# The Dynamics of Climate Agreements

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**Abstract**

I study dynamic private provision of public goods (or bads) when agents (or countries) can invest in cost-reducing technologies and sign incomplete contracts. The model leads to a dynamic common pool problem that is more severe than its static counter-part. Nevertheless, a sequence of short-term agreements on contribution levels makes everyone *worse off* since countries invest less when they anticipate future negotiations. Long-term agreements induce countries to invest more. The best agreement is more demanding if the time horizon of the agreement is short and the externality from investing large (e.g., if the patent system is weak). If investments can be subsidized, the subsidy should be larger if the agreement is short-lasting. The *first best* can always be implemented by long-term agreements with renegotiations. The results have implications for the optimal design of climate treaties and they hold whether permits are tradable, non-tradable or if instead emission taxes are used.

*Key words*: Dynamic private provision of public goods, dynamic common pool problems, dynamic hold-up problems, time horizon of agreements, renegotiation design, climate change and climate agreements

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## 1. Introduction

This paper studies dynamic private provision of public goods when the agents can invest in cost-reducing technologies. The unique Markov-perfect equilibrium is compared to situations where the agents can contract on provision levels but not on investment levels, and the optimal contract is derived.

While the model fits many contexts with private provision of public goods, climate change is a particularly important application. Environmental agreements (e.g. the Kyoto protocol) are specifying pollution levels but not investments in technology. They typically have a limited time horizon, and future commitments remain to be negotiated. To fix ideas, I therefore call the agents "countries", and I focus on a public bad instead of a public good (a public bad can easily be reformulated to a public good). The public bad is the stock of greenhouse gases, and all countries suffer from a cost that is a convex function of the pollution stock level. At the same time, each country finds it costly to reduce its own emission level. This creates a common-pool problem that is dynamic since pollution cumulates over time. In addition, I let the countries invest in technology. A country's investment increases its stock of technology, which may be interpreted as abatement technology (alternatively, it can be interpreted as its renewable energy sources). There might also be an externality from a country's investment, since other countries may be able to simply copy some of the generated ideas.

In the business-as-usual equilibrium, countries act non-cooperatively at all stages. If one country happens to pollute a lot, the other countries are, in the future, induced to pollute less since the problem is then more severe. At the same time, they find it optimal to invest more in technology, to be able to afford the anticipated reduction in emission. If a country invests a lot in abatement technology, on the other hand, everyone understands that this country is polluting less in the future, and the other countries find it optimal to increase their emission levels as well as reduce their investments in abatement technology. Anticipating these effects, a country is induced to pollute more and invest less than it would in a static model (or in the open-loop equilibrium). Thus, the dynamic common pool problem is more severe than its static counterpart.

Nevertheless, short-term agreements make everyone *worse off*. The reason is that a hold up problem is created when the countries negotiate emission levels: If one country has a large stock of technology, it can reduce its emission level fairly cheaply, and the other countries will demand that it bears the lion's share of the burden when emissions are reduced. Anticipating this, countries invest less when negotiations are anticipated, and this makes everyone worse off, particularly if the time horizon of an agreement is short and the number of countries large.

The hold-up problem may be mitigated by long-term agreements, if commitments are determined before the countries invest in technology. Then, a country cannot be hold up if it invests a lot in technology - at least not as long as the agreement lasts. Thus, countries invest more when agreements are long-lasting. Nevertheless, countries are likely to invest too little, also under long-term agreements, if (i) the externality is positive and large and (ii) the agreement is not lasting forever (since countries then anticipate that investments harm their future bargaining position). To encourage countries to invest more, the best long-term agreement is more ambitious (i.e., the emission levels are lower) if the externality is positive and large and the time horizon of the agreement short.

But a long-term agreement is not optimal ex post, once the investments are sunk and the state of the world realized. It may thus be tempting for the countries to renegotiate the agreement at that stage. By renegotiating the initial agreement, emission levels are negotiated to the ex post optimal level. The role of the initial agreement is then only to affect the incentives to invest. And, the more ambitious is the initial agreement, the more the countries invest. When the initial agreement is very ambitious, countries with poor technology has a bad bargaining position since they are going to be "desperate" when renegotiating the initial, ambitious, agreement. It is then the high-tech countries that are going to get the better deal. Anticipating this, countries invest more in technology, particularly if the initial agreement is very ambitious. Since investments are particularly beneficial if the externality is large and the time horizon short (i.e., when countries otherwise under-invest), the agreement should be more ambitious in these circumstances.

In sum, the analysis generates several lessons for the design of contracts in a dynamic setting. Short-term agreements can actually be worse than no agreement at all, and long-term agreements should be more ambitious than what is optimal ex post, particularly if the externality is large and the time horizon of the agreement short. Carefully designed long-term agreements with renegotiation implement the first best emission levels as well as investments.

The paper is organized as follows. After presenting a linear-quadratic model in the next section, Section 3 solves the model under four scenarios: (i) business as usual (no negotiations), (ii) short-term agreements (negotiations that take place after investments are chosen), (iii) long-term agreements (negotiations take place before the investment stage), and (iv) long-term agreements with renegotiation. Section 4 shows that the main result continues to hold if (i) the countries can patent and trade technologies and R&D can be subsidized; (ii) whether side transfers are feasible or not in the negotiations, and whether non-tradable quotas are replaced by tradable permits or emission taxes in the negotiations; and (iii) if the utility function is general (and not necessarily linear-quadratic). Related literature is reviewed in Section 5, while the final section concludes.

## 2. The Linear-Quadratic Model

This section presents a model where $n$ agents over time contribute to the public good and invest in technology. The purpose of the technology is to reduce the cost of providing public goods in the future. There may be technological spillovers, such that one agent may be able to learn and benefit from the other agents' investments. This section presents the model, while the next studies various contracting possibilities for the agents. I then assume that the agents can contract on the provision of public good, but not on how much each of them is supposed to invest. Private investments are observable but not verifiable, in line with the contracting literature.

Many types of public good provision can be captured by the model. To fix ideas, I will use climate change as the driving example. I will thus refer to the agents as "countries", the public good (or its negative counterpart; the public bad) as the stock of greenhouse gases, and the contributions as emissions.

The public bad is represented by the stock $G$, i.e., the stock of "greenhouse gases". $G$

can be interpreted as the stock of CO2 beyond what would be the natural level. Since the natural level is thus $G = 0$, there is a tendency of reverting to 0 for any given size of $G$, and I let $d_G$ measure the fraction of $G$ that "depreciates" every period. $G$ may increase, nevertheless, if a country $i$ selects a positive emission level, $g_i > 0$:

$$G = (1 - d_G)\, G_- + \sum_i g_i + \theta \tag{2.1}$$

$G_-$ represents the stock of greenhouse gases in the previous period (this way, I do not need subscripts for periods). Parameter $\theta$ is random, somehow capturing the uncertainty related to global warming. The main impact of $\theta$ is to make the marginal cost of adding emission random. $\theta$ is arbitrary distributed with the mean 0 and variance $\sigma^2$. Although $\theta$ is distributed iid across periods, the impact of $\theta$ is long-lasting: in line with (2.1), its effect depreciates at the rate $d_G$.

The other type of stock in the model is technology. For each country $i$, $R_i$ measures its technology stock. Technology depreciates over time at the rate $d_R$, but it may increase if country $i$ invests. Let $r_i$ measure the amount of resources (or private good) that country $i$ invests or spends on R&D in the current period.

When one country invests, other countries may benefit as well. R&D is a creative process and the ideas that are generated can be used also in other countries, although the environment there may differ somewhat. I let $e > 0$ measure this externality, while $b$ measures the impact of $i$'s investments on $i$'s own stock of technology. As long as the externality is not complete, $b > e$. In sum, the technology stocks follow a dynamic path given by:

$$R_i = (1 - d_R)\, R_{i,-} + br_i + e \sum_{j \neq i} r_j. \tag{2.2}$$

There are several interpretations of $R_i$ that are consistent with the model. For example, $R_i$ may measure country $i$'s abatement technology, i.e., how much of its emission $i$ can costlessly clean. If energy production, $y_i$, is generally polluting, the emission of country $i$ is given by:

$$g_i = y_i - R_i.$$

Alternatively, $R_i$ may measure the effectiveness of country $i$'s windmill park (or renewable energy sources). If the windmill park can generate $R_i$ units of energy, the total amount of energy produced is given by $y_i = g_i + R_i$, if the alternative to windmills is to use fossil fuel. Of course, $y_i$ can measure the general industrial production instead of energy in particular.

In each period, a country (i) suffers from the stock of greenhouse gases, (ii) benefits from consuming energy $y_i$, and (iii) pays the cost of investing in technology. I assume utilities are quadratic in the first two terms, but linear in the investment costs. Formally, $i$'s utility in a period is given by:

$$u_i = -\frac{c}{2}G^2 - \frac{v}{2}\left(\overline{y} - y_i\right)^2 - kr_i, \tag{2.3}$$

where $c > 0$ measures the cost of greenhouse gases, $\overline{y}$ is the bliss point for energy production, $v > 0$ represents the importance of energy and $k > 0$ is the unit cost when investing in technology.

