FINANCIAL TRANSFERS, COMPLIANCE TECHNOLOGY AND CLIMATE COOPERATION
(PRELIMINARY AND INCOMPLETE)

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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, 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.

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,...
>
> William Nordhaus (2015, p. 1339)

To be effective, any international agreement that addresses climate change must address the absence of an international institution with the power to ensure 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. The benefit of sustained cooperation in future years could be sufficient to deter opportunistic behavior today. Unfortunately, as nearly 30 years of climate negotiations have shown, generating and sustaining cooperation is not easy.

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One key challenge, on which this paper focuses, is that although efficient global mitigation generates the greatest joint gains from cooperation which supports cooperation, these gains are unevenly distributed across countries. Some countries that would, in an efficient world, reduce emissions rapidly are highly resource constrained and may not expect commensurate benefits from a more stable climate. Without resource transfers between countries, many of these countries will not agree to and would not comply with a globally efficient agreement. Only partial agreements with lower than efficient levels of mitigation ambition can be sustained.

This paper explores different stylized mechanisms for resource transfer within a game-theoretic framework. We seek to understand which transfer mechanisms are able to most effectively expand the set of cooperating countries and the global level of mitigation.

Harstad et al. (2017) (hereafter HLR) employ a repeated game framework of climate cooperation. They show that when some countries face high short-run costs to cooperate or low benefits, or equivalently are insufficiently patient to sustain the first best outcome in climate cooperation, second best strategies include over-investment in green technology and under-invest in brown and adaptation technologies to sustain low emissions as an SPE of the climate repeated game. Once these investment levels are achieved, the country's mitigation costs are lower (or in the case of under investment in adaptation, the benefit from global mitigation is higher) and the country's incentive to defect is reduced. The second-best strategies are equilibrium actions and can sustain a given level of global mitigation provided that all countries are sufficiently patient.

Our paper builds on HLR's basic model to explore how it might be possible to sustain higher levels of cooperation when not all countries are sufficiently patient to sustain the second-best cooperative equilibrium. We start by carefully studying the conditions for existence of the second-best equilibrium. We define the countries whose cooperation can be sustained as "members" of a climate club. We proceed to investigate the impact of side-payments 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.

We initially model three types of side payment agreements: upfront payments, investment-based payments, and results-based payments (payment after emissions are verified). We investigate how the size of transfers necessary to induce climate cooperation interacts with the investment levels studied in HLR. For each applicant there is a transfer-minimizing investment level; for each member, there is an investment level that maximizes the transfer they will be willing to make.

The agreements we consider involve compliance with emission levels, investment levels for both applicant and member countries, and required transfers from member countries. Results-based agreements allow the lowest transfers while ensuring that applicants comply by reducing emissions. We show that, if applicants that meet their emissions compliance constraint also automatically fulfil their investment compliance constraint, then the existence of a side payment scheme that implements lower emissions with any one of these three types of agreement implies the existence in the other two. In this case, investment-based and upfront-payment agreements will achieve the same cooperation in emissions reductions as results-based agreements.

Requirements for specific investments in technology as part of the equilibrium affect the transfers needed to comply with low emissions. As in HLR, countries may need to over-invest in green and under-invest in brown technologies in equilibrium. In contrast to an investment-based agreement, in an upfront or results-based agreement, the smallest transfer needed for compliance with the efficient emissions level may not be able to induce the over-investment in green technology needed. If they do not, then being able to implement cooperation with results based transfers implies being able to implement cooperation with investment-based transfers but not vice versa. If, for example, the cost of green investment is high for the applicant, a transfer-minimizing results based agreement may satisfy the applicant's emissions compliance constraint, but they may defect by not investing.

When both the member and applicant countries are "marginal" in the sense that the member would almost prefer not to make an agreement and the applicant's investment compliance constraints cannot be met with a minimum-transfer results-based agreement, then a balance between a lower level of green investment (than the transfer-minimizing level) and a lower transfer payment implemented within an investment agreement may be the only feasible option.

