Climate Treaties and Backstop Technologies

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Abstract

In this paper I examine the design of climate treaties when there exist two kinds of technology, a conventional abatement technology with (linearly) increasing marginal costs and a backstop technology ("air capture") with high but constant marginal costs. I focus on situations in which countries can gain collectively by using both technologies. I show that, under some circumstances, countries will be better off negotiating treaties that are *not* cost-effective. When countries prefer to negotiate self-enforcing agreements that *are* cost-effective, the availability of the backstop technology causes cooperation in abatement to increase significantly.

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1. Introduction

International environmental agreements are second best institutions. They can improve on unilateralism, but usually fall short of sustaining full cooperation. Climate change is a particularly difficult challenge. Because the marginal costs of reducing greenhouse gas emissions increase sharply, at least beyond some point, the incentives to free ride are substantial—and impossible for an international environmental agreement to overcome using the usual mechanism of reciprocity.

This is why other strategies need to be considered. A few papers have shown that, under certain circumstances, a technology-oriented strategy can help. Heal (1994) shows that cooperation can be facilitated when abatement costs are interdependent. Golombek and Hoel (2004) show that R&D spillovers may cause new technologies to be diffused globally—producing a kind of negative leakage. I have shown that R&D directed at technologies exhibiting strong network externalities can transform the problem of deterring free riding (Barrett 2006). Finally, Hoel and de Zeeuw (2009) show that cooperation in R&D can increase global abatement by reducing the costs of adopting a new technology. In this paper I explore a different perspective. This is to consider two technologies that lower atmospheric concentrations of greenhouse gases in very different ways—a conventional abatement technology that reduces emissions at increasing marginal cost and a novel technology that reduces atmospheric concentrations directly by removing CO_2 from the air. This novel technology, known generically as "air capture," has a constant but very high marginal cost.

There are a number of ways to remove CO_2 from the air (Barrett 2009). Several approaches exploit the process of photosynthesis. Credits for afforestation and reforestation are already incorporated in the Kyoto Protocol (avoided deforestation, the subject of ongoing negotiations, would limit additions to atmospheric concentrations). A related approach is to use biomass as a fuel for electricity generation, and then to capture and store the CO_2 from combustion, resulting in negative net emissions. Another idea is to fertilize iron-limited regions of the oceans, to stimulate the growth of phytoplankton, which, if they sink to the deep ocean, will cause the surface waters to extract CO_2 from the air to restore chemical balance. Unfortunately, the effects of all these biological approaches are difficult to verify, limited in scale, and prone to having worrying side effects.[1]

In this paper I consider "industrial" air capture. This involves a technology that brings air into contact with a chemical "sorbent" (an alkaline liquid). The sorbent absorbs CO_2 in the air, and the industrial process then separates out the CO_2, recycles the sorbent, and stores the captured CO_2 in geologic deposits, just like CO_2 removed from a power plant's stack gases. Industrial air capture has several desirable features (Sarewitz and Nelson 2008). It would be decoupled from our energy systems, and could be located near geologic sites for long-term carbon storage and away from population areas, where land has a low opportunity cost. It could also be scaled to any level. Conceivably, every other

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[1] Ocean fertilization is perhaps the most worrying of these proposals. In 2007, the 84 parties to the London Convention/Protocol endorsed a "statement of concern" about ocean fertilization, and urged parties "to use the utmost caution when considering proposals for large-scale ocean fertilization operations." (See OSPAR Decision 2007/02 on Storage of Carbon Dioxide Streams in Geological Formations, June 2007.)

aspect of the global economy could remain unaltered, and this technology be used to sustain virtually *any* desired reduction in atmospheric levels of carbon. From the perspective of emission reductions, industrial air capture is a true "backstop technology."

Industrial air capture is expensive. Estimates of marginal cost range from \$100-\$200/tCO_2. Industrial air capture is much more costly than the alternatives for reducing emissions, including power plant CO_2 capture and storage. Its marginal costs also exceed current estimates of the social cost of carbon, which range from about \$7-\$85/tCO_2. However, the marginal cost of industrial air capture is lower than estimates of the cost of meeting a 2° C temperature change target by means of abatement technology by around 2100.[2] In the future, use of industrial air capture may be collectively optimal.

