage–2 non–cooperative equilibrium influences the cooperative outcome because it describes the point of disagreement.

This section describes the non–cooperative Nash game at stage 2. The choices of λ_i for $i = 1,...n$ are given at stage 2. The decision problem of country i, which optimizes its choice of g_i for given λ_i under the Nash conjecture that its emission reduction choice g_i *does not affect the emission reductions* of others, can be described as follows. It maximizes (1) by its choice of g_i, subject to its budget constraint (2) and the non–negativity constraints $g_i \geq 0$ and $y_i \geq 0$. Emission reductions and consumption of the universal good cannot be negative. As is standard in the literature on private provision of a public good (see, e.g., Bergstrom, Blume and Varian 1986), this problem can be recast as a problem of choosing G, the aggregate emission reduction as to

(3) $$\max_G \; u(y_i,G)$$

s.t.

$$y_i + \lambda_i G \leq m + \lambda_i G_{-i}\,, \tag{4}$$

$$G - G_{-i} \geq 0\,, \tag{5}$$

$$y_i \geq 0\,. \tag{6}$$

Inequalities (5) and (6) express the requirement that a country's emission reductions $g_i = G - G_{-i}$ and that consumption should be non–negative. Here, $G_{-i} = \Sigma_{j \neq i}\, g_i$ is the reduction of emissions by all others. Inequality (4) is the new budget constraint that says that i's *imputed expenditure* (left hand side) is not larger than its *imputed income* and (4) follows from (2) by adding $\lambda_i G_{-i}$ to both sides. By its choice of g_i, country i implicitly chooses G; it considers its emission reductions as the marginal emission reductions, because it takes the reductions of all others as given.

A Nash equilibrium can be defined as a vector $(g_1^*,\ldots g_n^*)$ for given $(\lambda_1,\ldots \lambda_n)$ such that $G^* = \Sigma_i\, g_i^*$ solves the maximization problem (3) for i for given $G_{-i}^* = \Sigma_{j \neq i}\, g_j^*$, for all $i = 1,\ldots n$.

The paper makes the following normality assumption. There is a single–valued demand function for the public good, $f_i(\omega)$ [$i = 1,\ldots n$] which is the solution of (3) subject to (4), but ignoring the inequality constraints (5) and (6). This demand function is a differentiable function of imputed income ω given by the right hand side of (4). The marginal propensity to reduce emissions is greater than zero and smaller than $1/\lambda_i$ for $i = 1,\ldots n$: both private and public good are strictly normal goods. Under this condition the voluntary provision game has nice properties:

Proposition 1

The Nash equilibrium in pure strategies exists and is unique.

The proof of Proposition 1 is straightforward and follows precisely the lines of arguments in Bergstrom *et al.* (1986). The paper concentrates on a symmetric and

interior equilibrium with $\lambda = \lambda_1 = \lambda_2 = \ldots = \lambda_n$. By (3) and (4), it has the property that, for all i = 1,...n,

$$\lambda_i u_y(y_i,G) = u_G(y_i,G), \tag{7}$$

where subscripts y and G denote partial derivatives of u with respect to the first and the second argument. Each country chooses G such that it is indifferent between contributing a further unit emission reduction, which costs λ_i units of the universal private good, and consuming these λ_i units as private consumption. The equilibrium has the standard underprovision properties of Nash equilibria of voluntary provision of public goods. Immediately from (7),

$$n\, u_G > \lambda\, u_y, \quad \text{for } n \geq 2, \tag{8}$$

where the Samuelson–Lindahl condition for efficiency would require equality in (8). Given the assumptions about u, this implies that for $n \geq 2$ the reduction of emissions in a private provision game with Nash conjectures is too small compared to a welfare optimum.

The optimal amount and the Nash equilibrium amount of aggregate emission reduction depend on the choice of emission reduction technology. The next step in the analysis is to consider the incentives countries have in choosing their emission reduction technology, knowing that there will be a private provision game in the future. The idea is to show that the choice is biased by strategic considerations. A country with low reduction costs has a larger incentive to reduce emissions in the stage–2 Nash equilibrium. By choosing a reduction technology with high marginal costs, a country obtains a strategic advantage. It is expected to reduce emissions by less, and other countries will therefore increase their reductions. This kind of external effect of commitment leads to something like an arms race for reduction technologies with high cost of emission reduction.

