Technology Deployment Agreements: Increasing Participation in Climate Cooperation[*]

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Abstract

The role of technology cooperation in international climate policy has drawn considerable attention in recent years. In this article, I examine the strategic benefits of a technology deployment agreement. I find that although technology deployment produces mostly private benefits for each country, a formal treaty can strategically increase global pollution abatement efforts. If technology deployment allows countries to credibly commit to pollution abatement, the international community can form two coalitions. One deploys the technology and then abates pollution, whereas the other only abates pollution. Empirically, a technology deployment agreement is useful and feasible when the total number of concerned countries is high and technology deployment is very costly but effective in reducing the cost of future pollution abatement. In addition to revealing a new strategic rationale for technology deployment agreements, I offer a nuanced analytical distinction between deployment versus research and development. For practical policy formation, I characterize the conditions and form of successful technology deployment cooperation.

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1 Introduction

The international community has yet to organize an effective collective response to global warming. In the aftermath of the Copenhagen Conference in December 2009 – an international summit that failed to produce a global climate treaty to follow the Kyoto Protocol – the calls for innovative ways to break the negotiation gridlock have grown stronger. Both scholars and practitioners are increasingly skeptical as to the political feasibility of a comprehensive treaty architecture with legally binding targets for emissions reductions in the near term (Barrett 2003; Prins et al. 2009; Victor 2009).

Technology cooperation figures prominently in the contemporary debate, and this is so for two reasons. First, the cost of pollution abatement, and therefore international climate cooperation, depends crucially on the availability of new technologies that can help countries reduce emissions at a low cost (de Coninck et al. 2008). As Barrett (2009, 54) argues, deep cuts in global carbon dioxide emissions will require technological changes that "will have to be pervasive; they will have to involve markets; and they will have to be global in scope." Second, technology cooperation may produce ancillary benefits that endow countries with incentives to participate (Keohane and Victor 2010). As de Coninck et al. (2008, 336) argue, "renewable standards might help promote energy security by diversifying fuel sources, and energy-efficient technologies can lower operating costs. Such ancillary benefits might help promote greater participation and stringency in an international climate agreement."

Technology cooperation has many different forms, however, and it is not clear that they all feature similar strategic logics. In this article, I focus on the possibility of *technology deployment cooperation.* While much of the literature emphasizes research and development, promising energy technologies will not help unless they penetrate the market (Gallagher, Holdren, and Sagar 2006; Sandén and Azar 2005; Unruh 2000). In addition to subsidizing research and development, countries may benefit from collaboration on deploying new technologies, such as increasing renewables production or expanding the electric automobile fleet.

Can technology deployment cooperation improve the quality of climate policy under international anarchy? My approach to technology deployment cooperation is strategic (Barrett 2003). In my formal model, countries first decide on technology deployment and then engage in pollution abatement. If a country deploys new technology, it reduces its own marginal cost of subsequent pollution abatement, as opposed to providing the international public good that models of research and development emphasize (Böringer and Rutherford 2002; Bosetti et al. 2008). Following the convention in international relations, I assume that countries are fully sovereign and thus free to join and leave international agreements (Axelrod and Keohane 1985; Barrett 2003; Gilligan 2004). The key theoretical innovation of my analysis is that countries can not only contract on pollution abatement but also on technology deployment. I evaluate the ability of technology deployment agreements to shape the subsequent pollution abatement game.

My main finding is that if technology deployment is very costly but produces a large decrease in the cost of pollution abatement, a formal treaty can help countries significantly expand the total number of cooperators. In these circumstances, a group of L countries first agree on technology deployment, and thus credibly commit to pollution abatement in the future. At the pollution abatement stage, another coalition of K countries that have *not* deployed the technology will also contract on pollution abatement among themselves. Two international agreements with different provisions and members will emerge, so that the main contribution of the technology deployment agreement is to increase the number of cooperators from K to $L + K$. By contrast, in the absence of a technology deployment agreement, the total number of cooperating countries is at most K, as only a small number of countries can simultaneously have an incentive to join a pollution abatement coalition (Barrett 2003; Carraro and Siniscalco 1993).

The formal analysis allows us to also examine the empirical conditions such that a technology deployment agreement will enhance cooperation. Since the equilibrium coalition sizes, L and K, are fixed, the total number of countries must be large enough, $N > L + K$. Otherwise the deployment and abatement coalitions cannot simultaneously exist, and the equilibrium unravels. This finding indicates that technology deployment agreements are most valuable when governments find it difficult to commit to cooperation and the number of relevant countries is large. Importantly, both conditions seem to apply to global warming.

The analysis also adds to the literature on unilateral leadership and precommitment in international cooperation (Schreurs and Tiberghien 2007; Skodvin and Andresen 2006; Young 1991). The idea of unilateral leadership contains the core tension that if country A commits to cooperation, another country B may respond by cooperating less, as the logic of reciprocity is no longer necessary to induce country A to cooperate (Barrett 2003; Hoel 1991; Keohane 1986). But my formal analysis demonstrates that this reasoning may fail, as long as third parties can subsequently form their own coalitions. In a multilateral context, a credible commitment to cooperate by one or several countries need not reduce the size of the coalition among other countries, as long as the total number of relevant countries is large enough.

In practice, the present findings may provide valuable strategic insights into effective policy formation. The formal analysis demonstrates that somewhat counterintuitively, technology deployment cooperation is the most valuable if the international cooperation is difficult and the cost of technology deployment is too high for effective unilateralism. Given the magnitude of the decarbonization challenge, these scope conditions seem to apply to many key energy technologies, such as wind or solar energy and conservation techniques (Sandén and Azar 2005; Stern 2006; Unruh 2000). Not only research and development, but also technology deployment, may help the international community break the current negotiation gridlock in climate diplomacy.

The article is organized in the following fashion. First, I discuss the idea of technology deployment and pollution abatement. Second, I conduct the formal analysis. Third, I discuss the challenges of practical implementation from a policy perspective. Finally, I conclude with a summary of the broader implications of the analysis.

