Financial Transfers and Climate Cooperation

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Abstract

We investigate the impact of side-payments to countries that have a low net benefit from participating in efficient climate cooperation in a repeated games framework with investment in different technologies. We consider different timings of these payments and different degrees of commitment. If countries cannot commit ex ante to transfer funds to low-benefit participants to an agreement, then there is a trade-off. Investment based agreements, where transfers occur before emissions are realized, but after investments have been committed, maximize the scope of cooperation. Results-based agreements minimize transfers whenever these agreements implement cooperation. If countries can commit to transfer funds, then agreements in which countries with high benefits of climate cooperation pre-commit to results-based payments to countries with low benefits both maximize the scope of cooperation and minimize transfers.

Summary haiku

Transfers of money

Can help reduce free riding

When should we give them?

1   Introduction

> Notwithstanding great progress in scientific and economic understanding of climate change, it has proven difficult to forge international agreements because of free-riding,...
>
> <div align="right">William Nordhaus (2015, p. 1339)</div>

To be effective, any international agreement that addresses climate change must address the absence of an international institution with the power to enforce compliance. Such agreements must be self-enforcing: the shadow of the future must give participants sufficient incentives to comply with the negotiated emission constraints. Folk theorems suggest that, if countries are sufficiently patient, the first best outcome could be sustainable as a subgame perfect equilibrium (SPE) in a repeated game of climate cooperation. For that, each country's benefit of sustained cooperation in future years needs to be sufficient to deter opportunistic behavior today. Unfortunately, as nearly 30 years of climate negotiations have shown, generating and sustaining cooperation is not easy. A look at the rules of the game might be in order.

An important challenge to the nearly thirty years of climate negotiations, which we address in this paper, has been that the joint gains from efficient climate cooperation are unequally distributed across countries. Without resource transfers, many countries would not agree to a globally efficient agreement, and only partial agreements or agreements with lower than efficient mitigation levels can be sustained. Hence, a second rule of the game we can change concerns resource transfers among countries. Indeed, Fong and Surti (2009) show how side payments affect the optimal degree of cooperation in repeated prisoner's dilemmas. In the case of climate cooperation, resource transfers relax the emissions compliance constraint of recipient countries with low benefits or high costs from low emissions. Although the Paris Agreement allows for resource transfers, as did the Kyoto Protocol before it, the mechanisms to enable this have faced numerous – practical and conceptual – challenges and the actual resource flows and resulting additional mitigation have been limited.

For example, because a country's investment in compliance technology affects its costs and benefits from mitigation, its investment decisions need to be considered in the design of climate change agreements with resource transfers. Indeed, Harstad et al. (2019) (hereafter HLR) suggest to exploit the insight that a country's pay-offs from low or high emissions are critically dependent on its investments in compliance technology. HLR show that, where countries face too high costs or too low benefits to

sustain efficient climate cooperation, second-best strategies to sustain low emissions in the repeated climate cooperation game overinvest in green and underinvest in brown or adaptation technologies. This change in the investment increases the benefit and lowers the cost of mitigation and thereby reduces the country's incentive to increase emissions. Therefore, a deeper understanding of the roles of timing of payments, green investment, and pre-commitment can help inform the development of more effective transfer mechanisms.

In this paper, we seek to understand which transfer mechanisms are able to most effectively expand the set of cooperating countries and the global level of mitigation. We build on HLR's work and explore how to sustain higher levels of climate cooperation when not all countries have sufficiently high gains from low emissions to sustain HLR's second-best equilibrium. We start by carefully studying the conditions for existence of HLR's second-best equilibrium. We define the countries whose cooperation can be sustained in that equilibrium as *members of a climate club*. We then add the opportunity for countries to transfer resources to each other to HLR's basic setup and proceed to investigate the impact of transfers from members to countries that have a low net present value of benefits from participation and hence will not participate without support – defined as *applicants to the club*. We assume that if an applicant enters the club they will commit to the efficient level of emissions.[1]

Initially, we build stylized models for three types of side payment agreements: *upfront transfer agreements*, where members transfer resources to applicants before they decide their investments and emissions; *investment-based transfer agreements*, where transfers to an applicant country occur contingent on having observed its investments but before it decides about its emissions; and *results-based transfer agreements*, where transfers occur after the applicant country's emissions have been observed. The Brazilian Amazon Fund, for example, "a REDD+ mechanism created to raise donations for non-reimbursable investments in efforts to prevent, monitor and combat deforestation, as well as to promote the preservation and sustainable use in the Brazilian Amazon," has elements of all these three types of transfer agreements.[2]

For each agreement type, we study how the transfer needed to induce the efficient level of emissions depends on the recipient country's investment in compliance technology. In all three agreements, the applicant and member countries need to comply with investment and emissions levels, and members additionally need to comply with

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[1]One could consider partial cooperation and would obtain similar results.

[2]See http://www.amazonfund.gov.br/en/home/.

Figure 1: Timelines

the transfers.

Two features of our model are crucial. First, emissions are typically observed with a lag, leading to the free-rider problem to start with, and second, some length of time normally elapses between an investment decision and the time at which the compliance technology is fully operational. These lags imply that the size of the transfer needed for compliance and the incentives for investment and abatement differ across our three agreements.

Our first result is that, for each applicant, there is an investment level that minimizes the transfer level it needs to receive to comply with low emissions, while for member countries, there is an investment level that maximizes the transfer level they are willing to make and still comply with low emissions. At these investment levels, countries overinvest in green technology by even more than in the second-best solution in Harstad et al. (2019).

Next, we show that in all three types of agreements the levels of transfers and in-

vestment that induce *compliance of member countries* with low emissions automatically also induce their compliance with the necessary investment and the transfers. Furthermore, in investment-based transfer agreements (only), the levels of transfers and investment that induce *applicants* to comply with low emissions also automatically induce their compliance with the necessary investment.

In contrast, the automatic compliance with the investment level can fail to hold for applicant countries in upfront and results-based transfer agreements. If, for example, the marginal cost of green investment is low for an applicant country, then the investment level that minimizes the transfer necessary to comply with low emissions will be very large. In that case, the country may defect by investing less than necessary in the first place, causing a defection in the emissions stage as well.

Absent the need to incentivize over-investment in green technology, all three types of agreements would have the same scope for climate cooperation. Therefore, when applicants that fulfil their emissions compliance constraints automatically also fulfil their investment compliance constraints, then all three schemes maximize that scope and policy-makers can choose either one of them to implement low emissions. In this case, member countries would want to choose a results-based agreement because it minimizes the overall transfer needed for compliance of an applicant country, whereas applicants would prefer an investment-based agreement, and the final choice of the agreement depends on the negotiations between countries.

In contrast, we find that, when applicants that fulfil the emissions compliance constraint would have an incentive to violate the investment constraint in upfront and results-based payment agreements, then investment-based agreements can implement low emissions when upfront and results-based payment agreements cannot. In this case, low emissions could be achieved with higher overall transfers to the applicants than those necessary for compliance with low emissions only. This case, in which investment-based agreements implement more climate cooperation than results-based agreements, is empirically relevant. It applies to situations in which an applicant is small relative to the size of the world, has a low stock of green technology implying high gains from investing in green technology, has high costs for investment in green technology, and would be required to reduce emissions considerably.

We then introduce a credible third party, to which member countries transfer payments and which will give all the funds to the applicant if low emissions are observed. We only consider agreements with such a third party, which are upfront for member countries and results-based for applicants. We call them pre-commitment

agreements. With pre-commitment agreements, the minimum payment applicants are willing to accept are of the size of results-based agreements, however, the maximum transfers member countries are willing to pay are as high as in upfront payment agreements. We find that, being able to implement cooperation with investment-based transfers implies being able to implement cooperation with pre-commitment agreements but not vice versa. Hence, if countries were able to pre-commit, they would both maximize the scope of climate cooperation with side payments and minimize the payments from member countries to applicants.

In an extension, we explore how the more realistic case of imperfect public monitoring of emissions affects our results. In this environment, we assume that only noisy, aggregate emissions are publicly observed and used to self-enforce low emissions. Both type I and type II errors are possible: countries may observe high emissions amd enter a punishment phase when all countries emitted less; and they may observe low emissions and not enter a punishment phase even though some countries emitted more. As can be expected, the scope for self-enforcing agreements implementing low emissions falls. This is reminiscent of Levin (2003), which shows that, in labor markets, self-enforcement restricts promised compensation and affects incentive provision. However, the relative ability of up-front, investment-based, and results-based agreements to sustain low emissions, which we established with perfect monitoring, hold also in this environment. Further, with imperfect public monitoring, optimally sized transfers shorten equilibrium punishments phases and reduce the probability of their occurrence; and because the burden of transfers is shared among the member countries, having a higher number of them generally shortens punishment phases and reduces their likelihood.

We combine two strands of the literature on climate mitigation. First, by studying self-enforcing international environmental agreements, we add to a literature pioneered by Barrett (1994, 2005), Dutta and Radner (2004, 2006, 2009), Rubio and Ulph (2006), and McEvoy and Stranlund (2009).[3] While these papers acknowledge that international agreements must be self-enforcing, they do not consider the role technology investments and financial transfers play in the sustainability of low emissions within such agreements. Building on Harstad (2012, 2016) and Battaglini and Harstad (2016), Harstad et al. (2019) integrate technology investments into a repeated games

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[3] This approach complements both the mechanism design approach to environmental agreements as, for example, in Martimort and Sand-Zantman (2016), and the coalition formation approach as, for example, in Diamantoudi and Sartzetakis (2006), de Zeeuw (2008) or Hong and Karp (2012).

framework of climate cooperation.[4] They show that these investments are an integral part of second-best relational contracts because they affect the benefits from deviating from the agreement. We extend their approach by accounting for the possibility of side-payments between countries and show that, because investments take time to mature, the timing of side-payments matters for how much cooperation second-best agreements can achieve. Whereas Acemoglu et al. (2016) and Harstad et al. (2019) explicitly deal with both green and brown technologies, we concentrate on green technology.

Second, we add to a growing literature on international resource transfers in environmental agreements. This literature explains how financial transfers can be used to counter deforestation, and implicitly any other mitigation, with international emissions offset programs, as in van Benthem and Kerr (2013), Pfaff et al. (2013), Lubowski and Rose (2013), and Kerr (2013), and to incentivize developing countries to participate in climate mitigation, as in Kerr and Millard-Ball (2012). This approach to encourage climate cooperation complements the climate clubs and border carbon adjustments, as studied in Kosfeld et al. (2009), Moore (2011), Condon and Ignaciuk (2013), Nordhaus (2015), Kortum and Weisbach (2016), or Sakai and Barrett (2016). Finally, in our modelling, we avoid the inefficiencies that can be introduced by contingent side-payments, as shown in Jackson and Wilkie (2005), by restricting the set of actions in the emissions and investment game that these payments can be made contingent on.[5]

2 The baseline HLR model

2.1 The stage game

Consider a set $N = \{1, 2, \ldots, n\}$ of $n \geq 2$ countries. Each country $i \in N$ has a (population) size $s_i > 0$. The aggregate size is normalized to n; that is, $\sum_{i \in N} s_i = n$. The stage game consists of two sub-stages: the investment stage and the emission stage. At the former, countries i simultaneously decide their investment levels, $r_i \geq 0$, while, at the latter, all countries simultaneously choose to emit either more ($\overline{g}_i$) or less ($\underline{g}_i$) greenhouses gases, that is, $g_i \in \{\underline{g}_i, \overline{g}_i\}$ with $\underline{g}_i < \overline{g}_i$. Countries observe the actions of the previous

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[4] Other parts of that literature examine the effects of technology investments on a country's bargaining position in future climate negotiations, see for example Beccherle and Tirole (2011), or Harstad (2012, 2016); or a country's incentives to invest when their investments benefit other negotiation partners, see for instance Barrett (2006).

[5] We thank Murali Agastya for pointing this out.

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sub-stage before choosing the actions on the second sub-stage. The stage-game utility is given by

$$u_i = b_i(g_i, r_i) - h_i \sum_{j \in N} s_j g_j - k_i r_i,$$

where

- b_i is country i's per capita benefit function;

- $h_i \sum_{j \in N} s_j g_j$ specifies country i's (linear, with $h_i > 0$) per capita cost of environmental damage due to aggregate emissions;

- k_i is the marginal cost per unit of domestic investment.

