The Dynamics of Climate Agreements†

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Abstract

This paper provides a model in which countries over time pollute as well as invest in technologies (renewable energy sources or abatement technologies). Without a climate treaty, the countries pollute too much and invest too little, partly to induce the others to pollute less and invest more in the future. Nevertheless, short-term agreements on emission levels can *reduce* welfare, since countries invest less when they anticipate future negotiations. The optimal agreement is tougher and more long-term if intellectual property rights are weak. If the climate agreement happens to be short-term or absent, intellectual property rights should be strengthened, tariffs should decrease, and investments should be subsidized. Thus, subsidizing or liberalizing technological trade is a strategic substitute for tougher climate treaties.

Key words: Dynamic common pool problems, dynamic hold-up problems, incomplete contracts, contract-length, climate treaty design, intellectual property rights
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1. Introduction

Implementing efficient climate change policies is tremendously difficult. The climate is a public good and emissions cumulate over time, generating a dynamic common pool problem. In addition, a lasting solution may require investments in new technology.

Recent agreements have two distinct characteristics.[1] First, they have focused on emissions but ignored investments, perhaps because investment levels would be hard to verify by third parties. Second, the commitments are relatively short-term, since committing to the far future may be neither feasible nor desirable. How valuable is such an agreement? How does it affect the incentive to invest in technology? What is the optimal term of the agreement, and how do the answers hinge on existing trade policies and intellectual property rights?

These questions are immensely important, but we do not yet have clear answers, or a good framework for deriving them. This paper addresses the questions head-on by isolating the interaction among negotiations, emission levels, and investments. I present a dynamic framework in which, in every period, countries pollute as well as invest in technology. The pollution as well as the technology stocks depreciate but cumulate over time. The technology reduces the need to pollute, and it can be interpreted as either renewable energy sources or abatement technology.

While the model has a large number of subgame-perfect equilibria, the symmetric Markov perfect equilibria (MPEs) are selected since they are simple and robust. With this refinement, the equilibrium turns out to be unique and the analysis tractable, despite the large number of stocks in the model. Since the equilibrium is unique, tacit agreements enforced by trigger strategies are not feasible. But, by varying the countries' ability to negotiate, contract, and commit, and equilibrium contract is derived as a function of this ability. Since the equilibrium agreement is also the constrained optimum, the results can be interpreted normatively.

If all investments and emission levels were contractible, the first-best could be im-

[1] The two features characterize the current Kyoto Protocol as well as the 2009 Copenhagen Accord and the 2010 Cancun Agreement. The Kyoto Protocol specifies emission reductions for the five-year period 2008-12, while the Copenhagen Accord lists quantified targets for 2020. The Cancun Agreement, in addition, has a subsection on how to facilitate technology transfers (http://cancun.unfccc.int/).

plemented and the countries would negotiate and commit to the first-best actions in equilibrium. At the other extreme, suppose all decisions are made noncooperatively. If one country decides to pollute a lot, the other countries are induced to pollute less in the future since the problem is then more severe. They will also invest more in technology to be able to afford the necessary cuts in emissions. If a country decides to invest a lot in abatement technology, it can be expected to pollute less in the future. This induces the other countries to increase their emissions and reduce their own investments. Anticipating these effects, each country pollutes more and invests less than it would in an otherwise similar static model. The business-as-usual scenario is thus a particularly harmful dynamic common-pool problem.

In reality, climate agreements are neither complete nor absent. While some actions are negotiatable, others are not. To capture this, assume now the countries can negotiate emission levels - at least for the near future - but not investments. This is a characteristic of the Kyoto Protocol, and it pins down the countries' contributions without specifying whether a country complies by investing in a long-term solution rather than simply reducing current consumption.[2] This assumption is also in line with the incomplete contract theory literature, where investments are observable but not verifiable by a third party (Segal and Whinston, 2010). The result is hold-up problems at two levels. First, the incentive to develop technology is low if intellectual property rights are weak. Second, a government, considering to pay for such technology, may fear to be hold up by the others when negotiating emission quotas.[3] This setting generates several lessons for policy.

First, climate agreements can *reduce* welfare relative to business as usual. When negotiations are anticipated, countries fear the hold-up problem, and the incentive to invest is reduced. Consequently, everyone is worse off, particularly if intellectual property rights are weak, the length of the agreement is short, and the number of countries large.

Second, the optimal climate treaty is characterized. If the quotas are negotiated before a country invests, it cannot be held up by the other countries - at least not before

[2] Golombek and Hoel (2006: 2) argue that "it would hardly be feasible for a country (or some international agency) to verify all aspects of other countries' R&D policies."

[3] *Financial Times* reports that "Leaders of countries that want concessions say that nations like Denmark have a built-in advantage because they already depend more heavily on renewable energy" (October 17, 2008: A4).

the agreement expires. Thus, countries invest more when the agreement is long-term. Nevertheless, countries underinvest compared to the optimum if the agreement does not last forever or if intellectual property rights are weak. To compensate and encourage further investments, the best (and equilibrium) treaty is tougher (in that it stipulates lower emissions) relative to what is optimal ex post (once the investments are sunk). The weaker are the intellectual property rights, the tougher is the optimal (and equilibrium) climate treaty.

The optimal length of the agreement is also characterized. On the one hand, a longer time horizon is required to minimize the hold-up problem and to maximize the incentive to invest in technology. On the other, the future marginal cost of pollution is uncertain and stochastic in the model, and it is hard to guess on the ideal quotas in the far future. The optimal length trades off these concerns. If intellectual property rights are weak, for example, the optimal length increases.

The model can easily allow for technological trade, tariffs, or subsidies. With a high tariff on technological trade, or a low R&D subsidy, the incentive to invest is lower. As a result, a short-term agreement is more likely to be worse than business as usual, since short-term agreements are further reducing investments. The optimal climate agreement is both tougher and more long-lasting if tariffs are high or subsidies low.

The optimal climate treaty is thus a function of trade policies, but the reverse is also true: if the climate treaty is relatively short-term, it is more important to strengthen intellectual property rights, reduce tariffs, and increase subsidies on investments. Negotiating such trade policies is thus a strategic substitute for a tough climate agreement.[4]

By analyzing environmental agreements in a dynamic game permitting incomplete contracts, I contribute to three strands of literature.

The literature on climate policy and environmental agreements is growing.[5] While Nordhaus (2006) criticizes the Kyoto Protocol for not being sufficiently inclusive, cost effective, or ambitious, the current paper detects that, *even* without these weaknesses, this

[4] This argument is quite different from the question of whether a general liberalization of trade improves the environment (Copeland and Taylor, 2003; 2004).

[5] See Kolstad and Toman (2005) on climate policy and Barrett (2005) on environmental agreements. Aldy et al. (2003) and Aldy and Stavins (2007; 2009) discuss alternative climate agreement designs.

type of emission-agreement is fundamentally flawed. The literature usually emphasizes the positive effects of regulation on technological change,[6] and a typical recommendation is decade-long short-term agreements, partly to ensure flexibility (see, for example, Karp and Zhao, 2009). The present paper, in contrast, shows that short-term agreements reduce the incentive to invest in new technology and can be worse than business as usual. This builds on Buchholtz and Konrad (1994), who first noted that R&D might decrease prior to negotiations.[7] Beccherle and Tirole (2011) have recently generalized my one-period model and shown that anticipating negotiations can have adverse effects also if the countries, instead of investing, sell permits on the forward market, allow banking, or set production standards. With only one period, however, these models miss dynamic effects and thus the consequences for agreement design.

There is already a large literature on the private provision of public goods in dynamic games.[8] Since the evolving stock of public good influences the incentive to contribute, the natural equilibrium concept is Markov perfect equilibrium and it is quite standard to assume linear-quadratic functional forms.[9] As in this paper, equilibrium provision levels tend to be suboptimally low when private provisions are strategic substitutes (Fershtman and Nitzan, 1991; Levhari and Mirman, 1980). There are often multiple MPEs, however, so Dutta and Radner (2009), for example, investigate whether good equilibria, with little pollution, can be sustained by the threat of reverting to a bad one. Few authors complicate the model further by adding technological investments. Dutta and Radner (2004) is an interesting exception, but since their costs of pollution and investment are both linear, the equilibrium is "bang-bang" where countries invest either zero or maximally in the first period, and never thereafter. The contribution of this paper is, first, to provide a tractable model, with a unique MPE, in which agents invest as well as pollute over time. Second, incomplete contracts are added to the model. Incomplete contracts are necessary

[6] See, e.g., Jaffe et al. (2003), Newell et al. (2006), Golombek and Hoel (2005). Even when investments are made prior to negotiations, Muuls (2009) finds that investments increase when the negotiations are anticipated. Hoel and de Zeeuw (2010), in contrast, show that R&D can decrease if countries cooperate because they then reduce pollution even without new technology, although there is no negotiation in their model and their analysis hinges on a "breakthrough technology" and binary abatement levels.

[7] Analogously, Gatsios and Karp (1992) show how firms may invest suboptimally prior to merger negotiations.

[8] For treatments of differential games, see Başar and Olsder (1999) or Dockner et al. (2000).

[9] For a comprehensive overview, see Engwerda (2005).

when the question is how agreements on emissions affect the incentive to invest.[10]

By permitting contracts on emissions but not on investments, this paper is in line with the literature on incomplete contracts (e.g., Hart and Moore, 1988). But the standard model has only two stages and few papers study the optimal contract length. Harris and Holmstrom (1987) discuss the length when contracts are costly to rewrite but uncertainty about the future makes it necessary. To preserve the optimal incentives to invest, Guriev and Kvasov (2005) argue that the agents should continuously renegotiate the length. Ellman (2006) studies the optimal probability for continuing the contract and finds that it should be larger if specific investments are important. This is somewhat related to my result on how the optimal term increases in intellectual property rights. However, Ellman permits only two agents, one investment period, and uncertainty is not revealed over time. Finally, the result that short-term agreements can be worse than no agreement is certainly at odds with the literature above, focusing on bilateral trade.