2 Technology Deployment

To motivate my formal analysis, I begin by defining and discussing the concept of technology deployment. I will also briefly review the empirical record of technology deployment and the relevant scholarly literature. The empirical record shows that technology deployment cooperation remains shallow outside Europe, whereas the literature review demonstrates that scholars have yet to examine the strategic logic of technology deployment cooperation.

Definitions. By *technology deployment*, I refer to public support to the domestic commercialization and utilization of immature energy technologies. I focus on public actions and measures because my purpose is to understand how countries can achieve international cooperation on technology deployment. Admissible actions and measures include grid reform to facilitate the use of renewable energy, demonstration projects, feed-in tariffs or mandatory portfolio standards, investment subsidies, and so on (Lewis and Wiser 2007; Lipp 2007; Rai, Victor, and Thurber 2010; Wiser et al. 2007).

How does technology deployment differ from *research and development*? In the case of energy, both are similar in that they reduce the cost of pollution abatement (Grübler, Nakićenović, and Victor 1999). However, research and development produces positive international spillovers to a much greater degree, whereas the main effect of deployment is to reduce the domestic cost of pollution abatement in the particular country that deploys (del Río and Unruh 2007; Fischer and Newell 2008; Lewis and Wiser 2007). Research and development only generates expertise and information that diffuses effectively, whereas deployment also reduces the cost of pollution abatement directly by expanding clean energy capacity in a country. In other words, deployment can be thought of as a partially irreversible investment, or a "sunk cost" that commits a country to more ambitious pollution abatement in the future (Grossman and Hart 1986; Lake 2009; Rector 2009).

Technology deployment also directly reduces emissions. However, environmental economists widely agree that the most effective way to really reduce emissions is to impose an economywide price or quota on carbon dioxide (Fischer and Newell 2008; Stavins 2003). Technology deployment is relevant here, of course, as it reduces the cost of achieving a certain emissions reduction. In this article, I emphasize this effect under the assumption that while technology deployment may produce few direct mitigation benefits, it will significantly ease future pollution abatement.

Empirical record. Empirically, technology deployment agreements remain rare. In a recent survey, de Coninck et al. (2008) note that although technology cooperation is a promising approach to international climate policy, virtually all existing agreements are relatively shallow, comprising such provisions as information or cost sharing. To be effective, technology deployment requires substantial scaling up. Perhaps the only international initiative that contains provisions for aggressive technology deployment is the 2008 climate and energy package of the European Union. In addition to emissions reductions, it prescribes that union members must collectively produce one fifth of the total energy mix using renewable sources by the year 2020.[1]

Some countries have managed to unilaterally deploy new energy technologies. In the decades following the Second World War, many industrialized countries, and especially France, gave sub-

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[1] "EU Leaders Reach New Climate Deal." *BBC News* December 12, 2008.

stantial public funding to nuclear power (Cowan 1990). Denmark responded to the 1973 oil crisis by beginning a subsidy program for wind energy, and Germany began to allocate large subsidies to renewables in the aftermath of the 1986 Chernobyl nuclear accident (Jacobsson and Lauber 2006; Lipp 2007). In Spain, the government decided to support wind energy, both as a response to rapidly increasing electricity consumption and to create an innovation system around this promising new energy technology (del Río and Unruh 2007). However, a notable feature of each case is the presence of a visible exogenous shock or trend that gave the government an impetus to support technology deployment. Thus, they do not undermine the thesis that international cooperation is probably necessary to achieve substantial technology deployment on the global scale.

Literature. Why should countries cooperate on technology deployment in particular? The scholarly literature on technology cooperation provides a rationale: since technology deployment reduces the cost of pollution abatement, countries fail to internalize the full benefits of that cost reduction, as each individual country will only capture a part of the total benefit (Barrett 2007). This problem of free riding may be particularly difficult in the case of technology deployment because breaking the "carbon lock-in" of the energy sector in a country will require large investments and reforms (Sandén and Azar 2005; Unruh 2000). Thus, the cost of implementing an ambitious technology deployment program is probably so high that individual countries are unwilling to pay it unless they are cooperating with others.

The literature on the strategic dimensions of international environmental policy has paid scant attention to deployment cooperation. Barrett (2006) argues that "breakthrough technologies" generally cannot achieve much more cooperation than conventional pollution abatement, but this result is based on the assumption that breakthrough technologies are a substitute to pollution abatement. In my dynamic setting with technology deployment, this result does not hold because the deployment decision is made before the abatement decision. Hoel and de Zeeuw (2010) consider the strategic dimension of technology cooperation, but they also focus on research and development instead of deployment. Thus, they are unable to shed light on the benefits of technology deployment cooperation. Carraro and Siniscalco (1995) show that research and development can facilitate the enforcement of international environmental cooperation, but only if countries can, somewhat implausibly, form a "technology club" that produces substantial private gains to the members. In my model, no such as assumption is made.

The finding also relates to who Asheim et al. (2006) demonstrate that regional cooperation may dominate global cooperation in international environmental affairs. Two regional agreements may increase enforcement, as the threat to suspend regional cooperation is generally more credible than the threat to suspend global cooperation. However, their result only holds if countries are allowed to be collective irrational in another sense, namely by forming regional agreements to address a genuinely global problem. My main finding on technology deployment agreements as an instrument to broader cooperation has a similar flavor, but no assumption of collective irrationality is required. Indeed, my result is stronger in at least three ways. First, technology deployment agreements sometimes allow almost all countries to cooperate. Second, technology deployment agreements do not require the implausible assumption that countries prefer a regional solution to a global problem in the long run. Finally, the regional structure of the world economy does not condition the possibility of dual cooperation on technology deployment and pollution abatement.

The broader international cooperation literature is also directly relevant to this article. A key premise of this literature is that sovereign states can freely exit or enter international agreements (Barrett 2003; Keohane 1984; Koremenos, Lipson, and Snidal 2001). However, international cooperation theory does not have any direct implications for the relationship between cooperation on technology deployment and pollution abatement. My formal analysis contributes to international cooperation theory by showing how various cooperative arrangements interact with each other, a theme that is also explored in the "regime complexity" literature (Gehring and Obertür 2009; Raustiala and Victor 2004).