Since there are many periods, country $i$ ultimately cares about the present-discounted value of all future utilities. So, if $\delta$ represents the discount factor, $i$'s objective is to maximize

$$U_i = \sum_{\tau=t}^{\infty} u_{i,\tau}\delta^{\tau-t} = u_i + V\left(G, R_1, R_2, ...R_n\right),$$

where $V(.)$ is a country's continuation value as measured at the end of each period. Again, subscripts denoting period $t$ is skipped.

The timing of the model is the following: The investment stages and the pollution stages alternate over time. Somewhat arbitrary, I define "a period" to be such that the countries first (simultaneously) invest in technology, thereafter they (simultaneously) decide how much to pollute. In between these two stages, the parameter $\theta$ is realized. Information is symmetric at all stages.

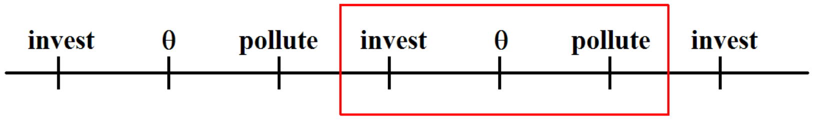


*Figure 1: The definiton of "a period"*

This model is used below to study the impact of environmental agreements and negotiations. Before polluting, the countries may get together to negotiate a climate agreement where they all commit to pollute less. I only allow the countries to negotiate this period's emission levels (or, stated differently, the length of the period represents the length of the agreement). All the countries have the same bargaining power and I study the outcome if each country gets $1/n$ of the bargaining surplus (this follows, for example, if using the Nash Bargaining Solution). The countries cannot negotiate the investments in technology, however, perhaps because these investments are harder to verify and monitor. To simplify further, side transfers are feasible at the negotiation stage, and negotiated emission quotas are not tradable across the countries. In this game, I am looking for a stationary Markov-Perfect Equilibrium (MPE) as defined by Maskin and Tirole (2001). Assuming that $V(.)$ is continuously differentiable, this equilibrium turns out to be unique for each of the situations studied below: Business as usual, short-term agreements, long-term agreements, and long-term agreements with renegotiations.

While the next section solves this simple model, Section 4 shows that the main results hold if (i) technologies can be patented and traded, (ii) side payments cannot be used, (iii) the utility function is more general (and not necessarily linear-quadratic). Section 4 also shows that the results are similar if the political instrument is tradable permits (instead of non-tradable quotas) or an emission tax.

## 3. Solutions

This section solves the game above under various scenarios for when the countries may negotiate. First, I assume negotiations never take place. The second subsection let negotiations take place after the investment stage; the third permits negotiations only before the investments; while the fourth subsection allows negotiations before as well as after investments are made. For each scenario, the countries negotiate the current period's emission levels only. This is actually not a severe constraint, since the length of a period is not specified and it can be arbitrarily long (by letting $\delta \to 0$).

### 3.1. Business as Usual

Suppose there is never any coordination or negotiations between the countries. At every stage, the countries make their decisions non-cooperatively. In this section, I solve each period by backwards induction, taking the continuation value function $V(.)$ as given.

The pollution stage should be solved for first. Since the technologies are given, at this stage, choosing $g_i$ is equivalent to choosing $y_i$. Country $i$'s first-order condition becomes:

$$\begin{aligned} 0 &= -cG + v(\overline{y} - y_i) - V_G \Rightarrow \\ y_i &= \overline{y} - \frac{cG + V_G}{v}, \end{aligned}$$

where $V_G \equiv \partial V / \partial G$. Intuitively, $i$ pollutes less if $c$ and $G$ are large, since the problem is then more severe.

By (2.1), $G$ is itself a function of the $y_i$s, and solving for these gives:

$$\begin{aligned} G^{bau} &= \frac{nv\overline{y} - nV_G + v((1-d_G)G_- + \theta - R)}{nc + v} \text{ and} \\ y_i^{bau} &= \frac{v\overline{y} - V_G - c((1-d_G)G_- + \theta - R)}{nc + v}, \text{ where} \\ R &= \sum R_j. \end{aligned}$$

Consistent with my remark above (where I took $G$ as given), $y_i$ is now smaller if $G_-$ is large, since that makes the problem more severe. Moreover, $y_i$ is large if $R_j$ is small, no matter $j$. The reason is that if technology stocks are large, pollution is going to be less for a given set of $y_j$, and country $i$ can enjoy some more energy without suffering terribly from the greenhouse gases. Since $g_i = y_i - R_i$, we can write

$$g_i^{bau} = \frac{v\overline{y} - V_G - c\left((1-d_G)G_- + \theta - \sum_{j \neq i} R_j\right)}{nc + v} - \left(1 - \frac{c}{nc + v}\right) R_i. \tag{3.1}$$

Thus, $i$ pollutes more if its own technology is good, since it can then consume a lot of energy without having to pollute. Symmetrically, $j$ pollutes less if $R_j$ is large, and this allows $i$, $i \neq j$, to increase its own emission level, since the problem is then less severe. This is why $g_i$ increases in $R_j$, $j \neq i$.

At the investment stage, $i$ takes all this into account. It understands that if it invests and makes $R_i$ large, it can pollute less, and $G$ is going to be less, as well. However, the other countries are going to find it optimal to increase their emissions, so parts of the gain is crowded out. As shown in the Appendix, the equilibrium R&D level is given by:

$$r_i^{bau} = \frac{(1-d_G)\,G_- - (1-d_R)\,R_-}{nB} + \frac{\overline{y}}{B} - \frac{V_G}{vB} - \frac{(k-V_R)\,(v+nc)^2}{cvnB\,(v+c)} + \frac{V_G\,(nc+v)}{cvnB} \tag{3.2}$$

where $B \equiv \partial R/\partial r_i = b + (n-1)\,e$.

Having solved for the investment levels, we can calculate $u_i$ and recursively derive $V(.)$. As shown in the appendix,

$$\begin{aligned} \partial V/\partial G &= -\frac{\delta d_R k}{Bn} \\ \partial V/\partial R_j &= \frac{\delta\,(1-d_R)\,k}{Bn} \forall j \in \{1,...n\}, \end{aligned} \tag{3.3}$$

and $V(.)$ is thus uniquely defined, assuming it is continuously differentiable. That $\partial V/\partial R_i = \partial V/\partial R_j \forall i,j$ shows that the stock of technology, $R$, is like a public good benefitting everyone, no matter who actually owns it. The reason is that the countries' energy production is going to be the same for all countries, not matter whether they have different technologies, and the impact of the technologies is thus only to reduce the emission levels, to the benefit of everyone. For this reason, equilibrium investment levels depend only on the total value it generates, $B$, and not on the private benefit $b$ in particular.

**Proposition 1:** *There is a unique Markov-Perfect equilibrium. (i) If $R_i$ is large, country $i$ pollutes less while country $j$, $j \neq i$, pollutes more. (ii) In equilibrium, $i$ is polluting according to (3.1) and investing according to (3.2).*

This is a "dynamic common pool problem" where each country's contribution (or investment) is strategically distorted in order to affect the other countries' emissions and investments. Compared to the static common pool problem (or the open loop equilibrium where each country commits to all future of $g_i$ and $r_i$), countries pollute too much, invest too little, and receives a lower utility.

### 3.2. Short-term Agreements

This subsection analyzes "short-term agreements". The label could alternatively be "spot contracts", since I am assuming that the countries, just before polluting non-cooperatively, get together and negotiate an emission-vector that is better for everyone. Since the technologies are fixed, at this point in time, negotiating $g_i$ is equivalent to negotiating $y_i$. Notice that the countries have identical preferences when it comes to $y_i$. When technologies are sunk (even if technology stocks may differ across the countries), the bargaining game is perfectly symmetric when considering the $y_i$s. Thus, the bargaining solution is simply that all $y_i$s are set at the socially optimal level:

$$\begin{aligned} 0 &= -cnG + v\left(\overline{y} - y_i\right) - nV_G \Rightarrow \\ y_i &= \overline{y} - \frac{cnG + nV_G}{v}. \end{aligned}$$

Since $G$ is, by (2.1), a function of the $y_i$s, we can write:

$$\begin{aligned} G^{st} &= \frac{nv\overline{y} - n^2V_G + v\left(\left(1-d_G\right)G_- + \theta - R\right)}{n^2c + v}, \\ y_i^{st} &= \frac{v\overline{y} - nV_G - nc\left(\left(1-d_G\right)G_- + \theta - R\right)}{n^2c + v}, \\ g_i^*\left(\mathbf{R}\right) &= \frac{v\overline{y} - nV_G - nc\left(\left(1-d_G\right)G_- + \theta - \sum_{j\neq i} R_j\right)}{n^2c + v} - \left(1 - \frac{nc}{n^2c+v}\right)R_i, \quad (3.4) \end{aligned}$$

where $\mathbf{R}= \left(R_1, ...R_n\right)$ and $g_i^*\left(\mathbf{R}\right)$ is the optimal (as well as the equilibrium) pollution level given the vector of technologies. Clearly, $i$ pollutes less if $R_i$ is large, since $i$ then can enjoy a large $y_i$ without having to pollute, and its marginal benefit of polluting is then smaller. The other countries take advantage of this fact, and require that $i$ reduces its pollution. This means that if $\sum_{j\neq i} R_j$ is large, the other countries are polluting less, the marginal cost of polluting one more unit is small, and $i$ is able to negotiate a larger pollution permit than if $\sum_{j\neq i} R_j$ were small. Thus, while $i$ pollutes less when $R_i$ is large, in the bargaining equilibrium, $j \neq i$ pollutes more. This is exactly as in the business-as-usual scenario, although for different reasons (since this is a bargaining outcome).