Several of the results generalize qualitatively. This is confirmed in the more technical companion paper (Harstad, 2012), which allows for general functional forms, heterogeneous investment costs, and renegotiation. That paper, however, abstracts from uncertainty, intellectual property rights, and trade policies, and it does not discuss short-term agreements. Also, by specifying quadratic utility functions, the following analysis goes further and describes when agreements are beneficial and how long they should last.

The model is presented in the next section. Section 3 presents the (complete contracting) first-best outcome as well as the (noncooperative) business-as-usual scenario. The fact that short-term agreements can be worse is shown in Section 4, while Section 5 characterizes the optimal agreement. Technological trade and trade policies are discussed in Section 6, revealing a close connection between trade policies and climate agreements. Section 7 discusses robustness and finds that the results hold no matter whether side transfers are available or the emission permits tradable. The final section concludes, before the proofs follow in the Appendix.

[10] Few papers study policies in differential games: Hoel (1993) studies a differential game with an emission tax, Yanase (2006) derives the optimal contribution subsidy, Houba et al. (2000) analyze negotiations over (fish) quotas lasting forever, while Sorger (2006) studies one-period agreements. Although Ploeg and de Zeeuw (1992) even allow for R&D, contracts are either absent or complete in all these papers.

2. The Model

2.1. Payoffs and Pollution

Pollution is a public bad. Let G represent the stock of greenhouse gases, and assume that the environmental cost for every country $i \in N \equiv \{1, ..., n\}$ is given by the quadratic cost-function:

$$C(G) = \frac{c}{2} G^2.$$

Parameter $c > 0$ measures the importance of climate change.

The stock of greenhouse gases G is measured relative to its "natural" level: G would, were it not for emissions, tend to approach zero over time and $1 - q_G \in [0, 1]$ measures the fraction of G that "depreciates" every period. The stock may nevertheless increase if a country's emission level g_i is positive:

$$G = q_G G_- + \sum_N g_i + \theta. \tag{2.1}$$

By letting G_- represent the stock of greenhouse gases in the previous period, subscripts for periods can be skipped.

The shock θ is arbitrarily distributed with mean 0 and variance σ^2. It is quite realistic to let the depreciation and accumulation of greenhouse gases be uncertain. The main impact of θ is that it affects the marginal cost of pollution. In fact, the model is essentially unchanged if the level of greenhouse gases is simply $\widehat{G} \equiv q_G G_- + \sum_N g_i$ while the marginal cost of pollution is stochastic and given by $\partial C / \partial \widehat{G} = c\Theta + c\widehat{G}$, where $\Theta \equiv q_G \Theta_- + \theta$. For either formulation, a larger θ increases the marginal cost of emissions. Note that, although θ is i.i.d. across periods, it has a long-lasting impact through its effect on G (or on Θ). The additive form in equation (2.1) is standard in the literature.[11]

The benefit of polluting g_i units is that country i can consume g_i units of energy. Country i may also be able to consume alternative or renewable energy, depending on its stock of nuclear power, solar technology, or windmills. Let R_i measure this stock and the

[11] The additive form of the *noise* is standard in the literature on differential games (Başar and Olsder, 1999: Section 6.4; Dockner et al., 2000, Section 8.2), particularly when using quadratic functions (Engwerda, 2005: Section 9.1). The additive form of $q_G G_-$ and the assumption that $q_G \in (0, 1)$ is particularly natural in pollution settings (Dutta and Radner, 2004 and 2009).

amount of energy it can produce. The total amount of energy consumed is thus:

$$y_i = g_i + R_i, \tag{2.2}$$

and the associated benefit for i is:

$$B_i(y_i) = -\frac{b}{2}(\overline{y}_i - y_i)^2. \tag{2.3}$$

The benefit function is thus concave and increasing in y_i up to i's bliss point $\overline{y}_i$, which can vary across countries. The bliss point represents the ideal energy level if there were no concern for pollution: a country would never produce more than $\overline{y}_i$ due to the implicit costs of generating, transporting, and consuming energy. The average $\overline{y}_i$ is denoted $\overline{y}$. Parameter $b > 0$ measures the importance of energy.

The green technology can alternatively be interpreted as abatement technology. Suppose R_i measures the amount by which i can at no cost reduce (or clean) its potential emissions. If energy production, measured by y_i, is generally polluting, the actual emission level of country i is given by $g_i = y_i - R_i$, implying (2.2), as before. The additive form of (2.2) has also been adopted elsewhere in the literature.[12]

2.2. Technology and Time

The technology stock R_i may change over time. On the one hand, the technology might depreciate at the expected rate of $1 - q_R \in [0, 1]$. On the other, if r_i measures country i's investment in the current period, then:

$$R_i = q_R R_{i,-} + r_i.$$

As described by Figure 1, the investment stages and the pollution stages alternate over time.[13] Without loss of generality, define "a period" to start with the investment stage and end with the pollution stage. In between, θ is realized. Information is symmetric at all stages.

[12] See, for example, Roussillon and Schweinzer (2010), analyzing how investment-contests can be designed to implement the first–best. If, instead, the model focused on technologies that reduced the emission *content* of *each* produced unit (as in Dutta and Radner, 2004), the below analysis would be

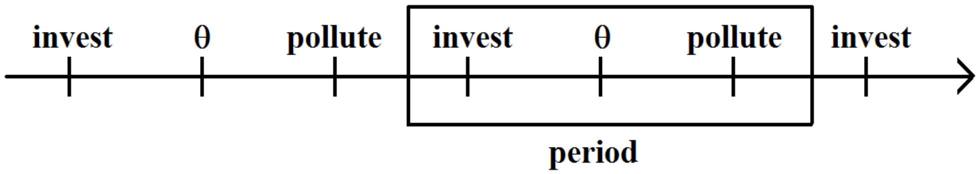

Figure 2.1: *Figure 1: The investment and emission stages alternate over time*

The cost of an invested unit is K. Thus, country i's flow utility is:

$$u_i = B_i(y_i) - C(G) - Kr_i, \tag{2.4}$$

and a country's objective is to maximize the present-discounted value of its utilities, i.e., its continuation value of the game:

$$U_{i,t} = \sum_{\tau=t}^{\infty} \delta^{\tau-t} u_{i,\tau},$$

where δ is the common discount factor.

Section 5 allows the investments to be verifiable, contractible, and subsidizable. But in most of this paper, the investments are assumed to be observable but not verifiable by third parties. This is in line with the literature on incomplete contracts and may lead to hold-up problems at the international as well as at the national level.

At the international level, it is difficult for countries to negotiate and contract on investment levels. If a country has promised to reduce g_i, it can comply by reducing its short-term consumption or by investing in more long-lasting technology. The difference may be hard to detect by third parties. Therefore, if a country has promised to invest a certain amount, it may be tempted to report other public expenditures as such investments. These problems may explain why the Kyoto Protocol has specified emission quotas, but not investment levels.

much harder.

[13]This assumption can be endogenized. Suppose the countries can invest at any time in the interval $[t-1, t]$, where t and $t+1$ denote emission stages, but that the investment must take place at least $\xi < 1$ units (measured as a fraction of the period-length) before time t, for the technology to be effective at time t. Then, all countries will invest at time $t - \xi$, never at time $t - 1$.

At the national level, a government purchasing technology may find it difficult to describe the exact requirements in advance. An innovator or entrepreneur will need to develop the technology first, and then hope the government is willing to pay for it. Let $\mu \in (0,1]$ be the fraction of the government's benefit that the innovator can capture. If the innovator sets the price, μ represents the innovators' intellectual property right, i.e., the fraction of an investment that is protectable for the innovator, while the fraction $1-\mu$ is available for the government to copy for free.[14] Alternatively, μ may represent the innovator's *bargaining power*.[15] In any case, investments take place until a government's marginal benefit, multiplied by μ, equals the cost of investment, K:

$$\partial \frac{B_i(\cdot) - C(\cdot) + \delta U_{i,+}(\cdot)}{\partial R_i} = \frac{K}{\mu}, \tag{2.5}$$

With free entry, innovators earn zero profit, charge the price K, and the government's utility is given by (2.4).

The model is more general than might at first appear: If the government is innovating in-house or intellectual property rights are fully enforced, then $\mu = 1$ and all the following results continue to hold. If the developers of technology are located in foreign countries, the model is unchanged, since such firms earn zero profit in any case. If an innovator can sell (or license) its ideas to several countries at the same time, let K represent the private cost of developing technology that has the potential to raise $\sum_N R_i$ by one unit, and the analysis below needs only small modifications. The previous version of the paper allowed for technological spillovers, and a larger spillover has the same effect as a smaller μ. The bliss points $\overline{y}_i$ can change over time without the need to change the analysis. Tariffs and subsidies on technological trade are discussed in Section 6, while Section 7 shows that all results continue to hold if quotas are tradable and no matter whether side transfers are allowed at the bargaining stage. The more technical companion paper (Harstad, 2012) deals with non-quadratic $B_i(.)$ and $C(.)$ functions, nonlinear and heterogeneous investment costs, continuous time, renegotiation, and it derives conditions under which

[14] This is a slight modification of Acemoglu, Antras, and Helpman (2007). In their model, μ is the fraction of the tasks for which effort can be specified.