3 Model

To examine the strategic logic of technology deployment, I use a simple formal model wherein countries $i = 1, ..., N$ begin with a technology deployment decision and then cooperate on pollution abatement. The sole benefit of technology deployment to a country is to reduce the domestic cost of pollution abatement. For simplicity, all countries are assumed to be symmetric *ex ante*.

Sequence of moves. I assume the following sequence of moves:

1. Each country i decides on technology deployment, $D_i \in \{0, 1\}$.
2. Each country i decides on pollution abatement, $A_i \in \{0, 1\}$.

This simple binary formulation is both tractable and intuitive. In reality, countries can obviously also choose the degree of technology deployment and abatement. However, continuous action spaces would greatly complicate the formal analysis and prompt cumbersome exposition. Given that the equilibrium of the pollution abatement subgame will obviously depend on technology deployment decisions, continuous strategy spaces would lead to the profusion of equilibria and indeterminacy more generally. As to the dynamic sequence of moves, I will explain below why a static version of the game would *not* allow increased participation. This discussion follows the presentation of the main result.

Following Barrett (2003), I model various international agreements as changes in the rules of the game. In the basic model, all countries individually decide on deployment and abatement in a non-cooperative fashion. In the variations that I explore, the countries are allowed to cooperate subject to the criterion that participation is voluntary. What is new is that countries can cooperate not only on abatement but also on deployment, and all this is modeled as a dynamic sequence.

In the formal analysis, I focus on participation at the expense of enforcement. While enforcement issues are very important for international cooperation, I prefer to simplify the formal analysis by assuming that states free ride by “exiting” climate treaties. The relationship between participation and enforcement is left for future research, as this article focuses on the distinctive features of technology deployment cooperation.

Payoffs. To begin with, consider the deployment stage. The cost of deployment, $D_i = 1$, to each country i is denoted by $c^D > 0$. For example, this cost could be thought of as the budget expenditure for a feed-in tariff, or the increase in energy prices from a mandatory portfolio standard for renewables. The only benefit of deployment is to change the cost of pollution abatement in the second period, as will be detailed shortly. Thus, it is clear that deployment is not forthcoming unless some countries also intend to abate. This observation allows me to substantially simplify the formal analysis.

At the abatement stage, without loss of generality, the benefit from pollution abatement by any country i to every country $j = 1, .., N$ is normalized to 1. Thus, if K countries abate, the benefit to each country is exactly K. The linear payoff structure simplifies exposition, but all key results would continue to hold even if the payoff K was replaced by a value function $V(K)$, where V would be an increasing but strictly concave function of the number of abaters K.

The individual abatement cost is denoted by c_i^A, where c_i^A is a function of deployment, $c_i^A = c_i^A(D_i)$. Specifically, the following formulation is used:

$$c_i^A = \begin{cases} \overline{c} & \mid D_i = 0 \\ \\ \underline{c} & \mid D_i = 1 \end{cases}, \tag{1}$$

where $0 < \underline{c} < \overline{c}$, so that deployment reduces the cost of pollution abatement. Thus, $\underline{c}$ can be thought of as the cost upon successful technology deployment, whereas $\overline{c}$ is the cost of pollution abatement without previous technology deployment. For example, the reason why $\underline{c} < \overline{c}$ may be that a high carbon tax is needed to induce emissions reductions unless the total capacity of wind and solar power is already high.

Given these payoffs, one way to conceive of technology deployment is to regard it as a sequential payment for pollution abatement. If a country deploys technology, it pays a given cost that allows it to next abate pollution at a lower cost. Alternately, the country could reject deployment and either (i) pay the full cost of pollution abatement or (ii) simply fail to abate pollution.

Since I focus on international cooperation, I assume throughout that $N > max\{\underline{c}+c^D, \overline{c}\}$. This condition says that regardless of deployment, the world will benefit from additional cooperation. This assumption excludes the uninteresting case wherein pollution abatement is not collectively beneficial. It is also a plausible assumption for climate change and other global environmental problems.

To simplify the analysis and avoid trivial equilibria, suppose $\underline{c} < 1 < \overline{c}$. This assumption conveys two ideas. First, in the absence of deployment, abatement is not individually rational, as $1 - \overline{c} < 0$. This is a core assumption in the study of international environmental cooperation. If it did not hold, cooperation would be trivial, as each country would abate pollution for purely domestic reasons. Pollution abatement is an international public good, so individual countries have incentives to free ride.

Second, conditional on deployment, abatement is individually rational, $1 - \underline{c} > 0$. This assumption is less obvious and may not hold in some circumstances. But it is not difficult to see that if it fails to hold, no formal analysis is required to understand why technology deployment is largely. If it were the case that $\underline{c} > 1$, technology deployment would not help a country to commit to pollution abatement. In this case, technology deployment would change the cost of pollution abatement without overturning the logic of international cooperation. Thus, I assume that the technology deployment measures and actions in focus are sufficient to induce a significant decrease in the cost of pollution abatement. Empirically, technology deployment can be viewed as the implementation of a "sustainable energy transition" that induces substantial emissions reductions without further individually irrational policy measures (Sandén and Azar 2005).

Another important relationship to consider is the size of $\overline{c}$ and $\underline{c}+c^D$. If $\overline{c} > \underline{c}+c^D$, deployment produces a decrease in the net cost of abatement for any country i that will ultimately abate. But if $\overline{c} < \underline{c} + c^D$, exactly the opposite is true, and technology deployment will not produce any direct economic benefits. As it turns out, however, it may nonetheless produce substantial strategic benefits.

On a final note, I have not assumed that $1 > \underline{c} + c^D$. Thus, I do not require that the combination of technology deployment and pollution abatement is individually rational. Indeed, the most interesting result from the analysis is that technology deployment cooperation may help countries protect the global environment even if $\underline{c} + c^D < 1$, so that no country has an individual incentive to deploy and then abate. Under this assumption, it is apparent that the benefits of technology deployment cooperation, if any, must have strategic origins.