Though costly, industrial air capture has offsetting advantages. Because it acts directly on reducing concentrations, industrial air capture offers more options for the timing of investment as compared with emission reductions (Pielke 2007). Even if the intention were not to deploy this technology, it may pay for us to develop it as a hedge against future climate change risks, given its unique ability to be scaled to reduce concentrations directly. Finally, unlike emission reductions, industrial air capture could be deployed by a single country, or by a "coalition of the willing."

In this paper my focus is on the effect of air capture on the design and efficiency of international treaty arrangements. How should climate treaties be designed when

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[2] All of these estimates can be found in Barrett (2009).

countries have the option not only to abate their emissions but also to employ industrial air capture as a backstop technology?

2. An abatement-only treaty

Begin by considering the abatement decisions of countries in the absence of a multilateral agreement. Let q_i denote country *i*'s abatement and let *Q* denote aggregate abatement; with *N* countries, $Q = \sum_{i=1}^{N} q_i$. Finally, let country *i*'s payoff be given by $\pi_i = bQ - c\,q_i^2/2$. If countries choose their abatement levels independently, there exists a unique Nash equilibrium in which every country *i* plays $q_i = b/c$. If countries were able to cooperate fully, each would play $q_i = bN/c$.

A treaty can be represented as the equilibrium of a stage game, with countries deciding whether to participate in stage 1, with parties choosing their abatement levels collectively in stage 2, and with non-parties choosing their abatement levels independently in stage 3. As is usual, we solve the game backwards.

Since the equilibrium of the earlier abatement game, $q_i = b/c$, is in dominant strategies, it must also be the equilibrium of the stage 3 game. Letting k_q denote the number of signatories to the abatement-only agreement, collective maximization by signatories implies that each signatory must play $q_s = bk_q/c$ in stage 2. Finally, letting π_s and π_n denote the payoff to a signatory and non-signatory, respectively, a Nash equilibrium of the stage 1 game is a participation level k_q^* satisfying $\pi_s(k_q^*) \geq \pi_n(k_q^* - 1)$ and $\pi_n(k_q^*) \geq \pi_s(k_q^* + 1)$. Upon substitution, it is easy to show that the equilibrium participation level is $k_q^* = 3$ for $N \geq 3$. Plainly, a treaty consisting of just 3 countries will not make much of a difference when *N* is large. The agreement increases aggregate abatement from bN/c to just $b(N+6)/c$, while full cooperation requires that abatement increase to bN^2/c.

Though this result emerges from a special model, it can be shown to be qualitatively robust (Barrett 2005). The result need not be taken literally to mean that only three countries will cooperate. If the assumption about credibility is weakened just a little, then, in a repeated game context, it can be shown that the level of participation can be increased all the way to *N*. The problem is that, as the participation level increases, the abatement level of each participant must fall in order for the agreement to be self-enforcing (Barrett 2002). A more general interpretation of this result is that a second best abatement treaty is likely to improve little on non-cooperation and fall far short of full cooperation. Though the model is implausibly simple, its prediction is consistent with the experience of negotiations thus far. The Kyoto Protocol may have caused some countries to reduce their emissions a little, but it has certainly not sustained full cooperation, and the Copenhagen Accord promises to do no better.

3. An air-capture-only treaty

Assume now that countries can only mitigate climate change by means of air capture. Let z_i denote country *i*'s level of air capture, and assume $z_i \in [0, \overline{z}]$. I noted previously that air capture can be scaled to virtually any level. However, in this paper I assume that air capture and abatement are comparable in their effects—both yielding equal and constant marginal benefits. It is thus reasonable to think of air capture as being bounded in this static model to a level perhaps not much different than a year's emissions.

Let *Z* denote the aggregate reduction in greenhouse gas concentrations (relative to business as usual) due to air capture; with *N* countries, $Z = \sum_{i=1}^{N} z_i$. Finally, let country *i*'s payoff be given by $\pi_i = bZ - \gamma z_i$. If countries choose their air capture levels independently, and if $\gamma > b$, then there will exist a Nash equilibrium in which every country *i* plays $z_i = 0$. If $\gamma > bN$, then this equilibrium will also be first best. Let us assume, however, that $\gamma < bN$ (this, as noted previously, is a situation in which we might find ourselves in the future). Then the above Nash equilibrium will be inefficient.