3. The non–cooperative equilibrium

To approach the problem of characterizing the perfect equilibrium choice of emission reduction costs of the 2–stage non–cooperative game the paper first derives the comparative static properties of a change of one country's choice of λ_i by $d\lambda_i$ in a symmetric situation with $\lambda = \lambda_1 = ... = \lambda_n$ at stage 2.

Proposition 2

For given $\lambda_1 = ... = \lambda_n$, a marginal change of λ_i changes the equilibrium emission reductions by

$$dg_i/d\lambda_i = c\,\frac{b + (n-2)a}{(b+(n-1)a)(b-a)} < 0\,, \tag{9}$$

$$dg_j/d\lambda_i = -ca\,\frac{1}{(b+(n-1)a)(b-a)} > 0 \text{ for } j \neq i, \tag{10}$$

and

$$dG/d\lambda_i = c\,\frac{1}{(b+(n-1)a)} < 0\,, \tag{11}$$

with

$$a \equiv \lambda u_{yG} - u_{GG} > 0\,, \tag{12}$$

$$b \equiv -\lambda^2 u_{yy} + 2\lambda u_{yG} - u_{GG} > 0\,, \tag{13}$$

$$c \equiv -u_y + \lambda u_{yy} g_1 - u_{yG} g_1 < 0\,. \tag{14}$$

A proof is given in the appendix. The expressions u_{yy}, u_{yG} and u_{GG} denote second partial derivatives of u with respect to y and G.

Proposition 2 allows an intuition to be derived concerning the strategic effect of choosing the technology that determines the unit costs of emission reduction. Consider the case with many countries. Country 1 reduces its emissions by less if it increases λ_i, and this effect does not vanish for large n. More specifically, $\lim_{n\to\infty} dg_i/d\lambda_i = c/(b-a) < 0$, and is bounded away from zero. The effect on

aggregate emission reduction is $\lim_{n\to\infty} dG/d\lambda_i = 0$. If the number of countries that contribute to global pollution is sufficiently large, then, if a country increases its emission reduction costs and therefore reduces less emission in the equilibrium, its increase of emissions is almost completely compensated by additional reductions of emissions by the other countries. This effect exists for any $n \geq 2$ and provides the strategic incentive to choose a more expensive emission reduction technology than would be efficient. It has to be shown that this incentive can dominate the cost advantage of choosing a technology with low unit costs of emission reduction. In the framework used here countries can choose the technology with lowest unit costs of emission reduction for the same price as any other technology; but they still may not want to do this. It appears to be better for a country to choose a technology with higher emission reduction costs; the benefits of additional future free riding on other's emission reductions outweighs the own cost disadvantage when reducing emissions in the future. A sufficient condition for this to happen is

$$\frac{du(y_i,G)}{d\lambda_i}\Big|_{\lambda_j = \lambda_{min} \text{ for } j = 1,\ldots n} > 0\,, \tag{15}$$

or,

$$\left[-g_i - \lambda_{min}\frac{dg_i}{d\lambda_i}\Big|_{\lambda_{min}}\right] u_y + \frac{dG}{d\lambda_i}\Big|_{\lambda_{min}} u_G > 0\,,$$

or, using the stage–2 Nash equilibrium condition (7),

$$g_i < \lambda_{min}\frac{dG_{-i}}{d\lambda_i}\Big|_{\lambda_{min}}\,. \tag{16}$$

The left–hand side is the marginal additional cost of increasing λ_i. The country pays higher emission reduction costs on all units of emission reduction in the stage–2 equilibrium. The right–hand side is the benefit of a commitment to higher unit

cost; By (10) and (11),

$$\frac{dG_{-i}}{d\lambda_i} = \frac{-(n-1)ca}{(b+(n-1)a)(b-a)} ,$$

and is positive. Other countries provide more emission reduction if country i increases its cost. In general, whether condition (16) is fulfilled depends on $u(y_i,G)$, λ_{min} and the number of countries:

Proposition 3

A choice $\lambda_i > \lambda_{min}$ is strategically advantageous for any $\lambda_{min} > 0$ if the number of countries is sufficiently large.