It is assumed that $b_{i,r}(g_i, r_i) \equiv \partial b_i / \partial r_i > 0$ and $b_{i,r^2}(g_i, r_i) \equiv \partial^2 b_i / \partial r_i^2 < 0$. With slight abuse of notation, let $b_i' \equiv b_{i,r}$ and

$$b_i''(r_i) \equiv \frac{b_i'(\overline{g}_i, r_i) - b_i'(\underline{g}_i, r_i)}{\overline{g}_i - \underline{g}_i}.$$

To study self-enforcing climate agreements, HLR consider the case in which countries' emission decisions constitute a prisoner's dilemma:

Assumption 1. Fix $i \in N$ and $r_i \in \mathbb{R}_+$,

1. $b_i(\underline{g}_i, r_i) - h_i(s_i \underline{g}_i + \sum_{j \neq i} s_j g_j) < b_i(\overline{g}_i, r_i) - h_i(s_i \overline{g}_i + \sum_{j \neq i} s_j g_j)$;

2. $b_i(\underline{g}_i, r_i) - h_i \sum_{i \in N} \underline{g}_i > b_i(\overline{g}_i, r_i) - h_i \sum_{i \in N} \overline{g}_i$.

These are the typical prisoner's dilemma assumptions. Part 1. states that, in the second sub-stage, it is individually rational to emit more; part 2. states that each country would be better off if neither country emitted more.
Define

$$r_i^*(\overline{g}_i) \equiv \arg\max_{r_i} b_i(\overline{g}_i, r_i) - h_i \sum_{j \in N} s_j \overline{g}_j - k_i r_i,$$

$$r_i^*(\underline{g}_i) \equiv \arg\max_{r_i} b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j - k_i r_i.$$

Using Assumption 1, HLR show that the strategy profile $(r_i^*(\overline{g}_i), \overline{g}_i)_{i \in N}$ forms a unique SPE of the stage game and call it a business-as-usual (BAU) equilibrium, denoted by $(r_i^b, \overline{g}_i)_{i \in N}$.[6]

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[6] HLR, in fact, define the BAU equilibrium in the context of the repeated game that will be discussed in Section 2.2. But since a Nash equilibrium of the stage game can always be sustained as an SPE in the repeated game, we could treat them the same without causing any confusion.

HLR consider green, brown and adaptation technologies, that is, three ways in which investments and emissions translate into utility. We retain for our purposes green technology, which is defined as follows:[7]

Definition 1. A technology is said to be green if $b_i''(r_i) < 0$.

HLR have shown that $r_i^* \equiv r_i^*(\underline{g}_i) > r_i^b$ for green technology and $r_i^* < r_i^b$ for brown technology.[8]

2.2 The repeated game

Let $\delta \in [0,1)$ be a common discount factor for all countries and let countries care about the discounted flow of future pay-offs in the stage games. HLR consider an infinitely repeated game with discounting where the stage game described in Section 2.1 is played infinitely at every period $t \in \{0,1,2,\dots\}$, with the purpose of studying the conditions under which $(r_i, \underline{g}_i)_{i \in N}$ in each period can be sustained as an SPE. HLR define $(r_i, \underline{g}_i)_{i \in N}$ in each period as a *best equilibrium*. In addition, if $r_i = r_i^*$; i.e., each country i chooses the utility-maximizing investment level, then the SPE is called the *first-best equilibrium*.

In HLR's baseline model, countries are assumed to have perfect monitoring; that is, each of them can observe all actions chosen by their counterparts.[9] HLR show that a country is always guaranteed the payoff from the BAU equilibrium, which always exists, and so BAU is the worst possible SPE. Thus, to derive better equilibria, they can without loss of generality focus on a simple trigger strategy where deviation – on or off the equilibrium path – immediately triggers infinite reversion to the BAU equilibrium. On the equilibrium path, deviations could be at the investment sub-stage or at the emission sub-stage. To sustain $(r_i, \underline{g}_i)_{i \in N}$ as an SPE, each country i must have incentives to comply with the agreement. These incentive are summarized by two compliance constraints described below.[10] Fix $i \in N$ and let

$$v_i(r_i) \equiv b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j - k_i r_i$$

[7] HLR also study adaptation technology, investing in which can lower the environmental damage from emissions and brown technology, investing in which is complementary to emissions.

[8] To be precise, they show this for the case in which emissions levels $\underline{g}_i$ and $\overline{g}_i$ are symmetric across countries. The step to asymmetric emissions levels is straightforward.

[9] HLR also consider an extension with imperfect monitoring, which we do not consider in this paper.

[10] This follows from what is called the one-shot deviation principle in the literature on repeated games, which says that a strategy profile is an SPE if and only if it is not profitable to use a different strategy for a single period (see, for example, Mailath and Samuelson (2006, p. 24)).

be the normalized (to one period) continuation value from complying with the SPE.[11] We will write $v_i(r_i)$ as v_i whenever no confusion arises. Likewise,

$$v_i^b \equiv b_i(\overline{g}_i, r_i^b) - h_i \sum_{j \in N} s_j \overline{g}_j - k_i r_i^b$$

is the continuation value of playing BAU equilibrium. It is worth noting that, by Assumption 1, we have

$$v_i(r_i^*) > v_i(r_i^b) > v_i^b.$$

The compliance constraint at the investment stage is

$$\frac{v_i}{1-\delta} \geq \left[\max_{r_i} b_i(\overline{g}_i, r_i) - h_i \sum_{j \in N} s_j \overline{g}_j - k_i r_i \right] + \frac{\delta v_i^b}{1-\delta}. \qquad (CC_{i,r})$$

It is easy to see that the above inequality can be rewritten as $v_i \geq v_i^b$. Since the investment is sunk, the compliance constraint at the emission stage becomes

$$b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j + \frac{\delta v_i}{1-\delta} \geq b_i(\overline{g}_i, r_i) - h_i\left[\sum_{j \neq i} s_j \underline{g}_j + s_i(\overline{g}_i - \underline{g}_i) \right] + \frac{\delta v_i^b}{1-\delta}. \qquad (CC_{i,g})$$

HLR show that if $(CC_{i,g})$ holds then so does $(CC_{i,r})$. Throughout the paper, we will call this $(CC_{i,g})$ implies $(CC_{i,r})$. Suppose that $(CC_{i,r})$ holds, then $(CC_{i,g})$ is equivalent to

$$\frac{\delta(v_i - v_i^b)}{1-\delta} \geq b_i(\overline{g}_i, r_i) - b_i(\underline{g}_i, r_i) - h_i s_i(\overline{g}_i - \underline{g}_i).$$

The left-hand side of the inequality represents country i's net discounted benefit from continuing to cooperate and the right-hand side its one-period net benefit from the extra emissions due to the deviation. To help with the analysis, we divide both sides by the difference of the two emissions levels $(\overline{g}_i - \underline{g}_i)$. Let $\gamma_i(\delta) \equiv \delta / [(\overline{g}_i - \underline{g}_i)(1-\delta)]$, which is strictly increasing in δ. When δ is sufficiently close to 1, $(CC_{i,g})$ is fulfilled for some r_i. We define

$$\psi_i(r_i) \equiv \frac{b_i(\overline{g}_i, r_i) - b_i(\underline{g}_i, r_i)}{\overline{g}_i - \underline{g}_i} - h_i s_i.$$

Because of Assumption 1, ψ_i is positive for all $r_i \geq 0$. Note that $\psi'(r_i) = b_i''(r_i)$; therefore for green technology, ψ_i is strictly decreasing in r_i. Let $\underline{\delta}_i > 0$ be the lowest value of δ such that $(CC_{i,g})$ holds. Let $\widetilde{r}_i$ be the corresponding level of investment. Then,

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[11] Let $\tilde{v}_i = b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j - k_i r_i$ be the per period value/utility from complying. Then the normalized continuation value should be $v_i = (1-\delta) \sum_{t=0}^{\infty} \delta^t \tilde{v}_i$. But $\tilde{v}_i$ is independent of t; hence $v_i = \tilde{v}_i$.
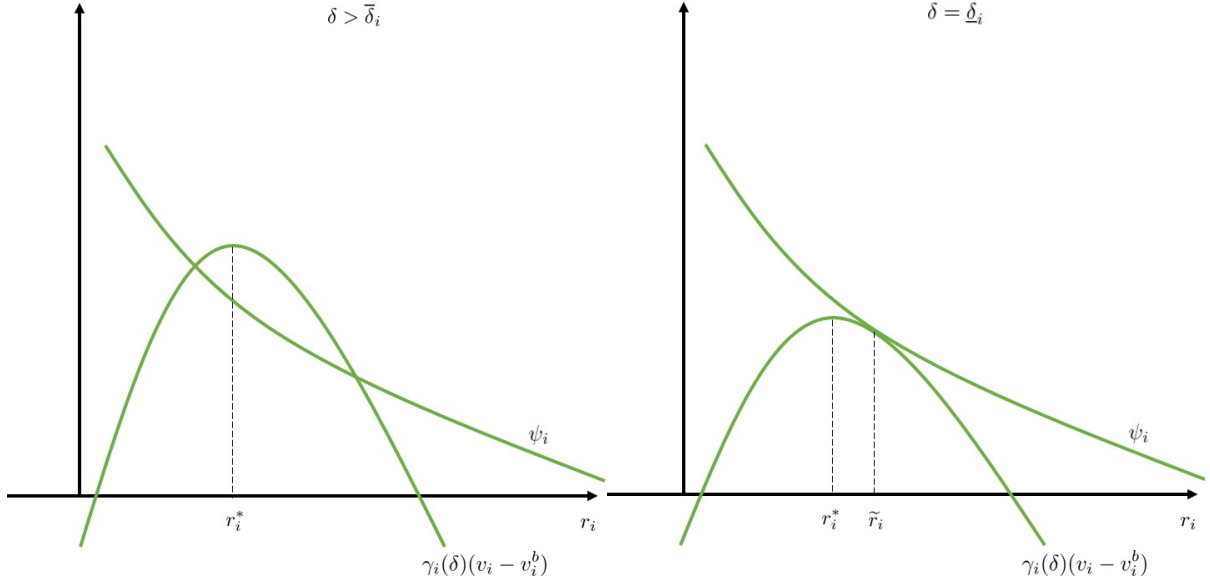
Figure 2: Graphical representation of the emissions compliance constraints in HLR's model for green technology. Left: $\delta > \overline{\delta}_i$. Country i's emissions compliance constraints hold for first best investment r_i^*. Right: $\delta = \underline{\delta}_i$. Country i's emissions compliance constraints just hold. For green technology, this implies a higher than the first best investment level.

whenever $\delta < \underline{\delta}_i$, $(CC_{i,g})$ is violated for any r_i. In addition, HLR define $\overline{\delta}_i$ as δ that solves $\gamma_i(\delta)(v_i(r_i^*) - v_i^b) = \psi_i(r_i^*)$.[12] It follows that the first-best equilibrium is sustainable if $\delta > \overline{\delta}_i$ for all $i \in N$. With $\underline{\delta}_i \leq \delta < \overline{\delta}_i$, country i is able to participate in the agreement but would not be able to invest at the level of r_i^*.

Figure 2 provides a graphical representation of the compliance constraint at the emissions stage, $(CC_{i,g})$. For green technology, $\gamma_i(\delta)(v_i - v_i^b)$ is a single-peaked curve with a maximum at $r_i = r_i^*$, which intersects the horizontal axis at values of r_i for which $v_i = v_i^b$. As mentioned above, the function ψ_i is downward-sloping for green technology. The left-hand-side panel depicts the situation where $\delta > \overline{\delta}_i$ and, hence, country i's emissions compliance constraints hold for the first-best investment level $r_i = r_i^*$. The right-hand-side panel depicts the situation where $\delta = \underline{\delta}_i$ and, hence, country i's emissions compliance constraints just hold. For green technology, this implies a higher investment level than r_i^*.

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[12] At $\delta = \overline{\delta}_i$, there exists another $r_i' > r_i^*$ such that $\gamma_i(\delta)[v_i(r_i') - v_i^b] = \psi_i(r_i')$.

3 Side payment models

Fix $\delta \in [0, 1)$. We assume that there exists at least one country i such that $\delta < \underline{\delta}_i$. That is, if the countries were interacting in the HLR repeated game, low emissions would not be sustainable in every period. Let $M \subsetneq N$ be a subset of countries in which each country i satisfies HLR's compliance constraint $(CC_{i,g})$. Let $A = N \setminus M$ and assume that HLR's $(CC_{i,g})$ is violated for every $i \in A$.

We will devise actions, which designate countries in M as member countries and countries in A as applicants. As defined in Section 2, all countries invest domestically; but member countries, in addition, transfer side payments to applicants. Formally, let p_{ij} be country i's per capita side payments to country j (the total side payments to country j is $s_i p_{ij}$). Let $p_{ij} > 0$ whenever $i \in M$ and $j \in A$ and let $p_{ij} = 0$, otherwise. Moreover, we let $p_{ji} = -s_i p_{ij}/s_j$. Following Fong and Surti (2009), we assume that side payments enter country i's utility function linearly:

$$u_i^P = b_i(g_i, r_i) - h_i \sum_{j \in N} s_j g_j - k_i r_i - \sum_{j \in N} p_{ij}.$$

The superscript P distinguishes utility functions in side payment models from those in HLR. In what follows, we present four such models, which differ in the timing of the side payments.