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, even though applicant countries may not have an incentive to comply with the investment level that minimizes the transfer ensuring their compliance with low emissions in a pre-commitment agreement, whereas they always do in an investment-based agreement, being able to implement cooperation with investment-based transfers implies being able to implement cooperation with pre-commitment agreements but not vice versa. Hence, the existence of such a credible third party would maximize the scope of climate cooperation with side payments. In addition, it minimizes the payments from member countries to applicants.

[Literature to be added]

Some relevant papers:

1. Sustainability of international environmental/climate agreement (IEA):
   Barrett (1994, 2005), Battaglini and Harstad (2016), Beccherle and Tirole (2011), Diamantoudi and Sartzetakis (2006), de Zeeuw (2008), Dutta and Radner (2004, 2006, 2009), Harstad (2012, 2016), Harstad et al. (2017), Hong and Karp (2012), Hong and Zhao (2014), Martimort and Sand-Zantman (2016), McEvoy and Stranlund (2009), Rubio and Ulph (2006)
2. International resources transfer (including REDD and/or REDD+):
   Angelsen and Rudel (2013), Kerr and Millard-Ball (2012), Kerr (2013), Lubowski and Rose (2013), Pfaff et al. (2013), van Benthem and Kerr (2013), Engel et al. (2008) (PES).

2. The baseline HLR model

2.1. The stage game. Consider a set $N = \{1, 2, \dots, n\}$ 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, every country i decides its investment level $r_i \geq 0$, while, at the latter, all the countries simultaneously choose to emit either more ($\overline{g}$) or less ($\underline{g}$) greenhouses gases. 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

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

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

Define

$$r_i^*(g) \equiv \arg\max_{r_i} b_i(g, r_i) - h_i ng - k_i r_i.$$

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

HLR consider three types of technologies, green, brown and adaptation technologies. We retain for our purposes green and brown technologies, which are defined as follows:[2]

Definition 1. For any investment level $r_i \in \mathbb{R}_+$:

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

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

2.2. **The repeated game.** Let $\delta \in [0, 1)$ be a common discount factor for all countries. 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 $(r_i, \underline{g})_{i\in N}$ in each period can be sustained as an SPE. HLR define $(r_i, \underline{g})_{i\in N}$ 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*.

[1] 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.

[2] HLR also study adaptation technology, investing in which can lower the environmental damage from emissions.

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.[3] HLR consider a simple grim-trigger strategy where any deviation immediately triggers a reversion to the BAU equilibrium. Deviation could be either from the agreed investment level or at the emission stage. To sustain $(r_i, \underline{g})_{i \in N}$ as an SPE, each country i must have incentives to comply with the agreement. These incentive are summarized by two compliance constraints described below.[4] Fix $i \in N$ and let

$$v_i(r_i) \equiv b_i(\underline{g}, r_i) - h_i n \underline{g} - k_i r_i$$

be the normalized (to one period) continuation value from complying with the SPE.[5] We will write $v_i(r_i)$ as v_i whenever no confusion arises. Likewise,

$$v_i^b \equiv b_i(\overline{g}, r_i^b) - h_i n \overline{g} - k_i r_i^b$$

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

$$\frac{v_i}{1-\delta} \geq \left[\max_{r_i} b_i(\overline{g}, r_i) - h_i n \overline{g} - k_i r_i\right] + \frac{\delta v_i^b}{1-\delta}. \tag{$CC_{i,r}$}$$

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

$$b_i(\underline{g}, r_i) - h_i n \underline{g} + \frac{\delta v_i}{1-\delta} \geq b_i(\overline{g}, r_i) - h_i \left[s_i \overline{g} + (n - s_i)\underline{g}\right] + \frac{\delta v_i^b}{1-\delta}. \tag{$CC_{i,g}$}$$

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

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

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 $(\overline{g} - \underline{g})$. Let $\gamma(\delta) \equiv \delta / [(\overline{g} - \underline{g})(1-\delta)]$,

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

[4]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)).

