Technology Transfers for Climate Change

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Abstract

This paper considers the transfer of cost-reducing technology in the context of contributions to climate protection. We analyze a two-period public goods model where later contributions can be based on better information, but delaying the mitigation effort is costly because of irreversible damages. Investments in technology affect the countries' timing of contributing. We show that countries have an incentive to provide cost-reducing technology because this can lead to an earlier contribution of other countries and therefore reduce a country's burden of contributing to the public good. Our results provide a rationale for the support of technology sharing initiatives.

Keywords: Private provision of public goods; Environmental public goods; Technology sharing; Uncertainty; Irreversibility

JEL Codes: H41; Q52; D62; D83; F53

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1 Introduction

Getting countries to commit to new post-Kyoto binding CO_2 emission reduction targets has hitherto remained an elusive goal. A continued success on an international scale, however, has been the support of renewable technology initiatives. For example, the Cancún Summit in 2011 declared the start of a $1 billion new initiative and fund for the exchange of climate change technology. Technology transfer mechanisms have always been a dimension of climate change agreements. Article 4.5 of the United Nations Framework Convention on Climate Change states that countries "shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties".[1] In fact, recent studies tracking the development of clean technologies show their steady and persistent rise.[2]

This development is not surprising, given the strong national policies in support of renewable technologies which are being implemented, most notably, by the US and the EU.[3] However, this support is often controversially debated. Investments in technology can be profitable if they are perceived as investments in new markets. But, in the public good framework of environmental protection, a particularly persistent argument has been that unilateral investments in technology hurt the investing country as other countries can reduce their effort on climate protection in return.[4] Given the strong international support for technology sharing initiatives, this paper provides an argument in favor of sharing cost-reducing technologies. A country may provide a new technology, because it can induce other countries not to delay their efforts but instead to contribute to climate protection today.

To develop this rationale, three distinctive features, which influence the decision of contributing to climate protection, are taken into consideration. First, efforts to mitigate global warming are, to a large extent, private contributions to a global public good. As such, the strategic interaction between countries causes strong incentives to delay one's own contribution since, in reaction to the high effort of one country, other countries can reduce their effort on climate protection. Second, international coordination is hampered by the fact that there is uncertainty with regard to the (country-specific) need for climate protection. The uncertainty connected with climate protection stems from the fact that the costs and benefits of environmental damage and its reduction remain largely uncertain. The assessment of the impact of climate change is not only highly reliant on projections of the impact of CO_2

[1] Chapter 16 of the Stern Review (2007) identified technology-based schemes as an indispensable strategy to tackle climate change.

[2] See, for instance, UNEP (2011).

[3] See Moselle et al. (2010) for an overview.

[4] For the effects of unilateral actions in a public goods framework see Hoel (1991), Buchholz and Konrad (1994, 1995), Buchholz et al. (2005), and Beccherle and Tirole (2011).

concentrations on temperatures, but even for a given rise in global temperature there are substantial uncertainties about the economic and social consequences for a country.[5] Consequently, such strong uncertainties should push policy-makers towards a later contribution to climate protection, i.e., after the resolution of the uncertainty. Third, greenhouse gas emissions have irreversible consequences and cause damages that may possibly be mitigated only at a very high cost. Therefore, delaying the fight against global warming may prove to be expensive. For example, the accumulation of CO_2 emissions in the atmosphere is difficult to reduce, and the damage to the ecosystems from an increase in global temperatures, from acidified lakes and streams, or from the clear-cutting of forests can be permanent.[6]

Our contribution is twofold. First, we extend the standard model of private provision of a public good[7] to a framework that incorporates the important trade-off that countries face when deciding on climate policies: uncertainty versus irreversibility of damages. Our model builds on the classic concept of irreversible investments and the option value of information; however, we consider investments that exhibit a positive externality and therefore affect other players' benefit from investing.[8] We derive the equilibrium contributions to climate protection and identify the main mechanisms driving the timing of the countries' contribution decisions. In a two-country model, we show that, for low degrees of irreversibility, both countries would like to wait until the resolution of the uncertainty, while for high degrees of irreversibility the opposite is the case. For intermediate ranges of irreversibility, an alternating equilibrium emerges where one country contributes early and the other country might contribute in a later period of the game; a result strongly in line with empirical observations.

Second, building on these results, we analyze how an investment in cost-reducing technology by one country alters both countries' timing decisions of the contributions to climate protection. We consider an investment in technology in the context of technology sharing where both countries have access to the cost-reducing technology. Here, we identify two scenarios where, by a targeted use of cost-reducing technology, one country can induce the other country to increase its current contribution and in this way reduce its own burden of contributing. This free-riding incentive for investments in technology is in sharp contrast to the usual argument that unilateral investments only increase the own burden of contributing.

Our model is related to the literature on the timing of environmental policy adoption. Mainly developed by Arrow and Fisher (1974) and Henry (1974) for the case of irreversible

[5] See Allen et al. (2009) for a summary on CO_2 impact projections and their variability.

[6] The 2007 IPCC report on climate change clearly outlines the long-term cost of a "business-as-usual" CO_2 emissions path (see Chapter 3 of the IPCC Synthesis Report). For an overview of different aspects of climate protection policies see, for instance, Aldy, Orszag, and Stiglitz (2001).

[7] For a seminal contribution see Bergstrom et al. (1986) who also treat the case of quasi-linear preferences.

[8] The results of a standard one-shot public goods game and a model of irreversible investments are obtained as special cases of our model.

investments, this literature analyzes the trade-off between uncertainty and irreversibility in a one-player setting and shows that there is an option value to waiting until the resolution of the uncertainty.[9] Our paper takes up the timing issue of policy adoption and introduces the notions of irreversibility and uncertainty in a standard two-player model where investments are contributions to a public good. This allows us to isolate the effects of uncertainty and irreversibility in the strategic context of contribution considerations.[10]

Methodologically, our study is related to the standard literature on private provision of a public good in a static framework.[11] In the simplest dynamic two-period framework, our model reinforces the free-riding incentives, as countries can also free-ride on the other players' *future* contributions, similar to the results of Fershtman and Nitzan (1991) and Admati and Perry (1991) in the context of dynamic contributions to a public good.[12] Lockwood and Thomas (2002) use the notion of irreversibility in the context of contributions to a public good where, in their model, irreversibility refers to the fact that investments in previous periods cannot be taken back, a feature which is also present in our model. Gradstein (1992) introduces incomplete information into a dynamic two-period model of contributions to a public good and shows that there is inefficient delay of individual contributions.

Bramoullé and Treich (2009) examine a framework with risk averse countries where the effect of pollution emissions is uncertain. In their model, uncertainty leads to higher climate protection efforts, while in our case there is an informational advantage of delaying contributions, which causes current contributions to be lower. In a related study, Boucher and Bramoullé (2010) analyze international cooperation when climate protection benefits are uncertain.[13] To our knowledge, our study next to Morath (2010) is the first to simultaneously analyze the effects of uncertainty and irreversibility in a context of private contributions to a public good.[14]

Focusing on the interaction between technology and contributions to climate protection, Buchholz and Konrad (1994, 1995) and Buchholz et al. (2005) show that the public good nature of environmental protection might induce countries to be "less green" in order to

[9] See also Conrad (1980) , Epstein (1980), McDonald and Siegel (1986), Pindyck (1991), Kolstad (1996), Ulph and Ulph (1997), Fisher (2000), Gollier et al. (2000), and Pindyck (2002).

[10] Issues of timing have continued to play a role in the environmental literature with the recent struggles of international coordination in the post-Kyoto era. See Schmidt and Strausz (2011) and Beccherle and Tirole (2011) who analyze the impacts of delayed negotiations.

[11] See the seminal work by Bergstrom et al. (1986) and Cornes and Sandler (1985). Also see Varian (1994) on sequential contributions to a public good.

[12] Compare also Marx and Matthews (2000), Compte and Jehiel (2003), and Kessing (2007).

[13] For aspects of the formation of international environmental treaties under uncertainty see also Na and Shin (1998) and, more recently, Kolstad and Ulph (2008) and Glazer and Proost (2012); see also the literature review in Barrett (2003, 2007).

[14] Morath (2010) analyzes countries' incentives to acquire information about the cost of climate change and shows that there can be a strategic advantage of remaining uninformed.

strengthen their bargaining position in the environmental policy coordination game.[15] This argument has been further generalized by Beccherle and Tirole (2011) and still holds true when introducing uncertainty or dynamics.[16] This robust result, however, stands in strong contrast to the steady rise of investments in renewable energy. Our model considers investments in technology in the context of technology transfer mechanisms; here, we identify scenarios where a cost-reducing investment, which is shared between both countries, generates an outcome where investments in green technology can actually reduce a country's burden of contributing to the public good.[17] Our model abstracts from bargaining over a cooperative outcome and highlights the public goods nature of mitigation policies. By affecting the time pattern of contributions, technology sharing can, in a non-cooperative approach, lead to a rise in current contributions to climate protection.

The paper is structured as follows: Section 2 introduces the model framework, and Section 3 solves for the equilibrium contributions. Section 4 isolates the effects of uncertainty, irreversibility, and free-riding on the timing of the contribution. Section 5 analyzes the impact of the technology sharing of a cost-reducing investment on the timing of the contributions. Section 6 discusses our main assumptions, and Section 7 concludes. All proofs are in the appendix.

2 Model framework

We consider a framework with two countries A and B and two periods t and $t+1$. In each period, countries simultaneously choose a contribution to a public good where $x_{i,\tau} \in \mathbb{R}_+$ denotes country i's contribution in period τ, $i \in \{A, B\}$ and $\tau \in \{t, t+1\}$.[18] Moreover, we denote by $\mathbf{x}_\tau = (x_{A,\tau}, x_{B,\tau})$ the vector of contributions in period τ. The marginal contribution costs in the two periods are assumed to be constant and identical for both countries and are denoted by $c_t(\kappa) > 0$ and $c_{t+1}(\kappa) > 0$; κ refers to the technology available to the countries, and c_t and c_{t+1} are assumed to be continuous and differentiable in κ (as explained below).[19]

[15] See also the results of Shah (2010) in the context of negotiations of emission caps.

[16] See Harstad (2012, 2014) and Konrad and Thum (2014).

[17] See Golombek and Hoel (2005, 2011) for international agreements and cooperation on investments in technology when technology investments have spillover effects. Note also that there is a literature in industrial organization which considers the timing of technology adoption and first-mover advantages (seminal contributions include Reinganum 1981 and Fudenberg and Tirole 1985; for a survey see Hoppe 2002).

[18] The subscripts $i \in \{A, B\}$ and $\tau \in \{t, t+1\}$ distinguish between country and time dimension. Whenever a variable is constant across time and countries, respectively, we drop the redundant index (such as for the country-independent marginal contribution cost c_τ and time-independent valuations θ_i; see below).

[19] Hence, while a country's total cost is assumed to be linear in the contribution $x_{i,\tau}$, the marginal cost c_τ is a function of the technology κ. Note that we only explicitly refer to κ whenever changes in κ are analyzed; otherwise we remove the variable κ to simplify the exposition (such as in equation (1), for instance).

Individual contributions in the two periods sum up to the total amount contributed to the public good. Country i's payoff is equal to

$$\pi_i(\mathbf{x}_t, \mathbf{x}_{t+1}) = \theta_i f\left(\sum_{k=A,B} \sum_{\tau=t,t+1} x_{k,\tau}\right) - c_t x_{i,t} - c_{t+1} x_{i,t+1},\ i \in \{A, B\}. \tag{1}$$

Here, function f translates climate protection effort into a mitigation outcome. As usual, f is assumed to be strictly increasing and concave, $f' > 0$, $f'' < 0$.[20]

Uncertainty. Countries only differ in their valuation of the public good, denoted by θ_A and θ_B. The heterogeneity in this valuation captures all country differences in the cost-benefit ratio of climate protection efforts (hence including differences in the cost of effort). These country-specific valuations of the public good are independent draws from two commonly known continuous distribution functions Φ_A and Φ_B with support $[0, \bar{\theta}]$. The functions Φ_A and Φ_B are assumed to be continuously differentiable on $(0, \bar{\theta})$. We will restrict the analysis to probability distributions with the following reverse hazard rate:

Assumption 1: $\frac{\Phi_i'(\theta)}{\Phi_i(\theta)} \leq \frac{1}{\theta}$ *for all* $\theta \in (0, \bar{\theta}),\ \ i = A, B.$

This assumption ensures that the countries' maximization problems in period t are well-behaved and that the objective function is concave.[21]

In period t, there is uncertainty about the valuations (θ_A, θ_B) of the public good, which will be resolved in period $t + 1$; both countries' valuations θ_A and θ_B become commonly known only between periods t and $t + 1$. Overall, no country has private information about its benefit from climate policy: Country-specific differences with respect to cost and benefit of climate protection are typically observed.[22] The uncertainty in the model, thus, reflects the difficulty of assessing the cost-benefit ratio and, hence, the valuation of climate protection.[23]

[20] To simplify the exposition, we will assume that $\theta f'(0)$ is sufficiently large for all $\theta > 0$ to ensure that all types $\theta > 0$ will prefer a strictly positive total amount of the public good. Note that we abstract from discounting. One can argue that discounting is already captured by the difference in marginal contribution costs c_t and c_{t+1} necessary to produce one contribution unit.