Proof. Consider the stage–2 private provision equilibrium for $\lambda_j = \lambda_{min}$ for all $j = 1,...n$. McGuire (1974) and Andreoni (1988) showed that, if $n \to \infty$, aggregate provision of the public good converges to some upper limit, $\overline{G}$. Therefore, $\lim_{n\to\infty} g_i \leq \lim_{n\to\infty} \overline{G}/n = 0$. However, $\lim_{n\to\infty} \frac{dG_{-i}}{d\lambda_i} = -\frac{c}{b-a} > 0$. This implies $\lim_{n\to\infty} \frac{du(y_i,G)}{d\lambda_i}\Big|_{\lambda_j = \lambda_{min}} = -\frac{c}{b-a} u_G > 0$. ■

This discussion can be summarized as follows. For many parameter values $\lambda_1 = ... = \lambda_n = \lambda_{min}$ is not a perfect equilibrium; the strategic incentive effect of an increase of λ_i can overcompensate the cost effect. It is useful to consider briefly the properties of a symmetric perfect equilibrium with $\lambda^* > \lambda_{min}$. This equilibrium requires λ^* such that, given the functional relation between λ^* and contributions $(g_1,...,g_n)$ in the stage–2 game, for all countries $i = 1,...n$,

$$\frac{du(y_i,G)}{d\lambda_i}\Big|_{\lambda_i = \lambda^*} = 0 ,$$

or, using the stage–2 Nash equilibrium condition (7),

$$\lambda^* = g_i^* / \frac{dG_{-i}}{d\lambda_i} \Big|_{\lambda^*} \tag{17}$$

Countries choose λ^* from an interval $[\lambda_{min},\lambda_{max}]$. Given the assumption that all technologies have the same set–up costs, efficiency would indicate that all countries choose the minimum unit cost of emission reduction. This would still lead to an underprovision of emission reduction in the second–stage equilibrium, but, compared to any other $\lambda^* > \lambda_{min}$, this would be a Pareto improvement. Condition (17) implies that the equilibrium value of λ may well be drawn from the interior of the interval $[\lambda_{min},\lambda_{max}]$, or a corner solution for $\lambda^* > \lambda_{max}$ may even result as the choice in the perfect equilibrium.

Equation (17) is only a necessary condition for an interior symmetric perfect equilibrium in pure strategies. In general, (17) may be fulfilled for several λ^*: the equilibrium quantity g_i^* of reductions is decreasing in λ^*; however, $\frac{dG_{-i}}{d\lambda_i}$ may decrease or increase in λ^*. A sufficient condition for (17) to characterize a perfect symmetric equilibrium would be to require that, for $\lambda_1 = ... = \lambda_{i-1} = \lambda_{i+1} = ... \lambda_n = \lambda^*$, u^i is concave in λ_i on the interval $[\lambda_{min},\lambda_{max}]$. In general, particularly if λ_{min} is sufficiently small compared to λ^*, a country may find it attractive to give in and to choose λ_{min}. In this case a pure–strategy equilibrium may not exist. But even in this case the equilibrium is not one in which all countries choose λ_{min} with probability one, but λ is strategically chosen too high from an efficiency perspective.

4. Cooperative solutions

Suppose now that countries know that at stage 2 they will meet at some environmental convention and bargain about emission reductions. The paper considers Nash bargaining with side payments. To apply standard Nash bargaining

concepts, and to avoid considerations of coalition formation between some countries, the number of countries is restricted to n = 2.

The choice of unit costs of emission reduction affects the outcome of the bargaining game in two ways. First, it affects the utility possibility frontier as shown in Figure 1.