[5]Let $\tilde{v}_i = b_i(\underline{g}, r_i) - h_i n \underline{g} - k_i r_i$ 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 $v_i = \tilde{v}_i$.

which is strictly increasing in δ. When δ is sufficiently close to 1, $(CC_{i,g})$ is fulfilled for some r_i. We define

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

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, while, for brown technology, ψ_i is strictly increasing 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, 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 $\gamma(\delta)(v_i(r_i^*) - v_i^b) = \psi_i(r_i^*)$.[6] 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 1 provides a graphical representation of the compliance constraint at the emissions stage, $(CC_{i,g})$. For both green and brown technologies, $\gamma(\delta)(v_i - v_i^b)$ 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 but upward-sloping for brown technology. Both left-hand-side panels depict the situation where $\delta > \overline{\delta}_i$ and, hence, country i's emissions compliance constraints hold for the first-best investment level $r_i = r_i^*$. Both right-hand-side panels depict the situation where $\delta = \underline{\delta}_i$ and, hence, country i's emissions compliance constraints just hold. For green technology, this implies a higher, and for brown technology, this implies a lower investment level than 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

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

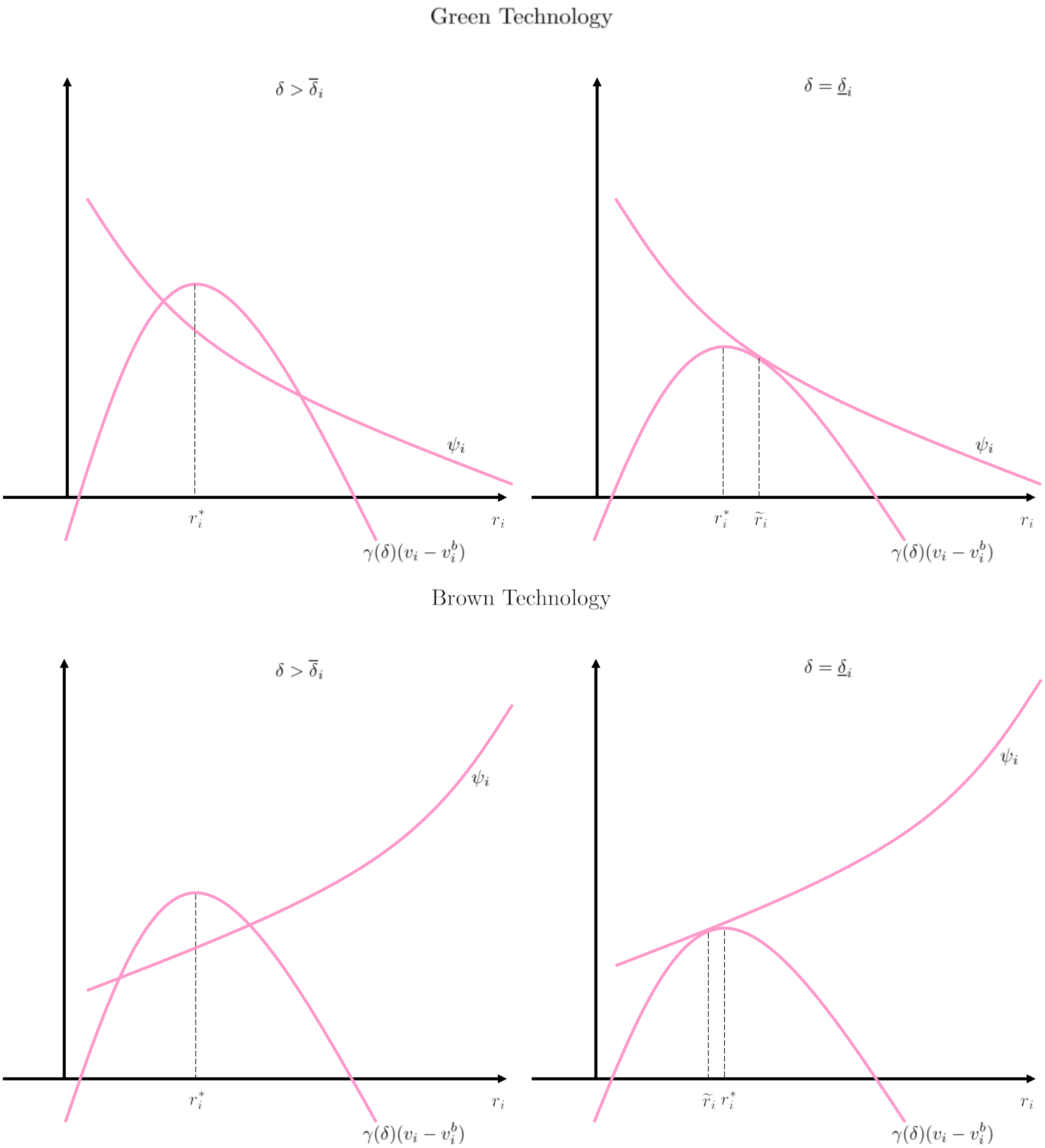

FIGURE 1. Graphical representation of the emissions compliance constraints in HLR's model. Top: Green technology, ψ_i slopes down. Bottom: Brown technology, ψ_i slopes up. Left: $\delta > \overline{\delta}_i$. Country i's emissions compliance constraints hold for first best investment r_i^*. Right: $\delta = \underline{\delta}_i$. Country i's emissions compliance constraints just hold. For green technology, this implies a higher, and for brown technology, this implies a lower than the first best investment level.