Can a treaty help? Let us see. In stage 3, non-signatories will plainly play $z_n = 0$. In stage 2, signatories will play $z_s = \overline{z}$ if $bk_z \geq \gamma$ and $z_s = 0$ otherwise, where k_z denotes the number of parties to the air-capture-only treaty. Finally, in equilibrium, the number of signatories will be k_z^* with $\gamma/b + 1 \geq k_z^* \geq \gamma/b$.

Note that, while the equilibrium number of signatories to an air capture protocol can be large, when this number is large the overall gains to cooperation will be small. As with an abatement-only treaty, an air-capture-only treaty can improve little on the non-cooperative outcome (though, as we shall see, unlike an abatement-only treaty, an air-capture-only treaty may come close to sustaining full cooperation).

4. A combined protocol

I have so far modeled abatement and air capture as independent choices. But the equilibrium levels of marginal cost vary substantially as between the two agreements. In the equilibrium abatement protocol, marginal cost is $3b$. In the equilibrium air capture protocol, marginal cost is γ. As explained previously, it is very likely that $\gamma >> 3b$. This means that, if abatement and air capture are addressed in separate protocols, mitigation will not be cost-effective.

It seems more plausible to assume that cooperating countries would want to negotiate a single agreement, with the decisions to abate and carry out air capture being optimized *jointly*. How might such a treaty be designed?

Because marginal benefits are assumed to be constant, the first order conditions for both abatement and air capture will be unchanged as compared with the previous analyses. Non-signatories will play $q_n = b/c$ and $z_n = 0$. Signatories will play $q_s = k_+ b/c$, where k_+ denotes the number of parties to the combined protocol; they will play $z_s = \overline{z}$ for $k_+ \geq \gamma/b$ and $z_s = 0$ for $k_+ < \gamma/b$. Of course, the non-cooperative and full cooperative outcomes will also be unchanged as compared with the earlier analyses.

While these conditions will remain unchanged, the treaty equilibria may be very different. So long as $\gamma >> 3b$, there will exist one treaty equilibrium in which parties to the agreement only abate their emissions. In this equilibrium, each of the $k_q^* = 3$ signatories will undertake three times the abatement as each non-signatory, and each non-signatory will undertake the same level of abatement as in the non-cooperative outcome. No country will undertake air capture in this equilibrium (again, assuming $\gamma >> 3b$).

If $bN > \gamma$ there may also exist a treaty equilibrium at $\gamma/b + 1 > k_z^* > \gamma/b$. However, we cannot be sure that an agreement comprising this number of parties will be self-enforcing. The reason is that, in a combined protocol, the countries investing in air capture must undertake abatement at the same marginal cost, and we know that such a high level of abatement cannot be sustained by an abatement-only agreement—the incentives to free ride are too great. For this second equilibrium to exist, therefore, the returns to air capture must be large enough to offset the returns lost by foregoing free riding.

For $\gamma/b + 1 > k_z^* > \gamma/b$ to be an equilibrium in a combined treaty we must have $\pi_n(k) \geq \pi_s(k+1)$ at k_z^*. That is, we require

$$b\left[(N-k)\frac{b}{c} + k^2\frac{b}{c} + k\overline{z}\right] - \frac{c}{2}\left(\frac{b}{c}\right)^2 \geq b\left[(N-k-1)\frac{b}{c} + (k+1)^2\frac{b}{c} + (k+1)\overline{z}\right] - \frac{c}{2}\left(\frac{b(k+1)}{c}\right)^2 - \gamma\overline{z},$$

which reduces to $b^2k(k-2)+(\gamma-b)2c\overline{z}\geq 0$. This condition will clearly be satisfied.

We also require $\pi_s(k)\geq \pi_n(k-1)$ at k_z^* or

$$b\left[(N-k)\frac{b}{c}+k^2\frac{b}{c}+k\overline{z}\right]-\frac{c}{2}\left(\frac{bk}{c}\right)^2-\gamma\overline{z}\geq b\left[(N-k+1)\frac{b}{c}+(k-1)^2\frac{b}{c}\right]-\frac{c}{2}\left(\frac{b}{c}\right)^2,$$

which reduces to

$$-b^2k^2+2b(c\overline{z}+2b)k-(3b^2+2\gamma c\overline{z})\geq 0. \tag{1}$$

This second condition may or may not be satisfied. It is more likely to be satisfied if *c* and $\overline{z}$ are "large" and γ is "small" (the effect of *b* is ambiguous).