[21] Note that, for instance, uniform or exponential probability distributions fulfill Assumption 1. This assumption is sufficient but not necessary for obtaining our results, and it simplifies the equilibrium analysis considerably.

[22] Research on the impact of climate change such as the studies by the IPCC and UNFCCC is usually publicly accessible. There are extensive studies on the impact of climate change on various regions with detailed analysis that clearly shows the different possible outcomes of climate change by regions.

[23] For example, in a review of impact estimates of climate change, Jamet and Corfee-Morlot (2009) identify five sources of uncertainty: greenhouse gas emission projections, the accumulation of emissions in the atmosphere and how these emissions affect global temperatures, the physical impacts of a given increase in temperature, the valuation of physical impacts in terms of GDP and the risk of abrupt climate change. While there is also substantial uncertainty about variables which affect all countries in a similar way, such as the

Contribution cost and irreversibility. The aspect of the irreversibility of foregone mitigation efforts is reflected in the contribution costs. We assume that the contribution cost in $t+1$ per unit of mitigation outcome is strictly larger than contribution cost in t per unit of mitigation outcome,

$$c_{t+1}(\kappa) > c_t(\kappa).$$

This assumption is built on the fact that CO_2 is a stock pollutant and hence current emissions cause long-term costs.[24]

Before proceeding we briefly address the two main assumptions on the contribution cost. First, we assume the objective functions to be quasi-linear. Due to the concavity of the production function, mitigation effort exhibits decreasing returns to scale, or in other words, the marginal cost of achieving one additional unit of mitigation outcome is increasing. Strategic interdependencies emerge through the production function f. The assumption of quasi-linear payoff function is mainly made for tractability; we further discuss this assumption in Section 6.2.

Second, we assume future mitigation to be more expensive than achieving the same mitigation outcome when acting already today: $c_{t+1} > c_t$. A general increase in average world temperature cannot be easily reduced, regardless of how advanced the abatement technology is. CO_2 stocks in the atmosphere dissipate very slowly and their impact can have considerable effects on the ecosystem. Similarly, counteracting deforestation is a slow and costly process; once large parts of the rainforest have been cut down, it will take a very long time and expensive measures for it to grow back.[25] Thus, due to the irreversibility of damages, delaying mitigation efforts may make future climate policy more expensive, in particular if it turns out that climate change imposes great risks, to economic development as well as to human health and security.

To illustrate this assumption, which is a shortcut of a more complex model of irreversible choices, define the public good as the reduction of cumulative emissions of greenhouse gases, compared to 'business as usual'. A reduction $z_{i,\tau}$ in the emissions path at marginal cost k (caused by, for instance, a subsidy on renewable energy infrastructure) reduces cumulative emissions by $\lambda_\tau z_{i,\tau}$ units, where $\lambda_t > \lambda_{t+1}$ since the earlier yearly reductions are imple-

relation between greenhouse gas concentration and the rise in global temperature, a given rise in temperature does not impose the same cost on all countries. Our model focuses on uncertainty about country-specific factors rather than common factors, that is, on the differential impact of climate change on countries.

[24] For an economic analysis of the cost of stabilization of CO_2 concentration see Chapters 9-11 of the Stern Review (2007) and the discussion in Mendelsohn (2008) and Dietz and Stern (2008).

[25] Furthermore, other environmental damages like acidified rain and lakes can have considerable irreversible consequences. Similar arguments can be made with respect to the melting of polar ice caps and glaciers; compare also the discussions of scientists and environmentalists about the "point of no return" in climate change.

mented (low-carbon power sources are used), the larger is the total reduction of the stock of greenhouse gases in the atmosphere.[26] Now define $x_{i,\tau} := \lambda_\tau z_{i,\tau}$ and $c_\tau := k/\lambda_\tau$. Then, $x_{i,t}$ and $x_{i,t+1}$ are perfect substitutes: They have the same marginal impact on the public good provision (greenhouse gas concentration). But the cost to produce one unit of $x_{i,t+1}$ is equal to $c_{t+1} = k/\lambda_{t+1}$ and hence strictly larger than the cost $c_t = k/\lambda_t$ to produce one unit of $x_{i,t}$.[27]

Intuitively, the assumption on the relative contribution cost implies the following: If climate change turns out not to have severe consequences for a country (θ_i is low), then this country's total contribution cost will not be much different today or tomorrow. But for a country that finds out to be strongly affected by climate change, delay will result in much higher cost of abatement. Although we think that there are good reasons to believe that the same mitigation outcome can be achieved at lower cost today than in the future (due to the foregone abatement opportunities), we are aware of the debate on climate change impacts and mitigation costs, which results in opposing views on the timing of climate policy. Section 4 shows how the prediction of our model changes if (expected) future marginal contribution cost is lower than today's contribution cost.

Investments in technology. Our main focus is on the effects of an investment in cost-reducing technology on the equilibrium climate protection outcome. We concentrate on the notion that the developed abatement technology is shared between countries. Generally, successful investments in R&D have strong spillover effects, for example, through trade magazines and reverse engineering by competitors. In addition, patent protection for new inventions and innovations only have a limited time frame. Furthermore, in the case of climate abatement technology, such spillovers are more strongly encouraged through large technology transfer initiatives. Thus, we consider investments in cost-reducing technology $\kappa \in [\kappa_0, \infty)$ which affect the marginal costs of both countries in the same way. κ_0 denotes the status quo and we analyze whether or not an ex ante improvement of the available technology will change the structure of the equilibrium contributions in periods t and $t+1$. We only consider the case where an improvement in technology (weakly) reduces both

[26] For predictions of the effects of delaying abatement efforts on cumulative emissions see, e.g., McKinsey (2009). In addition to this direct effect of delay on cumulative emissions, there can also be a "lock-in effect".

[27] Note that there can be an additional effect of current climate policies: they may reduce future contribution cost. In our model this relation is captured by the fact that today's and tomorrow's efforts are substitutes; hence, when having contributed already today, this reduces the need for high effort tomorrow and the total effort cost to be incurred in the future is lower. We abstract from a potential direct effect of $x_{i,t}$ on the *marginal* contribution cost c_{t+1}, but separate the provision of technology (which will in fact reduce both periods' marginal contribution cost) and the choice of a contribution based on the technology available.

periods' marginal contribution cost, that is,

$$\frac{\partial c_t(\kappa)}{\partial \kappa} \leq 0 \text{ and } \frac{\partial c_{t+1}(\kappa)}{\partial \kappa} \leq 0.$$

Note that technologies with a strong impact on today's contribution cost do not necessarily need to start being developed today, but they might build on progress achieved during the last decades, such as in the case of solar energy technology. To put differently, technologies that reduce c_t are sufficiently developed to be transferred immediately. Renewable energies are, in fact, a good example for this type of technology. Making solar cells with high energy conversion efficiency available (or subsidizing their transfer) reduces other countries' cost of increasing the share of renewable energies, both today and possibly in the future, even though the impact on future cost is less certain due to the innovation to be expected in the energy sector.

The game. Our analysis solves for the subgame-perfect Nash equilibrium of the following game.[28] In stage 0, nature independently draws the country-specific valuations of the public good from the distribution functions Φ_A and Φ_B, which are common knowledge. Investments in technology also take place in stage 0 and decrease the contribution costs of both countries in both periods, due to technology transfer. Our main analysis does not explicitly model the countries' investment choices but considers how changes in technology affect the equilibrium contribution pattern. An example will illustrate the consequences of the results obtained for a strategic game of technology investment.

In stage 1 of the game (period t), countries A and B simultaneously choose their contributions $x_{A,t} \geq 0$ and $x_{B,t} \geq 0$. Then, both contributions and the country-specific valuations of the public good become publicly observable. In stage 2 (period $t+1$) countries, again simultaneously, choose their contributions $x_{A,t+1} \geq 0$ and $x_{B,t+1} \geq 0$. The choice $x_{i,t+1}$ is a function of the observed valuations (θ_A, θ_B) and the observed period t contributions $(x_{A,t}, x_{B,t})$; hence, the stage 2 strategy of country i is a mapping

$$\sigma_i : \Theta \times \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$$

[28] In the game specified, no player has private information about his type at any point in time, but each player's type is only revealed after period t. Hence, to be precise, a complete characterization of the equilibrium would require specification of the players' beliefs about their own and their co-player's type. In our equilibrium analysis, we implicitly assume that, in period t, each player $i = A, B$ believes that his and his co-player's type are drawn from the distributions Φ_A and Φ_B, respectively, and we solve for the perfect Bayesian equilibrium under these beliefs. In period $t+1$, both types become common knowledge; thus, updating of beliefs does not play a role in our framework. For simplicity, we omit this more complex notation.

from the set Θ of pairs of valuations $\boldsymbol{\theta} = (\theta_A, \theta_B)$ and the set $\mathbb{R}^2_+$ of period t contributions $\mathbf{x}_t = (x_{A,t}, x_{B,t})$. Finally, payoffs are realized.

3 Contributions to Climate Protection

In this section, we characterize the countries' equilibrium public good contributions in the two periods. The countries' contributions are strategic substitutes, and, as we will show, the countries' optimal contributions depend not only on incentives to free-ride on the other country's (current and future) contributions but also on the trade-off between uncertainty and irreversibility of damages. We solve the game through backward induction.

3.1 Preferred provision levels in period $t+1$

Consider first period $t+1$. Here, the countries' valuations θ_A and θ_B are common knowledge and the game is strategically equivalent to a standard private provision game with a given contribution $X_t = x_{A,t} + x_{B,t}$. We define a country i's *preferred provision level* of the public good in $t+1$ as the quantity $Q_{i,t+1}(\theta_i)$ that solves i's first order condition

$$\theta_i f'(Q_{i,t+1}) - c_{t+1} = 0,$$

that is

$$Q_{i,t+1}(\theta_i) := \begin{cases} (f')^{-1}(c_{t+1}/\theta_i) & \text{if } \theta_i > 0 \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

$Q_{i,t+1}(\theta_i)$ denotes the level of contributions up to which i would like to increase total contributions and is useful to characterize i's equilibrium contribution (which can be different from $Q_{i,t+1}$). First, a country might only contribute a strictly positive amount in period $t+1$ if the total period t contributions X_t are lower than the preferred quantity $Q_{i,t+1}(\theta_i)$. Moreover, due to the quasi-linear payoff functions, in equilibrium one country at most will contribute in period $t+1$; this country will be the country i with the higher preferred provision level $Q_{i,t+1}(\theta_i)$ or, equivalently, the country i with the higher valuation θ_i for the public good.[29] This country i raises the contribution level up to its desired quantity $Q_{i,t+1}(\theta_i)$, and country

[29] This is in line with the standard textbook result for public goods models with quasi-linear utility functions; comparing the first order condition of both players, it becomes clear that the equilibrium must be at a corner solution.

$j \neq i$ free-rides and contributes zero. Hence, the equilibrium contributions are given by[30]

$$\left(x^*_{A,t+1}, x^*_{B,t+1}\right) = \begin{cases} \left(\max\left\{Q_{A,t+1}\left(\theta_A\right) - X_t, 0\right\}\ ,\ 0\right) & \text{if} \quad \theta_A > \theta_B \\ \left(0\ ,\ \max\left\{Q_{B,t+1}\left(\theta_B\right) - X_t, 0\right\}\right) & \text{if} \quad \theta_A < \theta_B. \end{cases} \tag{3}$$

3.2 Preferred provision levels in period t

Inserting the equilibrium contributions in period $t+1$ into country i's decision problem in period t, country i chooses $x_{i,t}$ to maximize its expected payoff given $\mathbf{x}^*_{t+1} = \left(x^*_{A,t+1}, x^*_{B,t+1}\right)$ and given $x_{j,t}$. With choices in $t+1$ denoted by

$$\boldsymbol{\sigma}\left(\boldsymbol{\theta}, \mathbf{x}_t\right) = \left(\sigma_A\left(\boldsymbol{\theta}, \mathbf{x}_t\right), \sigma_B\left(\boldsymbol{\theta}, \mathbf{x}_t\right)\right),$$

we define

$$\Pi_i\left(x_{i,t}, x_{j,t}\right) = E_{\boldsymbol{\theta}}\left[\pi_i\left(x_{i,t}, x_{j,t}, \boldsymbol{\sigma}\left(\boldsymbol{\theta}, \mathbf{x}_t\right)\right)\right]$$

as country i's expected payoff from the point of view of period t, given that the vector of strategies played in period $t+1$ is $\boldsymbol{\sigma}$. Hence, $\Pi_i\left(x_{i,t}, x_{j,t}\right)$ is equal to

$$\int_0^{\bar{\theta}} \int_0^{\theta_i} \left(\theta_i f\left(\max\{Q_{i,t+1}\left(\theta_i\right), X_t\}\right) - c_t x_{i,t} - c_{t+1} \max\left\{Q_{i,t+1}\left(\theta_i\right) - X_t, 0\right\}\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right)$$
$$+ \int_0^{\bar{\theta}} \int_{\theta_i}^{\bar{\theta}} \left(\theta_i f\left(\max\{Q_{j,t+1}\left(\theta_j\right), X_t\}\right) - c_t x_{i,t}\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right). \tag{4}$$

Taking contributions in period $t+1$ into account, country i weighs the expected probabilities of two possible cases: the case where it turns out that it has the higher valuation in period $t+1$ than country j (the first double integral in (4)), and the case where it has a lower valuation than country j (the second double integral in (4)).