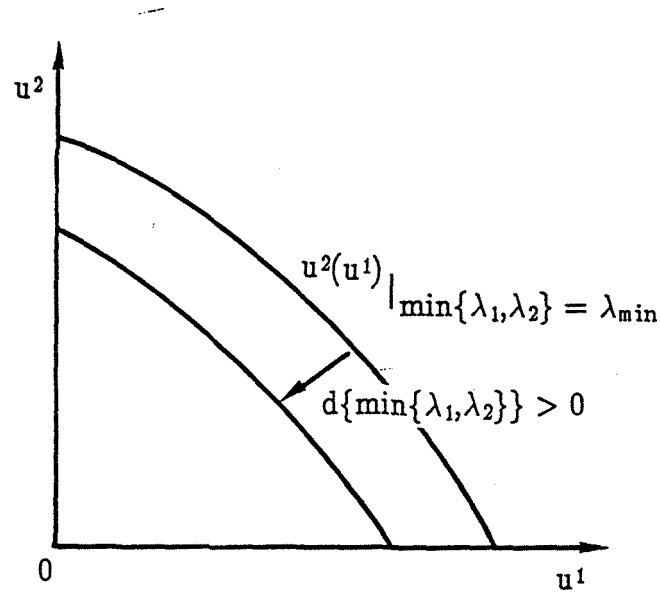

Figure 1

In a Nash bargaining game with side payments, the outcome is Pareto efficient, and, therefore, characterized as follows. For given emission reduction costs (say, $\lambda_1 \geq \lambda_2$), all emission reduction will be provided by the country with lower cost of emission reduction (for instance, country 2). If both countries have the same marginal cost of emission reduction, they may split aggregate emission reductions between them. The countries agree on emission reductions $g_1 + g_2 = G^0$ and side payments s^0 such that G^0 solves the problem of maximizing

(18) $$u^2(m-\lambda_2 G^0 + s^0, G^0)$$

s.t.

(19) $$\bar{u}^1 - u^1(m - s^0, G^0) \geq 0$$

for some value of $\bar{u}^1$. The set of Pareto efficient combinations (u^1,u^2) for given λ_1 and λ_2 is depicted in Figure 1 as $u^2(u^1)$. An increase of $\min\{\lambda_1,\lambda_2\}$ implies that, for the same quantity of G provided, the amount of the universal good that can be distributed between the two countries is smaller. Therefore, an increase of $\min\{\lambda_1,\lambda_2\}$ shifts the utility possibility frontier $u^2(u^1)$ inside.

Further, as seen in the previous section, the choice of emission reduction costs affects the outcome of the non–cooperative stage–2 game. This outcome is not the equilibrium in the cooperative game, but it affects the cooperative outcome because it is the disagreement point in the Nash bargaining game. Given these two channels, it appears likely that the choice of cost of emission reduction is made strategically.

Proposition 4

Suppose that the utility possibility frontier $u_2(u_1)$ is convex for given (λ_1,λ_2), and (15) is fulfilled for $\lambda_1 = \lambda_2 = \lambda_{min}$. Then countries have an incentive to choose an inefficiently high $\lambda > \lambda_{min}$ in the cooperative game.

Proof. Suppose that country 2 chooses $\lambda_2 = \lambda_{min}$. The utility possibility frontier $u^2(u^1)$ does not depend on country 1's choice of $\lambda_1 \geq \lambda_2$; the optimal amount of emission reduction can be carried out by using country 2's technology. This possibility frontier is drawn in Figure 2. The point A is the disagreement point if country 1 also chooses $\lambda_1 = \lambda_{min}$. Section 3 showed that country 1 can influence the non–cooperative equilibrium outcome. If (15) is fulfilled, then, by an increase of λ_1, country 1 can increase its utility in the non–coopaertive outcome; moreover, by (9), in this non–cooperative outcome country 1's emission reduction becomes smaller.

This implies that $\frac{du^{2*}}{d\lambda_1} < 0$ at $\lambda_1 = \lambda_2 = \lambda_{min}$ for the non–cooperative outcome. Therefore, by choosing $\lambda_1 > \lambda_{min}$, country 1 changes the point of disagreement: the utility levels in the non–cooperative stage–2 game move towards point B in Figure 2. If $u^2(u^1)$ is concave, then this implies that the bargaining outcome moves from the symmetric equilibrium (point C) toward a point D with higher utility of country 1. This can be shown as follows. The bargaining solution is determined by

$$(20) \qquad (u^2(u^1) - u^{2*})(u^1 - u^{1*}) \rightarrow \max,$$

where $u^2(u^1)$ is the utility possibility frontier, and u^{i*} is the utility level of i = 1,2 in the disagreement point. The first–order condition of (20) is

$$(21) \qquad \frac{du^2}{du^1}(u^1 - u^{1*}) + u^2(u^1) - u^{2*} = 0.$$

Differentiation with respect to u^{1*} and u^{2*} yields

$$(22) \qquad \left[\frac{d}{du_1}\left(\frac{du^2}{du^1}\right)(u^1 - u^{1*}) + 2\frac{du^2}{du^1}\right] du^1 = \frac{du^2}{du^1} du^{1*} + du^{2*}.$$