4 Benchmarks

To solve the game, I begin by analyzing three different benchmarks. The first is a standard subgame-perfect equilibrium. I use it to capture the logic of non-cooperative policy formation under anarchy (Axelrod and Keohane 1985). It serves as a useful baseline criterion, against which I can compare the effect of various forms of cooperation. The second is the global optimum: how would countries maximize their collective payoff if external enforcement was available? The third solution benchmark allows countries to voluntarily join a pollution abatement agreement, so that the signatories maximize their collective payoff while non-signatories free ride (Barrett 1994). In this case, however, I do not allow countries to engage in technology deployment cooperation. This equilibrium can be thought of as classical international environmental cooperation, whereby countries only contract on emissions reductions.

4.1 International Anarchy

In an anarchic world, the standard subgame-perfect equilibrium is played. In this case, each country i selects abatement A_i^* to maximize its individual payoff. Similarly, each country i selects deployment D_i^* to maximize its expected payoff from the game, given the expected subgame equilibrium in the second period. To solve the international anarchy game is quite straightforward. As always, I use backward induction. First, I find the vector of pollution abatement for a given vector of technology deployment. Second, I characterize the technology deployment decisions.

Abatement. Consider first the pollution abatement stage. At this stage, each country i maximizes its individual payoff. Thus, it abates if and only if $1 > c_i^A$. Recall that I have assumed $\overline{c} > 1$, so that no country i abates without deploying: if $D_i^* = 0$, then $A_i^* = 0$. Intuitively, the decision not to deploy technology is also a commitment not to abate pollution in the second stage. I have also assumed that $\underline{c} < 1$, so that conditional on deployment, each country i has an individual incentive to abate pollution. Thus, if $D_i^* = 1$, then $A_i^* = 1$. In this sense, the decision to deploy technology is a commitment to subsequently abate pollution. These observations already offer some insight into how countries play the deployment stage. If a country decides to deploy, it commits itself to pollution abatement. If a country does not deploy, it commits itself to free riding. Let us now examine the deployment stage.

Deployment. Consider now the deployment stage. With $\underline{c} < 1$, deployment $D_i^* = 1$ commits country i to abatement $A_i^* = 1$. Thus, the net payoff from deployment is

$$1 - \underline{c} - c^D \tag{2}$$

while the payoff from non-deployment is zero. Thus, country i deploys if and only if

$$1 \geq \underline{c} + c^D. \tag{3}$$

This condition says that the individual benefit from abatement must exceed the combined cost of deployment and abatement, $\underline{c}+c^D$. In other words, the combined strategy of technology deployment and pollution abatement must be individually rational as the game begins.

As the literature emphasizes, this condition is quite stringent (Barrett 2003; Carraro and Siniscalco 1993). The basic problem of international environmental cooperation is that the benefits are collective while the costs are individual. Thus, non-cooperative deployment and abatement suffices to solve the environmental problem at hand only if the total cost of deployment and abatement is so low as to produce an individual net benefit. While there are undoubtedly some environmental problems that feature such a payoff structure because they have a strong domestic component, the idea of a non-cooperative solution to global environmental problems appears incredible. In a world with almost 200 countries, no single country is willing to pay the price of solving global environmental problems without reciprocal international cooperation by other countries.

While deployment is ultimately a means to reduce the cost of pollution abatement, and hence a private good in the absence of complex strategic interactions, pollution abatement is a public good. This insight has limited relevance for non-cooperative equilibrium behavior, however, because no international cooperation is allowed. As I demonstrate below, this insight will be essential for understanding treaty participation in the context of deployment and abatement.

4.2 Global Optimum

Each country i decides on abatement A_i^* and deployment D_i^* to maximize the sum of payoffs to all countries. Let us again apply the principle of backward induction. First, consider the abatement decisions A_i^*. The global benefit of abatement, A_i^*, is N. The cost is c_i^A. Thus, country i abates if and only if $N > c_i^A$. By assumption, we have $N > \overline{c}$ so all countries abate, $A_i^* = 1$. What about technology deployment? It has no effect on the abatement decision, so technology deployment does not produce any benefits to foreign countries whatsoever. Thus, each country i deploys, $D_i^* = 1$, if and only if $\overline{c} < \underline{c} + c^D$.

4.3 Abatement Cooperation

As under international anarchy, deployments D_i^* are chosen by each country i in a non-cooperative fashion. However, abatements A_i^* are modeled as a treaty participation game:

1. Each country i decides whether to sign a pollution abatement treaty, $s_i^A \in \{0, 1\}$.

2. Each signatory i selects abatement A_i^* to maximize the collective payoff to all signatories while each non-signatory j selects abatement A_j^* to maximize its individual payoff.

This is a standard formulation of international environmental cooperation that Barrett (1994) has introduced in his seminal article on "self-enforcing international environmental agreements." Countries are free to enter and exit international agreements, so an environmental treaty is only self-enforcing if no country wants to exit it. I use this solution concept to investigate how non-cooperative technology deployment changes the strategic logic international cooperation for pollution abatement.

A key premise of the literature is that the countries can only form a single international agreement for pollution abatement. I also adopt this premise, as it appears perfectly reasonable in the context of a global public good. Asheim et al. (2006) relax the assumption by allowing different regions to form separate agreements. If I divided the world into R separate regions, and the number of countries in each region, $\frac{N}{R}$, was high enough, all my results would continue to hold. Thus, the assumption that regional cooperation is prohibited is not necessary for the results.

This is the classical mode of international environmental cooperation. Countries agree on emissions reductions and allow each country to decide on the domestic measures and actions that will achieve this goal. At first blush, this contract appears ideal because the domestic measures and actions to reduce the cost of pollution abatement do not produce international spillovers or externalities. Again, I apply backward induction.

Abatement decisions. Begin with the pollution abatement stage, and examine how signatories and non-signatories decide on pollution abatement. First, in this case, non-signatories behave exactly as above: they abate if and only if they have deployed previously. Since each non-signatory i maximizes its own payoff, it abates if and only if $1 > c_i^A$. I have assumed that $\overline{c} > 1 > \underline{c}$, so we have $A_i^* = D_i^*$.