[15] If the innovator and the government were bargaining over the price, the innovator would be able to capture the fraction $\widehat{\mu} \equiv \beta\mu$, where $\beta \in (0,1]$ is the innovator's share of the bargaining surplus (and thus represents its bargaining power) after the government has copied the fraction $1-\mu$ for free. In this case, all the results below continue to hold if only μ is replaced by $\widehat{\mu}$.

the results would hold if technologies and emission levels had to be nonnegative. This paper, in contrast, does not require g_i and r_i to be non-negative. In practice, a negative g_i is possible if carbon-capture is allowed, while a negative r_i would be possible if e.g. the technology could be employed for other purposes. Imposing nonnegativity constraints would complicate the analysis but not change the results under certain conditions.

2.3. Definition of an Equilibrium

There is typically a large number of subgame-perfect equilibria in dynamic games, and refinements are necessary. This paper focuses on Markov perfect equilibria (MPEs) where strategies are conditioned only on the pay-off relevant stocks (G and $\mathbf{R} \equiv \{R_1, ..., R_n\}$).

There are several reasons for selecting these equilibria. First, experimental evidence suggests that players tend toward Markov perfect strategies rather than supporting the best subgame perfect equilibrium (Battaglini et al., 2010). Second, Markov perfect strategies are simple, since they do not depend on the history in arbitrary ways.[16] This simplifies the analysis as well. Third, the unique MPE coincides with the unique subgame-perfect equilibrium if time were finite but approached infinity.[17] This is particularly important in our context, since the equilibrium is then robust to the introduction of real-world aspects that would make the effective time horizon finite. For example, since fossil fuel is an exhaustible resource, the emission game may indeed have a finite time horizon in the real world. Similarly, politicians' term-limits or short time horizon may force them to view time as expiring. Fourth, focusing on the MPEs is quite standard when studying games with stocks. By doing the same in this paper, its contribution to the literature is clarified. Fifth, in contrast to much of the literature, there is a unique MPE in the present game. This sharpens the predictions and makes institutional comparisons possible. Finally, since the unique MPE makes it impossible to enforce agreements by using trigger strategies, it becomes meaningful to focus instead on settings where countries can negotiate and

[16] Maskin and Tirole (2001:192-3) defend MPEs since they are "often quite successful in eliminating or reducing a large multiplicity of equilibria," and they "prescribe the simplest form of behavior that is consistent with rationality" while capturing that "bygones are bygones more completely than does the concept of subgame-perfect equilibrium."

[17] This can easily be seen by the recursive nature of the proofs. Fudenberg and Tirole (1991:533) suggest that "one might require infinite-horizon MPE to be limits of finite-horizon MPE."

contract on emission levels - at least for the near future. By varying the possibilities to negotiate and contract, I derive a unique equilibrium for each situation.[18]

At the negotiation stage, I assume the bargaining outcome is efficient and symmetric *if* it should happen that the game and the payoffs are symmetric. This condition is satisfied whether we rely on (i) the Nash Bargaining Solution, with or without side transfers, (ii) the Shapley value, or instead (iii) noncooperative bargaining where one country is randomly selected to make a take-it-or-leave-it offer specifying quotas and side payments. Thus, the condition is quite weak. Note that all countries participate in equilibrium, since there is no stage at which they can close the door to negotiations.

3. Benchmarks

3.1. Solution Method

While the $n+1$ stocks in the model is a threat to its tractability, the analysis is simplified by two of the model's deliberately chosen features. First, one can utilize the additive form in (2.2). By substituting (2.2) into (2.1), we get:

$$G = q_G G_- + \theta + \sum_N \widetilde{y}_i - R, \text{ where} \tag{3.1}$$

$$R \equiv \sum_N R_i = q_R R_- + \sum_N r_i \text{ and} \tag{3.2}$$

$$\widetilde{y}_i \equiv y_i + \overline{y} - \overline{y}_i. \tag{3.3}$$

Together with $u_i = -b(\overline{y} - \widetilde{y}_i)^2/2 - cG^2/2 - Kr_i$, the R_is as well as the $\overline{y}_i$s are eliminated from the model: they are *payoff-irrelevant* as long as R is given, and i's Markov perfect strategy for $\widetilde{y}_i$ or r_i is thus not conditioned on them.[19] A country's continuation value U_i is thus a function of only G_- and R_- and we can therefore write it as $U(G_-, R_-)$, without the subscript i.

[18] This paper does not attempt to explain *why* countries comply with their promises, but one possibility is that the treaty must be ratified domestically and that certain stakeholders have incentives to sue the government unless it complies.

[19] That is, there is no reason for one player to condition its strategy on R_i, if the other players are not doing it. Thus, ruling out dependence on R_i is in line with the definition by Maskin and Tirole (2001:202), where Markov strategies are measurable with respect to the coarsest partition of histories consistent with rationality.

Second, the linear investment cost is utilized to prove that the continuation value must be linear in R and, it turns out, in G. Naturally, this simplifies the analysis tremendously, and it leads to a unique symmetric MPE for each scenario analyzed below.[20]

PROPOSITION 0. (i) *There is a unique symmetric Markov perfect equilibrium for every contracting environment analyzed below.*
(ii) *In each case, the continuation value is a function of only G and R, and it has the slopes:*

$$\begin{aligned} U_R &= \frac{q_R K}{n}, \\ U_G &= -\frac{q_G K}{n}(1-\delta q_R). \end{aligned}$$

This result is referred to as Proposition 0 since it is the foundation for the propositions emphasized below. It holds for *every* scenario analyzed below, and it is proven in the Appendix when solving for each case.

3.2. The First-Best

If investments as well as emissions were contractible, the countries would agree to the first-best outcome. This follows from the observation (made in the previous subsection) that the bargaining game is symmetric, even if the R_is or the $\overline{y}_i$s would differ, and the outcome is thus efficient, as required in Section 2.3. The bargaining outcome would then coincide to the case where a benevolent planner made all decisions in order to maximize the sum of utilities.

PROPOSITION 1. (i) *The first-best emission levels are functions of the technology stocks,* $\mathbf{R} \equiv \{R_1, ..., R_n\}$:

$$g_i^*(\mathbf{R}) = \overline{y}_i - R_i - \frac{cn(n\overline{y} + q_G G_- + \theta - R) + \delta q_G (1-\delta q_R) K}{b + cn^2}. \tag{3.4}$$

[20] As the proposition states, this is the unique *symmetric* MPE. Since the investment cost is linear, there also exist asymmetric MPEs in which the countries invest different amounts (these are analyzed in Harstad, 2012).

(ii) *The first-best investments, given first-best emission levels, are:*

$$r_i^* = \overline{y} - \frac{q_R}{n}R_- + \frac{q_G}{n}G_- - (1-\delta q_R)\left(\frac{1-\delta q_G}{cn^2} + \frac{1}{b}\right)K.$$

(iii) *Combined, the pollution stock at the first-best is:*

$$G^* = \sum_N g_i^*(\mathbf{R}^*) + q_G G_- = \frac{(1-\delta q_G)(1-\delta q_R)}{cn}K + \frac{b}{b+cn^2}\theta. \tag{3.5}$$

3.3. Business as Usual

The other extreme scenario is where neither emissions nor investments are negotiated. This noncooperative situation is referred to as business as usual.

PROPOSITION 2. *With business as usual, countries pollute too much and invest too little:*

$$\begin{aligned} r_i^{bau} &= \overline{y} - \frac{q_R}{n}R_- + \frac{q_G}{n}G_- - \left(\frac{(b+cn)^2}{cb(b+c)n}\left(\frac{1}{\mu} - \frac{\delta q_R}{n}\right) - (1-\delta q_R)\frac{\delta q_G}{cn^2}\right)K \quad (3.6) \\ &< r_i^*, \\ g_i^{bau}\left(\mathbf{R}^{bau}\right) &= \overline{y}_i - R_i - \frac{c\left(n\overline{y} + q_G G_- + \theta - R\right) + \delta q_G(1-\delta q_R)K/n}{b+cn} \\ &> g_i^*\left(\mathbf{R}^{bau}\right) > g_i^*(\mathbf{R}^*). \end{aligned} \tag{3.7}$$

The first inequality in (3.7) states that each country pollutes too much compared to the first-best levels, conditional on the investments. A country is not internalizing the cost for the others.

Furthermore, note that country i pollutes less if the existing level of pollution is large and if i possesses good technology, but more if the other countries' technology level is large, since they are then expected to pollute less.

In fact, $\overline{y}_i - R_i - g_i^{bau} = \overline{y}_i - y_i$ is the same across countries, in equilibrium, no matter what the differences in technology are. While perhaps surprising at first, the intuition is straightforward. Every country has the same preference (and marginal utility) when it comes to reducing its consumption level relative to its bliss point, and the *marginal* impact on G is also the same for every country: one *more* energy unit generates one unit of emissions. The technology is already utilized to the fullest possible extent, and producing more energy is going to pollute.

Therefore, a larger R, which reduces G, must increase every y_i. This implies that if R_i increases but R_j, $j \neq i$, is constant, then $g_j = y_j - R_j$ must increase. In words: if a country has a better technology, it pollutes less but (because of this) all other countries pollute more. Clearly, this effect reduces the willingness to pay for technology, and generates another reason why investments are suboptimally low, reinforcing the impact of the weak intellectual property rights. The suboptimal investments make it optimal to pollute more, implying the second inequality in (3.7) and a second reason for why pollution is higher than its first-best level.

In sum, a country may want to invest less in order to induce other countries to pollute less and to invest more in the following period. In addition, countries realize that if G_{-} is large for a given R, (3.7) implies that the g_is must decrease. Thus, a country may want to pollute more today to induce others to pollute less (and invest more) in the future. These dynamic considerations make this dynamic common-pool problem more severe than its static counterpart.