The value of *k* that maximizes the LHS of (1) is $k=c\overline{z}/b+2$. Substituting this value into (1) yields

$$(c\overline{z}+2b)^2-(3b^2+2\gamma c\overline{z})\geq 0. \tag{2}$$

This condition is necessary for an agreement with *k* parties (where *k* is the smallest integer greater than γ/b) to be self-enforcing. Solving the quadratic in (1), this same value of *k* must lie between $\underline{k}$ and $\overline{k}$, where

$$\underline{k},\overline{k} = \left(\frac{c\overline{z}}{b}+2\right) \pm \frac{\sqrt{(c\overline{z}+2b)^2-(3b^2+2\gamma c\overline{z})}}{b}$$

For a combined treaty comprising k_+^* countries to be self-enforcing, with k_+^* being equal to the smallest integer greater than γ/b, we must have $k_+^* \in [\underline{k},\overline{k}]$.

Even though the model is very simple, I have been unable to obtain an analytical solution for the equilibrium, combined treaty. Table 1 presents simulations from which several conclusions follow:

1. An abatement-only treaty improves little over the non-cooperative outcome. The simulations thus confirm what we already knew.
2. The possibility of air capture can increase payoffs dramatically provided $\overline{z}$ is "large" or *c* is "large." If $\overline{z}$ is "large," the trigger for air capture (*k* being larger than γ / b) reduces concentrations dramatically, delivering a substantial benefit to every country. If *c* is "large" very little abatement is done, with or without an abatement-only treaty, and air capture can therefore make a substantial difference to the overall level of mitigation.
3. As illustrated by Simulation I, a combined (and, therefore, cost-effective) protocol may not be self-enforcing. Put differently, an insistence on cost-effectiveness may cause air capture not to be used, even though every country would be better off if it were used in a separate treaty, part of a package of cost-ineffective mitigation arrangements. This result makes an important point: that cost-effectiveness may

not be a feature of a second-best treaty arrangement; that a focus on cost-effectiveness could actually reduce welfare all around.

4. Comparison of Simulations I and II reveals that a combined protocol is more likely to be self-enforcing if the capacity for air capture, $\overline{z}$, is "large." This, of course, is because the gains to adding air capture to an abatement treaty must be large enough to overcome the incentive to free ride in abatement.
5. As suggested by a comparison of Simulations I and III, a higher marginal abatement cost, *c*, also helps to make a combined treaty self-enforcing. The reason is that, when c is "large," little abatement will be undertaken even if countries cooperate at a high level (k_+^*). The losses an individual country experiences by cooperating in abatement (at $k_+^* >> k_q^*$) will therefore be small, meaning that the benefits to cooperating in air capture do not need to be as large to make a combined treaty self-enforcing.
6. Comparison of Simulations I and IV shows that a lower marginal cost of air capture, γ, has a similar effect. However, in this case the equilibrium participation level falls. The losses to cooperating in abatement are reduced, but so are the gains to adding air capture.
7. Finally, comparison of Simulations IV and V shows that a higher marginal benefit to mitigation, *b*, also lowers the participation level in a self-enforcing, combined treaty (this is because the trigger for air capture is $k \geq \gamma / b$). Ironically, a higher marginal benefit shrinks the payoff to combining air capture and abatement.

In a combined treaty, air capture provides a vehicle for raising the participation level among countries that cooperate to reduce their emissions. However, this helps (in percentage terms) a lot only for Simulation IV, and in this case there is a wide gap (again, in percentage terms) between the aggregate payoff for a combined protocol and the full cooperative outcome.

I have so far emphasized the overall advantages and disadvantages of negotiating a combined treaty. What are the implications for individual countries? Table 2 summarizes the payoffs to individual countries for the simulations in Table 1. Two perspectives are important. The first is the perspective countries might take to negotiating a combined treaty *after* the abatement-only and air-capture-only treaties have been realized. The second is the perspective countries might take to combining treaties *before* any treaty has been developed. In the latter case, countries have a symmetric perspective on the decision to combine. In the former case, they do not.