In both cases ($\theta_i > \theta_j$ and $\theta_i < \theta_j$), potential contributions in period $t+1$ also depend on the amount X_t that has already been contributed in period t, since i might only contribute in period $t+1$ if its preferred provision level $Q_{i,t+1}\left(\theta_i\right)$ is strictly larger than X_t. Using (2) and the fact that $Q_{i,t+1}\left(\theta_i\right)$ is strictly increasing in θ_i we can define by

$$\hat{\theta} := \frac{c_{t+1}}{f'\left(X_t\right)} \tag{5}$$

the *critical valuation* for which a country's preferred provision level in $t+1$ is exactly equal

[30] If $\theta_A = \theta_B$ and $Q_{A,t+1}\left(\theta_A\right) > X_t$, there is a continuum of equilibria with $x^*_{A,t+1} + x^*_{B,t+1} = Q_{A,t+1}\left(\theta_A\right) - X_t$. For completeness, we assume that in this case the symmetric equilibrium with $x^*_{A,t+1} = x^*_{B,t+1}$ is played, although $\theta_A = \theta_B$ occurs with probability zero (due to the assumption of continuous distribution functions Φ_A and Φ_B).

to X_t. Consequently, only countries with a realized valuation $\theta > \hat{\theta}$ may contribute in $t+1$.

Now consider country i's expected marginal payoff of an increase in $x_{i,t}$. Suppose first that the given total contribution X_t is smaller than $Q_{i,t+1}(\bar{\theta})$ (where $Q_{i,t+1}(\bar{\theta})$ is the preferred provision level in $t+1$ of the type with the highest possible valuation $\bar{\theta}$). In this case, contributions in $t+1$ occur with strictly positive probability, and i's marginal expected payoff of an increase in $x_{i,t}$ is equal to[31]

$$\begin{aligned} \left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t < Q_{i,t+1}(\bar{\theta})} &= \int_0^{\hat{\theta}} \int_0^{\hat{\theta}} \left(\theta_i f'\left(X_t\right) - c_t\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right) \\ &\quad + \int_{\hat{\theta}}^{\bar{\theta}} \int_0^{\theta_i} \left(c_{t+1} - c_t\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right) \\ &\quad + \int_0^{\bar{\theta}} \int_{\max\left\{\theta_i, \hat{\theta}\right\}}^{\bar{\theta}} \left(-c_t\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right). \end{aligned} \tag{6}$$

This marginal expected payoff in (6) consists of three terms representing three different cases: First, if both countries' realized valuations are smaller than the critical valuation $\hat{\theta}$, then no contribution will take place in $t+1$. Hence, with the probability that $\theta_i \leq \hat{\theta}$ and $\theta_j \leq \hat{\theta}$, country i's marginal payoff of increasing the period t contribution is the difference between the marginal benefit of public good consumption and the marginal contribution cost in t (the first term in (6)).

Otherwise, if i's realized valuation is greater than the critical valuation (i.e., $\theta_i > \hat{\theta}$), then i would, in principle, be willing to make a contribution in $t+1$, and its equilibrium contribution in $t+1$ will depend on whether j has a lower or higher valuation for climate protection. The second term in (6) reflects the case where $\theta_i > \theta_j$ and hence i's equilibrium contribution in $t+1$ is strictly positive. Here, the marginal payoff of increasing the period t contribution is equal to the difference in the contribution costs, $c_{t+1} - c_t$: by increasing the period t contribution, country i will save the higher contribution cost in $t+1$. The third term in (6) represents i's marginal payoff given that country j has a higher valuation (and $\theta_j > \hat{\theta}$); in this case, country i's marginal benefit of increasing the period t contribution is zero because this contribution would have been made by j in period $t+1$ anyway, and a contribution only bears the marginal cost c_t.

Altogether, the three terms illustrate the trade-off between uncertainty (unknown realization of the valuation) and irreversibility (higher contribution cost in $t+1$) on the one hand and the incentives to free-ride on the other hand. While the effect of irreversibility in the second term in (6) is always positive and the free-riding effect in the third term is always

[31] For more details see the proof of Lemma 1 in the appendix.

negative, the sign of the first term depends on X_t. More precisely, the integrand in the first term in (6) is small and possibly negative for low realizations θ_i and increasing in θ_i.

If total early contributions $X_t = x_{A,t} + x_{B,t}$ are sufficiently high, they will crowd out all potential contributions in period $t+1$: $X_t \geq Q_{i,t+1}(\bar{\theta})$ is equivalent to $\hat{\theta} \geq \bar{\theta}$, and i's marginal payoff of an increase in $x_{i,t}$ reduces to

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t \geq Q_{i,t+1}(\bar{\theta})} = \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(X_t\right) - c_t\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right). \tag{7}$$

Regardless of which valuation is revealed in period $t+1$, no contribution will take place; consequently, considerations with regard to a potential cost or saving of a contribution in period $t+1$ do not play a role. In this case, the expected marginal benefit of increasing $x_{i,t}$ is simply equal to $E\left(\theta_i\right) f'\left(X_t\right)$ and the marginal cost is c_t.

Optimizing over $x_{i,t}$ yields a *preferred provision level* $Q_{i,t}$ in period t for country $i \in \{A, B\}$, taking into account that equilibrium contributions in $t+1$ are as in (3). Notice that $Q_{i,t} > 0$ does not imply that i's equilibrium contribution $x^*_{i,t}$ must necessarily be positive. Rather, $Q_{i,t}$ is the quantity that i would contribute to the public good in period t if j does not contribute. Compared to country i's preferred provision level in period $t+1$, which directly depends on θ_i, the preferred level $Q_{i,t}$ of period t depends on i's expectations of the realizations of θ_i and θ_j and the corresponding equilibrium contributions in the subgame in period $t+1$. The following lemma characterizes each country's preferred period t provision level. It is assumed, as for all following statements, that Assumption 1 holds.

Lemma 1 *Consider the quantity of the public good that country $i \in \{A, B\}$ would prefer to be provided in period t.*

(i) *Suppose that $E\left(\theta_i\right)/\bar{\theta} \geq c_t/c_{t+1}$. Then country i's preferred provision level in period t is equal to $Q_{i,t} = \left(f'\right)^{-1}\left(c_t/E\left(\theta_i\right)\right) \geq Q_{i,t+1}\left(\bar{\theta}\right)$.*

(ii) *Suppose that $E\left(\theta_i\right)/\bar{\theta} < c_t/c_{t+1}$.*

(a) *If*

$$E_{\theta_i}\left(\Phi_j\left(\theta_i\right)\right) \leq \frac{c_t}{c_{t+1}}, \tag{8}$$

then country i's preferred provision level in period t is equal to $Q_{i,t} = 0$.

(b) *If*

$$E_{\theta_i}\left(\Phi_j\left(\theta_i\right)\right) > \frac{c_t}{c_{t+1}}, \tag{9}$$

then country i's preferred provision level in period t is uniquely determined with $Q_{i,t} \in \left(0, \left(f'\right)^{-1}\left(c_t/E\left(\theta_i\right)\right)\right)$.

In Lemma 1(i), if the expected to maximum valuation ratio $E(\theta_i)/\bar{\theta}$ is higher than the cost ratio c_t/c_{t+1}, then country i prefers a provision level in t that is sufficiently high to crowd out all further contributions in $t+1$. (Here, $Q_{i,t}$ is higher than $Q_{i,t+1}(\bar{\theta})$, which is the preferred period $t+1$ provision level for the highest possible valuation.) In this case, $Q_{i,t}$ is determined irrespective of period $t+1$ and, hence, it is determined such that marginal cost c_t is equal to expected marginal benefit $E(\theta_i) f'(Q_{i,t})$ from contributing. We will refer to such a situation as the case of a "full" preferred provision level in period t, and it occurs if the expected valuation and/or the degree of irreversibility is high (where the degree of irreversibility is measured as the inverse cost ratio c_{t+1}/c_t).

If, however, $E(\theta_i)/\bar{\theta}$ is lower than the cost ratio c_t/c_{t+1}, then country i will never want a full provision in period t already. In this case, $\partial\Pi_i/\partial x_{i,t}|_{X_t=0} \leq 0$, or (8), is sufficient to ensure that i does not want to contribute in t, independently of $x_{j,t}$. This leads to Lemma 1(ii)a. By the same argument, if instead $\partial\Pi_i/\partial x_{i,t}|_{X_t=0} > 0$, or (9), then country i prefers a strictly positive provision level $Q_{i,t}$ in period t. Here, i prefers only a "partial" provision in t, accepting that, depending on the true valuations, it might contribute again in $t+1$ (Lemma 1(ii)b).[32]

Which country prefers a higher public good provision in period t? The mechanism of a standard private provision game persists in the contribution decision of period t. Due to the quasi-linear payoff functions, positive contributions by either country are perfect substitutes. Thus, in equilibrium only the country i with the higher preferred contribution level $Q_{i,t} > Q_{j,t}$ will contribute in t. Concretely, this country will contribute exactly $x^*_{i,t} = Q_{i,t}$, and the other country will contribute zero in period t.

Before turning to the characterization of the equilibrium, consider therefore the determinants of whether $Q_{i,t} > Q_{j,t}$. If both countries prefer a full provision in period t (as in Lemma 1(i)), the country with the higher expected valuation will bear the contribution cost since the preferred quantity is increasing in $E(\theta)$; hence i prefers a higher quantity if and only if $E(\theta_i) > E(\theta_j)$. If i prefers a full provision in t (Lemma 1(i)) and the other country j prefers a partial provision (Lemma 1(ii)b), this implies that $E(\theta_i)/\bar{\theta} \geq c_t/c_{t+1} > E(\theta_j)/\bar{\theta}$ and thus in this case country i, with $E(\theta_i) > E(\theta_j)$, is again the country that prefers the higher provision level.[33]

In the case where both countries prefer a "partial provision" in period t (Lemma 1(ii)b), the comparison of the expected valuations is no longer sufficient to determine which country

[32] Note that $E(\theta_i)/\bar{\theta} < c_t/c_{t+1}$ implies that $(f')^{-1}(c_t/E(\theta_i)) < Q_{i,t+1}(\bar{\theta})$. Hence, in Lemma 1(ii)b, $Q_{i,t} < Q_{i,t+1}(\bar{\theta})$: the highest type's preferred quantity in $t+1$ is strictly higher than what i prefers to be contributed in t.

[33] This holds due to $Q_{j,t} \leq (f')^{-1}(c_t/E(\theta_j)) < (f')^{-1}(c_t/E(\theta_i)) = Q_{i,t}$.

prefers a higher quantity to be provided in t. Consider the difference in the countries' marginal payoffs from contributing in t for a given X_t, which is equal to

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t} - \left.\frac{\partial \Pi_j}{\partial x_{j,t}}\right|_{X_t} = \Phi_i\left(\hat{\theta}\right)\Phi_j\left(\hat{\theta}\right)\left[E\left(\theta_i \mid \theta_i \leq \hat{\theta}\right) - E\left(\theta_j \mid \theta_j \leq \hat{\theta}\right)\right] f'\left(X_t\right) + c_{t+1}\left[\int_{\hat{\theta}}^{\bar{\theta}} \Phi_j\left(\theta_i\right) d\Phi_i\left(\theta_i\right) - \int_{\hat{\theta}}^{\bar{\theta}} \Phi_i\left(\theta_j\right) d\Phi_j\left(\theta_j\right)\right]. \quad (10)$$

As (10) reveals, differences in the countries' preferred provision levels in period t are driven by two comparisons: first, by differences in the expected benefit from contributing, conditional on there being no further contributions in $t+1$ (the first term: conditional expected valuation multiplied by $f'(X_t)$); and second, by differences in the expected equilibrium contribution cost in period $t+1$ (the second term: c_{t+1} multiplied by the probability that this cost has to be paid). If (10) is positive at $X_t = Q_{j,t}$, then i prefers a higher "partial provision" in t. Without making further assumptions on the cumulative distribution functions, it is not straightforward when (10) is positive. If $\partial \Pi_i / \partial x_{i,t}|_{X_t} - \partial \Pi_j / \partial x_{j,t}|_{X_t} > 0$ for all $X_t \geq 0$, it is clear that country i will have a higher preferred contribution level. This is the case, for instance, if the countries' distributions of the valuations can be ranked according to first-order stochastic dominance. In general, however, the first and the second term in (10) do not need to have the same sign, and whether $Q_{i,t} > Q_{j,t}$ will also depend on f and c_{t+1}.

3.3 Equilibrium contributions

The equilibrium contributions in period t follow directly from the analysis above, which is summarized in the following proposition.

Proposition 1 *The countries' equilibrium contributions in period t are determined such that*

(i) *if $Q_{A,t} = Q_{B,t} = 0$, then $x^*_{A,t} = x^*_{B,t} = 0$,*

(ii) *if $Q_{A,t} > Q_{B,t} \geq 0$, then $x^*_{A,t} = Q_{A,t}$ and $x^*_{B,t} = 0$,*

(iii) *if $Q_{B,t} > Q_{A,t} \geq 0$, then $x^*_{A,t} = 0$ and $x^*_{B,t} = Q_{B,t}$,*

(iv) *if $Q_{A,t} = Q_{B,t} > 0$, then there is a continuum of equilibria with $x^*_{A,t} + x^*_{B,t} = Q_{A,t}$,*

where the countries' preferred provision levels $Q_{A,t}$ and $Q_{B,t}$ are given in Lemma 1.