4. Harmful (Short-Term) Agreements

If countries can commit to the immediate but not the distant future, they may negotiate a "short-term" agreement. If the agreement is truly short-term, it is difficult to develop new technology during the time-span of the agreement and the relevant technology is given by earlier installations. This interpretation of short-term agreements can be captured by the timing shown in Figure 2.

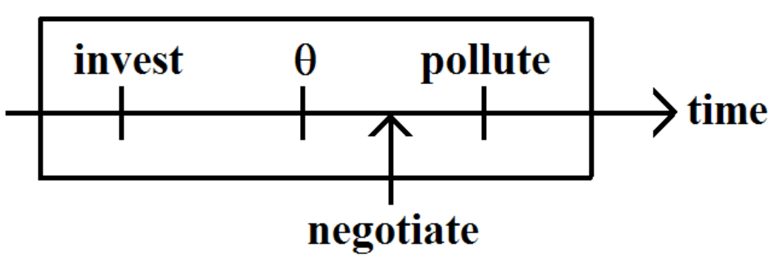

Figure 2: The timing for short-term agreements

Technically, negotiating the g_is is equivalent to negotiating the $\widetilde{y}_i$s as long as the R_is are sunk and observable (even if they are not verifiable). Just as in Section 3.1, (3.1)-(3.2) imply that the R_is are payoff-irrelevant, given R. Even if countries have different R_is, they face the same marginal benefits and costs of reducing y_i relative to $\overline{y}_i$, whether negotiations succeed or not. Symmetry thus implies that $\widetilde{y}_i$ is the same for every country in the bargaining outcome, while efficiency requires the $\widetilde{y}_i$s to be optimal. Consequently, the emission levels are equal to the first-best, conditional on past investments.

Intuitively, if country i has better technology, its marginal benefit from polluting is smaller, and i is polluting less with business as usual. This gives i a poor bargaining position, and the other countries can offer i a smaller emission quota. At the same time, the other countries negotiate larger quotas for themselves, since the smaller g_i (and the smaller G) reduces the marginal cost of polluting. Anticipating this hold-up problem, every country is discouraged from investing. This international hold-up problem provides a second reason why investments are suboptimally low, in addition to the domestic hold-up problem that arises when $\mu < 1$.

Consequently, although emission levels are ex post optimal, actual emissions are larger compared to the first-best levels since the two hold-up problems discourage investments and make it ex post optimal to pollute more.

Proposition 3. *With short-term agreements, countries pollute the optimal amount, given the stocks, but investments are suboptimally low:*

$$\begin{aligned} r_i^{st} &= r_i^* - \left(\frac{n}{\mu} - 1\right)\left(\frac{b + cn^2}{bcn^2}\right) K < r_i^*, \\ g_i^{st}\left(\mathbf{R}^{st}\right) &= g_i^*\left(\mathbf{R}^{st}\right) > g_i^*\left(\mathbf{R}^*\right). \end{aligned}$$

Deriving and describing this outcome is relatively simple because Proposition 0 continues to hold for this case, as proven in the Appendix. In particular, U_G and U_R are exactly the same as with business as usual. This does *not* imply that U itself is identical in the two cases: the levels can be different. But this does imply that when deriving actions and utilities for one period, it is irrelevant whether there will also be a short-term agreement in the next (or any future) period. This makes it convenient to compare short-term agreements to business as usual. For example, such a comparison will be independent of the stocks, since U_G and U_R are identical in the two cases.

By comparison, the pollution level is indeed less under short-term agreements than under business as usual. For welfare, however, it is also important to know how investments differ in the two cases.

PROPOSITION 4. *Compared to business as usual, short-agreements leads to:*
(i) *lower pollution,*

$$\mathrm{E}g^{st}\left(r^{st}\right) = \mathrm{E}g^{bau}\left(r^{bau}\right) - \left(\frac{1}{\mu} - \frac{\delta q_R}{n}\right)\frac{n-1}{n\left(b+c\right)}K;$$

(ii) *lower investments,*

$$r_i^{st} = r_i^{bau} - \left(\frac{1}{\mu} - \frac{\delta q_R}{n}\right)\frac{\left(n-1\right)^2}{n\left(b+c\right)}K;$$

(iii) *lower utilities if intellectual property rights are weak while the period is short, i.e., if*

$$\left(\frac{n}{\mu} - 1\right)^2 - \left(1 - \delta q_R\right)^2 > \sigma^2 \frac{\left(b+c\right)\left(bcn/K\right)^2}{\left(b+cn^2\right)\left(b+cn\right)^2}. \tag{4.1}$$

Rather than being encouraging, short-term agreements discourage investments. The reason is the following. First, the hold-up problem is exactly as strong as the crowding-out problem in the noncooperative equilibrium; in either case, each country enjoys only $1/n$ of the total benefit generated by its investments. In addition, when an agreement is expected, everyone anticipates that the pollution will be lower. A further decline in emissions, made possible by new technology, is then less valuable. Hence, each country is willing to pay less for technology.[21]

Since investments decrease under short-term agreements, utilities can decrease as well. This is the case, in particular, if investments are important because they are already well below the optimal level. Thus, short-term agreements are bad if intellectual property rights are weak (μ small), the number of countries is large, and the period for which the agreement lasts is very short. If the period is short, δ and q_R are large, while the uncertainty from one period to the next, determined by σ, is likely to be small. All changes make (4.1) reasonable, and it always holds when the period is very short ($\sigma \to 0$).

[21] A counter-argument is that, if an agreement is expected, it becomes more important to invest to ensure a decent energy consumption level. This force turns out to be smaller in the model above.

5. The Optimal (Long-Term) Agreement

The hold-up problem under short-term agreements arises because the g_is are negotiated after investments are made. If the time horizon of an agreement is longer, however, it is possible for countries to develop technologies within the time frame of the agreement. The other countries are then unable to hold up the investing country, since the quotas have already been agreed to, at least for the near future.

To analyze such long-term agreements, let the countries negotiate and commit to emission quotas for T periods. The next subsection studies equilibrium investment, as a function of such an agreement. Taking this function into account, the second subsection derives the optimal (and equilibrium) emission quotas, given T. Finally, the optimal T is characterized.

If the agreement is negotiated just before the emission stage in period 0, then the quotas and investments for that period are given by Proposition 3. For the subsequent periods, it is irrelevant whether the quotas are negotiated before the first emission stage, or instead at the start of the next period, since no information is revealed, and no strategic decisions are made, in between. To avoid repeating earlier results, I will focus on the subsequent periods, and thus implicitly assume that the T-period agreement is negotiated at the start of period 1, as described by Figure 3.

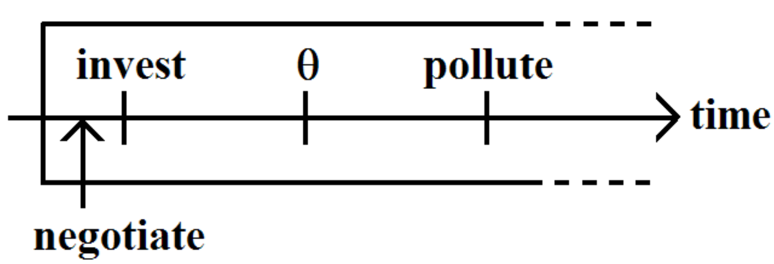

Figure 3: The timing for long-term agreements

5.1. Equilibrium Investments depend on the Agreement

When investing in period $t \in \{1, 2, ..., T\}$, countries take the quotas as given. A country is willing to pay more for innovations and investments if its quota, $g_{i,t}$, is small, since it is going to be very costly to comply if the sum $y_{i,t} = g_{i,t} + R_{i,t}$ is also small. Anticipating this, innovations and investments decrease in $g_{i,t}$.

Nevertheless, compared to the investments that are first-best conditional on the quotas, $r^*_{i,t}(g_{i,t})$, equilibrium investments are too low for two reasons. First, the innovators fear to be held up if $\mu < 1$, and thus they invest only up to the point where the countries' willingness to pay for μ units equals the cost of developing one unit of technology. Second, a country anticipates that having good technology will worsen its bargaining position in the future, once a new agreement is to be negotiated. At that stage, having good technology leads to a lower $g_{i,t}$ since the other countries can hold up country i when it is cheap for i to reduce its emissions.[22] Anticipating this, countries invest less in the last period, particularly if that period is short (δ large), the technology long-lasting (q_R large), and the number of countries large (n large).

Proposition 5. *Equilibrium investments are:*

(i) *decreasing in the quota* $g_{i,t}$ *and increasing in the intellectual property right* μ*;*

(ii) *less than the efficient level,* $r^*_{i,t}(g_{i,t})$*, if* $\mu < 1$*, for any given quota and period;*

(iii) *less in the last period than in earlier periods if* $\delta q_R > 0$:

$$\begin{aligned} r_{i,t}(g_{i,t}) &= r^*_{i,t}(g_{i,t}) - \frac{K}{b}\left(\frac{1}{\mu} - 1 + \delta q_R\left(1 - \frac{1}{n}\right)\right) \text{ for } t = T \\ &\leq \quad \text{(strict if } \delta q_R > 0) \\ r_{i,t}(g_{i,t}) &= r^*_{i,t}(g_{i,t}) - \frac{K}{b}\left(\frac{1}{\mu} - 1\right) \text{ for } t < T \\ &\leq \quad \text{(strict if } \mu < 1) \\ r^*_{i,t}(g_{i,t}) &= \overline{y}_i - q_R R_{i,-} - g_{i,t} - (1 - \delta q_R) K/b. \end{aligned}$$

5.2. The Optimal Quotas

At the emission stage, the *ex post* optimal pollution level is, as before, given by $g^*_i(\mathbf{R}^{lt})$, where $\mathbf{R}^{lt}$ is the equilibrium technology vector under long-term agreements. However, the countries anticipate that the negotiated $g_{i,t}$s are going to influence investments in

[22] Or, if no agreement is expected in the future, a large $R_{i,T+1}$ reduces $g_{i,T+1}$ and increases $g_{j,T+1}$, as proven in Section 3.3.

technology: the smaller the quotas, the larger the investments. Thus, since the investments are suboptimally low, the countries have an incentive to commit to quotas that are actually smaller than the expected $g_i^*\left(\mathbf{R}^{lt}\right)$, to further encourage investments. The smaller equilibrium investments are compared to the optimal investments, the lower are the negotiated $g_{i,t}$s, compared to the quotas that are *ex post* optimal.