3.1 Upfront Payment Agreements

Consider the case in which member countries agree to transfer side payments to applicants before they make investment and emissions decisions.

3.1.1 The stage game

The stage game has three sub-stages. In the first sub-stage, member countries transfer side payments to applicants. In sub-stage 2, countries decide their investment levels simultaneously. Countries determine their emissions at the last sub-stage. Following HLR, we assume that sub-stage 3 constitutes a prisoner's dilemma (Assumption 1).

In this model, there exists a unique SPE of the stage game such that member countries do not transfer any side payments and all countries play $(\overline{g}_i, r_i^b)_{i \in N}$. This SPE is tantamount to HLR's BAU equilibrium and, hence, it is assigned the same name.

Lemma 1. The stage game has a unique SPE such that $p_{ij} = 0$, $r_i = r_i^b$ and $g_i = \overline{g}_i$ for all $i, j \in N$.

Proof. We prove this lemma by backward induction. Since stage 3 constitutes a prisoner's dilemma, every country chooses $g_i = \overline{g}_i$. It follows that i would choose to invest at the level of r_i^b in stage 2. Now note that, for every $i \in M$,

$$\frac{\partial u_i^P}{\partial p_{ij}} = -1 < 0, \; j \in A;$$

therefore utility maximization gives a corner solution $p_{ij} = 0$ for all $j \in A$. □

3.1.2 The repeated game

Let the stage game described above be repeated infinitely. As a Nash equilibrium of the stage game, the BAU equilibrium is sustainable in the repeated game. Furthermore, it is the worst SPE. To investigate how side payments can help sustain cooperation in emitting less greenhouse gases, we can, therefore, concentrate without loss of generality on designing an *upfront payment agreement* (hereafter UP agreement) where cooperation is self-enforcing when facing a threat of permanent reversion to the BAU equilibrium. This agreement corresponds to the following grim-trigger strategy.

Definition 2. A UP agreement is designed as follows:

1 (Side-payment stage). Each member country $i \in M$ transfers side payments p_{ij} to every applicant $j \in A$.

2 (Investment stage). All countries invest at the same time if they do not observe any deviation in Stage 1, otherwise they revert to the BAU equilibrium immediately and permanently.

3 (Emissions stage). All countries emit less if there is no deviation in both Stages 1 and 2, otherwise the BAU equilibrium is played forever.

We assume the emissions occur continuously but are observed at long intervals. Investments take place at the beginning of the stage and are observed without delay; similarly transfers are observed without delay. To deal with discounting within the stage, we assume that (1) the benefit and environmental damage functions, $b_i(g_i, r_i)$ and $h_i \sum_{j \in N} g_j$, represent the stage, per capita benefit and environmental costs, discounted to the beginning of the stage. We normalize the length of an emissions observations interval to 1.

Fix an applicant $i \in A$ and let $p_i = \sum_{j \in N} \frac{s_j}{s_i} p_{ji}$. Note that the continuation value of i is still v_i^b, as defined in Section 2, if all countries emit more. Then applicant i's

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compliance constraint at the investment stage is

$$\frac{1}{1-\delta}\Big[b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j - k_i r_i\Big] + \frac{\delta}{1-\delta} p_i$$

$$\geq \max_{r_i \geq 0}\Big[b_i(\overline{g}_i, r_i) - h_i \sum_{j \in N} s_j \overline{g}_j - k_i r_i\Big] + \frac{\delta}{1-\delta} v_i^b.$$

This can be simplified as

$$v_i + \delta p_i \geq v_i^b, \tag{$AC_{i,r}^U$}$$

where v_i is defined as in Section 2. At the emissions stage, the compliance constraint becomes

$$b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j + \frac{\delta(v_i + p_i)}{1-\delta} \geq b_i(\overline{g}_i, r_i) - h_i\Big[s_i(\overline{g}_i - \underline{g}_i) + \sum_{j \neq i} s_j \underline{g}_j\Big] + \frac{\delta v_i^b}{1-\delta},$$

or, equivalently,

$$\gamma(\delta)(v_i + p_i - v_i^b) \geq \psi_i(r_i). \tag{$AC_{i,g}^U$}$$

Different from HLR, we do not have that $(AC_{i,g}^U)$ implies $(AC_{i,r}^U)$. But if $(AC_{i,g}^U)$ holds with a level of r_i such that $v_i \geq v_i^b$, then $(AC_{i,r}^U)$ is satisfied automatically.

Since we assume that $\gamma_i(\delta)(v_i - v_i^b) < \psi_i(r_i)$, $(AC_{i,g}^U)$ is fulfilled only with a positive p_i. Observe that a positive p_i corresponds to a parallel upward shift of the curve $\gamma_i(\delta)(v_i - v_i^b)$. It does not affect ψ_i; therefore there must be a level of $p_i > 0$ such that $(AC_{i,g}^U)$ is satisfied. We find the minimum level of p_i for which $(AC_{i,g}^U)$ holds resorting to the following minimization problem:

$$\min_{r_i \geq 0} \psi_i(r_i) - \gamma_i(\delta)(v_i - v_i^b). \tag{M}$$

The following assumption, which we maintain throughout the paper, assures that the second-order condition of this minimization problem holds in the relevant range of r_i.

Assumption 2. $\psi_i''(r_i) - \gamma_i(\delta)\frac{\partial^2 v_i(r_i)}{\partial r_i^2} > 0$ for $r_i \geq r_i^*$.

A sufficient condition for Assumption 2 is that $\psi_i''(r_i) \geq 0$. This means that the one-period payoff from cheating in the emissions substage is decreasing in r_i, at a decreasing rate. If a country has already invested much in green technology, then investing in another unit of green technology will not reduce the benefit from cheating by much.

Let $\widehat{r_i}$ be the investment level such that the first-order condition $\psi_i'(r_i) = \gamma_i(\delta)\frac{\partial v_i}{\partial r_i}$ holds. Since the second-order condition

$$\psi_i''(\widehat{r_i}) - \gamma_i(\delta)\frac{\partial^2 v_i(\widehat{r_i})}{\partial r_i^2} = \psi_i''(\widehat{r_i}) - \gamma_i(\delta) b_{i,r^2}(\underline{g}_i, \widehat{r_i}) > 0,$$

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the minimum p_i, denoted by $\widehat{p}_i = \psi_i(\widehat{r}_i)/\gamma_i(\delta) - \left[v_i(\widehat{r}_i) - v_i^b\right]$, corresponds to the minimum distance $\gamma_i(\delta)\widehat{p}_i$ between ψ_i and $\gamma_i(\delta)(v_i - v_i^b)$. The investment level that minimizes the deficit in the applicant i's emissions compliance constraint, $\widehat{r}_i$, always exists for green technology and $\widehat{r}_i > r_i^*$.[13] It is important to note that $(\widehat{r}_i, \widehat{p}_i)$ may violate $(AC_{i,r}^U)$ such that $\widehat{p}_i < \left[v_i^b - v_i(\widehat{r}_i)\right]/\delta$. The following proposition shows that, for green technology, in that case it is possible to increase p_i such that the applicant i complies with both of the constraints.

Proposition 1. For green technology there exists a unique pair $(\widehat{\widehat{r}}_i, \widehat{\widehat{p}}_i)$ such that $\widehat{\widehat{r}}_i > r_i^*$ and both $(AC_{i,r}^U)$ and $(AC_{i,g}^U)$ hold with equality.

Proof. Let $F = \gamma(\delta)\left[v_i(r_i) + p_i - v_i^b\right] - \psi_i(r_i)$ and substitute p_i by $\left[v_i^b - v_i(r_i)\right]/\delta$. Note that $v_i^b - v_i(r_i)$ must be nonnegative. After simplification, we have

$$F = \frac{v_i^b - v_i(r_i)}{\overline{g} - \underline{g}} - \psi_i(r_i).$$

Since $v_i^b - v_i(r_i)$ is strictly increasing and convex in r_i when $r_i > r_i^*$ but $\psi_i(r_i)$ is strictly decreasing in r_i, there exists a unique $\widehat{\widehat{r}}_i$ such that $F(\widehat{\widehat{r}}_i) = 0$. Let $\widehat{\widehat{p}}_i$ be the corresponding level of side payment. Hence the proof is complete. $\square$

Define

$$(\bar{r}_i, \bar{p}_i) \equiv \begin{cases} (\widehat{\widehat{r}}_i, \widehat{\widehat{p}}_i) & \text{if } \widehat{p}_i < \left[v_i^b - v_i(\widehat{r}_i)\right]/\delta \\ (\widehat{r}_i, \widehat{p}_i) & \text{otherwise} \end{cases},$$

where $\bar{p}_i$ is always the minimum possible level of side payment with which the applicant i can comply.

Now fix a member country $i \in M$ and let $t_i = \sum_{j \in N} p_{ij}$. Then i's compliance constraint at the side-payment stage is

$$\frac{1}{1-\delta}\left[b_i(\underline{g}_i, r_i) - h_i \sum_{j \in N} s_j \underline{g}_j - k_i r_i - t_i\right] \geq \frac{v_i^b}{1-\delta},$$

which can be rewritten as

$$v_i - t_i \geq v_i^b. \qquad (MC_{i,t}^U)$$

Then, similar to finding $(AC_{i,r}^U)$, the compliance constraint for the member country i at the investment stage is

$$v_i - \delta t_i \geq v_i^b. \qquad (MC_{i,r}^U)$$

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[13] It may not exist for brown technology. For brown technology, it can be either $\widehat{r}_i$ does not exist on $\mathbb{R}$ or $\widehat{r}_i < 0$.

Finally, the emissions compliance constraint is of the form

$$\gamma_i(\delta)(v_i - t_i - v_i^b) \geq \psi_i(r_i). \tag{$MC_{i,g}^U$}$$

Note that $(MC_{i,g}^U)$ implies $(MC_{i,t}^U)$, which, in turn, implies $(MC_{i,r}^U)$. Since the program

$$\max_{r_i \geq 0} \gamma_i(\delta)(v_i - v_i^b) - \psi_i(r_i)$$

is the dual of (M), we use $\widehat{r_i}$, without causing confusion, to denote the investment level that maximizes the net gains from cooperation in HLR's repeated game for the member country i. We let

$$e_i \equiv \gamma_i(\delta)\left[v_i(\widehat{r_i}) - v_i^b\right] - \psi_i(\widehat{r_i})$$

and call e_i the *maximum (per capita) slack in member country i's emissions compliance constraint*.[14] To incorporate side payments, we extend HLR's definition of a best equilibrium in the following way.

Definition 3. An SPE is said to be a best equilibrium if, at every period, it satisfies $g_i = \underline{g}_i$ for all $i \in N$ and the minimum possible amount of side payments to the applicants are implemented.

Since the definition requires every applicant i to invest at the level of $\bar{r}_i > r_i^*$, HLR's first-best equilibrium is not of our interest.[15] An SPE is called *a* best equilibrium rather than *the* best equilibrium because there might be different sharing rules of side payments among member countries. Our definition extends HLR's definition if $\delta \geq \underline{\delta}_i$ for all $i \in N$, in which the minimum amount of side payments necessary to sustain a best equilibrium is zero.

For the total amount of side-payment transfer, budget balance gives that $\sum_{i \in M} s_i t_i = \sum_{i \in A} s_i \bar{p}_i$. Then if member countries have enough slack in emissions compliance constraints, an UP agreement which specifies $(\bar{r}_i)_{i \in A}$ will be a best equilibrium.

Lemma 2. If $\sum_{i \in M} s_i e_i \geq \sum_{i \in A} \gamma_i(\delta) s_i \bar{p}_i$, then an UP agreement corresponds to a best equilibrium.

The *maximum* aggregate slack in the member countries' emissions compliance constraints, $\sum_{i \in M} e_i$, is achieved if every member $i \in M$ invests at $r_i = \widehat{r_i}$. If $\sum_{i \in M} e_i >$

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[14] Spagnolo (1999) terms this the slack of enforcement power in implicit agreements.

[15] Precisely, the first-best equilibrium here is referred to as an SPE in the side payment model such that at every period $r_i = r_i^*$ and $g_i = \underline{g}_i$ for all $i \in N$.

$\gamma_i(\delta) \sum_{i \in A} \bar{p}_i$, then this implies too large a sacrifice for the member countries and (many) best equilibria can be found. Because, in this paper, we are interested in whether best equilibria exist in the various climate agreements with transfers we concentrate on agreements that require the slack-maximizing investment by member countries.

3.2 Investment-based Agreements

Consider the case in which member countries agree to transfer side payments to applicants after they observe the applicants' investment decisions.