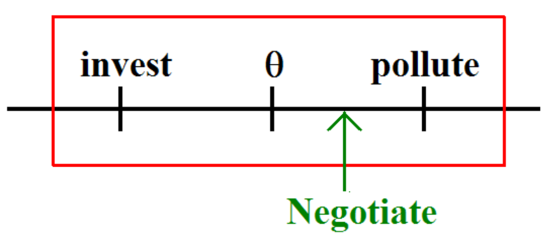


*Figure 2: The timing for "short-term agreements"*

Of course, $i$ anticipates all this at the investments stage. It understands that if it invests a lot, it will be hold up by the other countries and forced to pollute less. They know that $i$ is, in the end, going to accept such a request, since it does not find it too costly to reduce its pollution level. Anticipating this, investments are reduced. Appendix derives the equilibrium R&D level:

$$r^{st} = \frac{(1-d_G)\,G_- - (1-d_R)\,R_-}{nB} - \frac{(k-V_R)\,(n^2c+v)}{cvnB} + \frac{\overline{y}}{B} + \frac{V_G}{ncB}. \tag{3.5}$$

Clearly, $i$ invests more if $G_-$ is large, because the problem is then large, and if $R_-$ is small, since the existing technology is then poor.

Again, we can derive the utilities and the continuation value function. This turns out to be given by (3.3), also in this case. This does *not* mean that the continuation values are identical in the two situations, only that the marginal benefit w.r.t. $G$ and $R$ are the same whether the countries negotiate short-term agreements or if they do not.

**Proposition 2:** *There is a unique Markov-Perfect equilibrium. (i) If $R_i$ is large, country $i$ pollutes less while country $j$, $j \neq i$, pollutes more. (ii) In equilibrium, $i$ is polluting according to (3.4) and investing according to (3.5).*

Note that all the comparative static is similar to the business-as-usual situation: For example, a country is polluting less if it has invested a lot (part (i) of Proposition 1 and 2 are identical), and it invests more if $G_-$ is large and $R_-$ small. However, the levels of emission and R&D are different in the two cases. Since (3.3) holds in both cases, it is easy to compare the two cases.

### 3.2.1. Are short-term agreements worse than no agreement?

Since $V_G$ and $V_R$ are the same whether short-term agreements are negotiated or not, the equilibrium in this period is unrelated to whether there will be an agreement in the next period. Thus, it is enough to compare the utilities in one particular period to conclude whether short-term agreements are better than business as usual in that (or any) period: We do not need to make statements *conditional* on whether there will be agreements also in the future. The comparison itself is undertaken in the Appendix.

**Proposition 3:** *Relative to the business as usual, a short-term agreement (i) reduces pollution, (ii) reduces R&D levels, and (iii) is beneficial if and only if (3.6) holds.*

$$
\begin{aligned}
g^{st} &< g^{bau} \\
r^{st} &< r^{bau} \\
\left(1-\frac{1}{n}\right)^2 - \left(\frac{1-\delta\left(1-d_R\right)}{n}\right)^2 &< \frac{(v+c)\left(\sigma vcB/k\right)^2}{\left(n^2c+v\right)\left(nc+v\right)^2} \qquad (3.6)
\end{aligned}
$$

.Part (i) is obvious: The entire point of the agreement is to reduce emission. Part (ii), on the other hand, is disappointing. Instead of encouraging the countries to invest, they are actually investing *less* when an agreement is expected. The reason is the following: The hold-up problem, when negotiations are anticipated, is exactly as strong as the crowding-out problem in the business-as-usual scenario: In either case, each country only enjoys $1/n$ of the total benefits generated by its investments. In addition, when an agreement is expected country $i$ understands that the problem will be "taken care off", to some extent, since emission levels are going to be reduced. This implies that the marginal benefit of further reductions decline, and it is marginally less important to invest in technologies that would reduce future pollution. Hence, each country invests less.

Since investments decrease under short-term agreements, it may not be a surprise that utilities can decrease as well. This is the case, in particular, if each period is quite short. Then, $\delta$ is likely to be large, $d_R$ is likely to be small, and so is the uncertainty from one period to the next (i.e., $\sigma \approx 0$). All changes make (3.6) less likely to hold. Moreover, (3.6) is less likely to hold if $n$ is large, since then the under-investment problem is large, it is very important to increase investments, and this can be done by having the business-as-usual situation instead of a short-term agreement.

Thus, unless (3.6) holds, the countries would be better off if they could commit not to negotiate short-term agreements. One way of committing may be to commit to emission levels in advance, without allowing renegotiation after the investment stage. This is the scenario I turn to next.

### 3.3. Long-term Agreements

The hold-up problem in the previous subsection appeared because the $g_i$s were negotiated after investments were sunk. Suppose, instead, that the countries negotiate the $g_i$s before the investment stage. This can be done, for example, by having a long-term agreement, where the current period's $g_i$s are fixed already when countries invest in technologies. For real-world long-term agreements, it is indeed reasonable that future commitments are made for such a long time horizon that a country is able to invest between the time at which the promises were made, and the time at which the last promise is supposed to be kept.

Analyzing multi-period agreements turn out to be quite difficult in the present model, unfortunately. However, a sense of "long-term agreements" is still possible to study, even within each of the model's periods, if we simply assume that the countries negotiate this period's $g_i$s in the beginning of the period, before investments are made. While these agreements only last one period, they are indeed "longer" than the short-term agreements studied above. Moreover, each period can be quite long in the model, since we have not specified whether the discount factor, for example, is large or small.

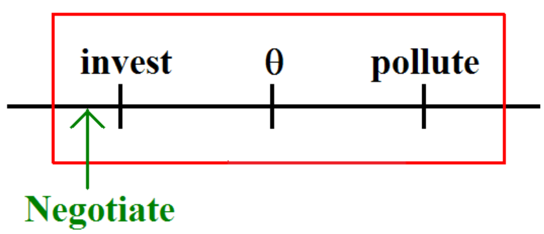


*Figure 3: The timing for "long-term agreements"*

In the model, the timing is now reversed: The countries first negotiate the $g_i^{lt}$s, then investments are chosen. When solving the model by backwards induction, we thus have to start with the investment stage, taking this period's $g_i^{lt}$s as given. This gives the first-order condition for country $i$'s $r_i$:

$$\begin{aligned} 0 &= vb\left(\overline{y} - g_i^{lt} - R_i\right) - k + V_R \Rightarrow \\ R_i &= \overline{y} - g_i^{lt} - (k - V_R)/vb. \end{aligned} \tag{3.7}$$

Obviously, a country wants a larger stock of technology if its quota, $g_i^{lt}$, is small, since otherwise it would find it very costly to comply.

Together with (2.2), (3.7) gives the countries' investment levels as a function of the negotiated pollution levels. Taking these into account, it is straightforward to calculate the bargaining outcome w.r.t. the $g_i^{lt}$s. This is done in the Appendix, but the result is presented here:

**Proposition 4:** *The bargaining outcome is given by (3.8). Thus, the quotas are smaller if the externality is large and if the time horizon of the agreement is short.*

$$g_i^{lt} = \mathrm{E}g_i^* \left(\mathbf{R}^{lt}\right) - \frac{k\,(n-1)}{B\,(n^2c+v)} \left(\frac{e}{b} + \frac{\delta\,(1-d_R)}{n}\left(1-\frac{e}{b}\right)\right), \tag{3.8}$$

where $\mathrm{E}g_i^*\,(\mathbf{.})$, defined by (3.4), is the expected optimal pollution level ex post (after $r_i$ and $\theta$ are realized) given the equilibrium technology vector. Thus, $g_i^{lt} < \mathrm{E}g^* \left(r^{lt}\right)$ unless $e = \delta\,(1-d_R) = 0$.

If $e = \delta\,(1-d_R) = 0$, then $g_i^{lt} = \mathrm{E}g^* \left(\mathbf{R}^{lt}\right)$, meaning that the commitments under the long-term agreement should be equal to the expected optimal pollution levels. Since, in this case, there are no externalities, and the countries are not concerned with how their technologies affect their future bargaining power, investments are first best.

However, if $e > 0$, there are externalities related to the investments, and a country is likely to under-invest. To encourage countries to invest closer to the optimal level, the optimal long-term agreement specifies commitments that are tougher than what is likely going to be optimal ex post. With tough commitments, each country is induced to invest more, and that is good when the externalities are positive. The larger are these externalities, the more ambitious the agreement should be (in that the $g_i^{lt}$s should be smaller).