PROPOSITION 6. (i) *The negotiated quotas are strictly smaller than the ex post optimal levels if* $\mu < 1$*:*

$$g_{i,t} = \mathrm{E}g_i^*\left(\mathbf{R}^{lt}\right) - K\frac{1/\mu - 1}{b + cn^2} \text{ for } t < T. \tag{5.1}$$

(ii) *For the last period, the negotiated quotas are strictly smaller than the ex post optimal quotas if either* $\mu < 1$ *or* $\delta q_R > 0$*:*

$$g_{i,t} = \mathrm{E}g_i^*\left(\mathbf{R}^{lt}\right) - K\frac{1/\mu - 1 + \delta q_R\left(1 - 1/n\right)}{b + cn^2} \text{ for } t = T. \tag{5.2}$$

If μ is small, the last terms of (5.1)-(5.2) are large, and every negotiated $g_{i,t}$ declines relative to $g_i^*\left(\mathbf{R}^{lt}\right)$. This makes the agreement more demanding or *tougher* to satisfy at the emission stage. The purpose of such a seemingly overambitious agreement is to encourage investments, since these are suboptimally low when μ is small. Encouraging investments is especially important in the last period, since investments are particularly low then, according to Proposition 5. Thus, the optimal agreement is tougher to satisfy over time.[23]

On the other hand, if $\mu = \delta q_R = 0$, the last terms of (5.1)-(5.2) are zero, meaning that the commitments under the best long-term agreement also maximize the expected utility ex post. In this case, there are no underinvestments, and there is no need to distort $g_{i,t}$s downwards.[24]

[23] This conclusion would be strengthened if the quotas were negotiated just before the emission stage in the first period. Then, the first-period quotas would be ex post optimal since these quotas would, in any case, have no impact on investments. It is easy to show that these quotas are expected to be larger than the quotas described by Proposition 6 - whether or not this is conditioned on investment levels.

[24] Interestingly, the equilibrium quotas, as described by Proposition 6, are in fact equal to the first-best emission levels *if* investments had been first-best:

$$g_{i,t} = \mathrm{E}g_i^*\left(\mathbf{R}^*\right).$$

5.3. The Optimal Length

If the countries are able to make commitments for any future period, they can negotiate the agreement-length, T. Since, as noted before, the countries are symmetric at the negotiation stage (no matter differences in R_is or $\overline{y}_i$s), they will agree on the optimal T. This trades off two concerns. On the one hand, investments are particularly low at the end of the agreement, before a new agreement is to be negotiated. This hold-up problem arises less frequently, and is delayed, if T is large. On the other hand, the stochastic shocks cumulate over time, and they affect the future marginal costs of pollution. This makes it hard to estimate the optimal quotas for the future, particularly when T is large.

In general, the optimal length of an agreement depends on the regime that is expected to replace it. This is in contrast to the other contracts studied above, which have been independent of the future regime. When the time horizon is chosen, it is better to commit to a longer-term agreement if everyone expects that, once it expires, the new regime is going to be bad (e.g., business as usual).

On the other hand, if future as well as present negotiators are able to commit to future emissions, then we can anticipate that the next agreement is also going to be optimal. Under this assumption, the optimal term is derived and characterized in the Appendix.

Proposition 7. (i) *The optimal length is finite,* $T^* < \infty$, *if and only if:*

$$\frac{q_G^2}{(1-q_G^2)(1-\delta q_G^2)}\left(\frac{\sigma}{K}\right)^2 > 2q_R\frac{1-1/n}{bc}\left[\frac{1}{\mu}+3\delta q_R\frac{1-1/n}{2}\right].$$

(ii) *Under this condition,* T^* *decreases in* μ, b, c, *and* σ, *but increases in* n, q_R, *and* K.

If θ were known or contractible, the optimal agreement would last forever. Otherwise, the length of the agreement should be shorter if future marginal costs are uncertain (σ large) and important (c large). On the other hand, a larger T is preferable if the underinvestment problem is severe. This is the case if the intellectual property rights are

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When selecting the optimal quotas, there is, as noted, good reasons for selecting small quotas in order to induce investments. As a counter-argument, the suboptimally low investments make it ex post optimal to permit larger emission levels. These two effects turn out to cancel, the Appendix shows. The technical reason is that, in this equilibrium as well as in the first-best outcome, y_i is independent of g_i, so a smaller g_i is only reducing G and increasing R_i. Since the marginal cost of increasing R_i is constant, the optimal G is the same in this equilibrium and in the first-best outcome.

weak (μ small), the technology is long-lasting (q_R large), and the number of countries large. If b is large while K is small, then consuming the right amount of energy is more important than the concern for future bargaining power. The hold-up problem is then relatively small, and the optimal T declines.

6. Trade and R&D Policies

So far, investments in technology have been noncontractible. But since, as a consequence, investments were suboptimally low, the countries have incentives to search for ways by which investments can be subsidized. This section allows for such subsidies and shows that the framework continues to provide important lessons.

Let the parameter ϕ be an ad valorem subsidy captured by the innovator or developer of technology. It may denote the share of research expenses borne by the government (as in Grossman and Helpman, 1991). As before, K is the cost of increasing R_i by one unit, while $\mu \in (0, 1]$ is the fraction of the purchaser's benefit that can be captured by the seller. With free entry of innovators, the equilibrium investments will be given by the following condition (replacing (2.5)):

$$\partial \frac{B_i(\cdot) - C(\cdot) + \delta U_{i,+}(\cdot)}{\partial R_i} = \frac{K(1-\phi)}{\mu}. \tag{6.1}$$

If the typical developer of technology for one country is located abroad, then ϕ can be interpreted as an import subsidy. If $\phi < 0$, then $-\phi$ may be interpreted as an import tariff.[25]

The Appendix analyzes each scenario as a function of ϕ. As suggested by (6.1), the effect of ϕ is similar to the effect of μ. If the subsidy is exogenous and low, or the tariff is

[25] Technically, this requires the tariff, or the import subsidy, to be proportional to the cost of developing technology. If, instead, the import subsidy $\widehat{\phi}$, or the tariff $-\widehat{\phi}$, were proportional to the sales value, (6.1) should be:

$$\partial \frac{B_i(.) - C(.) + \delta U_{i,+}}{\partial R_i} = \frac{K}{\mu\left(1+\widehat{\phi}\right)}.$$

Alternatively, with an estate subsidy $\widetilde{\phi}$, or tariff $-\widetilde{\phi}$, (6.1) should be:

$$\partial \frac{B_i(.) - C(.) + \delta U_{i,+}}{\partial R_i} = \frac{K}{\mu} - \widetilde{\phi}.$$

In these cases, the effects of $\widehat{\phi}$ and $\widetilde{\phi}$ would be similar to the effects of ϕ.

high, then investments decline. A further reduction in investment is then particularly bad, which implies that short-term agreements are worse than business as usual. To encourage more investments, the best climate agreement is tougher and longer-term.

PROPOSITION 8. *If the subsidy ϕ is low or the tariff $-\phi$ is high, then:*
(i) *short-term agreements are worse relative to business as usual;*
(ii) *the optimal agreement is tougher and longer-term.*

While Proposition 8 shows that the optimal climate treaty depends on the policy parameters, we may also ask the reverse question: What is the best ϕ and/or μ, as a function of the climate policy?

PROPOSITION 9. *The optimal subsidy ϕ and intellectual property right μ are larger if the agreement is short-term or absent. They are given by:*
(i) *Equation (6.2) for short-term agreements as well as for business as usual;*
(ii) *Equation (6.3) for a long-term agreement's last period;*
(iii) *Equation (6.4) for a long-term agreement, except for its last period:*

$$\phi_{st}^{*} = \phi_{bau}^{*} = 1 - \mu/n > \tag{6.2}$$

$$\phi_{lt,T}^{*} = 1 - \mu\left[1 - \delta q_R\left(1 - 1/n\right)\right] > \tag{6.3}$$

$$\phi_{lt,t}^{*} = 1 - \mu,\ t < T. \tag{6.4}$$

If the climate treaty is short-term, the hold-up problem is larger and it is more important to encourage investments by protecting intellectual property rights, subsidizing technological trade, and reducing tariffs. Such trade agreements are thus strategic substitutes for climate treaties: weakening cooperation in one area makes further cooperation in the other more important. As before, the optimal agreement is also going to be the equilibrium when the countries negotiate, since they are symmetric at the negotiation stage (w.r.t. $\overline{y}_i - y_{i,t}$) no matter what their technological differences are.

If the subsidy can be freely chosen and set in line with Proposition 9, short-term agreements are actually first-best: while the optimal subsidy induces first-best investments, the negotiated emission levels are also first-best, conditional on the investments. Long-term agreements are never first-best, however, due to the stochastic and non-contractible θ.

Proposition 10. *If ϕ and μ can be set according to Proposition 9, short-term agreements implement the first-best outcome, but long-term agreements do not.*

7. Policy Instruments and Robustness

This paper has focused on the interaction between investments in technology and climate agreements on emissions. To isolate these effects, the model abstracted from a range of real-world complications. While some assumptions have been crucial for the results, others can easily be relaxed.