3.2.1 The stage game

Similar to the one in Section 3.1, the stage game has three sub-stages. In the first sub-stage, applicants make investment decisions. Member countries decide their investment levels and transfer side payments simultaneously in the second sub-stage. In the last sub-stage, countries determine whether to emit more or emit less. We assume that the last sub-stage follows Assumption 1. In this stage game, there exists a unique BAU equilibrium. The proof is analogous to the one for Lemma 1 and hence ignored.

Lemma 3. The stage game has a unique SPE such that $p_{ij} = 0$, $r_i = r_i^b$ and $g_i = \overline{g}_i$ for all $i, j \in N$.

3.2.2 The repeated game

The repeated game is defined as an infinite repetition of the stage game described in Section 3.2.1. Again, as a Nash equilibrium of the stage game, the BAU equilibrium is sustainable in the repeated game. Furthermore, it is the worst SPE. Hence, we again concentrate without loss of generality on designing an *investment-based (IB) agreement* where cooperation is self-enforcing when facing a threat of permanent reversion to the BAU equilibrium. This agreement corresponds to the following grim-trigger strategy.

Definition 4. An IB agreement is defined as follows:

1 (Investment stage for applicants). Each applicant $i \in A$ invests at the level of $\widehat{r_i}$.[16]

2 (Investment and side-payment stage for member countries). Member countries invest at the levels of $(\widehat{r_i})_{i \in M}$ and transfer side payments simultaneously if they

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[16] These are the investment levels that minimize the deficit in the applicant i's emissions compliance constraint.

do not observe any deviation in Stage 1, otherwise they switch to the BAU equilibrium immediately.[17]

3 (Emissions stage) All countries emit less if no deviation is observed in both Stages 1 and 2, otherwise countries play permanently the BAU equilibrium.

Fix an applicant $i \in A$. Let us first suppose that i is required to invest r_i. Recall that $p_i = \sum_{j \in N} p_{ji}$. Then i's compliance constraint in Stage 1 is the following:

$$v_i + p_i \geq v_i^b. \qquad (AC_{i,r}^I)$$

Because in sub-stage 3 r_i and p_i are sunk, i's emissions compliance constraint becomes

$$\gamma_i(\delta)(v_i + p_i - v_i^b) \geq \psi_i(r_i). \qquad (AC_{i,g}^I)$$

Since ψ_i is always positive, $(AC_{i,g}^I)$ implies $(AC_{i,r}^I)$. We can observe that $(AC_{i,g}^I)$ has the same form of $(AC_{i,g}^U)$. So, for green technology, it follows from (M) that $\widehat{r_i}$ minimizes the side payment needed to fulfill $(AC_{i,g}^I)$ and that this level is given by $\widehat{p_i}$.

Let $i \in M$. If there is no applicant deviating in the first stage, then the member country i has

$$v_i(\widehat{r_i}) - t_i \geq v_i^b \qquad (MC_{i,rt}^I)$$

as the compliance constraint for the investment and side-payment stage. When $(MC_{i,rt}^I)$ holds, we can write the compliance constraint at the emissions stage as

$$\gamma_i(\delta)\left[v_i(\widehat{r_i}) - t_i - v_i^b\right] \geq \psi_i(\widehat{r_i}). \qquad (MC_{i,g}^I)$$

As we have seen, member countries have the maximum level of slackness when investing at $(\widehat{r_i})_{i \in N}$. Therefore, analogous to Lemma 2, if member countries have sufficient slack in their emissions compliance constraints, then an IB agreement constitutes a best equilibrium.

Lemma 4. If $\sum_{i \in M} s_i e_i \geq \gamma_i(\delta) \sum_{i \in A} s_i \widehat{p_i}$, then an IB agreement forms a best equilibrium.

3.3 Results-based Agreements

We now consider *RB agreements*. Here, countries transfer side payments to applicants after they observe the applicants' emissions. Because emissions are observed only in the end of the period, the transfer is to be discounted within the period.

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[17] Again, this investment requirement may imply too large a sacrifice for the member countries. Because we are interested in whether best equilibria exist in the various climate agreements with transfers we concentrate on agreements that require the slack-maximizing investment by member countries.

3.3.1 The stage game

The stage game here has three sub-stages. Countries make domestic investment decisions simultaneously in the first sub-stage. They choose their emissions in the second sub-stage. As before, the emissions sub-stage follows Assumption 1. In the last sub-stage, member countries transfer side payments to applicants. Once again, this stage game has a unique BAU equilibrium as follows.

Lemma 5. The stage game has a unique SPE such that $p_{ij} = 0$, $r_i = r_i^b$ and $g_i = \overline{g}_i$ for all $i, j \in N$.

3.3.2 The repeated game

We define the *RB agreements* as follows.

Definition 5. An RB agreement is such that:

1 (Investment stage). Each applicant i invests at $\bar{r}_i$ for all $i \in A$ and each member country i invests at $\widehat{r}_i$ for all $i \in M$.

2 (Emissions stage). All countries emit less if no country deviates in Stage 1, otherwise they play the BAU equilibrium immediately.

3 (Side-payment stage) Member countries transfer side payments if no deviation is observed in both Stages 1 and 2, otherwise all countries play permanently the BAU equilibrium.

Let i be an applicant. Then its compliance constraints at Stages 1 and 2 are

$$v_i(\bar{r}_i) + \delta p_i \geq v_i^b \qquad (AC_{i,r}^R)$$

and

$$\gamma(\delta)\left[v_i(\bar{r}_i) + p_i - v_i^b\right] \geq \psi_i(\bar{r}_i), \qquad (AC_{i,g}^R)$$

respectively. We can see that $(AC_{i,g}^R)$ does not imply $(AC_{i,r}^R)$ directly. According to (M), the minimum level of side payments needed for $(AC_{i,g}^R)$ to hold with equality is $\widehat{p}_i$. If $\widehat{p}_i$ does not satisfy $(AC_{i,r}^R)$, then we have to consider i investing at r_i such that both $(AC_{i,r}^R)$ and $(AC_{i,g}^R)$ hold with equality. This r_i is the same as $\widehat{r}_i$ defined in Section 3.1.

Now fix $i \in M$. The compliance constraint at the investment stage is the same as $(MC_{i,rt}^I)$:

$$v_i(\widehat{r}_i) - \delta t_i \geq v_i^b \qquad (MC_{i,r}^R)$$

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In the emissions sub-stage, investment is sunk. Hence, the emissions compliance constraint becomes

$$\gamma_i(\delta)\Big[v_i(\widehat{r_i}) - t_i - v_i^b\Big] \geq \psi_i(\widehat{r_i}). \qquad (MC_{i,g}^R)$$

Note that $(MC_{i,g}^R)$ implies $(MC_{i,r}^R)$ because $\delta \in (0,1)$. In the side-payment stage, the member country i has the compliance constraint

$$v_i(\widehat{r_i}) - t_i \geq v_i^b, \qquad (MC_{i,t}^R)$$

which is implied by $(MC_{i,g}^R)$ and implies $(MC_{i,r}^R)$. By budget balance, sufficient slack in member countries' emissions compliance constraint corresponds to

$$\sum_{i \in M} s_i e_i \geq \sum_{i \in M} \gamma_i(\delta) s_i t_i = \sum_{i \in A} \gamma_i(\delta) s_i \bar{p}_i.$$

Thus, by the same conditions as in Lemma 2, an RB agreement serves as a best equilibrium.

Lemma 6. If $\sum_{i \in M} s_i e_i \geq \sum_{i \in A} \gamma_i(\delta) s_i \bar{p}_i$, then an RB agreement constitutes a best equilibrium.

3.4 Illustration

Figure 3 illustrates the two constraints for upfront-transfer and results-based agreements. Each panel graphs the transfer necessary to satisfy the emissions compliance constraint, $\psi_i(r_i)/\gamma_i(\delta) - (v_i(r_i) - v_i^b)$, and the transfer necessary to satisfy the investment compliance constraint, $(v_i^b - v_i(r_i))/\delta$, both as functions of the investment level. Transfers on and above the curves ensure compliance, whereas transfers below it do not. The transfer necessary to satisfy compliance at the investment stage is minimized at r_i^*, whereas the one ensuring compliance at the emissions stage is minimized at $\widehat{r_i}$. The case, in which investment-based transfer agreements implement cooperation when upfront transfer and results-based agreements cannot is depicted in the panel on the right. Here, at the investment level that minimizes the transfer needed to ensure the emissions compliance constraint holds, the investment compliance constraint is violated for upfront-transfer and results-based agreements, but it would not be violated for investment-based agreements.

We can find conditions for which investment-based agreements implement cooperation when upfront-payment or results-based agreements do not by inspecting the
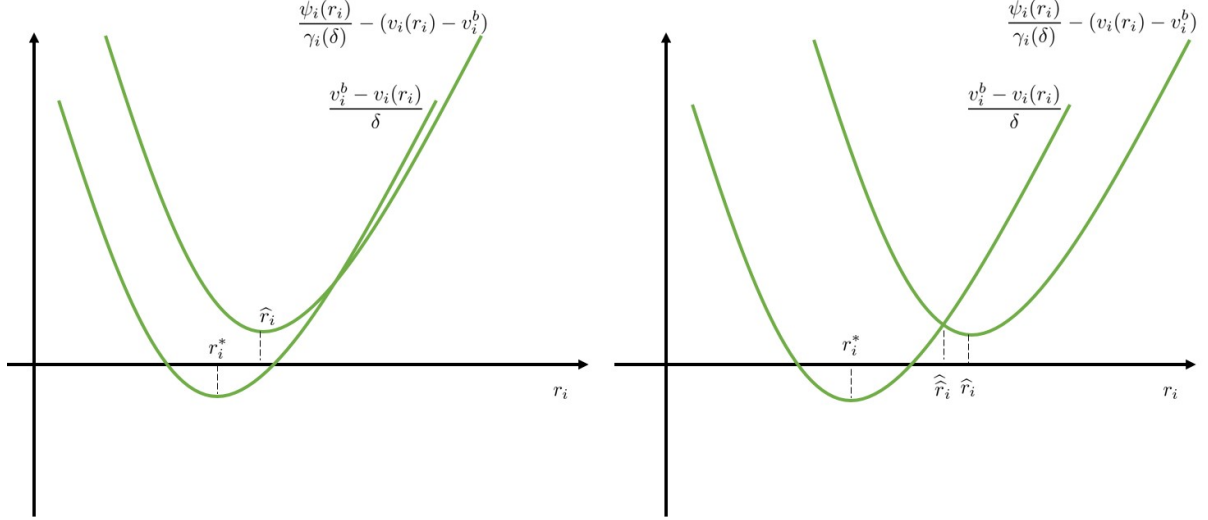
Figure 3: Left panel: For upfront-transfer and results-based agreements, the minimum transfer that ensures compliance at the emissions stage also ensures compliance at the investment stage. Right panel: For upfront-transfer and results-based agreements, the minimum transfer that ensures compliance at the emissions stage does not ensure compliance at the investment stage.

applicant countries' investment and emissions compliance constraints for these agreements. With investments that minimize the deficit in the applicant i's emissions compliance constraint, $\widehat{r_i}$ and their proper payments, $\widehat{p_i}$, i's investment compliance constraint in either agreement is violated – applicant i deviates by under-investing – if

$$\delta\widehat{p_i} < v_i^b - v_i(\widehat{r_i}) \iff$$

$$\left(b_i(\overline{g}_i, r_i^b) - k_i r_i^b\right) - \left(b_i(\overline{g}_i, \widehat{r_i}) - k_i\widehat{r_i}\right) > h_i\left(\sum_{j\in N} s_j\left(\overline{g}_j - \underline{g}_j\right) - s_i(\overline{g}_i - \underline{g}_i)\right). \quad (1)$$

The left-hand side of the inequality[18] corresponds to the extra benefit from deviating at the investment stage as compared to deviating at the emissions stage. This is a positive number. The right-hand side corresponds to the cost of the environmental damage from deviating at the investment stage rather than deviating at the emissions stage. Also this is a positive number. An applicant deviates by under-investing if the extra benefit from deviating at the investment stage as compared to deviating at the emissions stage is larger than the extra cost of environmental damage from doing so.