By concavity of $u^2(u^1)$ and by the negative slope of the efficiency frontier, this reveals that

$$(23) \qquad \frac{du^1}{du^{1*}} > 0 \quad \text{and} \quad \frac{du^1}{du^{2*}} < 0,$$

and, therefore,

$$(24) \qquad \frac{du^1}{d\lambda_1}\Big|_{\lambda_{min}} > 0.$$

Given that country 2 chooses λ_{min}, country 1 has an incentive to choose strategically a higher cost of emission reduction. ■

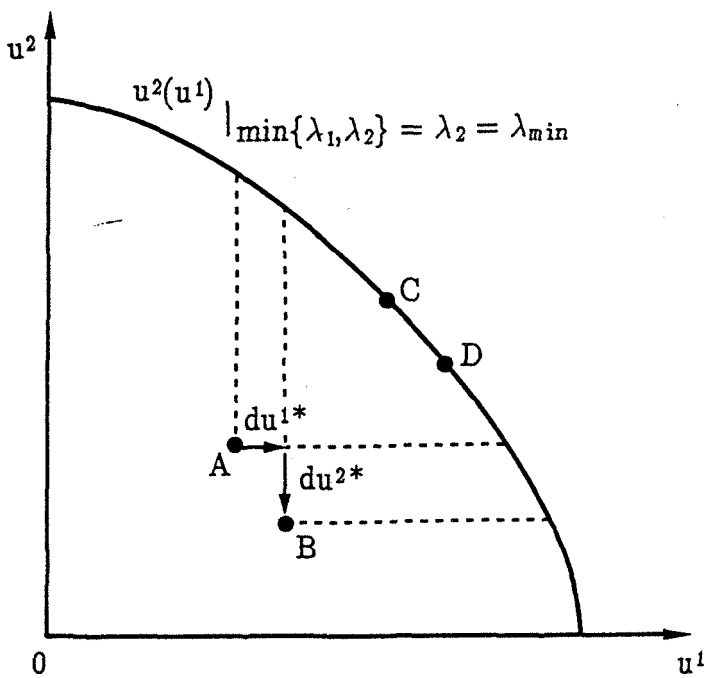

Figure 2

Suppose that $\lambda_1 = \lambda_2 = \lambda^*$, with λ^* the technology choice is a perfect non–cooperative equilibrium. It is then not a solution of the cooperative bargaining game. Suppose that $\lambda_2 = \lambda^*$ and consider whether, for $\lambda_1 = \lambda^*$, country 1 can improve its situation by changing λ_1. A marginal increase of λ_1 does not change the efficiency frontier, as $\min(\lambda_1,\lambda_2) = \lambda^*$ is unchanged. It also does not change country 1's utility at the disagreement point by definition of λ^* in (17), i.e., $\frac{du^{1*}}{d\lambda_1}\Big|_{\lambda^*} = 0$. However, it decreases country 2's utility u^{2*} at the disagreement point by

$$\frac{du(y_2,G)^*}{d\lambda_1}\Big|_{\lambda^*} = u_y\left[-\lambda^* \frac{dg_2}{d\lambda_1}\Big|_{\lambda^*}\right] + u_G \frac{dG}{d\lambda_1}. \tag{25}$$

By Proposition 2, $\frac{dg_2}{d\lambda_1}|_{\lambda^*} > 0$, and $\frac{dG}{d\lambda_1} < 0$, implying that $\frac{du^{2*}}{d\lambda_1}|_{\lambda^*} < 0$. Consequently, by (22), $\frac{du_1}{d\lambda_1}|_{\lambda^*} > 0$. Therefore, $\lambda_1 = \lambda_2 = \lambda^*$ cannot be a perfect equilibrium of the 2–stage cooperative game. If $\lambda_1 = \lambda_2 = \lambda^*$ is a unique perfect equilibrium of the non–cooperative game, then this argument shows that cooperation may even aggravate the problem of strategic choice of technology.