First, note that in every bargaining situation above, the countries are identical when considering $\widetilde{y}_i$ and r_i, no matter differences in the $\overline{y}_i$s or in the R_is. Thus, side transfers would be used neither on, nor off, the equilibrium path.

Proposition 11. *Propositions 0-10 survive whether or not side payments are available at the negotiation stage.*

Second, the discussion above has ignored trade in pollution permits. However, if the allowances were tradable, no trade would take place in equilibrium, and the possibility for such trade (off the equilibrium path) would not change the equilibrium investments or emission quotas.

Proposition 12. *Suppose the emission allowances are tradable.*
(i) *Propositions 0-11 survive.*
(ii) *The equilibrium permit prices under short-term agreements (p_{st}), the last-period of long-term agreements (p_T), the earlier periods of long-term agreements (p_t), and at the first best (p_*) are given by:*

$$\begin{aligned} \mathrm{E}p_{st} &= nK\left(\frac{1}{\mu}-\frac{\delta q_R}{n}\right) > \\ p_T &= K\left(\frac{1}{\mu}-\frac{\delta q_R}{n}\right) > \\ p_t &= K\left(\frac{1}{\mu}-\delta q_R\right) \geq \text{ (strict if } \mu<1) \\ p_* &= K\left(1-\delta q_R\right). \end{aligned}$$

Interestingly, the permit price increases toward the end of the agreement. Then, investments in green technology decline and the demand for being allowed to pollute goes up. However, even at $t < T$, the permit price is higher than it would have been at the first best (i.e., if investments were contractible). The reason is that the agreement is tougher than what is ex post optimal in order to motivate investments when $\mu < 1$. The expected price is highest for short-term agreements, since the technology stock is then small and so is the negotiated energy consumption. For each scenario, the equilibrium permit price is larger if intellectual property rights are weak. If there is a subsidy or tariff on technological trade, as in the previous section, then $1/\mu$ should be replaced by $(1 - \phi)/\mu$: the smaller is the investment subsidy, or the larger is the tariff, the higher is the equilibrium permit price at the optimal and equilibrium agreement.

The model above is stylized and a number of assumptions are made: the benefit and cost of pollution are quadratic, the investment cost is linear and identical across countries, renegotiation is impossible, and I have not imposed nonnegativity constraints on emissions or investments. All these assumptions are relaxed in the more technical companion paper (Harstad, 2012), and many of the results are shown to generalize.[26]

Future research may relax other assumptions as well. For example, the model above has predicted full participation in a climate treaty. This followed since there was no stage at which countries could opt out of the negotiation process. If such a stage were added to the model, free-riding may emerge. For example, in the one-period model analyzed by Barrett (2005), only three countries participate in equilibrium when utility functions are quadratic. One may conjecture, however, that the number could be larger in a dynamic model, like the one above: If just a few countries decided to participate, they may find it optimal to negotiate short-term agreements, rather than long-term agreements, in the hope that the nonparticipants will join later. Since the participants invest less under short-term agreements, this credible threat might discourage countries when considering to free-ride.

[26] Note, however, that Harstad (2012) rules out uncertainty and incomplete property rights, and it studies neither the harmful short-term agreements nor the optimal term of an agreement.

8. Conclusions

While mitigating climate change will require emission reduction as well as the development of new technology, recent agreements have focused on short-term emissions. What is the value of such an agreement? How does it influence the incentive to invest, and what is the best agreement? To address these questions, this paper provides a framework where countries over time both pollute and invest in environmentally friendly technologies. The analysis generates a number of important lessons.

First, the noncooperative outcome is particularly bad. With business as usual, countries pollute too much, not only because they fail to internalize the externality, but also because polluting now motivates the other countries to pollute less and invest more in the future. Similarly, each county invests too little in technology, to induce the other countries to invest more and pollute less.

Second, short-term agreements can, nevertheless, be worse. At the negotiation stage, a country with good technology is going to be hold up by the others, requiring it to reduce its pollution a great deal. Anticipating this, countries invest less when negotiations are coming up. This makes the countries worse off relative to business as usual, particularly if the agreement has a short duration and intellectual property rights are poorly enforced.

Third, the optimal agreement is described. A tough agreement, if long-term, encourages investments. The optimal and equilibrium agreement is tougher and longer-term if, for example, technologies are long-lasting and intellectual property rights weak.

Finally, trade policies and climate treaties interact. If technologies can be traded or subsidized, high tariffs and low subsidies discourage investments and, to counteract this, the climate treaty should be tougher and longer-term. If the climate treaty is absent or relatively short-lasting for exogenous reasons, then tariffs should decrease, intellectual property rights should be strengthened, and investments or trade in green technology should be subsidized. Negotiating such trade policies is thus a strategic substitute to a tough climate treaty: if one fails, the other is more important.

9. Appendix

The following proofs allow for the subsidy ϕ, introduced in Section 5; Propositions 0-6 follows by setting $\phi = 0$. To shorten equations, define $m \equiv -\delta\partial U_i/\partial G_-$, $z \equiv \delta\partial U_i/\partial R_-$, $\widetilde{R} \equiv q_R R_-$, $\widetilde{G} \equiv q_G G_- + \theta$ and $\widetilde{y}_i \equiv y_i + \overline{y} - \overline{y}_i$, where $\overline{y} \equiv \sum_N \overline{y}_i/n$. While U_i is the continuation value for a subgame starting with the investment stage, let W_i represent the (interrim) continuation value at (or just before) the emission stage.

Proof of Proposition 0 for the business-as-usual scenario. Just before the emission stage, θ is known and the payoff-relevant states are R and $\widetilde{G}$.[27] A country's (interrim) continuation value is $W(\widetilde{G}, R)$. Anticipating this, equilibrium investments are given by:

$$\frac{\partial \mathrm{E}W(\widetilde{G}, \sum_N R_i)}{\partial R_i} = \frac{\partial \mathrm{E}W(\widetilde{G}, \sum_N R_i)}{\partial R} = k \equiv \frac{K(1-\phi)}{\mu}, \tag{9.1}$$

where expectations are taken w.r.t. θ. The second-order condition holds because EW is concave. This implies, since the marginal cost of increasing R is constant, that the equilibrium R must be independent of R_-. Thus, when all countries invest the same, a marginally larger R_- implies that R will be unchanged and r_i will decline by q_R/n units. It follows that:

$$\frac{\partial U}{\partial R_-} = \frac{q_R K}{n}. \tag{9.2}$$

At the emission stage, a country's first-order condition for y_i is:

$$0 = b(\overline{y} - \widetilde{y}_i) - c\left(\widetilde{G} + \sum_N \widetilde{y}_j - R\right) + \delta U_G(\widetilde{G} - R + \sum_N \widetilde{y}_j, R), \tag{9.3}$$

implying that all $\widetilde{y}_i$s are identical. The second-order condition holds trivially. From (9.2), we know that $U_{RG} = U_{GR} = 0$, and U_G cannot be a function of R. Therefore, (9.3) implies that $\widetilde{y}_i$, G and thus $B(\widetilde{y}_i - \overline{y}) - C(G) \equiv \gamma(.)$ are functions of $\widetilde{G} - R$ only. Hence, write $G = \chi\left(\widetilde{G} - R\right)$. Then, (9.1) becomes:

$$\frac{\partial \mathrm{E}\left[\gamma(q_G G_- + \theta - R) + \delta U(\chi(q_G G_- + \theta - R), R)\right]}{\partial R} = k. \tag{9.4}$$

This requires $q_G G_- - R$ to be a constant, say ξ, which is independent of the stocks. Thus, $\partial r_i/\partial G_- = q_G/n$ and U becomes:

$$\begin{aligned}
U(G_-, R_-) &= \mathrm{E}\gamma(\xi + \theta) - Kr + \mathrm{E}\delta U(\chi(\xi + \theta), R) \\
&= \mathrm{E}\gamma(\xi + \theta) - K\left(\frac{q_G G_- - \xi - q_R R_-}{n}\right) + \mathrm{E}\delta U(\chi(\xi + \theta), q_G G_- - \xi) \Rightarrow \\
\frac{\partial U}{\partial G_-} &= -K\left(\frac{q_G}{n}\right) - \delta U_R q_G = -\frac{K q_G}{n}(1 - \delta q_R).
\end{aligned}$$

[27] As explained in Section 3, there is no reason for one country, or one firm, to condition its strategy on R_i, given R, if the other players are not doing it. Ruling out such dependence is consistent with the definition of Markov and Tirole (2001).

With U_G and U_R pinned down, (9.3) and (9.4) give a unique solution. QED

Proof of Proposition 1. Since the proof is analogous to the next proof, it is omitted here but included in the working paper version and available on request.