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 $(\overline{g}, r_i^b)_{i \in N}$. 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 $g_i = \overline{g}$ 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 $g_i = \overline{g}$. 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. To investigate how side payments can help sustain cooperation in emitting less greenhouse gases, we design 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 compliance constraint at the investment stage is

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

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

$$b_i(\underline{g}, r_i) - h_i n\underline{g} + \frac{\delta(v_i + p_i)}{1-\delta} \geq b_i(\overline{g}, r_i) - h_i\left[s_i\overline{g} + (n - s_i)\underline{g}\right] + \frac{\delta v_i^b}{1-\delta},$$

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 $\gamma(\delta)(v_i - v_i^b) < \psi_i(r_i)$, $(AC_{i,g}^U)$ is fulfilled only with a positive p_i. Observe that a positive p_i corresponds to a parallel upward shift of the curve $\gamma(\delta)(v_i - v_i^b)$. 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:

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

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. $\psi_i''(r_i) - \gamma(\delta)\frac{\partial^2 v_i(r_i)}{\partial r_i^2} > 0$ for $r_i \leq r_i^*$ with brown and for $r_i \geq r_i^*$ with green technology.

With green technology, Assumption 2 means that, for sufficiently large investments, the marginal benefit from an extra unit of investment falls faster for low than for high emissions, that is, $(1-\delta)b_{i,r^2}(\overline{g}, r_i) > b_{i,r^2}(\underline{g}, r_i)$. This seems not very restrictive: given $\psi_i(r_i) > 0$ for all i and given it slopes down, ψ_i must eventually be convex, which implies the assumption. For brown technology this assumption requires this inequality to hold for sufficiently small investments.