By contrast, the signatories maximize their collective benefits. If the number of signatories is K, each member abates if and only if

$$K > c_i^A. \tag{4}$$

If country i has deployed, $D_i^* = 1$, it will abate as a signatory, for $K > 1 > \underline{c}$. If the individual benefits of pollution abatement exceed the costs, the collective benefits must be even higher than that. A country that has not deployed, $D_i^* = 0$, will only abate if the number of signatories is so high that $K > \overline{c}$.

Abatement participation. What about the participation decision? Recall that with $\underline{c} < 1$, all countries i that have deployed will abate, signatories or not. Thus, if $D_i^* = 1$ for all countries $i = 1, ..., N$, the abatement treaty is irrelevant. Suppose this is not true, so that $D_i^* = 0$ for at least one country i. Any such country will abate as a signatory if and only if $K > c_i^A$. Thus, for the abatement treaty to have any effect on behavior, non-deployers should benefit from being signatories to the treaty. This requires that the decision to join have an effect on the decision to abate by other countries: mitigation by non-deployers must be contingent on participation of country i. With $1 - \overline{c} < 0$, we need

$$K > \overline{c} > K - 1. \tag{5}$$

When this condition holds, non-signatories also have no incentives to join because the current signatories will commit to pollution abatement in any case.

This condition is not enough because only those members of the coalition who did not deploy will actually react: countries that have already deployed will deploy technology in all circumstances because $1 - \underline{c} > 0$. If the number of non-deployers in the coalition is K^0, where $0 \leq K^0 \leq K$, it must also be that

$$K^0 > \overline{c}, \tag{6}$$

as K^0 is the number of non-deployers that respond to country i's exit by failing to abate pollution. With $K^0 \leq K$, it follows immediately that the real participation condition for any non-deployer i is

$$K^0 > \overline{c} > K^0 - 1. \tag{7}$$

This condition says that the cost $\overline{c}$ must fall below the collective benefits of abatement for non-deployers K, yet it must be so high that if country i fails to join the pollution abatement treaty, $K^0 - 1$ other non-deployers will not abate even though they are signatories.

We now see the logic of reciprocity in action. A non-deployer i joins the coalition, not out of altruism but because it wants to induce $K^0 - 1$ other non-deploying signatories to cooperate. Unless non-deployer i joins the coalition, the other non-deployers i will fail to abate. Thus, each non-deployer i must be pivotal for the other non-deploying members.

Clearly, we must also have a unique $K = K^0$. Strikingly, only non-deployers can join the abatement agreement. Deployers have no incentive to join the abatement agreement, because by doing so they would ensure that the agreement would fail to operate. This surprising result follows from the logic of reciprocity. If deployers join the agreement, they are nonetheless unable to condition pollution abatement on what other countries do, as it is a strictly dominant strategy for them to abate pollution unilaterally. The pollution abatement treaty can operate only if each member is pivotal, and so every member of the coalition must be a non-deployer.

Of course, this does not imply that deployers do not abate pollution. They will abate pollution for very selfish reasons, but they do so regardless of coalition formation. Thus, the total number of countries that somehow abate pollution is the sum of countries that deploy and K non-deployers. If K is impossible to meet, as the number of countries is too low for $K > \overline{c} > K - 1$ to be met, non-deployers obviously will not abate pollution.

Deployment. Consider now the deployment decision. Recall that deployers can never join the pollution abatement agreement in equilibrium. If a deployer decides not to deploy, the total number of other countries that abate thus either remains unchanged, assuming there are at least K or fewer than $K - 2$ non-deployers, or increases by exactly $K - 1$, assuming there are exactly $K - 1$ non-deployers. In the first case, the decision by country i to deploy has no effect on what other countries do. In the second case, the decision by country i to not deploy enables the formation of a pollution abatement coalitions by K non-deployers.

Two cases must be considered. First, suppose

$$1 - \underline{c} - c^D > 0, \tag{8}$$

so that first deploying and then abating is individually rational. In this case, two equilibria are possible. First, all countries deploy and abate because deployment and abatement is individually rational. Second, exactly $N - K$ countries deploy but all countries abate, as non-deployers form an agreement. Of the two equilibria, full deployment and pollution abatement is collectively optimal, so I assume it is played.

Second, suppose

$$1 - \underline{c} - c^D < 0, \tag{9}$$

so that a strategy of deployment and pollution abatement is not individually rational. Now an equilibrium with every country deploying and abating is obviously not possible, as each country has an incentive to deviate by neither deploying nor abating. This claim is obviously also true for any number of deployers strictly higher than $N - K$.

What about an equilibrium wherein exactly K countries only abate, while $N - K$ countries deploy and abate? For this configuration to be an equilibrium, it has to be verified that no deployer or non-deployer has an incentive to deviate. A non-deployer i clearly has no incentive to deviate. If it did, the other $K - 1$ countries would choose not to abate pollution because country i's abatement decision would no longer depend on treaty participation by the other $K - 1$ countries.

If a current deployer deviates the total number of countries that will somehow abate must decrease by one. Under the assumption that the deviator can be subsequently "punished" by having it join the pollution abatement agreement in equilibrium, the deviator has no incentive to deviate if and only if

$$K - \underline{c} - c^D > K - 1 - \overline{c}. \tag{10}$$

The left side is the payoff from deployment and the right side is the payoff failing to deploy but being next made a member of the pollution abatement coalition. This condition can be written as

$$1 - \underline{c} - c^D > -\overline{c}. \tag{11}$$

This condition may or may not hold. If it does hold, it is possible to sustain an equilibrium with $N - K$ deployers and K other abaters. Thus, full cooperation is possible. The threat of being made a member of the pollution abatement coalition without deployment is severe enough to induce exactly $N - K$ countries to deploy, and so full cooperation is possible without a technology deployment agreement.

Suppose next this condition does not hold. Now any equilibrium with positive numbers of deployers is impossible, as no country can affect the total number of abaters among other countries. To see this, suppose country i deploys, $D_i^* = 1$, in equilibrium. It thus commits to abating, as $1 - \underline{c} > 0$. If country i deviates by not deploying, $D_i^* = 0$, all other deployers continue to deploy while the number of countries in the pollution abatement coalition without deployment remains unchanged. Even if country i is made a member of this coalition, it prefers $-\overline{c}$ to $1 - \underline{c} - c^D$.