Proof of Proposition 2. From (9.3),

$$\widetilde{y}_i = \overline{y} - \frac{m+cG}{b} \Rightarrow y_i = \overline{y}_i - \frac{m+cG}{b} \Rightarrow \tag{9.5}$$

$$G = \widetilde{G} + \sum_N (y_i - R_i) = \widetilde{G} - R + n\left(\overline{y} - \frac{m+cG}{b}\right) = \frac{b\overline{y}n - mn + b\left(\widetilde{G} - R\right)}{b+cn} \tag{9.6}$$

$$y_i = \overline{y}_i - \frac{m}{b} - \frac{c}{b}\left(\frac{b\overline{y}n - mn + b\left(\widetilde{G} - R\right)}{b+cn}\right) = \overline{y}_i - \frac{c\overline{y}n + c\left(\widetilde{G} - R\right) + m}{b+cn} \Rightarrow$$

$$g_i = y_i - R_i = \overline{y}_i - \frac{c\overline{y}n + c\left(\widetilde{G} - R\right) + m}{b+cn} - R_i,$$

Simple algebra and a comparison to the first-best gives (3.7). Interrim utility (after investments are sunk) can be written as:

$$W_i^{bau} \equiv -\frac{c}{2}G^2 - \frac{b}{2}\left(\overline{y}_i - y_i\right) + \delta U(G,R) = -\frac{c}{2}\left(1+\frac{c}{b}\right)G^2 - \frac{Gmc}{b} - \frac{m^2}{2b} + \delta U(G,R).$$

Since $\partial G/\partial R = -b/\left(b+cn\right)$ from (9.6), equilibrium investments are given by:

$$k = \mathrm{E}\partial W_i^{bau}/\partial R = c\left(1+\frac{c}{b}\right)\left(\frac{b}{b+cn}\right)\mathrm{E}G + \frac{bm\left(1+c/b\right)}{b+cn} + z. \tag{9.7}$$

The second-order condition holds since EW is concave. Taking expectations of G in (9.6), substituting in (9.7) and solving for R gives:

$$R = \overline{y}n + \mathrm{E}\widetilde{G} - k\frac{\left(b+cn\right)^2}{bc\left(b+c\right)} + \frac{m}{c} + z\frac{\left(b+cn\right)^2}{bc\left(b+c\right)} \Rightarrow \tag{9.8}$$

$$r_i = \frac{R - q_R R_-}{n} = \overline{y} + \frac{q_G G_-}{n} - k\frac{\left(b+cn\right)^2}{bc\left(b+c\right)n} + \frac{m}{c} + z\frac{\left(b+cn\right)^2}{bc\left(b+c\right)n}.$$

Simple algebra and a comparison to the first-best gives (3.6). QED

Proof of Proposition 3. At the emission stage, the countries negotiate the g_is. g_i determines $\widetilde{y}_i$, and since countries have symmetric preferences over $\widetilde{y}_i$ (in the negotiations as well as in the default outcome), the $\widetilde{y}_i$s must be identical in the bargaining outcome and efficiency requires:

$$0 = b\left(\overline{y} - \widetilde{y}_i\right)/n - c\left(\widetilde{G} - R + \sum \widetilde{y}_i\right) + \delta U_G(\widetilde{G} - R + \sum \widetilde{y}_i, R). \tag{9.9}$$

The rest of the proof of Proposition 0 continues to hold: R will be a function of G_- only, so $U_{R_-} = q_R K/n$. This makes E$\widetilde{G} - R$ a constant and $U_{G_-} = -q_G\left(1 - \delta q_R\right)K/n$, just as before. The comparative static becomes the same, but the *levels* of g_i, y_i, r_i, u_i and U_i are obviously different from the previous case.

The first-order condition (9.9) becomes:

$$\begin{aligned}
0 &= -ncG + b\overline{y} - b\widetilde{y}_i - nm \Rightarrow y_i = \overline{y}_i - \frac{nm + ncG}{b}. \\
G &= \widetilde{G} + \sum_j (y_j - R_j) = \widetilde{G} + n\left(\overline{y} - \frac{nm + ncG}{b}\right) - R \Rightarrow \\
G &= \frac{b\overline{y}n - mn^2 + b\left(\widetilde{G} - R\right)}{b + cn^2}. \qquad (9.10)
\end{aligned}$$

The second-order condition holds trivially. Note that the interrim utility can be written as:

$$W_i^{st} = -\frac{c}{2}G^2 - \frac{b}{2}\left(\frac{nm + ncG}{b}\right)^2 + \delta U(G, R).$$

Since (9.10) implies $\partial G/\partial R = -b/\left(b + cn^2\right)$, equilibrium investments are given by:

$$\begin{aligned}
k &= \mathrm{E}\frac{\partial W_i^{st}}{\partial R} = \mathrm{E}G\left(c + \frac{c^2n^2}{b}\right)\left(\frac{b}{b + cn^2}\right) + \frac{cmn^2}{b}\left(\frac{b}{b + cn^2}\right) + m\left(\frac{b}{b + cn^2}\right) + z \\
&= c\mathrm{E}G + m + z. \qquad (9.11)
\end{aligned}$$

The second-order condition holds since EW is concave. Substituted in (9.10), after taking the expectation of it, and solving for R, gives

$$R^{st} = q_G G_- + n\overline{y} + \frac{m}{c} - \left(\frac{b + cn^2}{b}\right)\left(\frac{k}{c} - \frac{z}{c}\right).$$

The proof is completed by comparing r_i^* to $r_i^{st} = \left(R^{st} - q_R R_-\right)/n$:

$$\begin{aligned}
r_i^{st} &= \overline{y} - \frac{q_R R_-}{n} + \frac{q_G G_-}{n} - \left(\frac{b + cn^2}{bcn}\right)(k - \delta U_R) - \frac{\delta U_G}{cn} \\
&= r_i^* - K\left(\frac{b + cn^2}{bcn^2}\right)\left(\frac{nk}{K} - 1\right) < r_i^*. \text{ QED}
\end{aligned}$$

Proof of Proposition 4. Part (i) and (ii) follow from simple algebra when comparing emissions and investments for business as usual to short-term agreements. Substituted in u_i, which in turn should be substituted in $U = u_i + \delta U_+(.)$, we can compare U^{bau} and U^{st} (the steps are available on request and in the working paper version). QED

Proof of Proposition 5. In the last period, investments are given by:

$$\begin{aligned}
k &= b\left(g_{i,T} + R_{i,T} - \overline{y}_i\right) + z \Rightarrow \\
\widetilde{y}_i - \overline{y} &= -\frac{k - z}{b},\ R_{i,T} = \overline{y}_i - g_{i,T} - \frac{k - z}{b} \Rightarrow \qquad (9.12) \\
r_{i,T} &= \overline{y}_i - g_{i,T} - \frac{k - z}{b} - q_R R_{i,T-1}. \qquad (9.13)
\end{aligned}$$

Anticipating the equilibrium $R_{i,T}$, i can invest q_R less units in period T for each invested unit in period $T-1$. Thus, in period $T-1$, equilibrium investments are given by:[28]

$$\begin{aligned} k &= b\left(g_{i,T-1}+R_{i,T-1}-\overline{y}_i\right)+\delta q_R K \Rightarrow \\ R_{i,T-1} &= \overline{y}_i - g_{i,T-1} - \frac{k-\delta q_R K}{b} \Rightarrow \\ r_{i,T-1} &= \overline{y}_i - g_{i,T-1} - \frac{k-\delta q_R K}{b} - q_R R_{i,T-2}. \end{aligned} \tag{9.14}$$

The same argument applies to every period $T-t$, $t \in \{1,...T-1\}$, and the investment level is given by the analogous equation for each period but T. Proposition 5 follows since the optimal R_i and r_i, given g_i, are:

$$R_i^* = r_i^* + q_R R_{i,-} = \overline{y}_i - g_i - \frac{K\left(1-\delta q_R\right)}{b}. \text{ QED}$$

Proof of Proposition 6. If the negotiations fail, the default outcome is the noncooperative outcome, giving everyone the same utility. Since the r_is follow from the g_is in (9.13), negotiating the g_is is equivalent to negotiating the r_is. All countries have identical preferences w.r.t. the r_is (and their default utility is the same), so symmetry requires that r_i, and thus $\varsigma_t \equiv \overline{y}_i - g_{i,t} - q_R R_{i,t-1}$, is the same for every country in equilibrium.

For the last period, (9.13) becomes

$$r_{i,T} = \varsigma_T - \frac{k-\delta q_R K/n}{b}.$$

Anticipating the equilibrium investments, the utility for the last period can be written as:

$$U_i = -\frac{(k-z)^2}{2b} - \text{E}C\left(G\right) - Kr_{i,T} + \delta U\left(G,R\right).$$

Efficiency requires U_i to be maximized w.r.t. ς recognizing $g_i = \overline{y}_i - q_R R_{i,-} - \varsigma$ and $\partial r_i/\partial\varsigma = 1\forall i$. The f.o.c. is:

$$n\text{E}cG - K - n\delta U_G + n\delta U_R = 0 \Rightarrow \text{E}cG + m + z = K/n. \tag{9.15}$$

The second-order condition holds trivially. For $t < T$, $r_{i,t} = r_{j,t} = r_t$, given by:

$$r_t = \varsigma_t - \frac{k-\delta q_R K}{b}.$$

Note that for every $t \in \{2,...T\}$, $R_{i,t-1}$ is given by the quota in the *previous* period:

$$\begin{aligned} r_t &= \left(\overline{y}_i - g_{i,t} - q_R\left(\overline{y}_i - g_{i,t-1} - \frac{k-\delta q_R K}{b}\right)\right) - \frac{k-\delta q_R K}{b} \\ &= \overline{y}_i\left(1-q_R\right) - g_{i,t} + q_R g_{i,t-1} - \left(1-q_R\right)\frac{k-\delta q_R K}{b}. \end{aligned} \tag{9.16}$$

[28] This presumes that country i's cost of future technology is K, which is correct since, in equilibrium, country i pays $K\left(1-\phi\right)$ plus the subsidy ϕK (or minus the tax $-\phi K$), even if this price is for the remaining fraction μ, after the fraction $1-\mu$ has been copied for free.