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

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

the minimum p_i, denoted by $\widehat{p}_i = \psi_i(\widehat{r}_i)/\gamma(\delta) - \left[v_i(\widehat{r}_i) - v_i^b\right]$, corresponds to the minimum distance $\gamma(\delta)\widehat{p}_i$ between ψ_i and $\gamma(\delta)(v_i - v_i^b)$. The investment level that minimizes the deficit in the applicant i's emissions compliance constraint, $\widehat{r}_i$, always exists for green technology. It may not exist for brown technology.[7] If existing, by Definition 1, $\widehat{r}_i < r_i^*$ for brown technology and $\widehat{r}_i > r_i^*$ for green technology. It is important to note that $(\widehat{r}_i, \widehat{p}_i)$ may violate $(AC_{i,r}^U)$ for both types of technology, i.e. $\widehat{p}_i < \left[v_i^b - v_i(\widehat{r}_i)\right]/\delta$. The following proposition shows that whenever it happens it is always possible to increase p_i for green technology such that the applicant i can comply 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. □

However, $\widehat{\widehat{r}}_i$ may not exist for brown technology. Next proposition gives a condition under which $\widehat{\widehat{r}}_i$ exists for brown technology.

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

Proposition 2. For brown technology, if $v_i^b - v_i(0) \geq \psi_i(0)(\overline{g} - \underline{g})$ or, equivalently, $v_i^b \geq b_i(\overline{g}, 0) - h_i n\overline{g} + h_i(n - s_i)(\overline{g} - \underline{g})$, then there exists a unique pair $(\widehat{\widehat{r}}_i, \widehat{\widehat{p}}_i)$ such that $r_i^* > \widehat{\widehat{r}}_i \geq 0$ and both $(AC_{i,r}^U)$ and $(AC_{i,g}^U)$ hold with equality.

Proof. We use of F defined in the previous proof. Since the first term of F is strictly decreasing but the second term strictly increasing, the condition that

$$\frac{v_i^b - v_i(0)}{\overline{g} - \underline{g}} \geq \psi_i(0) \quad \Longleftrightarrow \quad v_i^b \geq b_i(\overline{g}, 0) - h_i n\overline{g} + h_i(n - s_i)(\overline{g} - \underline{g})$$

guarantees the existence of the unique $\widehat{\widehat{r}}_i$ and hence $\widehat{\widehat{p}}_i$. □

If neither $\widehat{r}_i$ nor $\widehat{\widehat{r}}_i$ exists for the applicant i with brown technology, then i is required to invest at $r_i = 0$. The corresponding side payment $p_i^0 \equiv \psi_i(0)/\gamma(\delta) - v_i(0) + v_i^b$ is given such that $(AC_{i,g}^U)$ holds with equality. One can show that, with p_i^0, $(AC_{i,r}^U)$ is fulfilled. Let $\sim \widehat{r}_i$ denote the case that $\widehat{r}_i$ does not exist or $\widehat{p}_i < \left[v_i^b - v_i(\widehat{r}_i)\right]/\delta$, and $\sim \widehat{\widehat{r}}_i$ the case that $\widehat{\widehat{r}}_i$ does not exist. Then we define

$$(\bar{r}_i, \bar{p}_i) \equiv \begin{cases} (0, p_i^0) & \text{if} \sim \widehat{r}_i \text{ and} \sim \widehat{\widehat{r}}_i \\ (\widehat{\widehat{r}}_i, \widehat{\widehat{p}}_i) & \text{if} \sim \widehat{r}_i \text{ and } \widehat{\widehat{r}}_i \geq 0 \\ (\widehat{r}_i, \widehat{p}_i) & \text{otherwise} \end{cases},$$

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

$$\frac{1}{1-\delta}\left[b_i(\underline{g}, r_i) - h_i n\underline{g} - k_i r_i - t_i\right] \geq \frac{v_i^b}{1-\delta},$$

which can be rewritten as

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

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

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

Finally, the emissions compliance constraint is of the form

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

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

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

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

$$e_i \equiv \gamma(\delta)\left[v_i(\widehat{r}_i) - v_i^b\right] - \psi_i(\widehat{r}_i)$$

and call e_i the *maximum (per capita) slack in member country i's emissions compliance constraint*.[8] 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 $g_i = \underline{g}$ 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 $\bar{r}_i > r_i^*$ for green and $\bar{r}_i < r_i^*$ for brown technology, HLR's first-best equilibrium is not of our interest.[9] 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 $\sum_{i \in M} s_i e_i \geq \gamma(\delta) \sum_{i \in A} s_i \bar{p}_i$, 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 $\sum_{i \in M} e_i > \gamma(\delta) \sum_{i \in A} \bar{p}_i$, 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.