If $\delta\,(1-d_R)$ is large, countries are likely to under-invest even if $e = 0$. The reason is that the countries do not fully take into account the total value of increasing $R$ for the future. If, in the next period, $R_i$ is large, then country $i$ is again going to get a smaller pollution quota, and the other countries are going to pollute more. A country is more concerned with this future hold-up problem if $\delta$ is large, i.e., the future is close, and if $d_R$ is small, since then today's investments have a large impact on tomorrow's technology stock. In words, the agreement should be more ambitious if (i) there are large technological spillovers and (ii) if the time horizon of the agreement is short.

**Note on multiperiod agreements:** A technical appendix (not attached in this version of the paper) derives multi-period agreements, and derives results consistent with those above. In particular, a two period agreement negotiated just before the first period's pollution level is identical to what is above labelled "short term agreement" in the first period, but a "long term agreement" in the second.

### 3.4. Long-term Agreements with Renegotiation

Long-term agreements, such they are defined above, is never first-best. First, the commitments are made before one knows the severity of the problem (determined by $\theta$). Second, the optimal long-term agreement (3.8) specifies pollution levels that are less than what is likely going to be optimal ex post, since the emission levels are trading off ex post optimality with ex ante incentives. The countries may thus be tempted to renegotiate the treaty, after $\theta$ and the investments are realized. What happens if such renegotiation is possible and allowed? Does it ruin the long-term agreement's intention of encouraging the countries to invest more?

To solve for this case, we must specify the default outcome: What happens if the renegotiation game breaks down? If, then, the outcome is the non-cooperative outcome, the bargaining outcome is going to be exactly the "short-term agreements" studied above, and so are the incentives to invest. Suppose, instead, the default outcome is the initial, long-term agreement.

In each period, the following events unfold. First, the countries negotiate the initial commitments $g_i^{de}$ (called the "default outcome"). Thereafter, the countries invest and $\theta$ is realized. Before carrying out their commitments, however, the countries get together and (re)negotiate another set of emission levels, $g_i^{re}$, where everyone understands that if this renegotiation game fails, the outcome is the default outcome agreed to initially.

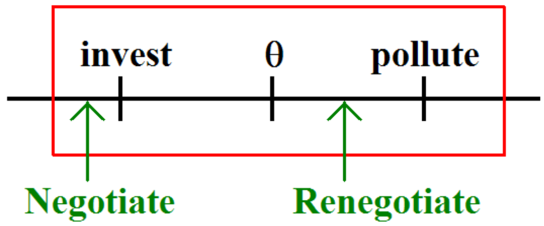


*Figure 4: The timing when renegotiation is possible*

When renegotiating the emissions, the countries find it optimal to pollute just as they would under short-term agreements (taking technology stocks as given), so $g_i^{re}(\mathbf{R}) = g_i^*(\mathbf{R})$. Anticipating that they will be able to renegotiate the agreement, aren't the countries induced to invest just as little as they did under short-term agreements?

The answer is no. When investing, the countries do, indeed, recognize that, after renegotiation, they will be able to pollute as they would do under a short-term agreement. But in the short-term-scenario, it was the countries with the poorest technology that got the better deal, since these countries were quite happy with the default outcome (i.e., the non-cooperative outcome) where they were able to pollute unconstrained. This makes the "technology-losers" reluctant to negotiate an agreement, giving them a better bargaining position. However, things are quite different when renegotiating a very ambitious agreement. Then, the technology-losers are desperate to reach a new agreement, replacing the very expensive commitments. These countries thus have a poor bargaining position, and they are, in equilibrium, going to get a quite bad deal (where they must pay the other countries to sign the renegotiated treaty). Fearing this situation, the countries are induced to invest more, particularly if the default pollution levels, the $g_i^{de}$s, are small.

Technically, each country can expect to enjoy the utility it would under the default agreement, plus $1/n$ of the benefit from renegotiation. When it chooses investments, it will thus seek to maximize

$$U_i^{de} + \frac{1}{n}\left(\sum_j U_j^{re} - \sum_j U_j^{de}\right).$$

All this will be taken into account when specifying the initial agreement, the $g_i^{de}$s. The more ambitious is this agreement, the more the countries invest. This is attractive, particularly in situations where the countries otherwise are tempted to under-invest, i.e., if the externality $e$ is large, and if $\delta(1-d_R)$ is large, since then the countries fear that more technology today hurts their bargaining position in the near future. Thus, the agreement should be more ambitious if $e$ and $\delta(1-d_R)$ are large. By setting the $g_i^{de}$s carefully, the first-best technology levels, $\mathbf{R}^*$, are induced. The final pollution levels are not going to be distorted, since the renegotiation stage ensures that, ex post, emission levels are set optimally. Thus, such an agreement implements the first best investment levels as well as the first best pollution level. Appendix derives the optimal contract.

**Proposition 5:** *With renegotiation, the initial agreement (3.9) implements first best investments as well as emissions. Thus, the initial agreement should be more ambitious if its time horizon is short and the R&D spillovers large.*

$$g_i^{de} = \mathrm{E}g_i^*(\mathbf{R}^*) - \frac{k}{Bv}\left[\delta(1-d_R) + \frac{en}{b-e}\right] \tag{3.9}$$

# 4. Robustness

The analysis above has relied on a number of strong assumptions. This section discusses how some of them can be relaxed. The proofs of the following propositions are similar to the analogical proofs above, and thus omitted (but they are available upon request).

## 4.1. Patents and R&D Subsidizes

Above, I simply assumed that a fraction of the innovation in one country, $e/b$, was free to copy for another country. Thus, there was no trade in technological products, and no transfers when one country copied another's idea.

To discuss intellectual property rights, suppose that a country can purchase or pay for the remaining fraction, $(b-e)/b$. Then, $e<b$ measures the weakness of the patent system, or the fraction of an innovation that cannot be protected. Let the timing, at the investment stage, be the following: First, each country chooses $r_i$. While innovator $i$'s technology stock immediately increases by $br_i$, the technology stock of another country increases by $er_i$, following $i$'s investment. However, a country $j$, $j \neq i$, can pay $i$ to license it the patent, and thus be able to increase $R_j$ by the full amount, $br_j$. At this stage, all

the investments are sunk and there will be a market price for such licenses that clear the market. Clearly, the price is lower if $e$ is large, and if the $r_i$s are large.

This model can be solved just the same way as that above. The value of owning technology determines the price of licensing, and the price, in turn, determines the incentives to invest in R&D. Just as before, it may be reasonable that the countries' investment levels are unverifiable. But the trade in technology is certainly verifiable, and that can make it possible to e.g. subsidize internationally trade in technologies. Let $s$ measure the subsidy, as a fraction of the numerical value of the transaction, paid by other countries when $j$ pays to learn $i$'s innovation. It does not matter whether this subsidy goes to the buyer or the seller (the price will adjust, of course, but not the transaction or the investment levels). Let $s$ be given. Qualitatively, the model gives the same results as those above. In particular, the first best can be achieved by renegotiation if the initial, long-term agreement, is given by:

$$\begin{aligned} g_i^{de} &= \mathrm{E}g_i^*(\mathbf{R}^*) - \frac{k}{bnv}\left[\delta(1-d_R) + \frac{n(1-z)}{z(n-1)}\right], \text{ where} \\ z &\equiv (1+s)(1-e/(b-e)). \end{aligned} \tag{4.1}$$

**Proposition 6:** *If $e < b$ measures the weakness of the patent system and $s$ the international subsidy when patents are licensed, the first best can be achieved by the initial agreement (4.1) and renegotiation.*

Just as before, the agreement should be more ambitious if the "externality is large", which in this case means that the patent system is weak. Then, countries tend to under-invest, and the commitments should be tougher to encourage more R&D. Moreover, the agreement should be more ambitious if the subsidy level is small, for the same reason.

Equation (4.1) can also tell us about the optimal subsidy level, $s$, for a given level of $e$ and $g_i^{de}$. Obviously, the subsidy level should be larger if $e$ is large, to compensate for the spillover that is created. In addition, $s$ should be larger if $\delta$ is large, i.e. if the agreement is quite "short-term", since then investments tend to be too low, unless such subsidizes are in place. Finally, $s$ should be larger if the $g_i^{de}$s are small, since that, too, lead to little investments.

### 4.2. Transfers, Taxes and Tradable Permits

In Section 2, I started out by assuming that the quotas cannot be traded, and that side transfers can be used when the countries (re)negotiate the agreement. Both assumptions can be relaxed, without changing any of the results. The reason for making the assumptions, in the first place, was only to simplify the proofs and the discussions.

**Proposition 7:** *If side transfers were not available in the (re)negotiations, all the results above continue to hold.*

A shallow intuition for this result is that, since the model is symmetric, no side transfers are going to take place in equilibrium, anyway. However, when considering whether to deviate, it is important to know that a deviation would be harmful when the effects on the side transfers are taken into account. What, then, if transfers are not possible? If they are not, a country can always pay in "relative contributions" what it cannot pay in direct transfers: Instead of a payment from $i$ to $j$, $i$ can simply reduce its emission level relative to $j$. Such a transfer "in kind" plays just the same role as a monetary transfer at the margin in the symmetric equilibrium (then, the deadweight costs of a marginal increase in "transfer in kind" is zero).