Table 2 shows that, if the decision to negotiate separate or combined treaties is made in a preliminary stage, the perspective of every country will be identical, and the decision to negotiate separate treaties or a combined treaty will be unanimous. If the parameter values correspond to Simulation I, every country will prefer to negotiate separate treaties. They will eschew possibilities for cost-effectiveness. If the parameter values correspond to Simulations II-V, every country will prefer to negotiate a combined treaty in which abatement and air capture are cost-effective.

If the decision of whether to combine treaties is made at a later stage, after countries have already negotiated separate abatement and air capture treaties, then countries may disagree. For Simulations II and III, non-signatories to the air-capture-only treaty will not want to negotiate a combined treaty, whether or not they are signatories to the abatement-only treaty (their payoffs would be expected to fall from over \$600,000 to just under \$127,000). However, for both simulations, parties to the air-capture-only treaty prefer a combined treaty, and since the equilibrium number of parties will be the same for a combined treaty, we can be sure that a combined treaty will be sustained.

TABLE 1
Simulations

Simulation		I	II	III	IV	V
Parameter values	b	1	1	1	1	5
	c	1	1	1,000	1	1
	γ	79.5	79.5	79.5	19.5	19.5
	$\bar{z}$	10	7,500	10	10	10
Non-cooperative outcome	q^o	1	1	0.001	1	5
	Q^o	100	100	0.1	100	500
	π^o	99.5	99.5	0.1	99.5	2,487.5
	Π^o	9,950	9,950	9.95	9,950	248,750
Abatement-only protocol	q_s^*	3	3	0.003	3	15
	Q^*	106	106	0.11	106	530
	π_n^*	105.5	105.5	0.11	105.5	2,637.5
	π_s^*	101.5	101.5	0.10	101.5	2,537.5
	Π_q^*	10,538	10,538	10.5	10,538	263,450
Air-capture-only protocol (no abatement)	k_z^*	80	80	80	20	4
	Z^*	800	600,000	800	200	40
	π_n^*	800	600,000	800	200	200
	π_s^*	5	3,750	5	5	5
	Π_z^*	16,400	12,300,000	16,400	16,100	19,220
Both protocols	$Q^* + Z^*$	906	600,106	800.11	306	570
	$\Pi_q^* + \Pi_z^*$	26,938	12,310,538	16,411	26,638	282,670
Combined protocol	k_+^*	--	80	80	20	4
	q_s	--	80	0.08	20	20
	$Q^* + Z^*$	--	606,420	806.42	680	600
	π_n	--	606,419.5	806.42	679.5	2,987.5
	π_s	--	6,970	8.22	480	2,800
	Π_+^*	--	12,685,990	16,786	63,960	298,000
Full cooperative outcome	q^c	100	100	0.1	100	500
	z^c	10	7,500	10	10	10
	$Q^c + Z^c$	11,000	760,000	1,010	11,000	51,000
	π^c	5,205	158,750	210	5,805	129,805
	Π^c	520,500	15,875,000	21,000	580,500	12,980,500

TABLE 2
Payoffs to individual countries

Simulation	I	II	III	IV	V
Non-cooperative outcome	99.5	99.5	0.1	99.5	2,487.5
Signatory to abatement-only treaty/Non-signatory to air-capture-only treaty	901.5	600,101.5	800.10	301.5	2,737.5
Non-signatory to abatement-only treaty/Signatory to air-capture-only treaty	110.5	3,855.5	5.11	110.5	2,642.5
Signatory to both treaties	106.5	3,851.5	5.10	106.5	2,542.5
Non-signatory to both treaties	905.5	600,105.5	800.11	305.5	2,837.5
Expected payoff with separate treaties	269.4	123,105.4	164.1	266.4	2,826.7
Non-signatory to combined treaty	105.5	606,419.5	806.42	679.5	2,987.5
Signatory to combined treaty	101.5	6,970	8.22	480	2,800
Expected payoff with combined treaty	102.3	126,859.9	167.9	639.6	2,980
Full cooperative outcome	5,205	158,750	210	5,805	129,805
Who would favor a combined treaty?	No one	Everyone ex ante; signatories to air-capture-only treaty or both treaties ex post.	Everyone ex ante; signatories to air-capture-only treaty or both treaties ex post	Everyone	Everyone

5. Air capture as a single project

In the above analysis, I modeled air capture as a technology employed separately by different countries. However, and as noted in the introduction, air capture, unlike abatement, needn't be undertaken by a very large number of countries to have a big effect. Air capture can be deployed as a single project. The capacity for air capture at a particular location might be limited by the availability of geologic storage, but if CO_2 were to be sequestered in silicate minerals, then this constraint would be eased (though at an additional cost).