Proposition 1 results directly from Lemma 1; hence, a proof is omitted. If the degree of irreversibility is low and hence the cost ratio c_t/c_{t+1} is close to 1 (to be precise, if c_t/c_{t+1}

is larger than $\max\{E_{\theta_i}(\Phi_j(\theta_i)), E(\theta_i)/\bar{\theta}\}$; compare Lemma 1), then both countries prefer not to contribute in t but instead to wait until period $t+1$ (case (i)). In this case, total expected contributions to the public good are equal to

$$E(X_{t+1}) = E_{\boldsymbol{\theta}}[\max\{Q_{A,t+1}(\theta_A), Q_{B,t+1}(\theta_B)\}]$$

since, in $t+1$, the country with the higher valuation will contribute its preferred provision level based on the contribution cost c_{t+1}.

For intermediate values of c_t/c_{t+1}, at least one country prefers a positive provision level in t (cases (ii) and (iii)), and only one country contributes in t. For such intermediate irreversibility ratios, it is optimal to choose only a partial provision in period t, and there will be further contributions in $t+1$. When c_{t+1} is high and, hence, the ratio c_t/c_{t+1} is low, the incentive to contribute early becomes even stronger; the country that contributes in t will choose a full provision in t which crowds out all possible contributions in $t+1$. Finally, if both countries prefer exactly the same (positive) provision level in t (for instance, if $\Phi_A = \Phi_B$), then there is a continuum of equilibria where the countries' contributions in t sum up to this preferred level (case (iv)).

The derived equilibrium contributions have several implications. First, it becomes clear that if there is a positive contribution to the public good in any period, then it will be borne by only one country (except for the special case in Proposition 1(iv)). Furthermore, the contribution decision is additionally affected by the possibility of "intertemporal free-riding". Depending on the degree of irreversibility c_{t+1}/c_t, the equilibrium contribution in the early period can be zero, a partial provision or a full provision.

4 Isolating the effects on timing

In the following, we isolate the different motivations that drive the timing of the countries' equilibrium contributions to climate protection.

The effects of uncertainty and irreversibility on the timing of the contribution. The analysis of the previous section has been crucially driven by the countervailing effects of uncertainty versus irreversibility. To further illustrate these effects, suppose that there is uncertainty about the valuations for climate protection but no irreversibility of foregone efforts to climate protection. When c_{t+1} approaches c_t (or even becomes lower than c_t), a contribution in t is strictly dominated, independently of the remaining parameters of the model, as for instance the probability distributions Φ_A and Φ_B. Both countries prefer to wait until the resolution of the uncertainty. A standard game of private provision of a public good, based on the realized valuations, will ensue in period $t+1$. Uncertainty is the predominant effect in case (i) of Proposition 1.

Now suppose instead that there is irreversibility but no uncertainty; that is, the variance of Φ_A and Φ_B goes to zero but the structure of the model remains unchanged. In the limit where the valuations are already known in period t, delaying the contribution until $t+1$ is strictly dominated, as contributions in $t+1$ cause a strictly higher marginal cost. Accordingly, both countries prefer to contribute in period t at the lower marginal cost c_t. This is comparable to cases (ii)-(iii) of Proposition 1, provided that the equilibrium contribution $x_{i,t}^* = Q_{i,t}$ ensures a full provision of the public good in t.

In summary, while uncertainty pushes the timing of the contribution to climate protection towards a later date, irreversibility pushes the timing towards an earlier date.

The effect of free-riding on the timing of the contribution. To isolate the effect of (intertemporal) free-riding on the optimal timing decision, suppose that there is only one country i which decides over its contribution to climate protection. The remaining structure of the model remains unchanged. Solving the model through backward induction, it is straightforward to see that the rationale driving the preferred provision level of period $t+1$ is identical to the two-country case. The only difference is that the preferred provision level $Q_{i,t+1}(\theta_i)$ automatically constitutes the country's equilibrium contribution in $t+1$.

Now turn to country i's optimal choice in period t, taking into account that $x_{i,t+1}^* = Q_{i,t+1}(\theta_i)$. Suppose that i's contribution in t is smaller than $Q_{i,t+1}(\bar{\theta})$ which ensures a positive contribution in $t+1$ with positive probability. Again, $\hat{\theta} = c_{t+1}/f'(x_{i,t})$ denotes the critical valuation below which there will be no contribution in $t+1$. In the one-country case, i's marginal expected payoff from increasing the contribution in t is equal to

$$\int_0^{\hat{\theta}} \left(\theta_i f'(x_{i,t}) - c_t\right) d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \left(c_{t+1} - c_t\right) d\Phi_i(\theta_i). \tag{11}$$

Let us compare this marginal payoff to the marginal payoff in the two-country case, as given in (6). Similar to (6), the first term in (11) describes the marginal payoff if there is no contribution in $t+1$ (because $\theta_i \leq \hat{\theta}$). This marginal payoff also emerges in the two-country case (the first term in (6)), but, there, only with the probability that j also has a valuation below the critical valuation ($\theta_j \leq \hat{\theta}$).

The second term in (11) represents the savings in marginal contribution cost in case i's valuation turns out to be high. In the one-country case, these savings are realized whenever $\theta_i > \hat{\theta}$, while in the two-country case, this positive effect on a period t contribution also depends on whether or not $\theta_j < \theta_i$. In the two-country case, even if i has a valuation above the critical valuation ($\theta_i > \hat{\theta}$), this does not necessarily imply that it has to pay the high marginal cost c_{t+1}, as j will bear the contribution cost whenever $\theta_j > \theta_i$; hence, in the two-country case, the probability that these savings are realized is lower. Finally, the two-country case identifies an additional negative effect on the marginal payoff which corresponds to the possibility to free-ride and is not present in the one-country case (the third term in (6)). In the two-country case, if it turns out that the other country has a higher valuation, having increased the contribution in t would have caused an unnecessary cost.

While the benefits from an early contribution in the two-country case are realized only with lower probability, the possibility of free-riding on the other country's future contribution adds a cost to a contribution in period t, which does not play a role in the one-country case. Consequently, the presence of another country and the strategic context of the public good problem cause a country's marginal payoff from an early contribution to be lower and, therefore, shift the timing of the contribution towards a later period.[34]

5 Investments in technology and the timing of contributions

Having analyzed the equilibrium contributions, we can now turn to our main question and consider the effect of an exogenous investment in cost-reducing technology κ on countries' timing of the contributions to climate protection. Recall that the cost-reducing technology κ is defined such that an increase in κ decreases the marginal contribution cost for both countries over both time periods. More specifically, the cost-reducing technology is denoted by κ, and κ_0 denotes the initial technology in use. The main propositions in this section focus on the consequences of (exogenous) changes in κ for the equilibrium outcome as regards the timing of contributions. The results obtained will directly clarify the implications for a strategic game of investments in technology (in stage 0 of the model), as we will illustrate by means of an example.

Our analysis mainly focuses on situations where the inverse irreversibility ratio c_t/c_{t+1} is strictly decreasing over the interval $[\kappa_0, \infty)$ of possible technology levels. This is the case when an investment in cost-reducing technology reduces the marginal contribution cost of period t relatively more strongly than the marginal contribution cost of period $t+1$. Intuitively, this can be interpreted as the notion that innovations in cost-reducing technology made today are more suited to tackle climate protection, given today's information, and that

[34]In this sense, the inclusion of a second country exhibits a similar free-riding rationale as derived in Admati and Perry (1991) and Fershtman and Nitzan (1991).

these technologies might be less effective with altered conditions or knowledge at a later date. For example, one can think of power plants whose efficiency is highly sensitive to a changing regulatory framework, environment, and fuel prices; as such it is likely that investments in this technology reduce the costs in the early period more effectively than in a later period. We concentrate our analysis on this type of investments in cost-reducing technologies as it is more in line with implemented technology transfer initiatives which focus on transferring green technologies to be used immediately. In Section 6.1, we further discuss the assumption of a decreasing irreversibility ratio as well as the opposite scenario in which investments in technology increase the cost ratio.

In the next two subsections, we first analyze how an investment in cost-reducing technology affects the preferred provision levels. Then, we identify cases where such changes in the provision level lead to a change in the equilibrium contribution pattern.

5.1 Categorical changes in the period t contributions

In the following, we identify how investments in cost-reducing technology can effect a "categorical change" in the preferred provision levels $Q_{A,t}$ and $Q_{B,t}$. We consider "categorical changes" to be changes which are linked with a change in the equilibrium contribution pattern. While marginal reductions in the contribution costs c_t and c_{t+1} always (weakly) increase total contributions, we focus cost reductions that affect one country's (or both countries') optimal timing of the contributions, i.e., that affect whether or not a country will choose a strictly positive contribution already in period t and which type of early contribution is preferred.[35] Hence, the conditions identified in Lemma 1 will be important: the ratio of expected valuation $E(\theta_i)$ to maximum valuation $\bar{\theta}$; and the expected value of the probability $\Phi_j(\theta_i)$ that j has a lower valuation than i $(\theta_j < \theta_i)$.

Proposition 2 *Suppose that the irreversibility ratio $\gamma(\kappa) := c_t(\kappa)/c_{t+1}(\kappa)$ is strictly decreasing in κ. Then, there are two country-specific thresholds*

$$\kappa_i^p := \gamma^{-1}\left(E_{\theta_i}\left(\Phi_j(\theta_i)\right)\right) \text{ and } \kappa_i^f := \gamma^{-1}\left(E(\theta_i)/\bar{\theta}\right)$$

for country $i \in \{A, B\}$ such that

(i) *if $\kappa < \kappa_i^f$ and $\kappa \leq \kappa_i^p$, then country i's preferred provision level in period t is $Q_{i,t} = 0$,*

(ii) *if $\kappa \geq \kappa_i^f$, then country i prefers a full provision $Q_{i,t} = (f')^{-1}(c_t/E(\theta_i))$ in period t,*

[35] An analysis of the marginal effects on already positive contribution levels is relegated to Appendix A.7.

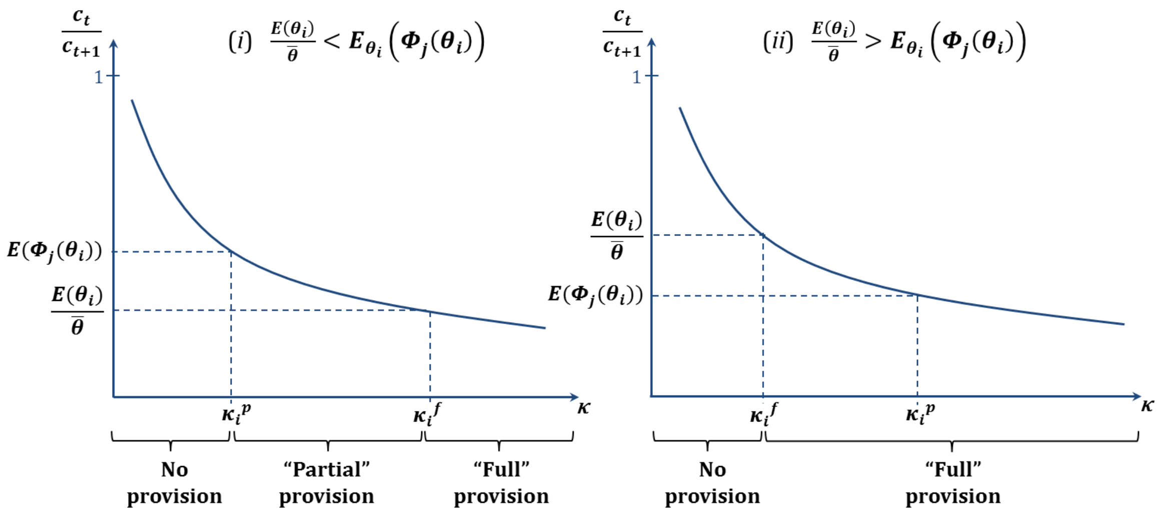

Figure 1: Country-specific technology thresholds for the preferred provision level in period t.

(iii) *if* $E(\theta_i)/\bar{\theta} < E_{\theta_i}(\Phi_j(\theta_i))$, *then* $\kappa_i^p < \kappa_i^f$ *and country* i *prefers a partial provision* $Q_{i,t} \in \left(0, (f')^{-1}(c_t/E(\theta_i))\right)$ *in period* t *for all* $\kappa \in (\kappa_i^p, \kappa_i^f)$.

As Lemma 1 has revealed, the relation of the inverse irreversibility ratio c_t/c_{t+1} to the expected probability $E_{\theta_i}(\Phi_j(\theta_i))$ of i having a higher valuation than j determines whether or not a country prefers a partial provision in t. The relation of c_t/c_{t+1} to the expected to maximum valuation ratio, $E(\theta_i)/\bar{\theta}$, determines whether or not a country prefers a full provision of the public good in t.[36] Thus, investments in technology can have an effect on the timing of the countries' contributions if they change the cost ratio $c_t(\kappa)/c_{t+1}(\kappa)$. Proposition 2 identifies the country-specific technology thresholds under which such investments in technology alter the timing decision from no contribution to a positive provision level and from a partial preferred provision level to a full provision level. For a shift of the contribution path towards an earlier provision, it is sufficient (but not necessary) that the inverse irreversibility ratio $c_t(\kappa)/c_{t+1}(\kappa)$ is strictly decreasing in κ over the interval $[\kappa_0, \infty)$ of possible technology levels. Notice that, for illustrational purposes, we have added the superscript p and f to the technology thresholds, to signal the type of period t provision preferred by country i: a partial or a full provision in period t.