For related reasons, the results above continue to hold if the quotas were tradable. The shallow intuition is that there will be no trade in permits anyway, in equilibrium, and, thus, it does not matter whether such trade is allowed. However, when considering whether to deviate and invest more or less in technology, then the value of investing more, when quotas are not tradable, is given by the country's own value of increasing $y_i$. When permits are tradable, the value of more technology is given by the equilibrium permit price. In the symmetric equilibrium, however, these two are equal and the equilibrium investment level is the same, as well. Because of this, all the results are exactly the same if permits are tradable.

**Proposition 8:** *If the pollution permits were tradable, all the results above continue to hold.*

Tradable permits and non-tradable quotas are just two possible political instruments.

Another popular instrument is Pigou taxes. Suppose that $t_i$ is the tax that country $i$ must pay, for each unit it pollutes. Suppose all the tax revenues are redistributed equally on all the countries (if country $i$'s payment were given back to $i$, the tax would of course have no effect). Instead of negotiating the emission levels, let now countries negotiate the taxes. The analysis would be different, but similar, to that above. A country with good technology can expect to pay little in taxes, and the negotiated $t_i$ is then going to be larger for this country. Anticipating this, countries are discouraged to invest, just as before. The first-best can be achieved, however, if renegotiation is possible when the initial, long-term, agreement is given by:

$$t_i^{de} = \mathrm{E}t_i^* + \frac{k}{bn}\left(\delta\left(1-d_R\right)+\frac{n(1-z)}{z\left(N-1\right)}\right), \tag{4.2}$$

where $\mathrm{E}t_i^*$ is the expected optimal emission tax ex post.

**Proposition 9:** *Suppose the countries negotiated Pigou taxes (that are redistributed evenly) and not emission levels. Abatement and investment levels are all first best if renegotiation is possible and the initial agreement is given by (4.2).*

Interestingly, the comparative static is just as before: The initial agreement should be more ambitious (in that the tax should be lower) if the externality is large (or patent protection weak), the subsidy small and the agreement is short-lasting (in that $\delta$ is large). After these high taxes have induced countries to invest a lot, fearing that they otherwise would have a bad bargaining position, the countries renegotiate to a set of taxes that are smaller, and optimal.

### 4.3. A More General Utility Function

By assuming quadratic utility functions and a linear cost of investing in R&D, all the above results could be analytically derived. The main result of this paper, however, does not rely on these functional forms. Suppose that a country's one-period utility is measured by:

$$u_i = c\left(G\right) + v\left(y_i\right) - k\left(r_i\right), \tag{4.3}$$

where $v(.)$ is increasing and concave while $c(.)$ and $k(.)$ are increasing and convex. If renegotiation is possible, the first best is implemented if the initial agreement specifies the $g_i^{de}$s such that:

$$v'\left(g_i^{de}+R_i^*\right)=\mathrm{E}v'\left(g_i^*+R_i^*\right)+\frac{k'\left(r_i^*\right)}{bn}\left(\delta\left(1-d_R\right)+\frac{n(1-z)}{z\left(n-1\right)}\right) \tag{4.4}$$

**Proposition 10:** *If utility is given by (4.3) rather than (2.3), both emission and investment levels are first best if renegotiation is possible and the initial agreement is given by (4.4).*

The comparative static is exactly the same as before. If $\delta$ is large and $z$ small, the right-hand side of (4.4) is large and the first best is thus achieved if the left-hand side is large as well, which implies that $g_i^{de}$ must be small relative to $g_i^*$. Naturally, (4.1) is a special case of (4.4), and it is straightforward to rewrite (4.1) to take the form of (4.4). Proposition 10 shows that the insight of the linear-quadratic case holds also for general utility functions, at least when it comes to the optimal agreement under renegotiation. The proof follows the same lines as for Proposition 5, and is thus omitted.

## 5. A Literature Review

The paper's title points to environmental agreements, and most of the results are novel to this literature. But climate change is just one application of the model. More generally, the paper combines differential games and incomplete contracts, and it contributes to both these strands of literature.

### 5.1. Differential games

Abstracting from the agreements in this paper, the model is one of private provision of public goods. Many of these models are differential games. A differential game (or a "difference game", if time is discrete) is a game where each player's action influences the future stock or state parameter (for overviews, see Friedman, 1974, Dockner et al., 2000). Given the emphasis on these stocks, the natural equilibrium concept is Markov Perfect Equilibrium (as defined by Maskin and Tirole, 2001). Typically, these paper finds that the public good is underprovided (Admati and Perry, 1991, Fehrstman and Nitzan, 1991), or the public bad is over-provided (leading to e.g. over-fishing, as in Levhari and Mirman, 1980). [1] This paper makes three contributions to this literature. The first is to allow for investments in technology in addition to the private provision of the public good (or bad). For example, Dutta and Radner (2009) study a differential game for climate change where a set of countries pollute over time and the stock of greenhouse gases cumulates. The technology stock is given. However, in Dutta and Radner (2006a), they briefly discuss the incentives to affect the technological parameters, and in Dutta and Radner (2004, 2006b) they allow for explicit investments in the technology. But since the cost of pollution (as well as the cost of R&D) is assumed to be linear, the equilibrium is "bang-bang" where countries invest zero or maximally in the first period, and never thereafter. One country's investment does not influence the other countries' actions, unlike the strategic effects emphasized in this paper.[2]

A second contribution of this paper is that I obtain a unique equilibrium. This follows from the way I model R&D, and the equilibrium strategies are linear in the state parameters. The linear MPE is typically selected in analyses (by e.g. Fehrstman and Nitzan, 1991), although there often exist multiple equilibria (Wirl, 1996, Tutsui and Mino, 1990). Consequently, many scholars attempt to derive asymptotically efficient nonlinear MPEs (Dutta and Radner, 2005, Dockner and Sorger, 1996, Sorger, 1998).

My most important contribution to the DG literature, however, is to allow for contracts and agreements: This is completely absent in all the papers discussed above.[3]

[1] These results arise when private provisions are strategic substitutes. If they were complements, e.g. because one contributes to a discrete public project, then efficiency is easier to attain (Marx and Matthews, 2000).

[2] By emphasizing investments, the paper is related to the literarure on difference games in IO (see the survey by Duraszelski and Pakes, 2007), where firms overinvest in capital to deter entry (Spence 1977, 1979, Dixit 1980) or to discourage the competitors from investmenting or producing (Reynolds, 1987, Maskin and Tirole, 1987).

[3] Only a few papers allow for some kind of cooperation. Hoel (1992) study a differential game with an emission tax, and the optimal tax is derived. Relatedly, Yanase (2006) studies the optimal contribution-subsidy. But these papers derives the optimal tax/subsidy without explaining where this may come from. Houba et al. (2000) study negotiations (over fish quotas) in a differential game where the agreement is assumed to last forever. Sorger (2006) let instead the agreement last only one period. Investments are not allowed, unlike in this paper. Ploeg and Zeeuw (1992), however, do discuss agreements when players can both extract and invest in R&D. In their paper, as well as all the papers just mentioned, contracts are assumed to be complete, such that R&D cannot be strategically chosen, as emphasized in this paper.

## 5.2. Incomplete contracts

By allowing the countries to negotiate emission levels, but not investments, the paper draws on the literature on incomplete contracts (going back to Hart and Moore, 1988). Harris and Holmstrom (1987) discuss optimal lengths of contracts where it is costly to rewrite contracts, but uncertainty about the future makes it necessary. Ellman (2006) studies the optimal contract length (or, rather, the probability for continuing the contract) where the optimal length increases if specific investments are important. This is similar to my result on the optimal time horizon, but Ellman (2006) has only two agents, one investment period and there is no uncertainty that is revealed over time. Renegotiation, studied here, is related to the literature on renegotiation design going back to Chung (1991) and Aghion et al. (1994). With renegotiation, the final outcome is likely going to be efficient, so the initial contract determines only the allocation of the barganining surplus, and thus the incentives to invest. Most similar is Guriev and Kvasov (2005) who show that a seller has first-best incentives to invest if the termination time T of the contract is appropriately specified. The contract is renegotiated at every point in time, to keep the remaining time horizon constant. Contribution levels (or traded quantities) are not negotiated, but negotiating the time horizon is quite similar to negotiating the quantity, as in Edlin and Reichelstein (1996): If the externality increases, Guriev and Kvasov find that the optimal contract length should increase, while Edling and Reichelstein show that the contracted quantity should increase. These results are in line with the results of this paper, where the time horizon and the emission levels are both endogenous, and they do depend on the externality. For the first best to be attainable, however, it is crucial that the externality is not dominating the direct effect of the investments. Otherwise, Che and Hausch (1999) find that the null-contract is optimal (these results are generalized and discussed by Segal and Whinston, 2002). While all these papers have only two periods (the exception is Guriev and Kvasov, 2005) and two agents, the present paper allows an arbitrary number of countries, and the time horizon is infinite.[4]

[4]The effect of contracts on investments is also studied in the IO literature. Quite related is Gatsios and Karp (92), who let two firms invest before, potentially, being allowed to (negotiate) merger. In parametrized example, they show that firms may invest more if they anticipate merger negotiations, and the profit may be smaller (prices lower) than if a merger is not allowed. Similarly, Ziss (1994) shows that

### 5.3. Environmental agreements

Emphasizing its importance for climate change agreements, the paper is related to the associated literature. There is a large literature on environmental agreements (Barrett, 2005, and Kolstad and Toman, 2005, provide some overview), but most of the papers study models that are static or with two periods. The recommendations are thus not in line with the normative results of this paper. For example, Karp and Zhao (2008) propose short-term agreements (of 10-year length) to ensure flexibility (without discussing the hold-up problem). But there is a large number of other papers studying the interaction between RD and pollution: In particular, Golombek and Hoel (2005) compare quota and tax agreements when R&D is chosen after the negotiations. In line with my results, they find that e.g. the optimal tax should be larger than the Pigouvian level if there are tehnological spillovers. But there is only two periods, so current R&D never affects future bargaining power. The only other paper I know of where parties invest in R&D before negotiating emissions is by Buchholtz and Konrad (1994). They find, as I do, that anticipating agreements may indeed reduce equilibrium R&D levels. However, their model includes only one period, which misses the dynamic effects (emphasized by DG) and the questions on how the agreement should be designed (time horizon, emission levels), which is the focus of this paper.