Under the assumption that $1 - \underline{c} - c^D < 0$, we now observe that the effectiveness of pure abatement cooperation depends critically on the relative size of $1 - \underline{c} - c^D$ and $-\overline{c}$. If $1 - \underline{c} - c^D$ exceeds the value of $-\overline{c}$, then full cooperation with partial deployment is sustainable. The reason is that a country that fails to deploy can be made part of the pollution abatement coalition without deployment. The total amount of pollution abatement decreases by one while the cost increases. Thus, it is possible to induce $N - K$ countries to deploy technology and have the remaining K countries also abate pollution. No formal treaty for technology deployment is required.

But if $-\overline{c}$ exceeds $1-\underline{c}-c^D$, so that deployment is very costly, no cooperation is possible. Quite surprisingly, non-cooperative technology deployment is completely useless. Exactly zero countries deploy the technology while only K countries are able to cooperate on pollution abatement without technology deployment.

Summarized in Table 1, this analysis provides several insights into why a technology deployment agreement may be useful. It demonstrates that unless full deployment and abatement by all countries is a matter of course, or the cost of technology deployment very low, no individual country can have incentives to deploy technology in equilibrium. Thus, it appears plausible that a technology deployment agreement will be useful because it changes these strategic incentives and allows deployment in equilibrium. In the following section, I demonstrate that such a possibility exists.

[TABLE 1 ABOUT HERE]

5 Deployment and Abatement Cooperation

The benchmark analyses show that in the absence of technology deployment cooperation, it is generally hard to sustain cooperation. My main solution concept allows countries to engage in cooperation on both fronts: technology deployment and pollution abatement. Countries can first join an international coalition for technology deployment. After the technology deployment stage, they can also form an international coalition for pollution abatement. The coalitions may also have different members. This solution concept demonstrates the value of adding a technology deployment agreement to international climate policy.

Formally, both stages are played as participation games. Thus, the abatement stage is as described above. Similarly, the deployment stage is as follows:

1. Each country i decides whether to sign a technology deployment treaty, $s_i^D \in \{0,1\}$.
2. Each signatory i selects deployment D_i^* to maximize the collective payoff to all signatories while each non-signatory j selects deployment D_j^* to maximize its individual payoff.

Now abatement cooperation is accompanied by deployment cooperation. It is the comparison between this solution and pure abatement cooperation that reveals the benefits of a technology deployment agreement.

The formation of the technology deployment coalition at the first stage is necessarily strategic. Technology deployment does not produce any direct benefits, so the only reason to form a technology deployment coalition is to somehow influence pollution abatement. Since pollution abatement is itself a game of coalition formation, the effect of technology deployment may be complex, however, as the deployment choices of any single country i will influence the pollution abatement incentives of every other country j.

Recall that even in the absence of a technology deployment agreement, full cooperation is possible whenever $1 - \underline{c} - c^D > 0$, so that first deploying and then abating is a strictly dominant strategy. Thus, we can ignore this case and suppose through instead that $1 - \underline{c} - c^D < 0$. We can also exclude the case of $1 - \underline{c} - c^D > -\overline{c}$, as in this case non-cooperative deployment will sustain full cooperation. The only remaining question is if a technology deployment agreement could somehow allow more pollution abatement when $1 - \underline{c} - c^D < -\overline{c}$.

We already know exactly how the abatement stage will be played. All countries that have deployed the technology will abate pollution. If the number of non-deployers is equal to or higher than K, a coalition of exactly K non-deployers will form on pollution abatement. Otherwise all non-deployers free ride. All that remains is to investigate how many signatories a putative technology deployment agreement will have.

In conducting the analysis, the total number of countries N will have an important role. For convenience, let us suppose momentarily that the number N is high, so that the number $N - K$ is also high. I will establish the greatest lower bound for a high N in the subsequent analysis. Then I will relax this assumption.

Deployment choices. Consider now the technology deployment stage, and examine the possibility of a technology deployment agreement with L members, where $1 < L \leq N - K$. Under $1 - \underline{c} < 0$, every country that signs the treaty will subsequently abate if and only if it is in the collective interest of the membership to deploy the technology. With $L \leq N - K$, a collective decision to deploy the technology will not influence the number of non-deployers that will abate pollution. Thus, each member of a technology deployment agreement with L members will deploy if and only if

$$L - \underline{c} - c^D > 0. \tag{12}$$

With $1 - \underline{c} - c^D < 0$, this defines a unique minimum $L > 1$. Unless L countries join the deployment treaty, it will not induce deployment by members.

Deployment participation. What about participation? First, it is immediate to establish that non-deployers have no incentives deviate from the equilibrium: with $1 - \underline{c} - c^D < -\overline{c}$, they do not benefit even if the total number of abaters remains unchanged. What about the deployers? Again, the incentive to participate cannot exist when other countries will not respond to deviation by stopping to deploy. This claim holds even if the deviator is made a member of the pollution abatement coalition, as $1 - \underline{c} - c^D < -\overline{c}$. By exiting the deployment treaty, country i should induce the remaining $L - 1$ members to forgo deployment. Thus, it must be the case that

$$L - 1 - \underline{c} - c^D < 0. \tag{13}$$

When this condition holds, no member country i has an incentive to deviate because $-\overline{c} < 0 < L - 1 - \underline{c} - c^D$. Thus, it suffices that

$$L > \underline{c} + c^D > L - 1. \tag{14}$$

In equilibrium, L countries join the technology deployment agreement and K countries join the pollution abatement agreement. Thus, the total number of cooperators is $L + K \leq N$.

Suppose now instead that $L > N - K$. Now the formation of the deployment coalition would prevent pollution abatement by non-deployers, as they are unable to form a viable coalition with K non-deploying members. Thus, we require $L \leq N - K$ for technology deployment cooperation and pollution abatement cooperation in the game. Otherwise we either have a technology deployment coalition with L members or a pollution abatement coalition with K members. But not both.