For low technology levels where $\kappa < \kappa_i^f$ and $\kappa \leq \kappa_i^p$, the relative cost of waiting is not too high, and it is a strictly dominant strategy for country i to wait until the uncertainty

[36]Note that if $\bar{\theta} \to \infty$, then $\kappa_i^f \to \infty$. This means that for any positive cost parameters, country i will never choose a full provision in period t. In other words, if θ_i can be infinitely large, there is always a positive probability that i contributes in the late period as well.

is resolved. For technology investments $\kappa \geq \kappa_i^f$, country i prefers a full provision in period t since the inverse irreversibility ratio is smaller than $E(\theta_i)/\bar{\theta}$; this high contribution in t crowds out any further contribution in $t+1$. For intermediate investment levels, due to the fact that $E(\theta_i)/\bar{\theta}$ can be smaller or larger than $E(\Phi_j(\theta_i))$, we need to distinguish between two cases which are illustrated in Figure 1. If $E(\Phi_j(\theta_i)) > E(\theta_i)/\bar{\theta}$, then $\kappa_i^p < \kappa_i^f$ (compare Figure 1(i)). In this case, there is a non-empty interval (κ_i^p, κ_i^f) of technology levels where a partial provision in period t is optimal for i. If instead $E(\Phi_j(\theta_i)) \leq E(\theta_i)/\bar{\theta}$, then $\kappa_i^p \geq \kappa_i^f$ (compare Figure 1(ii)). In this case, $E(\Phi_j(\theta_i))$ and the corresponding country-specific technology threshold κ_i^p is not relevant for i's period t contribution decision, as country i's preferred provision level in t will either be zero (if $\kappa < \kappa_i^f$) or the full amount $Q_{i,t} = (f')^{-1}(c_t/E(\theta_i))$ based on its expected valuation (if $\kappa \geq \kappa_i^f$).

Hence, one can distinguish between two occasions that constitute a "categorical change" in the preferred provision levels. The first is an investment in cost-reducing technology which changes a country's preferred early provision from zero to a positive amount. The second occasion is an investment in cost-reducing technology which changes a country's preferred early provision level from a partial provision to a full provision. In both scenarios, investments in technology can have an impact on the determination of the country that, in equilibrium, pays the contribution cost of an early provision of the public good in t.

5.2 Technology sharing to free-ride

The focus on a scenario in which all countries benefit from the cost reductions caused by investments in green technology adds an interesting layer to the analysis of the equilibrium contribution pattern. Investments in cost-reducing technology can shift the equilibrium burden of contributing from one country to the other; as a consequence, incentives to invest in technology are affected by strategic considerations and free-riding incentives. We identify the two "free-riding scenarios" where a categorical change of the equilibrium contribution pattern occurs: a situation where otherwise no contributions take place in period t, and a situation where, at the status quo, one country already contributes in period t.

Since the country-specific valuations for climate protection can be asymmetrically distributed in our model, it is clear that the thresholds κ_i^p and κ_i^f for $i = \{A, B\}$ (that is, the countries' incentives for an early contribution) can differ for the countries. Merging Figure 1 for the two countries, thus, allows us to identify the irreversibility ratios and corresponding technology ranges that are connected with the different equilibrium contribution patterns introduced by Proposition 1. An example is illustrated in Figure 2. In this example, the respective thresholds for country i are lower than those for country j, implying that i's

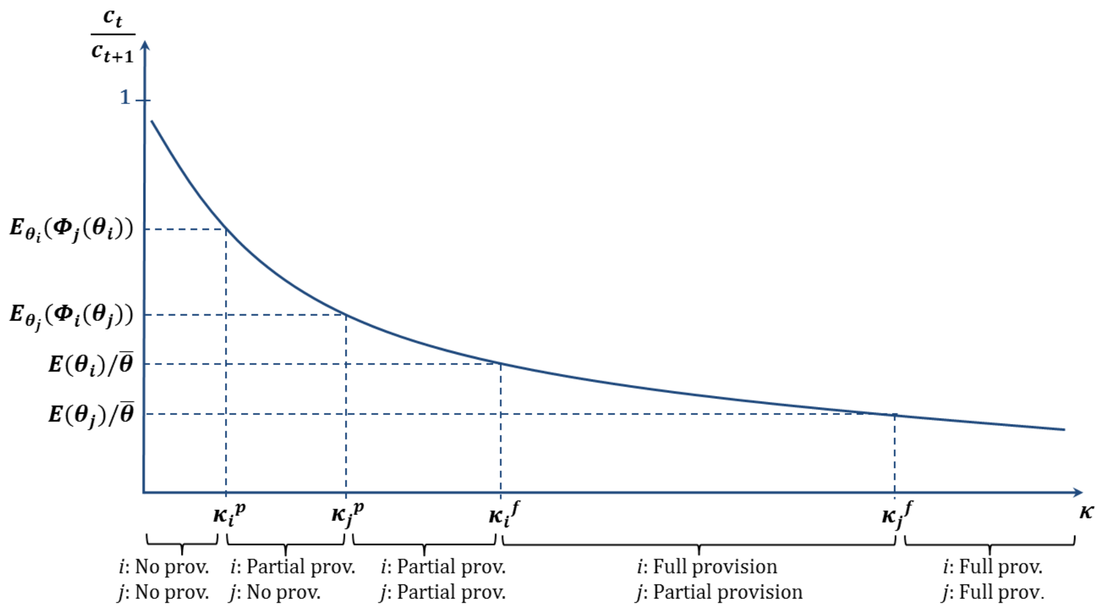

Figure 2: An example of categorical changes in the preferred period t provision level.

incentive to contribute early is stronger.

Scenario 1: no contributions in period t. First, we consider the effect of an investment in technology in a situation where, without cost-reducing technology, there would be no contribution to the public good in period t, but both countries prefer to delay their contribution until period $t+1$. This occurs in equilibrium if

$$\kappa_0 < \min\left\{\kappa_i^p, \kappa_i^f\right\} \text{ for } i = A, B, \tag{12}$$

that is, for both countries, κ_0 is smaller than the lowest technology level necessary to induce a positive early contribution (compare Figure 2).

Proposition 3 *Suppose that $c_t(\kappa)/c_{t+1}(\kappa)$ is strictly decreasing in κ and (12) holds such that, without investment in technology, equilibrium contributions in period t are zero. Define $i \in \{A, B\}$ and $j \neq i$ such that*

$$\max\left\{E_{\theta_i}\left(\Phi_j\left(\theta_i\right)\right), E\left(\theta_i\right)/\bar{\theta}\right\} > \max\left\{E_{\theta_j}\left(\Phi_i\left(\theta_j\right)\right), E\left(\theta_j\right)/\bar{\theta}\right\}. \tag{13}$$

Then, for all investments in cost-reducing technology with technology level

$$\kappa \in \left(\min\left\{\kappa_i^p, \kappa_i^f\right\}, \min\left\{\kappa_j^p, \kappa_j^f\right\}\right),$$

the resulting equilibrium contributions in period t *satisfy* $x^*_{i,t} > 0$ *and* $x^*_{j,t} = 0$.

Proposition 3 addresses the incentives to invest in cost-reducing technology in a situation where actually both countries prefer to delay their contribution to climate protection until period $t+1$. In this case, a targeted provision of cost-reducing technology κ by country j can raise country i's equilibrium contribution in period t from zero up to a strictly positive amount, while country j free-rides. Notice that the early contribution of i strictly decreases the expected burden of contributing that both countries face in period $t+1$.

To illustrate the result in Proposition 3, suppose there are two key players to climate protection, say China and the United States, and both prefer to delay their contributions at the status quo. Provided that China has the higher expected valuation of climate protection or/and the higher probability of having the higher valuation, the United States have a strategic benefit from developing green technology, which will be used domestically and as well as transferred to China. This strategic benefit emerges if the technology transfer changes the equilibrium pattern and leads to an increased current climate protection effort of China. The intuition behind this incentive to invest in cost-reducing technology hinges on the fact that, due to the different degrees of uncertainty which countries face, the incentives to contribute early react differently to changes in the inverse irreversibility ratio c_t/c_{t+1}. Thus, there is a range $(\min\{\kappa_i^p, \kappa_i^f\}, \min\{\kappa_j^p, \kappa_j^f\})$ of technology levels κ where the cost ratio decreases for both countries, but the preferred provision level in t is raised from zero to a positive amount only for one country.[37]

This strategic opportunity to benefit from an early contribution of the other country exists for the country j which requires a lower cost ratio to start developing a positive preferred period t provision level (more precisely, $j \in \{A, B\}$ is defined according to (13)). Thus, j has, in this case, a stronger incentive to invest in technology, as it does not only benefit from lower contribution cost but also from i's increased early contribution. Notice that it is unnecessary to distinguish between the type of positive contribution reached: j benefits if i chooses a partial or a full provision of the public good in period t. While Proposition 3 addresses the case where an investment in technology causes a "categorical change" in the preferred early contribution only for one country, the conditions given in Proposition 3 are sufficient but not necessary in the sense that very high levels of κ can of course yield a similar effect on equilibrium contributions in period t.

Scenario 2: positive equilibrium contribution in period t. Now consider a situation where, without investment in technology, the equilibrium contributions to the public good

[37] This effect cannot occur, of course, when countries are completely symmetric ex ante (i.e., their valuations are identically distributed).

are such that country j contributes a positive amount in period t, while country i free-rides and contributes zero. Again, investments in technology can cause a "categorical change" in the equilibrium and lead to the opposite scenario where, in equilibrium, the previously non-contributing country i is now contributing a major share to climate protection.

A situation where, without investment in technology, equilibrium contributions are $x^*_{i,t} = 0$ and $x^*_{j,t} > 0$ emerges if

$$\min\left\{\kappa^p_j, \kappa^f_j\right\} < \kappa_0 < \min\left\{\kappa^p_i, \kappa^f_i\right\}, \; i \in \{A, B\}, \; j \neq i. \tag{14}$$

Here, without investments in technology, i has a dominant strategy to delay its contribution (due to $\kappa_0 < \min\{\kappa^p_i, \kappa^f_i\}$), but j prefers a strictly positive contribution in t (due to $\kappa_0 > \min\{\kappa^p_j, \kappa^f_j\}$).

Proposition 4 *Suppose that $c_t(\kappa)/c_{t+1}(\kappa)$ is strictly decreasing in κ and (14) holds such that, without investment in technology, country j's equilibrium contribution in t is strictly positive.*

(i) *If $E(\theta_i) > E(\theta_j)$ and $E(\theta_i)/\bar{\theta} \geq E(\Phi_j(\theta_i))$, then, for all investments in cost-reducing technology with technology level $\kappa \in [\kappa^f_i, \infty)$, the resulting equilibrium contributions in period t satisfy $x^*_{i,t} > 0$ and $x^*_{j,t} = 0$.*

(ii) *If $E(\theta_i) > E(\theta_j)$ and $E(\theta_i)/\bar{\theta} < E(\Phi_j(\theta_i))$, then there exists $\delta > 0$ such that, for all investments in cost-reducing technology with technology level $\kappa \in (\kappa^f_i - \delta, \infty)$, the resulting equilibrium contributions in period t satisfy $x^*_{i,t} > 0$ and $x^*_{j,t} = 0$.*

The mechanism driving this proposition is straightforward: As above, an investment in cost-reducing technology that affects both countries may change the irreversibility ratio and, thus, elicit a different optimal response in the public good game. Country j may initially prefer a partial contribution in period t while i prefers to wait, but a targeted choice of investments in technology alters the trade-off that each country faces. If country i has the higher expected valuation ($E(\theta_i) > E(\theta_j)$), a sufficiently high investment in technology will shift the burden of contributing to country i, in case both countries prefer an early contribution (based on their expected valuation). Proposition 4 again distinguishes whether or not $\kappa^f_i \leq \kappa^p_i$ (compare Figure 1). In part (i), $\kappa^f_i \leq \kappa^p_i$, and country i prefers either a zero or a full contribution in period t; in this case, a technology level $\kappa \geq \kappa^f_i$ is necessary and sufficient to cause a situation where, in equilibrium, country i chooses a strictly positive early contribution. In part (ii), $\kappa^f_i > \kappa^p_i$, and there exists a range of technology levels κ where i prefers a partial early provision. In this case, if κ is lower but sufficiently close to κ^f_i (that is, $\kappa > \kappa_i^f - \delta$), the period t quantity preferred by i is larger than the quantity preferred by j, and thus i bears the burden of contributing early.

In this second scenario, summarized in Proposition 4, we capture a situation where the country that initially expects a higher potential saving from an early contribution is actually the country with the lower expected valuation for the public good. This country j with the lower expected valuation can still have a stronger incentive to contribute early, since, when a country chooses a partial contribution in period t, it trades off the marginal benefit from an early contribution (depending on the expected valuation) and the expected marginal contribution cost in $t+1$, which depends on the probability that it turns out it has the higher valuation. Thus, as long as the countries' differences in the expected valuation for climate protection $(E(\theta_i) - E(\theta_j))$ and the expected probability of having the higher valuation $(E(\Phi_j(\theta_i)) - E(\Phi_i(\theta_j)))$ do not go in the same direction, a targeted reduction of the irreversibility ratio via cost-reducing technology κ can result in a shift in the burden of the early contribution.[38] Country j with the lower expected value, which, for the initial degree of irreversibility, would prefer a positive early public good provision, has a strategic benefit of technology sharing: For a sufficiently high investment in cost-reducing technology, the other country i with the higher expected value also prefers a positive early provision and contributes in equilibrium.