## 6. Conclusions

This paper presents a dynamic model where a number of agents contribute to a public bad as well as invest in technology. The investments affect the future costs of contributing, and there may be externalities from the investments. The model fits many types of private provision to public goods; climate change is a leading example. The larger is a country's stock of abatement technology, the more the other countries choose to pollute. Moreover, the more one country pollutes, the less the other countries pollute, and the more they invest in R&D. Both effects induce countries to pollute more and invest less than they would have done in a one-shot model (or in the open loop equilibrium). In this setting,

firms may invest more at RD stage if they collude on prices afterwards.

I study agreements or contracts between the countries. I assume that the countries can negotiate and commit to future pollution levels, while they cannot contract on investment levels.

First, I find that a sequence of short-term agreements is *worse* than business as usual. At the negotiation stage, a country with good technology is going to be hold up by the other countries, demanding that the country reduces its pollution by a lot (since it can afford doing so). Anticipating this, countries invest less when negotiations are anticipated, and the countries may thus be better off if no such agreements were taking place.

Second, "long-term agreements" should be more ambitious (and specify lower emission levels) if its time horizon is relatively short and the externality from investing positive and large. The hold-up problem does not arise before the agreement expires, so countries tend to under-invest if the time horizon of the agreement is short. To encourage investments, the agreement should be more ambitious than what is optimal ex post, particularly if the time horizon is short and the externality (from investing in R&D) large, since then countries are otherwise under-investing. Therefore, if R&D can be subsidized, the subsidy should be larger if the time horizon is short.

Third, the first best can be implemented for all investment and emission levels if renegotiation is possible. Renegotiation ensures that the emission levels are ex post optimal, and the role of the initial agreement is only to affect incentives. Again, the agreement should be more ambitious if its time horizon is short and the externality large. The results hold no matter whether side transfers are feasible in the negotiations, whether permits are tradable or not, or whether an emission tax is negotiated instead of permits.

The results have important implications for any future climate agreement. If the time horizon of an agreement is short, it should be more demanding and R&D should be subsidized by more. A long-term agreements induces more R&D and is better, particularly when patents are imperfectly enforced. Flexibility can be ensured if the agreement is renegotiated.

While this paper establishes some benchmark results, it is only a small step towards a better understanding of good environmental agreements. I have assumed that countries are homogenous, able to commit to future pollution levels, there is no private information and everyone participate in the negotiations. Relaxing these assumptions is certainly the next thing to do!

# 7. Appendix - Solving the Model

## 7.1. Business as usual

To simplify, I have used the symbols $m = V_G$, $m' = V_{R_i}$, $R \equiv \sum_j R_j$, $R' = R_-(1-d_R)$ and $G' = G_-(1-d_G)$. Moreover, I have written $V(.)$ as a function of $G$ and $R \equiv \sum_j R_j$ only, and not the individual $R_i$s, anticipating that $V(.)$ is, indeed, going to be a function of $R_i$ only to the extent it is reflected by $R$. At the pollution stage, each country's first-order conditions is (when choosing $y_i$):

$$\begin{aligned}
0 &= -cG + v\overline{y} - vy_i - m \Rightarrow y_i = \overline{y} - \frac{m+cG}{v} \\
G &= \sum_j (y_j - R_j) + G' + \theta = G' + \theta + n\left(\overline{y} - \frac{m+cG}{v}\right) - \sum R_j \Rightarrow \\
G &= \frac{nv\overline{y} - nm + v(G' + \theta - R)}{nc+v} \Rightarrow \qquad (7.1) \\
y_i &= \overline{y} - \frac{m}{v} - \frac{c}{v}\left(\frac{nv\overline{y} - nm + v(G'+\theta-R)}{nc+v}\right) = \frac{v\overline{y} - m - c(G'+\theta-R)}{nc+v} \Rightarrow \\
g_i &= y_i - R_i = \frac{v\overline{y} - m - c\left(G' + \theta - \sum_{j\neq i} R_j\right)}{nc+v} - \frac{R_i(nc+v-c)}{nc+v}.
\end{aligned}$$

Interrim utility (after investments are sunk) can be written as:

$$\begin{aligned}
w_i^{bau} &\equiv -v(\overline{y} - y_i)^2/2 - cG^2/2 + V(G,R) \\
b &= -c(1+c/v)G^2/2 - Gmc/v + \frac{(v\overline{y})^2 - m^2}{2v} + V(G,R). \text{ Thus,} \\
\partial w_i^{bau}/\partial R_j &= c(1+c/v)G\left(\frac{v}{nc+v}\right) + \frac{vm(1+c/v)}{nc+v} + m' \qquad (7.2)
\end{aligned}$$

At the investment stage, each country sets $k/B$ $=$E$\partial w_i^{bau}/\partial R$, recognizing that one unit of investment increases $R$ by $B \equiv b + (n-1)e$ units. From (7.2):

$$\begin{aligned}
k/B &= c\mathrm{E}G\left(\frac{c+v}{nc+v}\right) + \frac{m(v+c)}{nc+v} + m', \text{ while from (7.1):} \\
\mathrm{E}G &= \frac{nv\overline{y} - nm + v(G' - R)}{nc+v}, \text{ implying} \\
R &= G' - \frac{k(v+nc)^2}{cvB(v+c)} + \overline{y}n + \frac{m'(v+nc)^2}{cv(v+c)} + \frac{m}{c}, \text{ or} \\
r_i nB &= -R' + G' - \frac{k(v+nc)^2}{cvB(v+c)} + \overline{y}n + \frac{m'(v+nc)^2}{cv(v+c)} + \frac{m}{c}.
\end{aligned}$$

We can now write:

$$
\begin{aligned}
y &= \overline{y} - \frac{(k/B - m')(v+nc)}{v(v+c)} - \frac{\theta vc}{v(nc+v)} \\
\mathrm{E}G &= \frac{k(nc+v)}{cB(c+v)} - \frac{m}{c} - \frac{m'(nc+v)}{c(c+v)} \\
G &= \mathrm{E}G + \frac{\theta v}{nc+v}. \\
\mathrm{E}G^2 &= (\mathrm{E}G)^2 + \left(\frac{\sigma v}{nc+v}\right)^2,
\end{aligned}
$$

which is helpful when calculating utility, which becomes:

$$
\begin{aligned}
u_i = & -\frac{c}{2}\left(\frac{k(nc+v)}{cB(c+v)} - \frac{m}{c} - \frac{m'(nc+v)}{c(c+v)} + \frac{\theta v}{nc+v}\right)^2 - \frac{v}{2}\left(\frac{(k/B-m')(v+nc)}{v(v+c)} + \frac{\theta vc}{v(nc+v)}\right)^2 \\
& -\frac{k}{nB}\left(-R' + G' - \frac{k(v+nc)^2}{cvB(v+c)} + \overline{y}n + \frac{m'(v+nc)^2}{cv(v+c)} + \frac{m}{c}\right)
\end{aligned}
$$

So,

$$
\begin{aligned}
\mathrm{E}u_i = & -\frac{c}{2}\left(\frac{k(nc+v)}{cB(c+v)} - \frac{m}{c} - \frac{m'(nc+v)}{c(c+v)}\right)^2 - \frac{v}{2}\left(\frac{(k/B-m')(v+nc)}{v(v+c)}\right)^2 \\
& -\frac{k}{nB}\left(-R' + G' - \frac{k(v+nc)^2}{cvB(v+c)} + \overline{y}n + \frac{m'(v+nc)^2}{cv(v+c)} + \frac{m}{c}\right) - \frac{cv(c+v)\sigma^2}{2(nc+v)}.
\end{aligned}
$$