Let us examine the determinants of under-investing. We begin by studying the impact of the *marginal cost of green investment*. An increase in the marginal cost of green investment, k_i, has two effects, both on the extra benefit from deviating at the

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[18]We derive inequality (1) in the appendix.

investment stage as compared to deviating at the emissions stage, that is, the left-hand side of inequality (1).

$$
\begin{aligned}
\frac{dLHS}{dk_i} &= r_i^b + \overbrace{\left(\frac{\partial b_i(\overline{g}_i, r_i^b)}{\partial r_i} - k_i\right)}^{=0} \frac{\partial r_i^b}{\partial k_i} - \widehat{r}_i - \overbrace{\left(\frac{\partial b_i(\overline{g}_i, \widehat{r}_i)}{\partial r_i} - k_i\right)}^{<0} \overbrace{\frac{\partial \widehat{r}_i}{\partial k_i}}^{<0} \\
&= r_i^b - \widehat{r}_i - \left(\frac{\partial b_i(\overline{g}_i, \widehat{r}_i)}{\partial r_i} - k_i\right) \frac{\partial \widehat{r}_i}{\partial k_i} < 0
\end{aligned}
$$

First, it increases the weight put on the strictly negative difference $r_i^b - \widehat{r}_i$, which decreases the left-hand side of the inequality. Second, it decreases $\widehat{r}_i$, which decreases the extra benefit from deviating at the investment stage rather than at the emissions stage, and further decreases the left-hand side of the inequality. Hence, lowering the marginal cost of green investment means the transfer-minimizing investment level, $\widehat{r}_i$, increases by so much that the country may defect in the investment stage and an applicant country is less likely to satisfy the investment compliance constraint with $\widehat{r}_i$.

Holding fixed $\sum_{j \in N} = n$, an increase in a *country's size relative to the rest of the world*, s_i, has no impact on either $\widehat{r}_i$ or r_i^b and, hence, it does not affect the left-hand side of inequality (1). However, it decreases the extra-environmental cost from deviating at the investment stage as compared to deviating at the emissions stage, that is, the right-hand side of inequality (1). Hence, a higher s_i means a country is more likely to satisfy the investment compliance constraint with $\widehat{r}_i$. An increase in the *marginal environmental damage*, h_i, again has no impact on either $\widehat{r}_i$ or r_i^b and, hence, it does not affect the left-hand side of inequality (1). It increases the extra-environmental cost from deviating at the investment stage as compared to deviating at the emissions stage, that is, the right-hand side of inequality (1). Hence, a higher h_i means a country is less likely to satisfy the investment compliance constraint with $\widehat{r}_i$.

Interestingly, the *discount rate* has no impact on whether a country that fulfils the emissions compliance constraint is likely to violate the investment compliance constraint.

To illustrate the conditions under which investment-based agreements implement low emissions and results-based agreements do not, we assume

$$
b_i(g_i, r_i) = -\frac{w_i}{g_i \sqrt{r_i}} + z_i g_i,
$$

where w_i and z_i are parameters. It is easy to verify that this benefit function satisfies the condition for green technology.

Using this functional form, we compute the BAU investment level for country i:

$$r_i^b = \arg\max_{r \geq 0} \left\{ -\frac{w_i}{\overline{g}_i \sqrt{r_i}} + z_i \overline{g}_i - h_i n \overline{g} - k_i r_i \right\} = \sqrt[3]{\left(\frac{w_i}{2\overline{g}_i k_i} \right)^2}.$$

Further, we compute the emissions compliance constraint deficit-minimizing investment level for recipient country i:

$$\widehat{r_i} = \arg\min_{r \geq 0} \left\{ \psi_i(r_i) - \gamma_i(\delta)\left(v_i - v_i^b \right) \right\} = \sqrt[3]{\left(\frac{1-\delta}{\delta} \frac{w_i}{2k_i} \left(\frac{1}{\underline{g}_i} - \frac{1}{\overline{g}_i} \right) \right)^2}.$$

Assumption 3. Let there be one applicant country, i, and $n-1$ member countries. Let $\overline{g}_{j \neq i} = \overline{g}_o$, $\underline{g}_{j \neq i} = \underline{g}_o$, and $\overline{g}_o - \underline{g}_o = \Delta_o \overline{g}_o$. Furthermore, assume $\sum_{j \in N} s_j = n$.

Then, (1) becomes

$$\frac{w_i}{\overline{g}_i} \left(\frac{1}{\sqrt[3]{\frac{1-\delta}{\delta} \frac{w_i}{2k_i} \left(\frac{1}{(1-\Delta_i)\overline{g}_i} - \frac{1}{\overline{g}_i} \right)}} - \frac{1}{\sqrt[3]{\frac{w_i}{2\overline{g}_i k_i}}} \right. $$
$$\left. - k_i \left(\sqrt[3]{\left(\frac{w_i}{2\overline{g}_i k_i} \right)^2} - \sqrt[3]{\left(\frac{1-\delta}{\delta} \frac{w_i}{2k_i} \left(\frac{1}{(1-\Delta_i)\overline{g}_i} - \frac{1}{\overline{g}_i} \right) \right)^2} \right) \right)$$
$$< h_i(n - s_i) \Delta_o \overline{g}_o.$$

In Figures 4 and 5, we plot the following illustrations for $n = 10$, $\overline{g}_o \equiv 50$, $\Delta_o \equiv .2$. Further, we assume $k_i \in [.1, 3]$, $h_i \in [0, 3]$, $\overline{g}_i \in [.5, 1.5]$ $\Delta_i \in [0, .2]$, $\delta = .5$; and $w \in [.5, 1.5]$ in Figure 4 and $w \in [.5, 10]$ in Figure 5. We see that investment-based agreements implement low emissions when results-based and upfront-payment agreements do not if (i) country i is small relative to the size of the world, (ii) the emissions reduction required, $\overline{g}_i - \underline{g}_i$ (or Δ_i), is large, (iii) country i's idiosyncratic per capita cost of environmental damage due to aggregate emissions, h_i, is large, (iv) country i's unit cost of investment, k_i, is small for green technology, and (v) country i's benefit function reacts strongly to increases green investment technology investments. All three agreements sustain best equilibria if all applicant countries' investment compliance constraints are slack instead.

3.5 Pre-commitment Agreements

So far, we have only considered agreements that do not require a third party that can credibly hold on to payments from member countries and pass them on to applicants
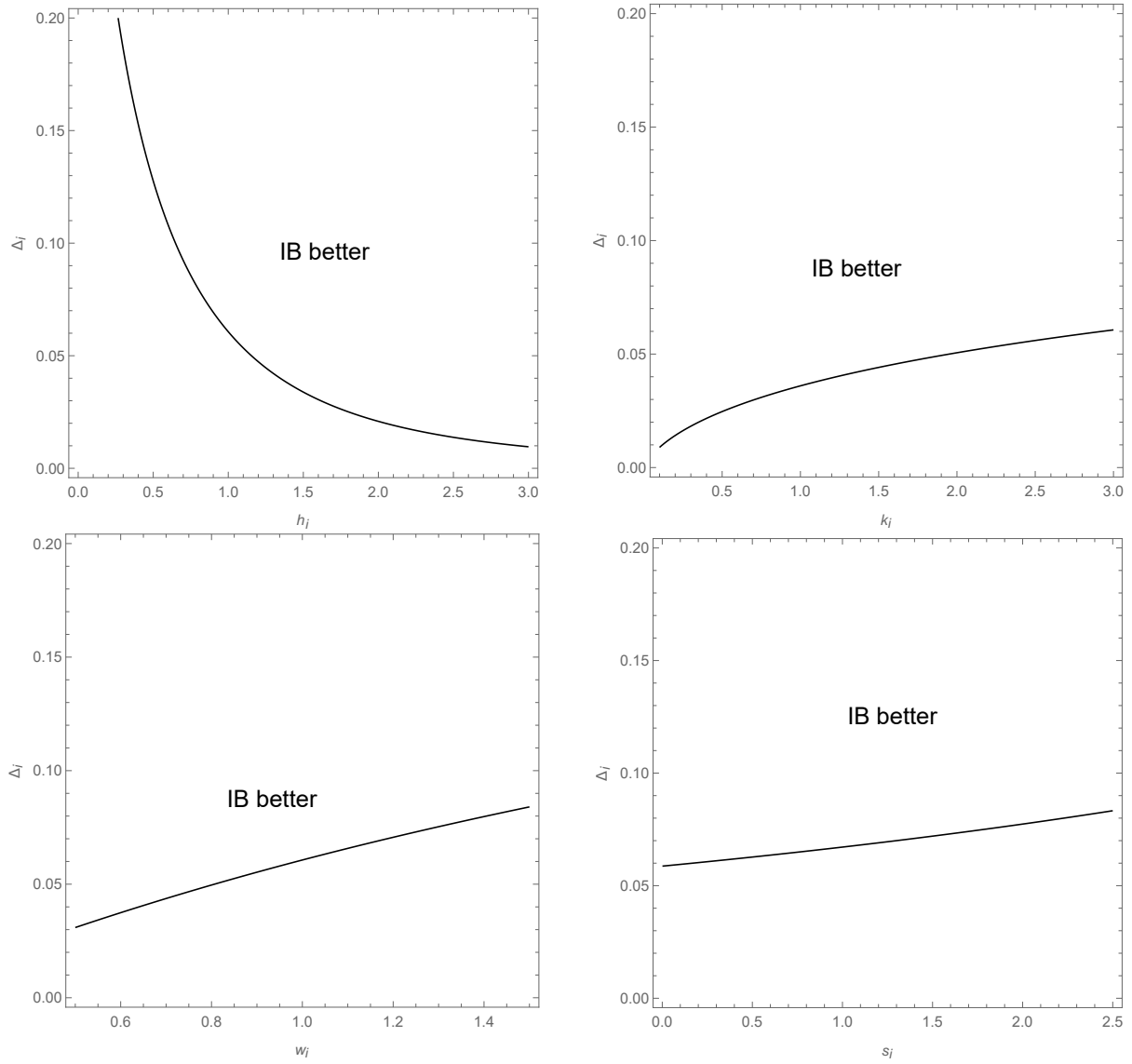
Figure 4: Investment-based agreements implement low emissions and results-based agreements do not for Δ_i-values above the lines. Assumptions: $b_i(g_i, r_i) = -\frac{w_i}{g_i\sqrt{r_i}} + z_i g_i$; n countries; one applicant country, i; $\overline{g}_{j\neq i} = \overline{g}_o \equiv 1$; $\underline{g}_{j\neq i} = \underline{g}_o$; $\Delta_o = (\overline{g}_o - \underline{g}_o)/\overline{g}_o \equiv .2$; $\sum_{j\in N} s_j = n \equiv 10$; $\delta \equiv .5$; $\overline{g}_i \equiv 1$. Top left: $k_1 \equiv 3$; $s_i \equiv .25$; $w_i \equiv 1$. Top right: $h_1 \equiv 1$; $s_i \equiv .25$; $w_i \equiv 1$. Bottom left: $k_1 \equiv 3$; $h_1 \equiv 1$; $s_i \equiv .25$. Bottom right: $k_1 \equiv 3$; $h_1 \equiv 1$; $w_i \equiv 1$.