All countries have the same preferences over the ς_ts. Dynamic efficiency requires that the countries are not better off after a change in the ς_ts (and thus the $g_{i,t}$s), given by $(\Delta\varsigma_t, \Delta\varsigma_{t+1})$, such that G is unchanged after two periods, i.e., $\Delta\varsigma_{t+1} = -\Delta\varsigma_t q_G$, $t \in [1, T-1]$. From (9.16), this implies

$$\begin{aligned} -n\mathrm{E}C'(G_t)\Delta\varsigma_t + \Delta g_t K + \delta(\Delta\varsigma_{t+1} - \Delta g_t q_R) K - \delta^2 \Delta g_{t+1} q_R K &\leq 0 \forall \Delta\varsigma_t \Rightarrow \\ (1-\delta q_R)(1-\delta q_G)\frac{K}{cn} &= \mathrm{E}G = \mathrm{E}G^*. \end{aligned}$$

Thus, neither G_t nor $g_{i,t}$ (and, hence, neither R) can be functions of R_-. At the start of period 1, therefore, $U_R = q_R K/n$, just as before, and U_G cannot be a function of R (since $U_{RG} = 0$). Since EG is a constant, we must have $\varsigma_1 = \overline{y} - (\mathrm{E}G^* - q_G G_0)/n - q_R R_0/n$. Eq. (9.13) gives $\partial r_{i,t=1}/\partial G_- = (\partial r_i/\partial g_i)(\partial g_i/\partial\varsigma)(\partial\varsigma/\partial G_-) = q_G/n$. Hence, $U_G = -q_G K/n + \delta U_R q_G = -q_G(1-\delta q_R)K/n$, giving a unique equilibrium. Substituted in (9.15), EG_T =EG^*, just as in the earlier periods. Thus, $g_{i,t} = g_i^*(\mathbf{R}_i^*)$ in all periods.

Proposition 6 follows since, from (3.4), $\partial g_i^*/\partial r_j = -b/(b+cn^2)$, so $g_{i,t} = g_i^*(\mathbf{R}_i^*) = g_i^*\left(\mathbf{R}_{i,t}^{lt}\right) - \left(r_i^* - r_{i,t}^{lt}\right) b/(b+cn^2)$. QED

Proof of Proposition 7. The optimal T balances the cost of underinvestment when T is short and the cost of the uncertain θ, increasing in T. In period T, countries invest suboptimally, not only because of the domestic hold-up problem, but also because of the international one. When all countries invest less, u_i declines. The loss in period T, relative to any period $t < T$, can be written as:

$$\begin{aligned} H &= -\frac{b}{2}(y_{i,t} - \overline{y}_i)^2 - \frac{b}{2}(y_{i,T} - \overline{y}_i)^2 - K(r_{i,t} - r_{i,T})(1-\delta q_R) \\ &= -\frac{b}{2}\left(\frac{k - \delta q_R K}{b}\right)^2 + \frac{b}{2}\left(\frac{k-z}{b}\right)^2 - K\left(\frac{k-z}{b} - \frac{k - \delta q_R K}{b}\right)(1-\delta q_R) \\ &= \delta q_R K^2 \frac{1-1/n}{b}\left[\frac{1-\phi}{\mu} + 3\delta q_R \frac{1-1/n}{2}\right]. \end{aligned}$$

Note that H increases in n, q_R, K, but decreases in μ, ϕ, and b.

The cost of a longer-term agreement is associated with θ. Although EC' and thus EG_t is the same for all periods,

$$\begin{aligned} \mathrm{E}\frac{c}{2}(G_t)^2 &= \mathrm{E}\frac{c}{2}\left(\mathrm{E}G_t + \sum_{t'=1}^{t} \theta_{t'} q_G^{t-t'}\right)^2 = \frac{c}{2}(\mathrm{E}G_t)^2 + \mathrm{E}\frac{c}{2}\left(\sum_{t'=1}^{t} \theta_{t'} q_G^{t-t'}\right)^2 \\ &= \frac{c}{2}(\mathrm{E}G_t)^2 + \frac{c}{2}\sigma^2 \sum_{t'=1}^{t} q_G^{2(t-t')} = \frac{c}{2}(\mathrm{E}G_t)^2 + \frac{c}{2}\sigma^2\left(\frac{1-q_G^{2t}}{1-q_G^2}\right). \end{aligned}$$

The last term is the loss associated with the uncertainty regarding future marginal costs. For the T periods, the total present discounted value of this loss is given by:

$$\begin{aligned} L(T) &= \sum_{t=1}^{T} \frac{c}{2}\sigma^2 \delta^{t-1}\left(\frac{1-q_G^{2t}}{1-q_G^2}\right) = \frac{c\sigma^2}{2(1-q_G^2)} \sum_{t=1}^{T} \delta^{t-1}\left(1-q_G^{2t}\right) \\ &= \frac{c\sigma^2}{2(1-q_G^2)}\left[\frac{1-\delta^T}{1-\delta} - q_G^2\left(\frac{1-\delta^T q_G^{2T}}{1-\delta q_G^2}\right)\right]. \end{aligned} \tag{9.17}$$

If all future agreements last $\widehat{T}$ periods, the optimal T for this agreement is given by

$$\min_T L(T) + \left(\delta^{T-1} H + \delta^T L\left(\widehat{T}\right)\right)\left(\sum_{\tau=0}^{\infty} \delta^{\tau \widehat{T}'}\right) \Rightarrow$$

$$0 = L'(T) + \delta^T \ln\delta \left(H/\delta + L\left(\widehat{T}\right)\right) = L'(T) + \delta^T \ln\delta \left(H/\delta + L\left(\widehat{T}\right)\right)$$

$$= \quad -\delta^T \ln\delta \left[\frac{c\sigma^2/2}{1-q_G^2}\left(\frac{1}{1-\delta} - \frac{q_G^{2T+2}\left(1+\ln q_G^2/\ln\delta\right)}{1-\delta q_G^2}\right) - \frac{H/\delta + L\left(\widehat{T}\right)}{1-\delta^{\widehat{T}'}}\right], \quad (9.18)$$

assuming some T satisfies (9.18). Since $\left(-\delta^T \ln\delta\right) > 0$ and the bracket-parenthesis increases in T, the loss decreases in T for small T but increases for large T, and there is a unique T minimizing the loss (even if the loss function is not necessarily globally concave). Since G_- and R_- does not enter in (9.18), T satisfying (9.18) equals $\widehat{T}$, assuming $\widehat{T}$ will be optimally set. Substituting for $\widehat{T} = T$ and (9.17) in (9.18) gives:

$$H/\delta = \frac{c\sigma^2 q_G^2}{2\left(1-q_G^2\right)\left(1-\delta q_G^2\right)}\left(\frac{1-\delta^T q_G^{2T}}{1-\delta^T} - q_G^{2T}\left(1 + \frac{\ln\left(q_G^2\right)}{\ln\delta}\right)\right), \quad (9.19)$$

where the r.h.s. increases in T. $T = \infty$ is optimal if the left-hand side of (9.19) is larger than the right-hand side even when $T \to \infty$:

$$\frac{c\sigma^2 q_G^2}{2\left(1-q_G^2\right)\left(1-\delta q_G^2\right)} \leq H/\delta. \quad (9.20)$$

If k/K and n are large, but b small, H is large, (9.20) is more likely to hold and, if it does not, the T satisfying (9.19) is larger. If c or σ^2 are larger, (9.20) is less likely to hold and, if it does not, (9.19) requires T to decrease. QED

Proof of Proposition 8. In the proofs above, k is already a function of ϕ.[29] QED

Proof of Proposition 9. Note that, under short-term agreements (as well as business as usual), if interrim utility is $W\left(\widetilde{G}, R\right)$, investments are given by $\mathrm{E}W_R = k$ while they should optimally be $\mathrm{E}W_R = K/n$, requiring (6.2). For long-term agreements, investments are optimal in the last period if $k - \delta q_R K/n = K\left(1-\delta q_R\right)$, requiring (6.3). For earlier periods, the requirement is $k = K$, giving (6.4). QED

Proof of Proposition 10. The proof follows from the text. QED

Proof of Proposition 11. As noted in Section 3 as well as in the above proofs, in every bargaining situation, the countries were symmetric when considering $\widetilde{y}_i$ and the (induced)

[29] Some caution is necessary, however. The proofs of Propositions 4-6 are unchanged only if the innovator receives the subsidy or pays the tariff *before* negotiating the price. With the reverse timing, ϕ would have no impact when the buyer is a government. In that case, the subsidy must be paid by foreign countries (as an international subsidy), and the proofs of Propositions 4-6 would need minor modifications, although the results would continue to hold. The proofs of Propositions 0-3 can stay unchanged in all these cases.

investment costs. Thus, no side transfers would take place, no matter differences in the R_is or the $\overline{y}_i$s, neither on nor off the equilibrium path. QED

Proof of Proposition 12. (i) First, note that there is never any trade in permits in equilibrium. Hence, *if* country i invests as predicted in Sections 3-5, the marginal benefit of more technology is the same whether permits are tradable or not. Second, if i deviated by investing more (less), it's marginal utility of a higher technology decreases (increases) not only when permit-trade is prohibited, but also when trade is allowed since more (less) technology decreases (increases) the demand for permits and thus the equilibrium price. Hence, such a deviation is not attractive.

(ii) Note that the benefit of being allowed to pollute one is equal to $B_i'(\cdot)$ when the total number of permits is fixed. Thus, $B_i'(\cdot)$ must equal the permit price when no country has market power in the permit market. For short-term agreements, (9.9) together with (9.11) implies that the quota price is:

$$\begin{aligned} B_i'(.) &= ncG + nm = nc\theta + nc\mathrm{E}G + nm = nc\theta + n(k - m - z) + nm \\ &= nc\theta + n(k - \delta q_R K/n). \end{aligned}$$

For the last period in long-term agreements, (9.12) implies that $B_i'(y_{i,T}) = k - z = k - \delta q_R K/n$. For earlier periods, (9.14) implies $B_i'(y_{i,t}) = k - \delta q_R K$, while, at the first-best, $B_i'\left(y_{i,t}^*\right) = K - \delta q_R K$. QED

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