The intuition behind Proposition 4 lies in the fact that the degree of uncertainty interacts with the optimal timing of the contributions. A key player like the European Union, for instance, might have a rather low expected valuation of climate protection, but also a low variance, while other countries have a higher expected valuation but also a higher variance. For the latter types of countries, the incentive to delay the contribution might be stronger at the status quo since they still have the option to contribute in the future. But if the trade-off is resolved in favor of a contribution today, then their current contribution will be relatively high. Proposition 4 implies that the provision of green technology by, say, Europe can generate a strategic advantage if it increases the early contribution of a country with a high expected valuation, say China, and in this way reduces Europe's burden of contributing.

The results in Propositions 3 and 4 have direct implications for the effect of an investment in technology by country j on the other country's payoff and on total payoffs. First of all, note that, in scenario 1, i's expected payoff increases if j provides and transfers the new technology because j's early contribution is the same with and without technology investment (there is no crowding-out). And contributions of the "receiving" country i are less costly based on

[38] Intuitively, this scenario can occur when the distribution function Φ_i with the higher expected value also exhibits thicker tails. An example for distribution functions with $E(\theta_i) > E(\theta_j)$ but $E(\Phi_j(\theta_i)) < E(\Phi_i(\theta_j))$ is $\Phi_i \equiv Gamma(1,3)$ and $\Phi_j \equiv Gamma(0.5,8)$.

the new technology κ. Thus, abstracting from direct cost of providing the technology, both countries are strictly better off.

In scenario 2, the investment in technology shifts the burden of an early contribution from j to i; this has a negative effect on i's expected payoff, which is stronger the larger the amount j would have contributed in period t without investment in technology. On the other hand, i's marginal contribution cost is reduced and the public good provision increases. Therefore, in scenario 2, country i would join the technology transfer mechanism without additional incentives if and only if the positive effects of lower marginal cost and an increased public good provision outweigh the negative effect of an increased burden of contributing. Otherwise, i might decide against adopting a new technology although technology sharing would increase total expected payoffs. In both scenarios, however, whenever the investment costs (the resources to be expended for developing a new technology) are sufficiently low (or there are benefits in addition to the increased climate protection), the investing country j is better off by providing the technology κ.

While there is clearly a strategic benefit of investing in technology whenever such investments increase the other country's early contribution, the set of equilibria of a strategic game of technology investments depends, of course, on additional assumptions on the technology production function (in particular, on potential spillover effects if both countries can choose positive investments). The following example illustrates the results in Propositions 3 and 4 and their consequences for a simple technology investment game in stage 0 in which the countries make simultaneous binary investment decisions.

An illustrative example. Suppose that Φ_A is a Gamma distribution on $[0, \infty)$ with shape parameter 1 and scale parameter 3 and that Φ_B is a Gamma distribution with shape parameter 0.5 and scale parameter 8. Note that $E(\theta_A) = 1 \cdot 3 < 0.5 \cdot 8 = E(\theta_B)$. Moreover, let $f(X) = \ln(X)$. We consider the extended game where in stage 0 (prior to periods t and $t+1$), countries make a simultaneous binary choice of whether or not to invest in technology at level $\hat{\kappa}$ at a given cost. If at least one country invests, technology $\hat{\kappa}$ is provided.[39]

We first determine a country i's technology threshold for which is prefers a strictly positive early provision level $Q_{i,t} > 0$. Note that the technology thresholds are a function of the probability distributions Φ_A and Φ_B only. Due to the support $[0, \infty)$, countries will never

[39] This is, of course, a very simplified version of a strategic game of technology investment, with the purpose to illustrate the implications of Propositions 3 and 4. It abstracts from investment spillovers and joined efforts and considers only one possible type of technology. But the strategic benefit of technology transfer will also appear in a more complex modeling of technology investments involving, for instance, continuous and possibly complementary choices of the countries.

choose a full provision of the public good in t ($\kappa_i^f \to \infty$). Moreover, we get

$$E_{\theta_A}\left(\Phi_B\left(\theta_A\right)\right) \approx 0.522 \text{ and } E_{\theta_B}\left(\Phi_A\left(\theta_B\right)\right) \approx 0.478$$

which implies that $\kappa_A^p < \kappa_B^p$ (compare Figure 2). Even though $E\left(\theta_A\right) < E\left(\theta_B\right)$, the range in which a country's preferred provision level in t is zero (i.e., where $\kappa \leq \kappa_i^p$) is larger for B than for A. To derive the countries' equilibrium contributions, we have to further specify the cost parameters.

Scenario 1: Suppose that initially $c_t\left(\kappa_0\right) = 2$ and $c_{t+1}\left(\kappa_0\right) = 3$ and consider the option to provide a technology level $\hat{\kappa}$ which reduces both countries' contribution cost to $c_t\left(\hat{\kappa}\right) = 1$ and $c_{t+1}\left(\hat{\kappa}\right) = 2$. Using Lemma 1(ii)a, since

$$E_{\theta_B}\left(\Phi_A\left(\theta_B\right)\right) < E_{\theta_A}\left(\Phi_B\left(\theta_A\right)\right) < \frac{c_t\left(\kappa_0\right)}{c_{t+1}\left(\kappa_0\right)} = \frac{2}{3},$$

in equilibrium no country contributes in period t at the initial technology κ_0: that is, $x_{A,t}^*\left(\kappa_0\right) = x_{B,t}^*\left(\kappa_0\right) = 0$. The corresponding expected equilibrium payoffs are $\pi_A^*\left(\kappa_0\right) \approx -0.041$ and $\pi_B^*\left(\kappa_0\right) \approx 1.096$.[40]

At technology $\hat{\kappa}$, however, we get

$$E_{\theta_B}\left(\Phi_A\left(\theta_B\right)\right) < \frac{c_t\left(\hat{\kappa}\right)}{c_{t+1}\left(\hat{\kappa}\right)} = \frac{1}{2} < E_{\theta_A}\left(\Phi_B\left(\theta_A\right)\right).$$

Thus, it follows that $x_{B,t}^*\left(\hat{\kappa}\right) = 0$ but $x_{A,t}^*\left(\hat{\kappa}\right) > 0$. Using A's marginal benefit of increasing $x_{A,t}$ in (6) yields $x_{A,t}^*\left(\hat{\kappa}\right) \approx 0.542$ and, thus, expected equilibrium payoffs of $\pi_A^*\left(\hat{\kappa}\right) \approx 1.189$ and $\pi_B^*\left(\hat{\kappa}\right) \approx 3.235$. The equilibrium contributions in period t and the expected equilibrium payoffs are summarized in Figure 3.

The implications for the countries' incentives to provide the technology $\hat{\kappa}$ are straightforward. Note first that both countries' expected payoffs are higher under technology level $\hat{\kappa}$ than under technology level κ_0. This implies that technology is a public good, and both countries are better off when adopting technology $\hat{\kappa}$. In analogy to Proposition 3, however, country $j = B$ (which free-rides in period t under the improved technology) benefits more from technology $\hat{\kappa}$:

$$\pi_B^*\left(\hat{\kappa}\right) - \pi_B^*\left(\kappa_0\right) > \pi_A^*\left(\hat{\kappa}\right) - \pi_A^*\left(\kappa_0\right).$$

Hence, if the cost of technology level $\hat{\kappa}$ is smaller than $\pi_A^*\left(\hat{\kappa}\right) - \pi_A^*\left(\kappa_0\right)$, the reduced form

[40] This can be easily verified by plugging in all relevant parameters into (4) and using the fact that $Q_{i,t+1}\left(\theta_i\right) = \theta_i / c_{t+1}$ for $f\left(X\right) = \ln\left(X\right)$. (Note that the negative expected payoff of A is due to $\ln\left(X\right) < 0$ for $X < 1$.)

	Inverse irreversibility ratio		Preferred provision level in period t		Expected equilibrium payoff	
			$Q_{A,t}$	$Q_{B,t}$	π_A^*	π_B^*
Scenario 1 (high → interm.)	high	$c_t = 2, c_{t+1} = 3$ ($\frac{c_t}{c_{t+1}} = 0.667$)	0	0	-0.041	1.096
Scenario 2 (interm. → low)	interm.	$c_t = 1, c_{t+1} = 2$ ($\frac{c_t}{c_{t+1}} = 0.5$)	**0.542**	0	1.189	3.235
	low	$c_t = 0.5, c_{t+1} = 1.25$ ($\frac{c_t}{c_{t+1}} = 0.4$)	3.353	**4.567**	5.113	4.881

Figure 3: Example for equilibrium contributions and expected payoffs depending on the cost ratio c_t/c_{t+1} (for $\Phi_A = Gamma\,(1,3)$, $\Phi_B = Gamma\,(0.5,8)$, $f\,(X) = \ln\,(X)$).

game of technology provision has two equilibria in pure strategies such that exactly one country $k \in \{A, B\}$ provides the technology $\hat{\kappa}$. For intermediate cost of technology, there is a unique equilibrium in which country B (with the incentive to free ride) provides the technology. And for high cost of technology, no country invests in technology.[41]

Scenario 2: To illustrate the second type of strategic investments in technology, suppose instead that initially $c_t\,(\kappa_0) = 1$ and $c_{t+1}\,(\kappa_0) = 2$, which results in equilibrium contributions and payoffs just as above. Consider again the option to provide a technology at level $\hat{\kappa}$ which now reduces both countries' contribution cost to $c_t\,(\hat{\kappa}) = 0.5$ and $c_{t+1}\,(\hat{\kappa}) = 1.25$. Hence, at technology $\hat{\kappa}$, we get

$$\frac{c_t\,(\hat{\kappa})}{c_{t+1}\,(\hat{\kappa})} = \frac{2}{5} < E_{\theta_B}\left(\Phi_A\,(\theta_B)\right) < E_{\theta_A}\left(\Phi_B\,(\theta_A)\right).$$

By Lemma 1, $Q_{i,t}\,(\hat{\kappa}) > 0$ for $i = A, B$; both countries prefer a positive early provision and the equilibrium contribution pattern depends on whether $Q_{A,t}\,(\hat{\kappa}) > Q_{B,t}\,(\hat{\kappa})$ (compare Proposition 1). For the assumed parameters of the model, $Q_{A,t}\,(\hat{\kappa}) \approx 3.353$ and $Q_{B,t}\,(\hat{\kappa}) \approx 4.567$. Therefore, $x^*_{A,t}\,(\hat{\kappa}) = 0$ and $x^*_{B,t}\,(\hat{\kappa}) = 4.567$, with corresponding equilibrium payoffs of $\pi^*_A\,(\hat{\kappa}) \approx 5.113$ and $\pi^*_B\,(\hat{\kappa}) \approx 4.881$.

In analogy to Proposition 4, country $j = A$ initially contributes in period t. But an investment in technology can change the equilibrium contribution pattern: at technology

[41] Here we assume for simplicity that the cost of technology is the same for both countries, which is obviously a strong assumption, not only because of differences in R&D capacities but also because of country differences in the cost of public funds.

$\hat{\kappa}$, country $i = B$ chooses an early contribution and country $j = A$ free rides. Therefore, while both countries' expected payoffs are higher under $\hat{\kappa}$, country A benefits more from the cost-reducing technology.

The consequences for a reduced form game of technology provision in stage 0 are similar to Scenario 1. For a low cost of technology $\hat{\kappa}$ there are two pure strategy equilibria each with one of the countries investing. For intermediate cost of technology $\hat{\kappa}$, country A invests in equilibrium. Since both countries are made better off in terms of expected payoffs, country B will join the technology transfer mechanism even though doing so reduces A's early contribution. This holds in the example because the reduced contribution costs cause a sufficiently strong benefit for B to compensate for the increased burden of public good provision.

Welfare implications. Investments in technology have direct and indirect effects on *ex ante expected welfare* being defined as the sum of the countries' expected payoffs. First, there is a direct cost in terms of resources to be expended for developing the technology, and there is a direct benefit in terms of reduced marginal contribution cost (compare the example above). In addition, however, there are *indirect* welfare effects from investments in technology in situations where the countries' timing of contributions is affected. As shown in Propositions 3 and 4, investments in technology can shift the countries' equilibrium contributions towards the early period. The direct effect of an increase in κ is obvious; the following considerations isolate the indirect effect on the timing decisions. This timing effect alone has an impact on total expected equilibrium contributions to the public good and hence on welfare.