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

[9] 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 $g_i = \underline{g}$ for all $i \in N$.

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 $g_i = \overline{g}$ 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. We design an *investment-based (IB) agreement* in the following way.

Definition 4. An IB agreement is defined as follows:

1 (Investment stage for applicants). Each applicant $i \in A$ invests at the level of $\widehat{r}_i$. If $\widehat{r}_i$ does not exist, then i invests $r_i = 0$.[10]

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 do not observe any deviation in Stage 1, otherwise they switch to the BAU equilibrium immediately.[11]

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:

$$v_i + p_i \geq v_i^b. \tag{$AC^I_{i,r}$}$$

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

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

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

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

[11]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.

does not exist for brown technology, the applicant i is required to have zero investment, which associates the minimum possible amount of side payment p_i^0.

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

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

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

$$\sum_{i\in M} s_i e_i \geq \gamma(\delta) \sum_{i\in A} s_i \Big[\frac{\psi_i(r_i)}{\gamma(\delta)} - v_i(r_i) + v_i^b\Big],\ r_i = \max\{\widehat{r}_i, 0\},$$

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.

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 $g_i = \overline{g}$ 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

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

and

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

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 $\widehat{\widehat{r}}_i$ defined in Section 3.1. Recall that $\widehat{\widehat{r}}_i$ may not exist for brown technology, therefore applicant i invests at $\bar{r}_i$, with side payment $\bar{p}_i$, in our design.

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

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

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

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

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

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

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

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

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

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

3.4. **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 whenever low emissions have been observed.[12] 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.

3.4.1. *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 $g_i = \overline{g}$ for all $i, j \in N$.

3.4.2. *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

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

and

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

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

[12] 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.

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

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

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

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

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

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

Proposition 3 (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 4 (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. To be added. □

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 5 (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. To be added. □

4. Extensions

4.1. **Renegotiation proofness.**

[To be completed]

4.2. **Stochastic compliance costs.**

[To be completed]

4.3. **Bargaining power with applicants.**

[To be completed]

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 conditions for which such higher discount factors are required by inspecting the applicant countries' investment and emissions compliance constraints for upfront and results-based payments agreements. Assuming the investment level that minimizes the transfer needed for an applicant country to comply with low emissions, $\widehat{r}_i$, is positive, the corresponding transfer to applicant i is $\delta \widehat{p}_i$ for the results-based and $\widehat{p}_i/\delta$ for the upfront payments agreement. With these payments, country i's investment compliance constraint in either agreement is violated if

$$\widehat{p}_i < \frac{v_i^b - v_i(\widehat{r}_i)}{\delta} \quad \Longleftrightarrow \quad b_i(\overline{g}, r_i^b) - b_i(\overline{g}, \widehat{r}_i) - k_i(r_i^b - \widehat{r}_i) < h_i(n - s_i)(\overline{g} - \underline{g}).$$

This is more likely the case if (i) country i is small relative to the size of the world, (ii) the emissions reduction required, $\overline{g} - \underline{g}$, 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 brown and large for green technology, and (v) country i's benefit function reacts strongly to increases in investment for green and weakly to increases in investment for brown technology. 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.

We observe, however, that the existence of a credible third party to which member countries can commit to transfer funds, and which will pass on that payment to applicants upon compliance, brings us close to a world in which climate agreements are enforced by some institution other than an implicit contract. But, even though member countries would like to pre-commit, 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.

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