Intuitively, the equilibrium logic of coalition formation is the following. First, consider the technology deployment stage. Suppose the governments of L countries have initiated formal negotiations, and each now considers the costs and benefits of joining. If the number L is low enough relative to N, they understand that even if they form a technology deployment coalition, another group of K countries will subsequently form the pollution abatement coalition. Second, in the pollution abatement stage, these K countries will form the coalition, as they have a collective incentive to do so. Thus, we have exactly $L + K$ countries abating pollution in equilibrium.

Empirically, we have now identified the precise conditions under which deployment cooperation may prove useful. It must be that the total size of the equilibrium deployment and abatement coalitions, $L + K$, falls below N. In that case, L countries will deploy and abate while K countries will only abate. It follows that the number of countries N must be large enough.

Another important empirical condition is that technology deployment must be costly yet effective, $1 - \underline{c} - c^D < -\overline{c}$ but $1 - \underline{c} > 0$. This dual condition ensures that technology deployment will commit a country to pollution abatement, but technology deployment is so costly that it is not worth the while without a technology agreement that is based on reciprocity. If one of these conditions fails, either technology deployment is completely useless or non-cooperative technology deployment suffices to sustain full cooperation. These findings are summarized in TABLE 2.

[TABLE 2 ABOUT HERE]

For this result, the dynamic sequence of moves is critically important. To see why, suppose countries could simultaneously decide on technology deployment and pollution abatement. If a country abates pollution, the global benefit is exactly N. The cost to the country is either $\overline{c}$ or $\underline{c} + c^D$. If $\overline{c} > \underline{c} + c^D$, any treaty coalition would unambiguously prefer technology deployment. If $\overline{c} < \underline{c} + c^D$, any treaty coalition prefers pure pollution abatement. Thus, it is impossible for two treaty coalitions that rely on different policy instruments to form. While Asheim et al. (2006) achieve multiple treaty coalitions by assuming that countries can form regional environmental agreements, my result does not depend on such artificial assumptions.

6 Practical Implementation

In the formal analysis, I have uncovered the conditions under which technology deployment cooperation may increase total pollution abatement to the collective benefit of the countries. In particular, I found that if technology deployment is very costly yet effective, a technology deployment agreement may increase the number of countries that engage in pollution abatement. This follows from the emergence of two separate coalitions with different aims and members. In this section, I investigate obstacles to practical implementation and lessons for institutional design.

Begin with the basic notion that technology deployment cooperation is only necessary when noncooperative behavior does not allow a simple solution. On the one hand, technology deployment should obviously not be individually rational. This condition is almost surely met in the case of climate change and other difficult global environmental problems. On the other hand, and less obviously, it must also be the case that technology deployment is actually quite costly, so that a country may prefer to join the pollution abatement coalition without technology deployment, even though this also reduces the total number of countries abating pollution by one. This condition implies that technology deployment agreements may not help solving easy cooperation problems, but they could be quite useful in addressing some of the more difficult collective action failures that characterize global warming politics in the present.

How does a technology deployment agreement help? It helps by changing the rules of the game. When individual technology deployment and subsequent abatement are very costly from the perspective of an individual country, it may be useful to collectively commit to technology deployment. Although an individual country does not obtain a net benefit from deployment and abatement, the members of a technology deployment agreement may collectively benefit. In these circumstances, it is useful to form a technology deployment agreement, as the number of countries that will ultimately abate grows from K to $L+K$.

Technology deployment must constitute a credible commitment to abatement. This conditions appears rather plausible for many technologies, especially renewable energy sources. If a country increases the share of renewables in power generation, it is not too difficult to subsequently reduce emissions in the electricity sector. While other measures might also be needed elsewhere in the economy, at least for the sector in focus, technology deployment should have the potential to commit an individual country to pollution abatement. Simply put, countries that have already decarbonized the energy sector have few reasons to continue generate high carbon dioxide emissions.

Another essential feature is that the number of actors must be relatively high. Remember that technology deployment cooperation may crowd out abatement cooperation, so it is better if both deployment and abatement cooperation are possible. This requires that $L + K \leq N$, though it would obviously be collectively best if $L + K = N$, so that full cooperation is attainable. For practical purposes, this requirement implies that while technology deployment agreements may feature a lower number of countries, L, the relevant group of countries in the sector or area in focus should be as large as possible. Ideally, it would be almost global, encompassing all major emitters in all continents.

This is an important observation, as it may favor sectoral approaches to technology deployment cooperation. It is not necessary at all that the technology deployment agreement itself will encompass the globe, but the sectors in focus should be relevant for many countries. From this perspective, the climate and energy package of the European Union actually appears in rather favorable light. It has potent provisions for renewables in electricity generation. Since electricity generation is a key issue for any industrialized or industrializing society, the number of relevant countries in the sector is relatively high. Ideally, by committing to technology deployment, the European Union could increase the number of countries in other regions that are ultimately willing to somehow join the global climate regime.

Regarding the relationship between technology deployment and subsequent abatement, the treaty should be designed such that it does not impede abatement cooperation. This requires a partial deployment treaty: some countries deploy and abate, while others abate without deploying. Of course, there is a distributional problem here: one of the strategies will produce a higher payoff to each individual country. Here, asymmetries between countries – something I was not able to include in my formal model – may help identify the politically feasible and economically cost-effective technology deployment coalition.

It is also essential that abatement cooperation will *not* be conditioned on previous technology deployment. Indeed, exactly the opposite should be encouraged: countries that deploy should operate on their own, whereas countries that do not deploy should cooperate among themselves. This is how the total number of countries that cooperate can be maximized under the requirement that sovereign governments have real incentives to join international agreements (Barrett 2003).

Even voluntary technology agreements, such as the Asia-Pacific Partnership on Clean Development and Climate, may have their benefits (Karlsson-Vinkhuyzen and van Asselt 2009). While they do not lead to actual emissions reductions in the near term, they allow technology deployment without firm commitments to abatement. Consequently, other countries have incentives to develop their own abatement collaboration. Indeed, this is the relationship between the Kyoto Protocol and the Asia-Pacific Partnership on Clean Development and Climate. While some scholars have correctly criticized the disruptive relationship between the two that stems from the hostility of the Bush administration in the United States between years 2000 and 2008, the fact that they are not perfectly unified may nonetheless be something that could help in other circumstances (Eckersley 2007; Vihma 2009).