Corollary 1 *Total expected equilibrium contributions are strictly increasing in the contribution X_t^* in period t.*

The result in Corollary 1 is straightforward: Higher early contributions *strictly* increase total equilibrium contributions to the public good. Intuitively, while higher early contributions just crowd out late contributions in case at least one country's valuation turns out to be high, there is no crowding out in case both θ_A and θ_B turn out to be low (both lower than the critical valuation $\hat{\theta}$, see (5)). Hence, overall we get

$$\frac{\partial}{\partial X_t} \left(X_t + E_{\boldsymbol{\theta}} \left(X_{t+1}^* \mid X_t \right) \right) \bigg|_{X_t = X_t^*} = \Phi_A \left(\hat{\theta} \right) \Phi_B \left(\hat{\theta} \right) \geq 0$$

with strict inequality for all $X_t^* > 0$. Since $\hat{\theta}$ depends on c_{t+1}, this also takes into account that contributions in period $t + 1$ are less likely due to the higher marginal cost. Thus, even disregarding the direct effect on the contribution costs, investments in technology cause total contributions to be higher when they affect the timing of contributing as in Propositions 3 and 4. In turn, this effect on the countries' timing of contributing is also welfare-improving:

Corollary 2 *Ex ante expected welfare is strictly increasing in total contributions X_t^* in period t.*

Corollary 2 addresses the indirect welfare effects of investments in technology caused by a change in the equilibrium contribution pattern (abstracting from direct cost effects). Here, even though higher early contributions lead–with higher probability–to an overcontribution from an individual country's point of view, a change in the countries' timing of the contributions in line with Propositions 3 and 4 increases welfare, because of two reasons. First, since, in equilibrium, there is underprovision of the public good, an increase in total contributions $X_t^* + X_{t+1}^*$ (as in Corollary 1) is welfare-improving. Second, in equilibrium, early contributions X_t^* are inefficiently low due to 'intertemporal free-riding' (compare the discussion of the one-country case in Section 4); thus, increasing early contributions is again welfare-improving.

To summarize, investments in technology have direct costs and benefits, but, in addition, there are indirect effects caused by the impact on the countries' timing of equilibrium contributions: A shift towards early contributions increases welfare because it mitigates the underprovision problem. Even if the investment cost exceeds the investing country j's benefit from providing the technology or if the receiving country i bears higher expected contribution costs, welfare can still be higher if investments in technology are carried out and technology transfer mechanisms are implemented. In such situations of a non-cooperative game of contributions to climate protection, the support of technology sharing mechanisms at the supranational level will be welfare-enhancing.

6 Discussion

6.1 Effect of technology on the irreversibility ratio

The main analysis has focused on investments in technology that are relatively more effective and useful to reduce current greenhouse gas emissions and, hence, have a stronger impact on current contribution cost, compared to the future cost of climate protection. A substantial share of low carbon technologies has this property that they are useful to reduce emissions today and in the near future. In light of potential technologies such as nuclear fusion and carbon capture and storage, the importance of many currently used abatement technologies for the distant future is rather uncertain.[42] But there are also other types of technology investments which rather aim at long-term gains, providing a potential for future cost reductions. And our analysis in the previous sections (Propositions 1 and 2) can be used to shed light on incentives to share this second type of technologies.

In particular, the result in Proposition 2 shows that investments in technology which *increase* the inverse irreversibility ratio c_t/c_{t+1} (by strongly reducing c_{t+1}) lead to (weakly) lower equilibrium contributions in period t. Referring back to "categorical changes" in the equilibrium pattern, a country's preferred provision level in t may change from a full provision to a partial provision or from a partial provision to no provision if c_t/c_{t+1} is increased (recall the thresholds κ_i^p and κ_i^f). Even when investments in cost-reducing technology increase the cost ratio c_t/c_{t+1}, they have a direct positive effect on a country's payoff (disregarding the cost of technology provision), caused by the lower marginal contribution cost. But when this type of technologies (with strong impact on c_{t+1}) is shared, this reduces country j's early provision, which is bad for i since it increases the own burden of contributing. This countervailing negative effect can, in fact, dominate the positive effect of lower contribution cost.

To see this, consider again the example of the previous section where, in case of $c_t = 0.5$ and $c_{t+1} = 1.25$, we get $x_{j,t}^* = 4.567$ and $\pi_i^* = 5.113$. Now suppose that i could invest in the context of a technology sharing initiative and reduce the future contribution cost to $c_{t+1} = 1.1$. This increases the cost ratio and, as a result of the improved future climate protection opportunities, country j's early equilibrium contribution is reduced to $x_{j,t}^* \approx 2.612$ (while $x_{i,t}^* = 0$ remains unchanged). And i's expected equilibrium payoff decreases to $\pi_i^* \approx 4.369$ (disregarding cost of technology which decrease i's payoff even further), due to the reduced free-riding opportunities. Therefore, in this example, i would not implement the technology with a stronger impact on future contribution cost.[43] Obviously if both periods' contribution cost is reduced sufficiently strongly, then π_A^* and π_B^* are increased, independently of whether the ratio c_t/c_{t+1} increases or decreases and whether early contributions are crowded out.

In general, the investment in cost-reducing technology has two effects: a direct positive effect of reducing the contribution cost and a strategic effect on the equilibrium contribution pattern. Investments in technology which increase the other countries' early contribution are always strategically advantageous, while types of technologies which decrease the other

[42] Examples include biofuels, hybrid electric vehicles and coal-fired power generation technologies even though predictions must be viewed with caution (compare the boom in natural gas due to hydraulic fracturing, for instance).

[43] Note that since we are interested in the strategic aspects of technology transfer mechanisms we only consider investments in cost-reducing technology which is available to both countries. Unilateral cost reductions are less desirable from a strategic point of view because they shift the burden of contributing more strongly to the country with the lower cost.

country's early contribution reduce the free-riding opportunities. Thus, a country's incentive for technology transfer are strongest for types of technology which are of immediate use and decrease the cost ratio c_t/c_{t+1}.

6.2 Convex contribution cost

Although the one-sided contribution pattern described in (3) and in Proposition 1 is clearly an extreme scenario, it crucially simplifies the analysis by separating the two countries' optimization problems and reducing the problem to a comparison of the preferred quantities. While being stylized, the contribution patterns which evolve are qualitatively in line with climate protection efforts; the empirical pattern of implementing effective climate change policies is, in reality, highly asymmetric.[44]

Quasi-linear payoff functions are a good approximation in the range of investments in climate protection in which climate change policies are currently discussed and implemented.[45] Due to the concavity of the "production function" f, the countries' objective functions exhibit decreasing returns in each dollar invested by the country itself as well as by the other country. Quasi-linear payoff functions have the advantage that they highlight most clearly the countries' strategic considerations and keep the analysis tractable. To shed light on the robustness of our model this section considers the case of convex contribution cost, showing that the strategic considerations are similar though weakened.[46]

In what follows we maintain all assumptions of the previous sections, except that we

[44] In terms of timing, many European countries and (more recently) the United States, for instance, set goals to reduce greenhouse gas emissions while other countries such as China or India do not currently choose comprehensive climate protection policies. But also among advanced economies there are clear asymmetries in the sense that some countries like Germany and the UK, for instance, choose relatively high investments in renewable energies whereas other countries like Australia and Canada rather delay abatement efforts. For recent comparisons of climate change policies across countries see, for instance, the Climate Change Performance Index at https://germanwatch.org/en/indices.

[45] Empirical estimates of (country-specific) abatement cost curves are difficult to obtain, due to behavioral reactions, macroeconomic interactions and many other factors. Moreover, marginal abatement cost curves have to incorporate the many different policy options available, including improving energy efficiency, adopting more climate-friendly energies, lowering demand, and measures such as avoiding deforestation. Therefore, constant marginal cost is not unrealistic to assume unless abatement becomes very high. Moreover, instruments such as the Clean Development Mechanism (CDM) allow to make use of regional differences in abatement potential. For discussions and estimates of empirical abatement cost curves see, for instance, Wetzelaer et al. (2007), McKinsey (2009), and Kesicki and Ekins (2012).

[46] Note already that the case of convex cost is an extreme case as well, yielding zero marginal contribution cost for the first contribution unit within a period, independently of the contribution of the other period. This introduces a "cost-smoothing argument" which blurs the trade-off between uncertainty and irreversibility and which we can abstract from by assuming constant marginal cost.

assume the contribution cost in period $\tau \in \{t, t+1\}$ to be given by

$$C_\tau(x_{i,\tau}) = \frac{1}{2} c_\tau x_{i,\tau}^2,\ i = A, B,$$

where $c_\tau \in \mathbb{R}_+ \setminus \{0\}$ and $c_t < c_{t+1}$. Thus, country i's payoff for a given contribution profile and a given valuation θ_i is equal to[47]

$$\pi_i(\mathbf{x}_t, \mathbf{x}_{t+1}) = \theta_i f\left(\sum_{i=A,B}\sum_{\tau=t,t+1} x_{i,\tau}\right) - \frac{c_t}{2} x_{i,t}^2 - \frac{c_{t+1}}{2} x_{i,t+1}^2,\ i \in \{A, B\}. \tag{15}$$

First of all, contributions in period $t+1$ have to satisfy

$$\frac{x_{A,t+1}^*}{x_{B,t+1}^*} = \frac{\theta_A}{\theta_B}.$$

The optimal choice $x_{i,t+1}^*$ is a function of $\boldsymbol{\theta} = (\theta_A, \theta_B)$ and $X_t = x_{i,t} + x_{j,t}$. Due to $\partial C_{t+1}/\partial x_{i,t+1}|_{x_{i,t+1}=0} = 0$ (for all $\mathbf{x}_t$), both countries' equilibrium contributions in period $t+1$ are strictly positive. The country with the higher valuation, however, chooses a higher contribution. Moreover, we get

$$\frac{\partial x_{i,t+1}^*}{\partial X_t} \in (-1, 0),$$

that is, an increase in X_t leads to a crowding out of country i's contribution in $t+1$, but to less than 100%. The same holds for total future contributions X_{t+1}^*.

Define again $\Pi_i(x_{i,t}, x_{j,t})$ as country i's reduced form expected payoff from the point of view of period t, given that both countries choose their period $t+1$ contribution optimally. Then, i's marginal benefit from increasing $x_{i,t}$ can be written as

$$\frac{\partial \Pi_i}{\partial x_{i,t}} = \int_0^{\bar\theta}\int_0^{\bar\theta}\left(c_{t+1} x_{i,t+1}^*(\boldsymbol{\theta}, X_t)\left(1 + \frac{\partial x_{j,t+1}^*}{\partial X_t}\right) - c_t x_{i,t}\right) d\Phi_j(\theta_j)\, d\Phi_i(\theta_i). \tag{16}$$

Due to the zero marginal cost of the first contribution unit, the case of convex cost does not involve discrete changes in the equilibrium pattern as the case of linear cost. Still, the trade-off between uncertainty and irreversibility as well as the free-riding problem can also be seen in (16). Ignoring the term $\left(1 + \partial x_{j,t+1}^*/\partial X_t\right)$ in (16) for a moment, an increase in $x_{i,t}$ yields a marginal benefit of $c_{t+1} x_{i,t+1}^*(\boldsymbol{\theta}, X_t)$, which is equal to the cost saving from an early contribution given that the pair of true valuations turns out to be $\boldsymbol{\theta}$. This marginal benefit approaches zero if $\theta_i \to 0$ and is increasing in θ_i. In contrast, the marginal cost of increasing $x_{i,t}$ (the term $c_t x_{i,t}$) is independent of $\boldsymbol{\theta}$. Therefore, if θ_i turns out to be high, it

[47] A more detailed derivation of the subsequent results can be found in Appendix A.8.

would have been better to have chosen a high early contribution, in particular as $c_{t+1} > c_t$. But if θ_i turns out to be low, and θ_j turns out to be high, a high early contribution would have been in vain. Balancing expected benefit and cost leads to a similar trade-off between uncertainty and irreversibility as with linear cost.

The fact that the marginal benefit in (16) is weighted by the factor $\left(1 + \partial x^*_{j,t+1}/\partial X_t\right) < 1$ illustrates the intertemporal free-riding problem. When choosing $x_{i,t}$, i anticipates that j's contribution in $t+1$ is decreasing in $x_{i,t}$; hence, the incentive to increase $x_{i,t}$ is weaker than without strategic reaction of j. Moreover, i's marginal benefit in (16) is also decreasing in j's early contribution $x_{j,t}$, as the countries' contributions are strategic substitutes.

Closer inspection of (16) also shows that the main qualitative conclusions on the effects of technology transfer carry over to variations in the cost functions. First, investments in technology κ affect the trade-off between acting today and delaying the contribution. A country's marginal payoff from an increase in the early contribution (as in (16)) is increasing in κ if and only if the impact of κ on c_t is sufficiently strong compared to the impact on c_{t+1}. Intuitively, in the one extreme case in which κ only affects today's contribution cost, the incentive to contribute early is strictly increased. In the other extreme case in which κ is only useful for future contributions, the incentive to contribute early is strictly reduced. The qualitative effects of cost-reducing technology on the timing of the contributions are, hence, similar to the case of linear cost.[48]

Second, if technology transfer increases j's early contribution $x^*_{j,t}$, this generates an additional benefit for country i by reducing i's burden of contributing. In Appendix A.8 we show that the effect of a marginal increase in κ on i's expected equilibrium payoff can be split up into two effects: a direct effect of reduced contribution cost; and an indirect effect caused by a change in the other country's early contribution. This indirect effect is positive if and only if j's early contribution $x^*_{j,t}$ is increasing in κ. Thus, it is most attractive to implement technology sharing initiatives for types of technologies which reduce today's contribution cost relatively more strongly and, as a consequence, increase the other country's early contribution.