Figure 5: Investment-based agreements implement low emissions and results-based agreements do not for Δ_i-values above the lines. Assumptions: $b_i(g_i, r_i) = -\frac{w_i}{g_i \sqrt{r_i}} + z_i g_i$; n countries; one applicant country, i; $\overline{g}_{j \neq i} = \overline{g}_o \equiv 1$; $\underline{g}_{j \neq i} = \underline{g}_o$; $\Delta_o = (\overline{g}_o - \underline{g}_o)/\overline{g}_o \equiv .2$; $\sum_{j \in N} s_j = n \equiv 10$; $\delta \equiv .5$; $\overline{g}_i \equiv 1$. Top left: $k_1 \equiv 3$; $s_i \equiv .25$; $w_i \equiv 10$. Top right: $h_1 \equiv 1$; $s_i \equiv .25$; $w_i \equiv 10$. Bottom left: $k_1 \equiv 3$; $h_1 \equiv 1$; $s_i \equiv .25$. Bottom right: $k_1 \equiv 3$; $h_1 \equiv 1$; $w_i \equiv 10$.
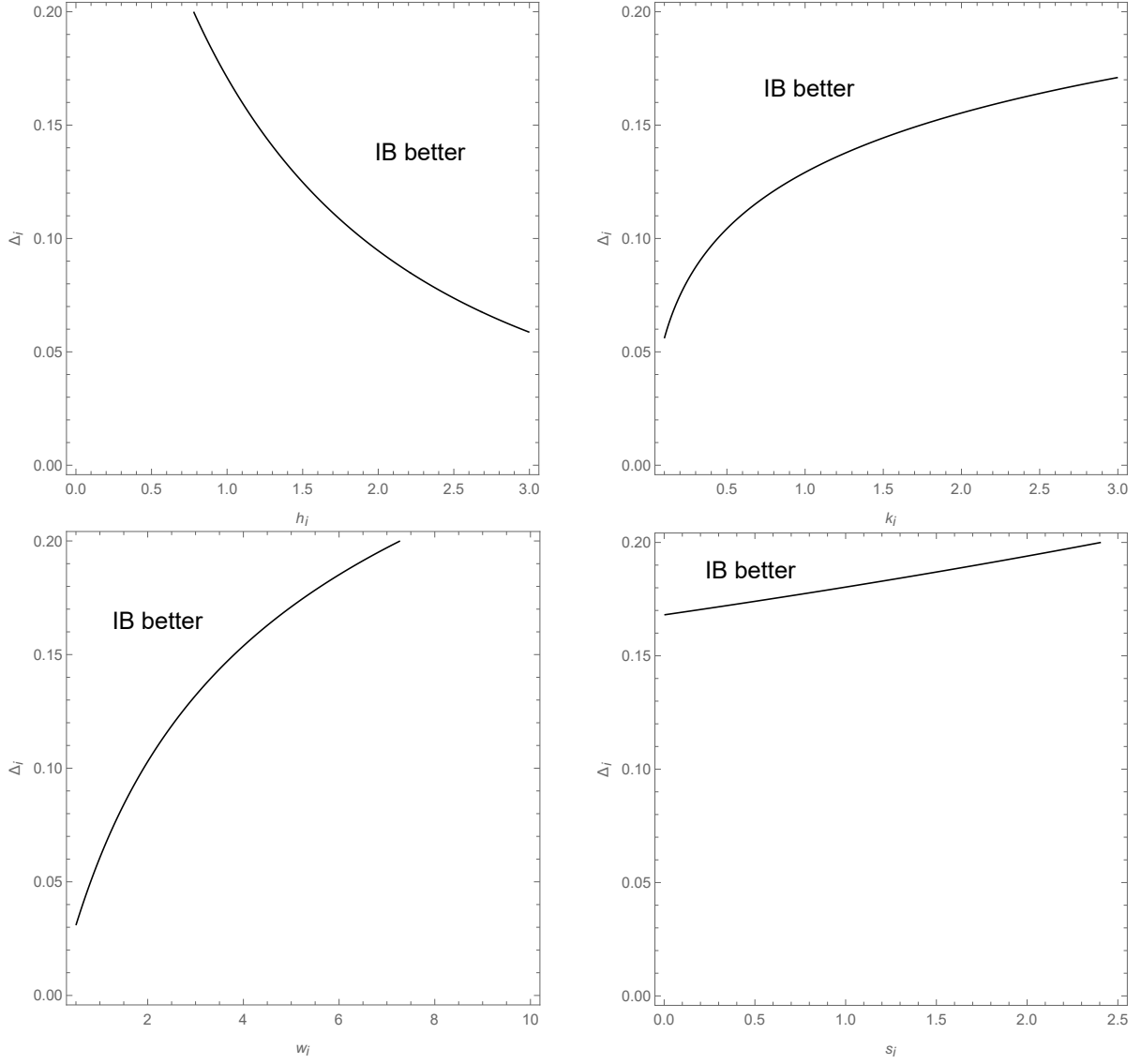
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whenever low emissions have been observed.[19] Under the assumption that such a third party exists, we can consider *pre-commitment (PC) agreements*, where member countries transfer upfront payments to a credible third party, who will give all the funds to the applicant if low emissions are observed.

3.5.1 The stage game

The stage game has three sub-stages. In the first sub-stage, member countries transfer side payments to a credible third party. In sub-stage 2, countries decide their investment levels simultaneously. Countries determine their emissions at the last sub-stage. We assume that stage 3 constitutes a prisoner's dilemma (Assumption 1). Any applicant who has made low emissions will receive side payments from the third party. Once again, this stage game has a unique BAU equilibrium as follows.

Lemma 7. The stage game has a unique SPE such that $p_{ij} = 0$, $r_i = r_i^b$ and $g_i = \overline{g}_i$ for all $i, j \in N$.

3.5.2 The repeated game

We define the *PC agreements* as follows.

Definition 6. A PC agreement is such that:

1 (Side-payment stage). Each member country $i \in M$ transfers the agreed levels of side payments to a credible third party.

2 (Investment stage). Each applicant i invests at $\bar{r}_i$ for all $i \in A$ and each member country i invests at $\widehat{r_i}$ for all $i \in M$ if there is no deviation in Stage 1.

3 (Emissions stage). All countries emit less if no country deviates in both Stage 1 and Stage 2, otherwise they play the BAU equilibrium immediately. Applicants receive side payments after making low emissions.

A PC agreement is equivalent to the case that the member signs an UP agreement but the applicant signs an RB agreement. Therefore, for any applicant $i \in A$, its compliance constraints at Stages 1 and 2 are

$$v_i(\bar{r}_i) + \delta p_i \geq v_i^b \qquad (AC_{i,r}^C)$$

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[19] Alternatively, this is a third party, vis-à-vis which member countries can credibly commit themselves to a transfer of funds that would be passed on to applicants in case of low emissions.

and

$$\gamma_i(\delta)\left[v_i(\bar{r}_i) + p_i - v_i^b\right] \geq \psi_i(\bar{r}_i). \qquad (AC_{i,g}^C)$$

Once again, $(AC_{i,g}^C)$ does not imply $(AC_{i,r}^C)$.

Similarly, for a member country $i \in M$, its compliance constraints at Stages 1, 2 and 3 are

$$v_i(\widehat{r}_i) - \delta t_i \geq v_i^b, \qquad (MC_{i,t}^C)$$

$$v_i(\widehat{r}_i) - \delta^2 t_i \geq v_i^b, \text{ and} \qquad (MC_{i,r}^C)$$

$$\gamma_i(\delta)\left[v_i(\widehat{r}_i) - \delta t_i - v_i^b\right] \geq \psi_i(\widehat{r}_i). \qquad (MC_{i,g}^C)$$

Note that $(MC_{i,g}^C)$ implies both $(MC_{i,t}^C)$ and $(MC_{i,r}^C)$.

These constraints take into account that the third party only pays out to the applicants in the end of the period and, hence, discounts as members and applicants would. Analogous to Lemmas 2, 4 and 6, we find the following condition for the existence of a PC agreement as a best equilibrium.

Lemma 8. If $\sum_{i \in M} s_i e_i \geq \sum_{i \in A} \gamma_i(\delta) s_i(\delta \bar{p}_i)$, then a PC agreement forms a best equilibrium.

3.6 Results

In the following propositions, we summarize common features shared by the agreements and the relationship among them.

Proposition 2 (Side payment-minimizing investments)**.**

1. If it exists, each applicant i' emissions-constraint deficit-minimizing investment, $\widehat{r}_i$, is the same in all four agreements. Furthermore,

   (a) $\widehat{r}_i > r_i^*$ for green technology, and

   (b) $\widehat{r}_i < r_i^*$ for brown technology.

2. The side payment-minimizing investment for each applicant i, $\widehat{\widehat{r}}_i$, whenever $\widehat{r}_i$ does not work, is the same across UP, RB and PC agreements. Furthermore,

   (a) $\widehat{r}_i > \widehat{\widehat{r}}_i > r_i^*$ for green technology, and

   (b) $\widehat{r}_i < \widehat{\widehat{r}}_i < r_i^*$ for brown technology.

Proposition 3 (Size of side payments to applicants)**.** UP agreements need the biggest size of side payment, IB agreements the second-biggest, and PC and RB agreements the smallest.

Proof. Follows directly from the text. □

We next present the relationship among all four agreements. In terms of implementability, RB and UP agreements are the least implementable, IB agreement the second-least, and PC agreement the most.

Proposition 4 (Relationship among best equilibria)**.**

1. An RB agreement is a best equilibrium if and only if a UP agreement is a best equilibrium.

2. If an RB agreement (or a UP agreement) is a best equilibrium, then there exists an IB agreement which is a best equilibrium, but not vice versa.

3. If an RB agreement (or a UP agreement) is a best equilibrium, then there exists a PC agreement which is a best equilibrium, but not vice versa.

4. If an IB agreement is a best equilibrium, then there exists a PC agreement which is a best equilibrium, but not vice versa.

Proof. Follows directly from the text. □

4 Extension: Imperfect Public Monitoring

Assume that investment and transfer decisions are perfectly observable, whereas emissions cannot be observed perfectly. As in HLR, let aggregate emissions, be given by

$$g = \sum_{i=0}^{n} g_i,$$

where player g_0 are nature's emissions, drawn from the cdf $F(\cdot)$ and i.i.d. over time. Country-specific emissions levels are not observable and instead, all countries observe g at the end of each period. For simplicity, we concentrate on the case of green technology in this section.

As HLR, we restrict ourselves to public perfect equilibria. The best PPE $(r, \underline{g})$ is be sustained by the following class of grim-trigger strategies: Comply by transferring t, investing r, and emitting $\underline{g}$ as long as (i) no country deviated in the investment stage

and (ii) the observed aggregate pollution level is below a threshold, that is, $g \leq \widehat{g}$, for some threshold in every earlier period. If countries observe $g > \widehat{g}$, they play BAU for $T \leq \infty$ periods before returning to the PPE. If a country deviates in the transfer stage or the investment stage, countries play BAU forever after.

Denote by $q \equiv 1 - F(\widehat{g} - n\underline{g})$ the probability that aggregate emissions exceed the threshold $\widehat{g}$ despite low emissions by every country and by $1 - p \equiv F(\widehat{g} - (\overline{g} + (n - 1)\underline{g}))$ the probability that aggregate emissions do not exceed the threshold despite the cheating of one country. Note: $p > q$.

To simplify the analysis in this subsection, assume the following holds throughout this section.

Assumption 4. There are $n - 1$ homogeneous member countries and one applicant country. Further, $s_i = 1$.

As in HLR, there are two cases to consider: the one in which a finite punishment suffices for cooperation to be sustainable and the one in which an infinite duration of the punishment is necessary. However, given the applicant country would not comply without a transfer, the optimal length will be infinite.

4.1 Upfront payment agreements

4.1.1 Applicants

The applicants' objective function is

$$\frac{u_i(r_i)}{1 - \delta} = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i + \frac{\delta}{1 - \delta}\left[(1 - q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]. \quad (2)$$

At the investment stage, the transfer is sunk. Hence, the investment compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + \frac{\delta}{1 - \delta}\left[(1 - q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]$$

$$\geq \max_{r_i \geq 0}\left[b_i(\overline{g}, r_i) - h_i n\overline{g} - k_i r_i\right] + \frac{\delta}{1 - \delta}u_i^b. \quad (3)$$

At the emissions stage, both the transfer and the investment are sunk. Hence, the emissions compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n\underline{g} + \frac{\delta}{1 - \delta}\left[(1 - q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]$$

$$\geq b_i(\overline{g}, r_i) - h_i\left[\overline{g} + (n - 1)\underline{g}\right] + \frac{\delta}{1 - \delta}\left[(1 - p)\overline{\omega}_i(r_i) + p\underline{\omega}_i(r_i)\right], \quad (4)$$

or shorter

$$\frac{\delta}{1-\delta}\frac{p-q}{\overline{g}-\underline{g}}\left[\overline{\omega}_i(r_i) - \underline{\omega}_i(r_i)\right] \geq \psi_i(r_i).$$

Finally, the continuation values $\overline{\omega}_i(r_i)$ and $\underline{\omega}_i(r_i)$ need to satisfy

$$u_i(r_i) \geq \overline{\omega}_i(r_i) \tag{5}$$

$$\underline{\omega}_i(r_i) \geq u_i^b. \tag{6}$$

In the best equilibrium, it is clear that $\underline{\omega}_i(r_i)$ must be as large as the emissions compliance constraint (4) permits and $\overline{\omega}_i(r_i) = u_i(r_i)$. This implies

$$\underline{\omega}_i(r_i) = u_i(r_i) - \frac{(1-\delta)(\overline{g}-\underline{g})}{\delta(p-q)}\psi_i(r_i). \tag{7}$$

Substituting (7) into (2) gives

$$\frac{u_i(r_i)}{1-\delta} = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i +$$

$$\frac{\delta}{1-\delta}\left[(1-q)u_i(r_i) + q\left[u_i(r_i) - \frac{1-\delta}{\delta}\frac{\overline{g}-\underline{g}}{p-q}\psi_i(r_i)\right]\right]$$

or

$$u_i(r_i) = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i - \frac{q}{p-q}(\overline{g}-\underline{g})\psi_i(r_i). \tag{8}$$

Substituting (8) and (6) into (7), we get the following expression for the emissions compliance constraint of an applicant country

$$u_i^b \leq b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i - \frac{q}{p-q}(\overline{g}-\underline{g})\psi_i(r_i) - \frac{(1-\delta)(\overline{g}-\underline{g})}{\delta(p-q)}\psi_i(r_i) \tag{9}$$

Note: $u_i^b = v_i^b$ is the BAU payoff for the applicant country. Further, as before, denote $v_i(r_i) = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i$. Then, we can rewrite this expression as the applicant country's emissions compliance constraint with imperfect public monitoring,

$$\gamma(\delta)\left[v_i(r_i) + p_i - v_i^b - \frac{q}{p-q}(\overline{g}-\underline{g})\psi_i(r_i)\right] \geq \psi_i(r_i). \tag{$AC_{i,g}^{U,IPM}$}$$

Substituting (8) and (6) into (3) gives

$$v_i(r_i) + \frac{\delta}{1-\delta}\left\{(1-q)\left[v_i(r_i) + p_i - \frac{q}{p-q}(\overline{g}-\underline{g})\psi_i(r_i)\right] + \right.$$

$$\left. q\left[v_i(r_i) + p_i - \frac{q}{p-q}(\overline{g}-\underline{g})\psi_i(r_i) - \frac{1-\delta}{\delta}\frac{\overline{g}-\underline{g}}{p-q}\psi_i(r_i)\right]\right\} \geq \frac{v_i^b}{1-\delta}.$$

We can rewrite this as the applicant country's investment compliance constraint with imperfect public monitoring,

$$v_i(r_i) + \delta p_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0. \qquad (AC_{i,r}^{U,IPM})$$

Comparing inequalities $(AC_{i,g}^{U,IPM})$ and $(AC_{i,r}^{U,IPM})$, it can be seen that – as in the perfect monitoring case – satisfying the emissions compliance does not imply satisfying the investment compliance constraint.