Thus, $\partial V/\partial R = \partial V_-/\partial R_-$ and

$$
\partial V_-/\partial G_- = -\frac{\delta k d_R}{Bn}.
$$

**Proof for unique equilibrium (sketch of proof):**

There are two relevant types of stages in the game: The time at which $r_i$ is chosen, and the time at which $g_i$ is chosen (or negotiated). At each stage, notice that every $R_i - R_j$ is payoff irrelevant: If $i$ does not condition its actions upon them, there is no reason for $j$ to do, either. So, the states are the previous stocks of $G$ and $R$, implying that $y_i$ and $g_i$ are going to be functions of $G'$ and $R$ only. Let $W$ measure the interrim continuation utility, after the investments are chosen but before $\theta$ is realized. At the investment stage, $i$ maximizes:

$$
W(G', R) - kr_i,
$$

implying that $R$ is going to be a function of $G'$, given implicitly by $BW_2(G', R) = k$ and explicitly by, say, $R(G')$. The interrim utility can thus be written as

$$W(G', R(G')) - k\left(\frac{R(G') - q_R R^-}{NB}\right),$$

where $q_R \equiv 1 - d_R$, and similar for $q_G \equiv 1 - d_G$. Clearly,

$$\begin{aligned} m'/\delta &= \frac{\partial V}{\delta \partial R} = \frac{q_R k}{NB} \text{ and} \\ \frac{\partial m'}{\partial G'} &= \frac{\partial^2 V}{\partial G' \partial R} = 0. \end{aligned}$$

Thus, $m = \partial V/\partial G$ cannot be a function of $R$. From the first-order condition for $y_i$, both $y_i$ and $G$ are functions of $G' - R$ and we can write write interrim utility as

$$w\left(G' - R\right) + V\left(G(G' - R), R\right),$$

where $w = -cG^2/2 - v\left(\overline{y} - y_i\right)^2/2$.Max wrt $r_i$ gives

$$-w'\left(G' - R\right) - V_G G' + V_R = k/B,$$

where $V_G$ is not a function of $R$ and thus $G' - R$ is equal to a constant $\xi$, while $V_R$ is a constant. So, $G' - R$ will be a constant. Notice that

$$V_-\left(G_-, R_-\right) = \delta u\left(G_-, R_-\right) + \delta V\left(G, R\right). \tag{7.3}$$

This further implies

$$\begin{aligned} V/\delta &= w - k\left(\frac{\xi + G' - q_R R}{NB}\right) + V(G, R), \text{ so} \\ m/\delta &= -V_G/\delta = \frac{kd_G}{NB} - V_R q_G \\ &= \frac{kd_G}{NB} - \frac{q_G \delta q_R k}{NB} \\ &= \frac{kd_G\left(1 - \delta q_R\right)}{NB}. \end{aligned}$$

Same argument can be used for st-agreements. Hence, we can write

$$V\left(.\right) = \frac{\delta k\left(1 - d_R\right)}{Bn} R - \frac{\delta k d_G\left(1 - \delta q_R\right)}{Bn} G, \tag{7.4}$$

plus some constant. The $n + 1$ stocks can thus be represented by one state parameter. Notice that there are multiple equilibria wrt to how the total investments are shared among the countries. Assuming symmetry pins down the contribution. This assumption is natural in that for long-term agreements, studied below, symmetry wrt investment levels follow and is not assumed.

### 7.2. Short-term agreements

When choosing $y_i$ in negotiations, notice that the countries have the same preferences over $y_i$. At the bargaining stage, the continuation value is:

$$-\frac{c}{2}G^2 - \frac{v}{2}\left(\overline{y} - y_i\right)^2 + V\left(G, R\right).$$

If bargaining fails, continuation values are also independent of $R_i$, for $R$ given. Thus, the problem is symmetric (even if $R_i$s should differ) when negotiating $y_i$, and if assuming that each country gets an equal share of the bargaining surplus (which would be the case under Nash bargaining solution, for example), the outcome is simply that all $y_i$s are the same, and they are such that $u_i$ is maximized:

$$\begin{aligned}
0 &= -ncG + v\overline{y} - vy_i - nm \Rightarrow y_i = \overline{y} - \frac{nm + ncG}{v} \\
G &= \sum_j \left(y_j - R_j\right) + G' + \theta = G' + \theta + n\left(\overline{y} - \frac{nm + ncG}{v}\right) - R \Rightarrow \\
G &= \frac{nv\overline{y} - n^2 m + v\left(G' + \theta - R\right)}{n^2 c + v} \Rightarrow \\
y_i &= \overline{y} - \frac{nm}{v} - \frac{nc}{v}\left(\frac{nv\overline{y} - n^2 m + v\left(G' + \theta - R\right)}{n^2 c + v}\right) \\
&= \frac{v\overline{y} - nm - nc\left(G' + \theta - R\right)}{n^2 c + v} \Rightarrow \\
g_i &= \frac{v\overline{y} - nm - nc\left(G' + \theta - R\right)}{n^2 c + v} - R_i. \qquad (7.5)
\end{aligned}$$

Interrim utility is

$$\begin{aligned}
w_i^{st} &= -\frac{c}{2}G^2 - \frac{v}{2}\left(\frac{nm + ncG}{v}\right)^2 + V\left(G, R\right), \text{ so} \\
\partial w_i^{st}/\partial R_j &= \left(cG + \frac{nc\left(nm + ncG\right)}{v}\right)\left(\frac{v}{n^2 c + v}\right) + m\left(\frac{v}{n^2 c + v}\right) + m' \\
&= cG + m + m'.
\end{aligned}$$

So, a country invests until the marginal costs of investment is

$$
\begin{aligned}
k/B &= \mathrm{E}cG + m + m' \Rightarrow \mathrm{E}G = \frac{k}{Bc} - \frac{m+m'}{c} \Rightarrow \\
R &= G' + n\left(\overline{y} - \frac{nm + nc\mathrm{E}G}{v}\right) - \mathrm{E}G = G' + n\overline{y} - \frac{n^2 m}{v} - \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bc} - \frac{m+m'}{c}\right) \Rightarrow \\
rnB + R' &= G' + n\overline{y} - \frac{m}{c} - \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bc} + \frac{m'}{c}\right) \text{ and} \\
G &= \frac{k}{Bc} - \frac{m+m'}{c} + \frac{v\theta}{n^2 c + v} \\
\overline{y} - y_i &= \frac{nm}{v} + \frac{nc}{v}\left(\frac{k}{Bc} - \frac{m+m'}{c} + \frac{v\theta}{n^2 c + v}\right) = \frac{n}{v}\left(\frac{k}{B} - m' + \frac{vc\theta}{n^2 c + v}\right)
\end{aligned}
$$

Similarly to before, we can write

$$
\begin{aligned}
u_i^{st} &= -\frac{c}{2}G^2 - \frac{v}{2}\left(\overline{y} - y_i\right)^2 - kr_i \\
&= -\frac{c}{2}\left(\frac{k}{Bc} - \frac{m+m'}{c} + \frac{\theta v}{n^2 c + v}\right)^2 - \frac{n^2}{2v}\left(\frac{k}{B} - m' + \frac{\theta vc}{n^2 c + v}\right)^2 - kr_i
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{E}u_i^{st} = {} & -\frac{c}{2}\left(\frac{k}{Bc} - \frac{m+m'}{c}\right)^2 - \frac{n^2}{2v}\left(\frac{k}{B} - m'\right)^2 \\
& -\frac{k}{nB}\left(G' - R' + n\overline{y} + \frac{m}{c} - \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bc} - \frac{m'}{c}\right)\right) + \frac{\sigma^2 vc}{2}.
\end{aligned}
$$

The argument following (7.3) continues to hold, leading to (7.4).

### 7.2.1. A comparison

First, notice that

$$
\begin{aligned}
R^{bau} &= G' - \frac{k\left(v + nc\right)^2}{cvB\left(v + c\right)} + \overline{y}n + \frac{m'\left(v + nc\right)^2}{cv\left(v + c\right)} + \frac{m}{c} \text{ and} \\
R^{st} &= G' + n\overline{y} - \frac{m}{c} - \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bc} - \frac{m'}{c}\right) \text{ so} \\
R^{bau} - R^{st} &= -\frac{k\left(v + nc\right)^2}{cvB\left(v + c\right)} + \frac{m'\left(v + nc\right)^2}{cv\left(v + c\right)} + \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bc} - \frac{m'}{c}\right) \\
&= \frac{-1}{cv\left(v + c\right)}\left(\left(v + nc\right)^2 - \left(n^2 c + v\right)\left(v + c\right)\right)\left(\frac{k}{B} - \frac{\delta k\left(1 - d_R\right)}{Bn}\right) > 0.
\end{aligned}
$$

Comparing the utilities (after a lot of algebra) leads to the following condition. $U^{st} > U^{bau}$ if and only if

$$
\left(1 - \frac{1}{n}\right)^2 - \left(\frac{1 - \delta\left(1 - d_R\right)}{n}\right)^2 < \frac{\left(v + c\right)\left(\sigma vcB/k\right)^2}{\left(n^2 c + v\right)\left(nc + v\right)^2}.
$$

### 7.3. Long-term Agreements

Again, we solve each period by backwards induction, taking the continuation value $V(.)$ as given. After the R&D stage, a country's interrim utility is given by:

$$w_i^{lt} = -\frac{c}{2}\left(G' + \theta + \sum g_i^{lt}\right)^2 - \frac{v}{2}\left(\overline{y} - g_i - R_i\right)^2 + V(.).$$