Given this result, my formal analysis lends some theoretical support for the idea of a coordinated "regime complex" (Keohane and Victor 2010). While technology deployment should be somewhat separate from actual mitigation efforts, so that participation in the technology deployment agreement is not viewed as a precondition for joining the actual climate treaty, these two efforts should nonetheless be coordinated. As my formal analysis shows, the stability of both the technology deployment and pollution abatement agreements depends on finding an ideal multilateral coalition, so that no member has an incentive to exit them in the expectation that others continue to cooperate. Thus, a coordinating body may be useful for ensuring that the composition of each coalition meets the participation constraint for international cooperation under anarchy.

Finally, the intricate relationship between technology deployment and pollution abatement has implications for participation requirements as well. It is not uncommon for international environmental agreements to contain explicit provisions that condition entry into force on the membership of a certain number of countries, or even specific identities. Such requirements can be useful, because the composition of the technology deployment agreement will influence the composition of the pollution abatement agreement.

7 Conclusion

In this article, I have investigated the strategic design of technology deployment to increase participation in climate cooperation. I have envisioned technology deployment as a credible commitment by a country to pollution abatement in the future. In the resulting dynamic model, I have examined the strategic logic of technology deployment and pollution abatement, especially in view of the benefits of a formal technology deployment treaty.

In certain circumstances, a technology deployment agreement will help countries achieve international climate cooperation. When technology deployment is very costly but nevertheless effective in committing the deployer to future mitigation, a technology deployment agreement can expand the total number of countries that abate pollution in equilibrium. One coalition of countries forms to deploy technology, and as long as the number of countries needed to form this coalition is not too high, another coalition will subsequently form to abate pollution without technology deployment. Technology deployment allows countries to choose between cooperating with and without it, and this option allows greater participation in two different formal treaties.

What is more, my formal analysis has allowed me to characterize the conditions for effective technology deployment agreements. Two conditions are paramount. First, the number of relevant countries must be high, as otherwise countries cannot sustain two separate coalitions in equilibrium. Second, technology deployment must be relatively costly but rather effective. Both conditions seem to apply well to such complex global problems as climate change, so it is my hope that the present analysis is particularly relevant for the current debate.

These results contribute to the literature in several ways. In addition to offering a new and counterintuitive strategic rationale for technology deployment agreements, the findings emphasize the need for nuanced but analytically rigorous distinctions between various forms of technology cooperation. While technology cooperation is often viewed as a generic concept that leaves a positive impression, in reality such activities as research and development or deployment, as well as many others, may feature very diverge strategic logic. To understand their potential and pitfalls, it is thus necessary to continue the analytical refinement of the variegated forms of technology cooperation.

These findings also have several policy implications worth repeating here. To begin with, the empirical conditions for successful technology deployment cooperation help identify promising technologies and country groups for this form of collaboration. It may be a good idea to consider sectoral approaches, and they should be such that they have global relevance and require costly technology deployment with significant domestic ratifications. Nonetheless, it is not necessary that the technology agreements themselves have large number of members. It is certainly not to be expected that they will have universal membership.

The formal analysis has broader implications for international cooperation theory. First, the analysis demonstrates that multidimensional forms of cooperation may mitigate the participation and compliance problems that the possibility of free riding induces (Axelrod and Keohane 1985; Barrett 2003; Gilligan 2004). In my model, technology deployment increases cooperation because it does not deprive other countries of their incentives to cooperate among themselves. Second, the analysis provides a new strategic rationale for leadership in international cooperation (Skodvin and Andresen 2006; Young 1991). Far from inducing other countries to free ride, minilateral cooperation among frontrunners may expand the total number of cooperators.

Much remains to be done. From a theoretical perspective, I have not investigated the features of specific technologies. They may feature very different strategic problems in regards to deployment, as well as research and development. Thus, theoretical models of different technological categories will probably prove useful in future research. Similarly, I have not allowed more complex interactions between deployment versus research and development, or considered such issues as bargaining or compliance and monitoring (Dai 2002; Fearon 1998; Gilligan 2004). As to empirical research, several approaches seem to hold promise. I have not conducted a detailed investigation of the ability of existing technology agreements to promote deployment. Although it is probably limited, such initiatives as the Asia-Pacific Partnership on Clean Development and Climate may nonetheless offer useful lessons for scholars and policymakers. I have also not examined the role of technology deployment in other issue areas. It appears reasonable to assume that many other forms of international cooperation that feature science and technology will provide useful examples and ideas for the role of technology deployment cooperation in international climate policy. Finally, although the present strategic analysis is simple, it might be useful to calibrate it to real technologies and country groups. Ideally, such calibrations could help focus costly negotiations efforts on the most promising instances.

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Equilibrium	**Condition**	**Individual Benefits**
FULL DEPLOYMENT, FULL ABATEMENT	$1-\underline{c}-c^D>0$	Extremely high
PARTIAL DEPLOYMENT, FULL ABATEMENT	$-\overline{c}<1-\underline{c}-c^D<0$	Relatively high
NO DEPLOYMENT, PARTIAL ABATEMENT	$1-\underline{c}-c^D<-\overline{c}$	Low to medium

Table 1. Equilibria of the abatement cooperation game without technology deployment. As long as the individual benefits of deployment and abatement are relatively high, no technology deployment cooperation is required.

Equilibrium	**Condition**	
	Non-cooperative	Cooperative
Full deployment, full abatement	$1 - \underline{c} - c^D > 0$	$1 - \underline{c} - c^D > 0$
Partial deployment, full abatement	$-\overline{c} < 1 - \underline{c} - c^D < 0$	$-\overline{c} < 1 - \underline{c} - c^D < 0$
No deployment, partial abatement	$1 - \underline{c} - c^D < -\overline{c}$	$\emptyset$
Partial deployment, partial abatement	$\emptyset$	$1 - \underline{c} - c^D < -\overline{c}$

Table 2. Equilibria under non-cooperative and cooperative technology deployment.