As in the perfect monitoring case, we assume $\gamma(\delta)[v_i(r_i) - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)] < \psi_i(r_i)$. Hence, the emissions compliance constraint is fulfilled only with a positive p_i. As with perfect monitoring, p_i does not affect ψ_i. Hence there must be a level $p_i > 0$ such that $(AC_{i,g}^{U,IPM})$ is satisfied. Let

$$\widehat{r}_i^{IPM} \equiv \arg \min_{r_i \geq 0} \psi_i(r_i) - \gamma(\delta)[v_i(r_i) - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)]$$

denote the investment level that minimizes the transfer to applicant country i necessary for its emissions compliance constraint to hold. Under Assumption 2, the second-order condition of this minimization problem holds in the relevant range or r_i.

Comparing this minimization program to that from the perfect monitoring case, we conclude that the transfer minimizing investment level with imperfect monitoring exceeds that with perfect monitoring: $\widehat{r}_i^{IPM} > \widehat{r}_i$.

Further, denote by $\widehat{p}_i^{IPM} \equiv \psi_i(\widehat{r}_i^{IPM})/\gamma(\delta) - [v_i(\widehat{r}_i^{IPM}) - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)]$ the corresponding transfer level. It is important to note that $(\widehat{r}_i^{IPM}, \widehat{p}_i^{IPM})$ may violate $(AC_{i,r}^{U,IPM})$, i.e., $\widehat{p}_i^{IPM} < [v_i^b - v_i(\widehat{r}_i^{IPM}) + \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(\widehat{r}_i^{IPM})]/\delta$. If it does, as in the perfect monitoring case, there exists a pair there exists a unique pair $(\widetilde{\widehat{r}}_i^{IPM}, \widetilde{\widehat{p}}_i^{IPM})$ such that $\widetilde{\widehat{r}}_i^{IPM} > r_i^*$ and both $(AC_{i,g}^{U,IPM})$ and $(AC_{i,r}^{U,IPM})$ hold with equality.

Define

$$(\overline{r}_i^{IPM}, \overline{p}_i^{IPM}) \equiv \begin{cases} (\widetilde{\widehat{r}}_i^{IPM}, \widetilde{\widehat{p}}_i^{IPM}) & \text{if } \widehat{p}_i^{IPM} < \left[v_i^b - v_i(\widehat{r}_i^{IPM}) + \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(\widehat{r}_i^{IPM})\right]/\delta \\ (\widehat{r}_i^{IPM}, \widehat{p}_i^{IPM}) & \text{otherwise} \end{cases},$$

where $\overline{p}_i^{IPM}$ is always the minimum possible level of side payment with which the applicant i can comply.

4.1.2 Members

Following the steps from the Applicants' section, we can find the following constraints for member countries with an upfront payments agreement:

$$v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0, \qquad (MC_{i,t}^{U,IPM})$$

$$v_i(r_i) - \delta t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0, \qquad (MC_{i,r}^{U,IPM})$$

$$\gamma(\delta)\left[v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)\right] \geq \psi_i(r_i). \qquad (MC_{i,g}^{U,IPM})$$

Define, as before, the maximum slack per capita in member country i's emissions compliance constraint by

$$e_i^{IPM} \equiv \gamma(\delta)\left[v_i(\widehat{r}_i^{IPM}) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(\widehat{r}_i^{IPM})\right] - \psi_i(\widehat{r}_i^{IPM}).$$

Then we can state

Lemma 9. If $\sum_{i\in M} e_i^{IPM} \geq \gamma(\delta)\sum_{i\in A} \bar{p}_i^{IPM}$, then an UP agreement corresponds to a best equilibrium with imperfect public monitoring.

4.2 Investment-based payment agreements

4.2.1 Applicants

The applicants' objective function is

$$\frac{u_i(r_i)}{1-\delta} = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i + \frac{\delta}{1-\delta}\left[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]. \qquad (10)$$

At the investment stage, nothing is sunk. Hence, the investment compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + p_i + \frac{\delta}{1-\delta}\left[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]$$
$$\geq \max_{r_i \geq 0}\left[b_i(\overline{g}, r_i) - h_i n\overline{g} - k_i r_i\right] + \frac{\delta}{1-\delta}u_i^b. \qquad (11)$$

At the emissions stage, both the transfer and the investment are sunk. Hence, the emissions compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n\underline{g} + \frac{\delta}{1-\delta}\left[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\right]$$
$$\geq b_i(\overline{g}, r_i) - h_i\left[\overline{g} + (n-1)\underline{g}\right] + \frac{\delta}{1-\delta}\left[(1-p)\overline{\omega}_i(r_i) + p\underline{\omega}_i(r_i)\right]. \qquad (12)$$

Finally, the continuation values $\overline{\omega}_i(r_i)$ and $\underline{\omega}_i(r_i)$ need to satisfy

$$u_i(r_i) \geq \overline{\omega}_i(r_i) \tag{13}$$

$$\underline{\omega}_i(r_i) \geq u_i^b. \tag{14}$$

Following the steps from the upfront payments agreement section, we find an applicant country's emissions compliance constraint,

$$\gamma(\delta)\Big[v_i(r_i) + p_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)\Big] \geq \psi_i(r_i), \tag{$AC_{i,g}^{I,IPM}$}$$

as well as its investment compliance constraint,

$$v_i(r_i) + p_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0. \tag{$AC_{i,r}^{I,IPM}$}$$

Comparing inequalities ($AC_{i,g}^{I,IPM}$) and ($AC_{i,r}^{I,IPM}$), it can be seen that – as in the perfect monitoring case – satisfying the emissions compliance implies satisfying the investment compliance constraint.

4.2.2 Members

Following these steps, we find the following constraints for member countries with an investment-based payments agreement:

$$v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0, \tag{$MC_{i,rt}^{I,IPM}$}$$

$$\gamma(\delta)\Big[v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i)\Big] \geq \psi_i(r_i). \tag{$MC_{i,g}^{I,IPM}$}$$

Then we can state

Lemma 10. If $\sum_{i \in M} e_i^{IPM} \geq \gamma(\delta) \sum_{i \in A} \widehat{p}_i^{IPM}$, then an IB agreement corresponds to a best equilibrium with imperfect public monitoring.

4.3 Results-based payment agreements

4.3.1 Applicants

At the emissions stage, investments are sunk. Because aggregate emissions are uncertain, payments are uncertain. They happen with probability $1 - p$ and they occur after emissions have been observed, hence are discounted with δ.

The applicants' objective function is

$$\frac{u_i(r_i)}{1-\delta} = b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i + \delta(1-q)p_i + \frac{\delta}{1-\delta}\big[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i)\big]. \tag{15}$$

At the investment stage, nothing is sunk. So the investment compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n \underline{g} - k_i r_i + \delta(1-q) p_i + \frac{\delta}{1-\delta} \left[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i) \right]$$

$$\geq \max_{r_i \geq 0} \left[b_i(\overline{g}, r_i) - h_i n \overline{g} - k_i r_i \right] + \frac{\delta}{1-\delta} u_i^b. \quad (16)$$

At the emissions stage, the investment is sunk, but the transfer is not. Hence, the emissions compliance constraint is given by

$$b_i(\underline{g}, r_i) - h_i n \underline{g} + \delta(1-q) p_i + \frac{\delta}{1-\delta} \left[(1-q)\overline{\omega}_i(r_i) + q\underline{\omega}_i(r_i) \right]$$

$$\geq b_i(\overline{g}, r_i) - h_i \left[\overline{g} + (n-1)\underline{g} \right] + \delta(1-p) p_i + \frac{\delta}{1-\delta} \left[(1-p)\overline{\omega}_i(r_i) + p\underline{\omega}_i(r_i) \right]. \quad (17)$$

Finally, the continuation values $\overline{\omega}_i(r_i)$ and $\underline{\omega}_i(r_i)$ need to satisfy

$$u_i(r_i) \geq \overline{\omega}_i(r_i) \quad (18)$$

$$\underline{\omega}_i(r_i) \geq u_i^b. \quad (19)$$

Again, following the steps from the upfront payments agreement section, we find the emissions compliance constraint of an applicant country,

$$\gamma(\delta) \left[v_i(r_i) + p_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \right] \geq \psi_i(r_i), \quad (AC_{i,g}^{R,IPM})$$

and its investment compliance constraint,

$$v_i(r_i) + \delta p_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0. \quad (AC_{i,r}^{R,IPM})$$

Once more, comparing inequalities $(AC_{i,g}^{R,IPM})$ and $(AC_{i,r}^{R,IPM})$, it can be seen that – as in the perfect monitoring case – satisfying the emissions compliance does not necessarily imply satisfying the investment compliance constraint.

4.3.2 Members

Similarly, we find the following constraints for member countries with an results-based payments agreement:

$$v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0, \quad (MC_{i,t}^{R,IPM})$$

$$v_i(r_i) - \delta t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \geq 0, \quad (MC_{i,r}^{R,IPM})$$

$$\gamma(\delta) \left[v_i(r_i) - t_i - v_i^b - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(r_i) \right] \geq \psi_i(r_i). \quad (MC_{i,g}^{R,IPM})$$

Then we can state

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Lemma 11. If $\sum_{i \in M} e_i^{IPM} \geq \gamma(\delta) \sum_{i \in A} \bar{p}_i^{IPM}$, then an RB agreement corresponds to a best equilibrium with imperfect public monitoring.

4.4 Results

The previous section shows that the – realistic – case of imperfect public monitoring does not alter the insights from the full information environment. Upfront payments and results-based payments agreements implement low emissions for the same parameter values. Whenever results-based payment agreements implement low emissions, they will be preferred by member countries because they imply the lowest transfers. However, there are instances, in which investment-based agreements implement low emissions when results-based agreements do not. These instances are empirically relevant, as the next section will demonstrate.

4.5 Transfers, imperfect public monitoring and equilibrium path punishments

The previous subsections showed that, with imperfect public monitoring, the insights on the relative scopes of implementing low emissions with our three basic transfer agreements, which we gained in the perfect monitoring environment, continue to hold. Countries maximize the scope for implementing low emissions with investment-based agreements.

Note that the applicant country's emissions compliance constraint can be relaxed with a higher transfer, p_i. This implies countries can implement low emissions with less likely equilibrium punishments by increasing transfers to a recipient country, for which the emissions compliance constraint binds at $T \rightarrow +\infty$. Given punishments take place on the equilibrium path, this may well be optimal for member countries.

To simplify the exposition of this point, in this subsection, we assume that countries agree on investment-based transfers. As we saw earlier, this implies we only need to take care of the emissions compliance constraints.

Assumption 5. Countries agree on investment-based transfers.

Assuming the member countries' emissions compliance constraint has sufficient slack, the relevant emissions compliance constraint is the one of the applicant country, $i \in A$, which can be written as:

$$u_i^b \leq b_i(\underline{g}, \widehat{r_i}) - h_i n \underline{g} - k_i \widehat{r_i} + p_i - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_i(\widehat{r_i}) - \frac{(1-\delta)(\overline{g} - \underline{g})}{\delta(p-q)}\psi_i(\widehat{r_i}). \tag{20}$$

Denote global emissions by $g \equiv g_0 + \sum_{i \in N} g_i$, where $g_0 \sim \mathcal{N}(0,1)$. The best equilibrium specifies a threshold $\widehat{g}(p_i)$, above which the countries enter a punishment phase. The punishment phase is triggered by mistake if $g_0 > \widehat{g}(p_i) - n\underline{g}$. Therefore, it is beneficial to raise the threshold $\widehat{g}(p_i)$ as far as possible. For that, T or p_i needs to be raised for the emissions compliance constraint to be satisfied.