Let us then consider a situation in which the amount of air capture undertaken *overall* is constrained, such that $\sum_{i=1}^{N} z_i \le \bar{Z}$. Then, k_z^* will again be the smallest integer greater than or equal to γ/b. However, the level of air capture undertaken for this k will now be $\bar{Z}$ rather than $k_z^* \bar{z}$ (these values could, by chance, be equal). In this case, changes in the equilibrium participation level, k_z^*, will not change the amount of air capture undertaken in an air-capture-only treaty. In contrast to the previous analysis, the amount of air capture undertaken will be efficient. What will change, as participation changes, is the arrangement for cost sharing.

When air capture is undertaken as a single project, the variable z_i is best thought of as a financing share. That is, for $k_z \ge \gamma / b$, each party to the treaty contributes an amount γz_i, with $\sum_i \gamma z_i = \gamma \bar{Z}$. In this model, countries are symmetric, and so the only plausible financing equilibrium is one in which parties share the total cost equally—this amount being $\gamma \bar{Z} / k_z^*$.

Using this formulation, for $k_z^* \in [\gamma / b, \gamma / b + 1]$, $\pi_n(k_z^*) \geq \pi_s(k_z^*)$ implies

$$b\left[(N-k)\frac{b}{c} + k^2\frac{b}{c} + \bar{Z}\right] - \frac{c}{2}\left(\frac{b}{c}\right)^2 \geq b\left[(N-k-1)\frac{b}{c} + (k+1)^2\frac{b}{c} + \bar{Z}\right] - \frac{c}{2}\left(\frac{b(k+1)}{c}\right)^2 - \frac{\gamma \bar{Z}}{(k+1)}$$

which reduces to $b^2 k(k-2)(k+1) + 2c\gamma\bar{Z} \geq 0$. This condition will clearly be satisfied.

We also require $\pi_s(k_z^*) \geq \pi_n(k_z^* - 1)$. Upon substituting, we get

$$b\left[(N-k)\frac{b}{c} + k^2\frac{b}{c} + \bar{Z}\right] - \frac{c}{2}\left(\frac{bk}{c}\right)^2 - \frac{\gamma \bar{Z}}{k} \geq b\left[(N-k+1)\frac{b}{c} + (k-1)^2\frac{b}{c}\right] - \frac{c}{2}\left(\frac{b}{c}\right)^2$$

which reduces to

$$-b^2 k^3 + 4b^2 k^2 + b(2c\bar{Z} - 3b)k - 2c\gamma\bar{Z} \geq 0. \tag{3}$$

This second condition may or may not be satisfied.

Once again, I rely on simulations. The simulations shown in Table 3 correspond to the ones in Table 1 with the exception of air capture capacity. So that the results are broadly compatible, I assume that aggregate capacity is identical; that is, I take it that $\bar{Z} = \bar{z}N$. In comparing Tables 1 and 3, we can see that mitigation levels and payoffs are higher when air capture can be undertaken as a single project. In percentage terms, the difference is particularly noticeable for Simulations IV and V. In these cases, a relatively small number of countries deploy air capture in a self-enforcing treaty. For the simulations in Table 1, these countries undertake relatively little air capture, since the maximum amount per country is fixed. For the simulations in Table 3, these countries undertake a lot more, since only the total amount of air capture is fixed.

6. Conclusions

The literature on international environmental agreements has tended to put technology is a "black box." However, an emerging literature shows that technologies may have features that affect the incentives for countries to cooperate, and the design of self-enforcing-treaties. This paper extends this body of research. Starting from the canonical model of cooperation in reducing emissions, I allow countries to employ a "backstop technology," either in a separate treaty or a combined treaty. For climate change, this backstop technology is industrial "air capture."