The first-order condition, when choosing $r_i$, is therefore:

$$\begin{aligned}
0 &= v\left(\overline{y} - g_i - R_i\right) b + m'B - k \Rightarrow \\
R_i &= \overline{y} - g_i - \frac{k - m'B}{vb} \\
R_i' + br_i + \sum_{j \neq i} er_j &= \overline{y} - g_i - \frac{k - m'B}{vb},
\end{aligned}$$

where I have used $R_i' \equiv R_{i,-}(1 - d_R)$. In equilibrium, $R_i' + g_i$ is going to be identical across countries, implying that all $r_i$s will be identical (and equal to, say, $r$):

$$Br = \overline{y} - \left(g_i + R_i'\right) - \frac{k - m'B}{vb}.$$

This taken into account, a country's expected utility before the investment stage (but after the initial commitments are made) is given by:

$$-\frac{c}{2}\left(G' + \sum g_i^{lt}\right)^2 - \frac{v}{2}\left(\frac{k - m'B}{vb}\right)^2 - \frac{k}{B}\left(\overline{y} - \left(g_i + R_i'\right) - \frac{k - m'B}{vb}\right) + V(.) - \frac{c\sigma^2}{2}.$$

Negotiating the $g_i$s is equivalent to negotiating the $(g_i + R_i')$s, and all countries have symmetric and identical preferences over these terms. Thus, the $(g_i + R_i')$s are going to be equal in equilibrium, and they are going to be chosen such that $u_i$ is maximized. This gives the first-order condition for increasing all the $g_i$s is:

$$\begin{aligned}
0 &= -cn\left(G' + \sum g_i^{lt}\right) + \frac{k}{B} - nm - nm' \Rightarrow \\
\sum g_i^{lt} &= \frac{k}{Bcn} - \frac{m}{c} - \frac{m'}{c} - G' \Rightarrow \\
g_i^{lt} &= \frac{k}{Bcn^2} - \frac{m}{cn} - \frac{m'}{cn} - \frac{G'}{n} + \left(R' - R_i'\right).
\end{aligned}$$

This can be compared to the emission levels that would be optimal (to negotiate to) ex post, after $\theta$ (and the investments) are realized. These emission levels are given by

(7.5) above, where we have to substitute for the technology levels under the long-term agreement:

$$G' + \sum g_i + \theta = \frac{nv\bar{y} - n^2 m + v\left(G' + \theta - R\right)}{n^2 c + v}$$

$$\begin{aligned}
\mathrm{E}g_i^* &= \frac{v\bar{y} - nm + v\left(G' - R^{lt}\right)/n}{n^2 c + v} - G'/n \\
&= \frac{v\bar{y} - nm - ncG'}{n^2 c + v} - \frac{v}{n^2 c + v}\left(\bar{y} - g_i^{lt} - \frac{k - m'B}{vb}\right) \\
&= \frac{\left(k - m'B\right)/b - nm - ncG'}{n^2 c + v} + \frac{v g_i^{lt}}{n^2 c + v}.
\end{aligned}$$

Thus,

$$\begin{aligned}
\left(\mathrm{E}g_i^* - g_i^{lt}\right)\left(n^2 c + v\right) &= \left(\frac{k - m'B}{b}\right) - nm - ncG' - n^2 c g_i^{lt} \\
&= \left(\frac{k - m'B}{b}\right) - nm - ncG' - n^2 c\left(\frac{k}{Bcn^2} - \frac{m}{cn} - \frac{m'}{cn} - \frac{G'}{n}\right) \\
&= \left(\frac{k - m'B}{b}\right) - n^2 c\left(\frac{k}{Bcn^2} - \frac{m'}{cn}\right).
\end{aligned}$$

Calculating $u_i$ gives $m' = \delta k\left(1 - d_R\right)/Bn$, just as before. Anticipating and substituting this, we get:

$$\begin{aligned}
\left(\mathrm{E}g_i^* - g_i^{lt}\right)\left(n^2 c + v\right)B/k &= B\left(\frac{1 - \delta\left(1 - d_R\right)/n}{b}\right) - 1 + \delta\left(1 - d_R\right) \\
&= \left(b + (n-1)e\right)\left(\frac{1 - \delta\left(1 - d_R\right)/n}{b}\right) - 1 + \delta\left(1 - d_R\right) \\
&= (n-1)e\left(\frac{1 - \delta\left(1 - d_R\right)/n}{b}\right) + \delta\left(1 - d_R\right)\left(1 - 1/n\right) \\
&= \frac{(n-1)e}{b} + \delta\left(1 - d_R\right)\left(1 - 1/n\right)\left(1 - \frac{e}{b}\right).
\end{aligned}$$

### 7.4. Long-term Agreements with Renegotiation

In each period, the timing is as follows: First, the countries negotiate a set of emission levels, $g_i^{de}$. Thereafter, countries invest, $\theta$ is realized, and the countries renegotiate or negotiate another set of emission levels, $g_i^{re}$. Finally, countries pollute their allowed levels, and utilities are realized. If the renegotiations fail, the initial agreement is the default outcome. If the initial negotiation fails, the non-cooperative equilibrium is the outcome. As always, each period is solved by backwards induction.

Under the default outcome, a country's (interrim) utility is:

$$w_i^{de} = -\frac{c}{2}\left(G' + \theta + \sum g_j^{de}\right)^2 - \frac{v}{2}\left(\overline{y} - g_i^{re} - R_i\right)^2 + V\left(.\right).$$

The sum of the utilities after renegotiation is (optimal) as after a short-term agreement is negotiated

$$\begin{aligned}
\sum \frac{w_i^{st}}{n} &= -\frac{c}{2}G^2 - \frac{v}{2}\left(\frac{nm + ncG}{v}\right)^2 + V\left(G, R\right), \text{ where} \\
G &= \frac{nv\overline{y} - n^2 m + v\left(G' + \theta - R\right)}{n^2 c + v}.
\end{aligned}$$

From the envelope theorem,

$$\partial\left(\sum \frac{w_i^{st}}{n}\right)/\partial R_i = \left(m + cG\right) + m',$$

and the optimal investment level is given by

$$\begin{aligned}
k/B &= mn + nc\mathrm{E}G + nm' \Rightarrow \\
\mathrm{E}G &= G' + \sum g_j^* = \frac{k}{Bnc} - \frac{m + m'}{c} \Rightarrow \\
R^* &= G' + n\overline{y} - \frac{n^2 m}{v} - \left(\frac{n^2 c + v}{v}\right)\left(\frac{k}{Bnc} - \frac{m + m'}{c}\right).
\end{aligned} \tag{7.6}$$

Since $i$ gets $1/n$ of the renegotiation-surplus, in addition to its default utility, $i$'s utility can be written as:

$$w_i^{de} + \frac{1}{n}\sum_j \left(w_i^{st} - w_i^{de}\right).$$

Maximizing this expression w.r.t. $r_i$ gives the equilibrium first-order condition

$$0 = bv\left(\overline{y} - g_i^{de} - R_i\right) + Bm' - B\left(\frac{v\left(\overline{y} - g_i^{de} - R_i\right)}{n} + m'\right) - k + \frac{B}{n}\partial\left(\sum w_i^{st}\right)/\partial R$$

If investments are first-best, the last term is equal to $k/n$. Substituting this (hoping that equilibrium investments are first-best), we get

$$\begin{aligned}
0 &= v\left(\overline{y} - g_i^{de} - R_i\right)\left(b - B/n\right) - k\left(1 - 1/n\right) \Rightarrow \\
R_i^{de} &= \overline{y} - g_i^{de} - \frac{k\left(1 - 1/n\right)}{v\left(b - B/n\right)}.
\end{aligned}$$

Investments are first best, indeed, if $nR_i^{de} = R^*$, requiring

$$\begin{aligned}
n\overline{y} - ng_i^{de} - \frac{k(n-1)}{v(b-B/n)} &= G' + n\overline{y} + \frac{m}{c} - \left(\frac{n^2c+v}{v}\right)\left(\frac{k}{Bnc} - \frac{m'}{c}\right) \Rightarrow \\
ng_i^{de} &= -\frac{k(n-1)}{v(b-B/n)} - G' - \frac{m+m'}{c} - \frac{m'n^2}{v} + \left(\frac{n^2c+v}{v}\right)\frac{k}{Bnc}.
\end{aligned}$$

On the other hand, the expected optimal pollution level is given by (7.6)

$$ng_i^* = \frac{k}{Bnc} - \frac{m+m'}{c} - G', \text{ so}$$

$$ng_i^* - ng_i^{de} = \frac{k(n-1)}{v(b-B/n)} + \frac{m'n^2}{v} - \frac{kn}{Bv}.$$

Again, anticipating $m' = \delta k(1-d_R)/Bn$, we can write

$$\begin{aligned}
\left(g_i^* - g_i^{de}\right)\frac{Bv}{k} &= \delta(1-d_R) + \frac{(n-1)}{(bn/B-1)} - 1 \\
&= \delta(1-d_R) + \frac{n(1-b/B)}{bn/B-1}
\end{aligned}$$

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