Lemma 12 (HLR). There exists a unique threshold $\widehat{g}(p_i)$, such that, in the best equilibrium, continuation values of the applicant country $i \in A$ are given by

$$\omega_i(g, \widehat{r}) = \begin{cases} \overline{\omega}_i(\widehat{r}) = u_i(\widehat{r}) & if \quad g < \widehat{g}(p_i), \\ \underline{\omega}_i(\widehat{r}) = u_i^b & if \quad g \geq \widehat{g}(p_i). \end{cases}$$

Given this threshold, in equilibrium, type I errors occur with probability $q = 1 - \Phi\left(\widehat{g}(p_i) - n\underline{g}\right)$ and type II errors occur with probability $1 - p = \Phi\left(\widehat{g}(p_i) - (n-1)\underline{g} - \overline{g}\right)$. The member countries can further reduce the probability of (erroneous) punishment on the equilibrium path, q, by increasing $\widehat{g}(p_i)$. To do so, they need to decrease the applicant country's temptation to defect. They can do so by increasing p_i.

Proposition 5. There exists a best equilibrium if and only if $\sum_{i \in M} e_i^{IPM} \geq \gamma(\delta) \sum_{i \in A} \widehat{p}_i^{IPM}$. For each $i \in N$, it supports $g_{i,t} = \overline{g}$, $r_{i,t} = r_i^b$, and $p_i = 0$ if $g_{i,\tau} > \widehat{g}(p_i)$ for some $\tau < t$. Otherwise, for each $i \in N$, $g_{i,t} = \underline{g}$, and for each $a \in A$ and $m \in M$, $r_{a,t} = \widehat{r}_a > r^*$; and $p_a = \widehat{p}_a^{IPM}$ solves the first-order condition

$$\frac{1}{n-1} = (\overline{g} - \underline{g})\psi_m(r_m)\frac{d}{d\widehat{g}}\left[\frac{p}{p-q}\right]\frac{d\widehat{g}(\widehat{p}_a^{IPM})}{dp_a},$$

where

$$\frac{d\widehat{g}(\widehat{p}_a^{IPM})}{dp_a} = \left(\frac{\partial}{\partial\widehat{g}}\left[\frac{1-\delta(1-q)}{\delta(p-q)}\right](\overline{g} - \underline{g})\psi_a(\widehat{r}_a)\right)^{-1}.$$

Hence, side payments to applicant countries not only relax the applicant countries' investment and emissions constraints; their size also determines the optimal probability of entering a punishment phase on the equilibrium path. The optimality condition in Proposition 5 shows that this optimal probability of punishment on the equilibrium path depends negatively on the number of member countries.

5 Discussion

We observe the following for agreements that do not use a third party. To start with, the conditions for an equilibrium with low emissions in each period (a best equilibrium) to exist with *upfront payments* and *results-based agreements* are the same, so a

best equilibrium with upfront payment agreements exists if and only if there is a best equilibrium with results-based agreements. However, the payment necessary to induce compliance of an applicant country, both in the investment and the emissions stages, is higher with upfront than with results-based payments. Hence, upfront payment agreements are dominated in our framework.

Next, it is possible to satisfy the emissions compliance constraints of best equilibria for all member and applicant countries with *upfront payments* and *results-based agreements* if and only if it is possible to do so with *investment-based agreements*. However, in contrast to under an investment-based agreement, under upfront or results-based agreements satisfying the emissions compliance constraint does not imply that the investment compliance constraint is also satisfied. Hence, if best equilibria exist with *upfront payment* and *results-based agreements*, then they also exist with *investment-based agreements*, but not vice versa. When the investment compliance constraint of an applicant country is binding, then with upfront payment and results-based agreements, these equilibria require higher discount factors than with investment-based agreements. We find that these results are robust to more realistic informational environments where it is not possible to perfectly monitor a country's emissions.

We find that investment-based agreements implement low emissions when results-based and upfront-payment agreements do not if (i) country i is small relative to the size of the world, (ii) the emissions reduction required is large, (iii) country i's idiosyncratic per capita cost of environmental damage due to aggregate emissions is large, (iv) country i's unit cost of investment is large for green technology, and (v) country i's benefit function reacts strongly to increases green investment technology investments. All three agreements sustain best equilibria if all applicant countries' investment compliance constraints are slack instead.

If countries can use a credible third party to pre-commit to an agreement that treats the member countries as an upfront payments agreement would and the applicant countries as a results-based agreement would, we find the following additional results. If best equilibria with *upfront payment* and *results-based agreements* exist, then they also exist with *pre-commitment agreements*, but not vice versa. Best equilibria with upfront payment and results-based agreements and no pre-commitment are always harder to sustain than best equilibria with pre-commitment agreements because the latter combines the advantages of both of the former: member countries cannot renege ex-post on the transfers and applicant countries can renege ex-post on emissions. This implies a high *willingness to pay* on part of the member countries and a low *willingness*

to accept on part of the applicants. In spite of requiring additional incentives to invest at the transfer-minimizing level on part of the applicant countries, best equilibria with pre-commitment agreements always exist when they exist with investment-based agreements, but not vice versa. Also, member countries will prefer pre-commitment to investment-based agreements because they require lower transfers to achieve the same low emissions.

Such a credible third party is essentially an international institution with something close to the power to ensure compliance. Member countries would like to pre-commit to such an institution. However, there will likely be institutional limits to their ability to do so. Beyond these limits, member countries need to trade off between the scope of cooperation, which is the highest with an investment-based agreement, and the size of the payment, which is the lowest with a results-based agreement. Then, in empirically relevant situations, in which results-based agreements do not provide sufficient incentives to invest in green technology, investment-based payment agreements may. It is worth giving them a look.

A Proofs and derivations

Derivation of inequality (1)

$$\frac{\delta}{1-\delta}\frac{1}{\overline{g}_i-\underline{g}_i}\widehat{p}_i = \psi_i(\widehat{r}_i) - \frac{\delta}{1-\delta}\frac{1}{\overline{g}-\underline{g}}(v_i(\widehat{r}_i) - v_i^b)$$

$$\delta\widehat{p}_i = (\overline{g}_i-\underline{g}_i)(1-\delta)\psi_i(\widehat{r}_i) - \delta(v_i(\widehat{r}_i) - v_i^b)$$

We violate the investment compliance constraint if

$$\delta\widehat{p}_i < v_i^b - v_i(\widehat{r}_i)$$

$$(\overline{g}_i-\underline{g}_i)(1-\delta)\psi_i(\widehat{r}_i) - \delta(v_i(\widehat{r}_i) - v_i^b) < v_i^b - v_i(\widehat{r}_i)$$

$$(\overline{g}_i-\underline{g}_i)\psi_i(\widehat{r}_i) < v_i^b - v_i(\widehat{r}_i)$$

$$b_i(\overline{g}_i,\widehat{r}_i) - b_i(\underline{g}_i,\widehat{r}_i) - h_i s_i(\overline{g}_i-\underline{g}_i) < v_i^b - v_i(\widehat{r}_i)$$

$$b_i(\overline{g}_i,\widehat{r}_i) - b_i(\underline{g}_i,\widehat{r}_i) - h_i s_i(\overline{g}_i-\underline{g}_i) < \left(b_i(\overline{g}_i,r_i^b) - h_i\sum_{j\in N}s_j\overline{g}_j - k_i r_i^b\right) - \left(b_i(\underline{g}_i,\widehat{r}_i) - h_i\sum_{j\in N}s_j\underline{g}_j - k_i\widehat{r}_i\right)$$

$$\left(b_i(\overline{g}_i,r_i^b) - k_i r_i^b\right) - (b_i(\overline{g}_i,\widehat{r}_i) - k_i\widehat{r}_i) > h_i\sum_{j\in N}s_j\left(\overline{g}_j-\underline{g}_j\right) - h_i s_i(\overline{g}_i-\underline{g}_i).$$

Proof of Lemma 12. We reproduce the proof of the comparable Lemma from Harstad

et al. (2017). Continuation values must maximize

$$\frac{u_m(r_m)}{1-\delta} = b_m(\underline{g}, r_m) - h_m n\underline{g} - k_m r_m - \frac{p_a}{n-1} + \frac{\delta}{1-\delta} \int_g \omega_m(g, r_m)\phi(g|n\underline{g})dg, \; s.t.$$

$$\frac{u_a(r_a)}{1-\delta} \geq b_a(\overline{g}, r_a) - h_a((n-1)\underline{g} + \overline{g}) - k_a r_a + p_a + \frac{\delta}{1-\delta} \int_g \omega_a(g, \widehat{r_a})\phi(g|(n-1)\underline{g} + \overline{g})dg,$$

$$\tag{21}$$

$$u_i(r_i) \geq \omega_i(g, \widehat{r}) \geq u_i^b.$$

Let ν be the multiplier associated with the applicant country's emissions compliance constraint, (21). Then, for $m \in M$ and $a \in A$, by the monotone likelihood property and given that g is continuous, there is a unique $\widehat{g}(p_a)$ for which

1. $\omega_m(\widehat{g}, r_m)\phi(\widehat{g}(p_a)|n\underline{g})/\omega_a(\widehat{g}, \widehat{r_a})\phi(\widehat{g}(p_a)|(n-1)\underline{g} + \overline{g})) = \nu$,

2. if $g > \widehat{g}(p_a)$, then $\omega_m(g, r_m)\phi(g(p_a)|n\underline{g})/\omega_a(g, \widehat{r_a})\phi(g(p_a)|(n-1)\underline{g} + \overline{g})) < \nu$, and

3. if $g < \widehat{g}(p_a)$, then $\omega_m(g, r_m)\phi(g(p_a)|n\underline{g})/\omega_a(g, \widehat{r_a})\phi(g(p_a)|(n-1)\underline{g} + \overline{g})) > \nu$.

Hence, we must have $\omega_i(g, r_i) = u_i^b$ for $g \geq \widehat{g}(p_a)$ and $\omega_i(g, r_i) = u_i(r)$ otherwise. $\qquad\square$

Proof of Proposition 5. We follow Harstad et al. (2017). To determine the best equilibrium, we must solve the constrained optimization problem

$$\frac{u_m(r_m)}{1-\delta} = b_m(\underline{g}, r_m) - h_m n\underline{g} - k_m r_m - \frac{p_m}{1-n} + \frac{\delta}{1-\delta}[(1-q)\overline{\omega}_m(r_m) + q\underline{\omega}_m(r_m)] \; s.t.$$

$$u_a(\widehat{r_a}) \geq b_a(\overline{g}, \widehat{r_a}) - h_a(n-1)\underline{g} - h_a\overline{g} - k_a\widehat{r_a} + \delta[(1-p)\overline{\omega}_a(\widehat{r_a}) + p\underline{\omega}_a(\widehat{r_a})]$$

where $\overline{\omega}_i(r) = u_i(r) \geq u_i^b$ and $\underline{\omega}_i(r) \geq u_i^b$ for the levels of $\widehat{g}(p_a)$ and $\widehat{p}_a$. We have $q = 1 - \Phi(\widehat{g}(p_a) - n\underline{g})$ and $p = 1 - \Phi(\widehat{g}(p_a) - (n-1)\underline{g} - \overline{g})$. We write the emissions compliance constraint of the applicant country as

$$0 \leq b_a(\underline{g}, \widehat{r_a}) - h_a n\underline{g} - k_a\widehat{r_a} - u_a^b + p_a - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_a(\widehat{r_a}) - \frac{(1-\delta)(\overline{g} - \underline{g})}{\delta(p-q)}\psi_a(\widehat{r_a}). \tag{22}$$

Differentiating (22) w.r.t. $\widehat{g}$ and δ, we obtain $d\widehat{g}/d\delta \approx \partial[(1-\delta(1-q))/(\delta(p-q))]/\partial\widehat{g}$. Abandoning cooperation means aggregate emissions fall in the upper tail of their distribution, i.e., into $[\widehat{g}, +\infty)$. Here, the monotone likelihood ratio property implies $d\widehat{g}/d\delta > 0$. Differentiating (22) w.r.t. p_a and $\widehat{g}$, we get

$$\frac{d\widehat{g}(p_a)}{dp_a} = \left(\frac{\partial}{\partial\widehat{g}}\left[\frac{1-\delta(1-q)}{\delta(p-q)}\right](\overline{g} - \underline{g})\psi_a(\widehat{r_a})\right)^{-1}.$$

Substituting $\overline{\omega}_m(r_m) = u_m(r_m)$ and $\underline{\omega}_m(r_m) = u_m^b$ into the member countries' objective function, we get

$$u_m(r_m) = b_m(\underline{g}, r_m) - h_m n \underline{g} - k_m r_m - \frac{p_a}{n-1} - \frac{q}{p-q}(\overline{g} - \underline{g})\psi_m(r_m). \tag{23}$$

Maximising (23) w.r.t. p_a then solves

$$\frac{1}{n-1} = (\overline{g} - \underline{g})\psi_m(r_m) \frac{d}{d\widehat{g}}\left[\frac{p}{p-q}\right]\frac{d\widehat{g}(\widehat{p_a})}{dp_a}.$$

$\square$

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