The model developed here offers three important insights. First, while economists have overwhelmingly favored cost-effective treaty designs, this paper shows that there are situations in which separate treaties pertaining to different technologies may be superior overall, even though the resulting mitigation is not cost-effective. Second, where a combined treaty is to be preferred to separate treaties, the reason is not only that the combined treaty sustains cost-effective abatement. It is that deployment of the backstop technology ratchets up cooperation in ordinary abatement. Finally, if countries persist in failing to reduce emissions substantially, and marginal damages increase as a consequence, use of the backstop technology will eventually be triggered. In an extreme scenario in which the capacity for undertaking air capture is very, very great, and air capture can be undertaken as a single project, marginal damages overall will be limited and equal to the marginal cost of the backstop technology.

TABLE 3
Simulations: Single Project

Simulation		I	II	III	IV	V
Parameter values	b	1	1	1	1	5
	c	1	1	1,000	1	1
	γ	79.5	79.5	79.5	19.5	19.5
	$\bar{Z}$	1,000	750,000	1,000	1,000	1,000
Non-cooperative outcome	q_0	1	1	0.001	1	5
	Q_0	100	100	0.1	100	500
	π^o	99.5	99.5	0.1	99.5	2,487.5
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Abatement-only protocol	q_x^*	3	3	0.003	3	15
	Q^*	106	106	0.11	106	530
	π_n^*	105.5	105.5	0.11	105.5	2,637.5
	π_s^*	101.5	101.5	0.10	101.5	2,537.5
	Π_q^*	10,538	10,538	10.5	10,538	263,450
Air-capture-only protocol (no abatement)	k_z^*	80	80	80	20	4
	Z^*	1,000	750,000	1,000	1,000	1,000
	π_n^*	1,000	750,000	1,000	1,000	5,000
	π_s^*	6.25	4,687.5	6.25	25	125
	Π_z^*	20,500	15,375,000	20,500	80,500	480,500
Both protocols	$Q^* + Z^*$	1,106	750,106	1,000.11	1,106	1,530
	$\Pi_q^* + \Pi_z^*$	31,038	15,385,538	20,510.5	91,038	743,950
Combined protocol	k_+^*	--	80	80	20	4
	q_s^*	--	80	0.08	20	20
	$Q_+^* + Z_+^*$	--	756,420	1,006.42	1,480	1,560
	π_n^*	--	756,419.5	1,006.42	1,479.5	7,787.5
	π_s^*	--	7,907.5	9.47	3,050	2,725
	Π_+^*	--	15,760,990	20,886	124,460	758,500
Full cooperative outcome	q^c	100	100	0.1	100	500
	z^c	10	7,500	10	10	10
	$Q^c + Z^c$	11,000	760,000	1,010	11,000	51,000
	π^c	5,205	158,750	210	5,805	129,805
	Π^c	520,500	15,875,000	21,000	580,500	12,980,500

TABLE 4
Payoffs to individual countries

Simulation	I	II	III	IV	V
Non-cooperative outcome	99.5	99.5	0.1	99.5	2,487.5
Signatory to abatement-only treaty/Non-signatory to air-capture-only treaty	1,101.5	750,101.5	1,000.10	1,101.5	7,537.5
Non-signatory to abatement-only treaty/Signatory to air-capture-only treaty	111.75	4,793	6.36	130.5	2,762.5
Signatory to both treaties	107.75	4,789	6.35	126.5	2,662.5
Non-signatory to both treaties	1,105.5	750,105.5	800.11	1,105.5	7,637.5
Expected payoff with separate treaties	310.38	153,855.4	166.3	325.4	3,734.5
Non-signatory to combined treaty	105.5	756,419.5	1,006.42	1,479.5	7,787.5
Signatory to combined treaty	101.5	7,907.5	9.47	3,050	2,725
Expected payoff with combined treaty	102.3	157,609.9	208.9	1,793.6	6,775
Full cooperative outcome	5,205	158,750	210	5,805	129,805
Who would favor a combined treaty?	No one	Everyone ex ante; signatories to air-capture-only treaty ex post.	Everyone ex ante; signatories to air-capture-only treaty ex post	Everyone	Everyone ex ante; everyone except signatories to one but not both of the individual treaties ex post

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