5. Conclusions

Decisions on the quantity of emission reduction and on the technology chosen often do not occur simultaneously. Often a basic decision for a particular type of technology is made, and later emission standards are set and appropriate emission *reduction devices* are installed. A country can influence the technological decision and can also regulate emissions by the different instruments that are well discussed in the literature on environmental economics. If environmentally harmful emissions lead to damage that is a public good, interaction between countries has to be considered. Countries choose their quantities of emission reduction, either cooperatively or non–cooperatively.

The paper considers this two stage decision by countries. They have to decide on irreversible investment today, knowing about the interaction between countries with respect to emission reduction in the future, as reduction of environmentally harmful emissions is globally a public good. Countries are shown to have a strategic incentive to irreversibly choose a technology with high unit costs of emission reduction today, even if a technology with cheaper per unit costs of emission reduction is available at no extra cost. Investment in a technology with high emission reduction costs is a way of making a commitment. In the future, if country A is commited to having a technology with high marginal costs of emission reduction, it is easy and credible for this country to claim that it will not reduce

emission by much. In a game of private voluntary provision of emission reduction, other countries will reduce more and will partially compensate for country A's high emissions. But also in the case where countries cooperate in the future, commitment to high costs gives country A a strategic advantage, because it shifts the disagreement point in a favorable direction.

The case considered here is perhaps counter intuitive at first sight. It is in line with recent work on intertemporal strategic behavior, though. Anticipation of future interaction leads to strategic behavior. Examples in the literature are entry deterrence in oligopoly theory, preemptive behavior in upcoming contests (Dixit 1987), principal agent theory, or the public choice literature on political decision making in an intertemporal context (see, e.g., Glazer 1989, Tabellini and Alesina 1990).

The outcome of the games considered here is not very satisfying from a welfare perspective. Even if set–up costs are identical, countries have an incentive not to prefer a technology with lower emission reduction costs. If countries also could cooperate at the stage when technology is chosen, they would collectively agree on a technology with lower emission reduction costs. But precisely because they interact in the future, they have an incentive to choose the one with the higher unit costs. In a way, of course, the dimension of the problem is reduced by the fact that most emission reduction occurs via choosing the less polluting technology when investing in a new plant. Strategic commitment is not possible if technology choice and emission reduction choice occur simultaneously. However, the effect this paper stresses applies in situations where durable capital goods have a sufficiently long lifespan so that emission reduction does not occur via replacement, but via changes in the existing plant. Further, sometimes countries may choose a path of industrial development that uses one or the other technology and a switching of technologies may turn out to be very expensive, e.g., because of network externalities or because of high R&D costs. In this case, it is not the lifespan of a single plant that

determines the time of commitment, but the much larger time span of a particular industrial development path. An example may be the decision for nuclear power plants versus conventional coal burning plants. This example may highlight the fact that switching from one technology to the other is sufficiently costly for a country to be credibly commited to retaining its existing technology.

This paper reveals a mechanism that has more applications in other fields of economics. In the international context there are numerous public goods. Some of them are artificially created by the political structure. Examples within the European Community are the reduction of agricultural excess production, development aid to underdeveloped countries, the reduction of subsidies and reduction of national protection of declining industries, or abstinence from arms export. In some of these cases the aggregate quantity of the particular public good is determined non–cooperatively, in some other cases by cooperative agreements. But often countries can make binding commitments that allow them to shift a larger share of the burden of provison of the public good to other countries. As this paper shows, cooperation in a later stage does not necessarily reduce such commitment incentives. The opposite may be the case.

Appendix

Differentiate the system of n equations

$$\lambda_j u_y(m-\lambda_j g_j, G) - u_G(m-\lambda_j g_j, G) = 0 \quad \text{for } j = 1,\ldots n$$

at $\lambda = \lambda_1 = \ldots = \lambda_n$ with respect to a particular λ_i, say $i = 1$. This yields the system of equations (with a,b and c defined in Proposition 2,)

$$\begin{bmatrix} b & a & a & \ldots & a \\ a & b & a & \ldots & a \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ a & a & a & \ldots & b \end{bmatrix} \begin{bmatrix} dg_1 \\ \\ \vdots \\ \\ dg_n \end{bmatrix} = \begin{bmatrix} c \\ 0 \\ \vdots \\ \\ 0 \end{bmatrix} d\lambda_1 .$$

$$\Leftrightarrow \qquad X\,[dg] \;=\; [c]\, d\lambda_1.$$

Note that $\det X = \det \begin{bmatrix} b & a & a & \ldots & a \\ a-b & b-a & 0 & \ldots & 0 \\ a-b & 0 & b-a & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a-b & 0 & 0 & \ldots & b-a \end{bmatrix} =$

$$= \det \begin{bmatrix} b & a & a & \ldots & a \\ 0 & b-a & 0 & \ldots & a-b \\ 0 & 0 & b-a & \ldots & a-b \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a-b & 0 & 0 & \ldots & b-a \end{bmatrix} = \det \begin{bmatrix} b & a & a & \ldots & a \\ 0 & b-a & 0 & \ldots & a-b \\ 0 & 0 & b-a & \ldots & a-b \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & (b-a)\frac{a}{b} & (b-a)\frac{a}{b} & \ldots & (b-a)+(b-a)\frac{a}{b} \end{bmatrix} =$$

$$\det \begin{bmatrix} b & a & a & \ldots & a \\ 0 & b-a & 0 & \ldots & a-b \\ 0 & 0 & b-a & \ldots & a-b \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & (b-a)\frac{a}{b} & \ldots & (b-a)+2(b-a)\frac{a}{b} \end{bmatrix} =$$

$$\det \begin{bmatrix} b & a & a & \dots & a \\ 0 & b-a & 0 & \dots & a-b \\ 0 & 0 & b-a & \dots & a-b \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & (b-a)+(n-1)(b-a)\frac{a}{b} \end{bmatrix} =$$

$$= b\,(b-a)^{n-2}[(b-a) + (n-1)(b-a)\tfrac{a}{b}]$$
$$= (b-a)^{n} + na(b-a)^{n-1}$$
$$= [b + (n-1)a](b-a)^{n-1}.$$

Note further that

$$\det [CX_1] \equiv \det \begin{bmatrix} c & a & a & \dots & a \\ 0 & b & a & \dots & a \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & a & a & \dots & b \end{bmatrix} = c \det \begin{bmatrix} b & a & \dots & a \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a & a & \dots & b \end{bmatrix} = c\,[b + (n-2)a](b-a)^{n-2}.$$

Applying Cramer's rule yields

$$dg_1/d\lambda_1 = \frac{\det\ [CX_1]}{\det\ X} = \frac{c[b\ +\ (n-2)a]}{[b\ +\ (n-1)a]\ (b-a)}\ .$$

Similarly, note that

$$\det [CX_2] \equiv \det \begin{bmatrix} b & c & a & \dots & a \\ a & 0 & a & \dots & a \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ a & 0 & a & \dots & b \end{bmatrix} = -c \det \begin{bmatrix} a & a & \dots & a \\ a & b & \cdot & a \\ \vdots & \vdots & \cdot & \vdots \\ a & a & \dots & b \end{bmatrix}$$

$$= -c \det \begin{bmatrix} a & a & \dots & a \\ 0 & b-a & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & b-a \end{bmatrix} = -c\,a(b-a)^{n-2}.$$

Applying Cramer's rule,

$$dg_2/d\lambda_1 = \frac{\det[CX_2]}{\det X} = \frac{-ca}{[b + (n-1)a](b-a)}\ ,$$

and, by symmetry, $dg_j/d\lambda_1 = dg_2/d\lambda_1$ for all $j = 3,\dots n$. This is used to calculate the effect on aggregate emission reduction in the equilibrium,

$$dG/d\lambda_1 = \Sigma_i\,(dg_i/d\lambda_1) = \frac{c}{b - (n-1)a}\ .$$

But $c < 0$, $a > 0$ and $b > 0$ by concavity of u. ■

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