To conclude this section, we illustrate by means of an example how different degrees of uncertainty which countries face make them react differently to incentives to contribute early. Suppose that country A's valuation is drawn from a binary distribution function, $\theta_A \in \{0, \theta_h\}$ where $\theta_A = \theta_h$ with probability p_A and $\theta_A = 0$ with probability $1 - p_A$. Moreover, suppose that there is no uncertainty about country B's valuation of climate protection, that

[48] Note, however, that the effects of changes in technology are more complex due to the additional interdependencies of the countries' choices within a given period; in particular, changes in the irreversibility ratio c_t/c_{t+1} are not sufficient to predict the change in a country's equilibrium contribution.

is, θ_B is known ex ante. Let $0 < \theta_B < \theta_h$. In this very simplified example, closed form solutions can be obtained, for instance, for $f(X) = -\frac{1}{2}(1-X)^2$. Here, the incentive to contribute early is stronger for B than for A unless p_A is very high (see Appendix A.8). In particular, there is a non-empty interval $(\theta_B/\theta_h, \bar{p}_A)$ such that for all $p_A \in (\theta_B/\theta_h, \bar{p}_A)$, country B chooses a higher early contribution than A ($x^*_{B,t} > x^*_{A,t}$) even though B has the lower expected valuation for climate protection ($\theta_B < E(\theta_A)$). Intuitively, country A which faces the greater uncertainty commits to delay part of its potential contribution until period $t+1$. Similarly, country A's early contribution reacts relatively weakly to investments in technology that reduce the early contribution cost c_t, again unless p_A is high. Altogether, the beliefs about benefits from climate protection captured by Φ_A and Φ_B are crucial for the trade-off between contributing today and delaying the contribution to climate protection as well as for the countries' strategic benefits from technology sharing initiatives.

7 Conclusion

In this paper we have shown how the timing of the contribution to climate protection is affected by uncertainty, irreversibility, and the possibility to free-ride. Uncertainty about the country-specific benefit of climate protection creates an incentive to delay the contribution decision towards a later contribution date where the uncertainty is resolved, while the irreversibility of damages makes an earlier contribution more desirable. Furthermore, the fact that mitigation efforts are contributions to a global public good shifts the contribution more strongly towards a later contribution date, since, in anticipation of a free-riding possibility in the future, countries prefer to delay their contribution to climate protection. In other words, the positive externalities caused by investments in climate protection increase a country's option value of waiting. In such a situation, investments in cost-reducing technology have an important impact on the trade-off that countries face and, hence, on the timing of the contributions.

In the game of private contributions to the public good with potentially asymmetric but known valuations for climate protection, the country with the highest valuation for climate protection will face the major burden of contributing. The fact that countries have different expected probabilities of obtaining the higher valuation in the later period of the game makes them react differently to changes in the degree of irreversibility caused by investments in cost-reducing technology. The degree of irreversibility refers to the cost ratio of early and late mitigation efforts; the expected probability of having the higher valuation in the later period can be interpreted as the expected savings from an early contribution (since when having the higher valuation the country contributes in the late period at higher cost). The country which expects a higher potential saving from an early contribution has a stronger incentive to contribute early. Consequently, investments in cost-reducing technology can change the equilibrium contribution pattern. In particular, they can increase a country's early equilibrium contribution and, thus, the other country's free-riding opportunities. We identify two main scenarios where such a potential for free-riding exists and investments in technology affect the countries' timing of contributions. In the first scenario, at the status quo, the countries have a dominant strategy of not contributing before the resolution of the uncertainty; in the second scenario, one country j would contribute already in period t, even if no country invests in cost-reducing technology. In both cases, if the investment in technology changes the degree of irreversibility, one country will be more sensitive to this change and will prefer an early contribution. In turn, the other country can reduce its contribution.

Our analysis puts emphasis on investments in technology which lower the inverse irreversibility ratio c_t/c_{t+1}, that is, on types of technologies which are relatively more useful for current than for future abatement. Being in line with implemented technology transfer initiatives, we also show that the transfer of technologies which are relatively more effective in reducing current contribution costs has a strategic benefit. By strengthening the other countries' incentives to contribute early, providing such technologies may be beneficial, due to the public good nature of climate protection and the positive externality of others' (early) contributions. On the other hand, sharing technologies with a strong impact on future contribution cost may be strategically disadvantageous and lead to a higher own burden of contributing.

The two-country model can be interpreted as the case of a strategic interaction between two key players (i.e., large regions) that decide over their contribution to climate protection and decide whether or not to implement technology sharing initiatives. This assumption, however, is not particularly restrictive. Assuming quasi-linear preferences, only the countries who potentially have the largest net benefit may choose positive contributions. In a model with $n > 2$ countries, the equilibrium probability of contributing will depend on all other countries' (expected) valuations, which makes the analysis more complex and substantially increases the number of cases to be distinguished. The main insights obtained from the two-country model and the resulting trade-off between uncertainty and irreversibility should, however, carry over when considering more than two countries.

In our model framework, investments in technology affect the timing of contributions and can achieve a change in the equilibrium contribution pattern and, hence, a change in the investing country's payoff (disregarding cost of technology investments). Moreover, in the two scenarios considered, the cost-reducing technology strictly increases the quantity of the public good provided early and therefore the overall amount contributed to climate protection: First, for a given valuation, the optimal early provision level is strictly higher than the optimal late provision level because of the lower marginal contribution cost, and second, early contributions also occur in situations where a country's valuation turns out to be low. (If the valuation turns out to be high, the country can still increase its contribution in the late period.) Both effects cause the total equilibrium quantity of the public good to be higher if the provision is shifted to the early period. Even if, ex post, a country has over-contributed from an individual perspective, because its early contribution has been higher than what would have been optimal based on the true valuation, such over-contributions from an individual perspective are welfare-increasing, due to the underprovision of the public good. Moreover, early contributions are inefficiently low due to 'intertemporal free-riding'. Abstracting from the cost of providing cost-reducing technologies, the shift of the countries' equilibrium contributions towards early contributions has a positive effect on welfare.

Hindered by the large uncertainties and heterogeneity across countries, international agreements to increase climate protection efforts have been difficult to implement and have remained rather ineffective. Our paper argues that technology sharing mechanisms can, in a non-cooperative setting, induce countries to increase their current contributions to climate protection and in this way make technology sharing beneficial for the country that invested in green technology. Promoting technology sharing may, thus, be a promising approach in the fight against climate change.

A Appendix

A.1 Proof of Lemma 1

First note that $\Pi_i (x_{i,t}, x_{j,t})$ in (4) is equivalent to

$$\int_0^{\hat{\theta}} \int_0^{\hat{\theta}} \theta_i f(X_t) \, d\Phi_j(\theta_j) \, d\Phi_i(\theta_i) + \int_0^{\hat{\theta}} \int_{\hat{\theta}}^{\bar{\theta}} \theta_i f(Q_{j,t+1}(\theta_j)) \, d\Phi_j(\theta_j) \, d\Phi_i(\theta_i)$$
$$+ \int_{\hat{\theta}}^{\bar{\theta}} \int_0^{\theta_i} [\theta_i f(Q_{i,t+1}(\theta_i)) - c_{t+1}(Q_{i,t+1}(\theta_i) - X_t)] \, d\Phi_j(\theta_j) \, d\Phi_i(\theta_i)$$
$$+ \int_{\hat{\theta}}^{\bar{\theta}} \int_{\theta_i}^{\bar{\theta}} \theta_i f(Q_{j,t+1}(\theta_j)) \, d\Phi_j(\theta_j) \, d\Phi_i(\theta_i) - c_t x_{i,t}. \tag{17}$$

Deriving (17) with respect to $x_{i,t}$ yields

$$\frac{\partial \Pi_i}{\partial x_{i,t}} = \begin{cases} \int_0^{\hat{\theta}} \int_0^{\hat{\theta}} \theta_i f'(X_t)\, d\Phi_j(\theta_j)\, d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i)\, c_{t+1} d\Phi_i(\theta_i) - c_t & \text{if } \ 0 \leq X_t < Q_{i,t+1}\left(\bar{\theta}\right) \\ E(\theta_i)\, f'(X_t) - c_t & \text{if } \quad X_t \geq Q_{i,t+1}\left(\bar{\theta}\right). \end{cases}$$

(This differentiation takes, of course, into account that $\hat{\theta} = c_{t+1}/f'(X_t)$ depends on $x_{i,t}$; it holds, however, that $(\partial \Pi_i/\partial \hat{\theta})(\partial \hat{\theta}/\partial x_{i,t}) = 0$, as in an envelope theorem. Further, note that $\partial \Pi_i/\partial x_{i,t}$ is continuous in $X_t = x_{A,t} + x_{B,t}$.) Moreover,

$$\frac{\partial^2 \Pi_i}{\partial x_{i,t}^2} = \begin{cases} \left[\Phi_j(\hat{\theta}) - \hat{\theta}\Phi_j'(\hat{\theta})\right] \int_0^{\hat{\theta}} \theta_i f''(X_t)\, d\Phi_i(\theta_i) & \text{if } \ 0 \leq X_t < Q_{i,t+1}\left(\bar{\theta}\right) \\ E(\theta_i)\, f''(X_t) & \text{if } \quad X_t \geq Q_{i,t+1}\left(\bar{\theta}\right). \end{cases}$$

Hence, if Assumption 1 holds, then $\partial^2 \Pi_i/\partial x_{i,t}^2 \leq 0$ for all X_t.

Part (i): Suppose that $E(\theta_i)/\bar{\theta} \geq c_t/c_{t+1}$. This implies that

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t = Q_{i,t+1}(\bar{\theta})} = E(\theta_i)\, f'\left(Q_{i,t+1}\left(\bar{\theta}\right)\right) - c_t = E(\theta_i)\, f'\left((f')^{-1}\left(c_{t+1}/\bar{\theta}\right)\right) - c_t \geq 0.$$

Due to concavity of Π_i, we get $Q_{i,t} \geq Q_{i,t+1}\left(\bar{\theta}\right)$ and $Q_{i,t}$ is uniquely determined by

$$E(\theta_i)\, f'(Q_{i,t}) - c_t = 0,$$

which yields $Q_{i,t} = (f')^{-1}(c_t/E(\theta_i))$.[49] Since $(f')^{-1}(c_t/E(\theta_i)) \geq Q_{i,t+1}\left(\bar{\theta}\right)$, there will be no contribution in $t+1$.

Part (ii): Suppose that $E(\theta_i)/\bar{\theta} < c_t/c_{t+1}$. This implies that

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t = Q_{i,t+1}(\bar{\theta})} = E(\theta_i)\, f'\left(Q_{i,t+1}\left(\bar{\theta}\right)\right) - c_t = E(\theta_i)\, f'\left((f')^{-1}\left(c_{t+1}/\bar{\theta}\right)\right) - c_t < 0.$$

Hence, $0 \leq Q_{i,t} < Q_{i,t+1}\left(\bar{\theta}\right)$. (Since $Q_{i,t+1}\left(\bar{\theta}\right)$ is the highest type's preferred contribution level in $t+1$, i might contribute again in $t+1$.) Moreover, the following relation holds at

[49] To be precise, if $E(\theta_i)/\bar{\theta} = c_t/c_{t+1}$ and $\pi_i''(x_{i,t}; X_t) = 0$ for $X_t \in \left(Q_{i,t+1}\left(\bar{\theta}\right) - \delta, Q_{i,t+1}\left(\bar{\theta}\right)\right)$, $\delta > 0$, then i is indifferent between all $Q_{i,t} \in \left(Q_{i,t+1}\left(\bar{\theta}\right) - \delta, Q_{i,t+1}\left(\bar{\theta}\right)\right)$. For simplicity, we assume that $Q_{i,t} = Q_{i,t+1}\left(\bar{\theta}\right)$ in this special case.

any $X_t < Q_{i,t+1}\left(\bar{\theta}\right)$:

$$\begin{aligned}\frac{\partial \Pi_i}{\partial x_{i,t}} &= \int_0^{\hat{\theta}} \Phi_j\left(\hat{\theta}\right)\theta_i f'\left(X_t\right)d\Phi_i\left(\theta^i\right) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j\left(\theta_i\right)c_{t+1}d\Phi_i\left(\theta_i\right) - c_t \\ &= \int_0^{\hat{\theta}} \Phi_j\left(\hat{\theta}\right)\theta_i f'\left(X_t\right)d\Phi_i\left(\theta_i\right) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j\left(\theta_i\right)\hat{\theta} f'\left(X_t\right)d\Phi_i\left(\theta_i\right) - c_t \\ &< \int_0^{\hat{\theta}} \theta_i f'\left(X_t\right)d\Phi_i\left(\theta_i\right) + \int_{\hat{\theta}}^{\bar{\theta}} \theta_i f'\left(X_t\right)d\Phi_i\left(\theta_i\right) - c_t.\end{aligned}$$

Hence,

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t=(f')^{-1}(c_t/E(\theta_i))} < E\left(\theta_i\right)f'\left(\left(f'\right)^{-1}\left(c_t/E\left(\theta_i\right)\right)\right) - c_t = 0,$$

and thus $Q_{i,t}$ must be strictly smaller than $\left(f'\right)^{-1}\left(c_t/E\left(\theta_i\right)\right)$. Finally,

$$\left.\frac{\partial \Pi_i}{\partial x_{i,t}}\right|_{X_t=0} = \int_0^{\bar{\theta}} \Phi_j\left(\theta_i\right)c_{t+1}d\Phi_i\left(\theta_i\right) - c_t > 0$$

or, equivalently, $E\left(\Phi_j\left(\theta_i\right)\right) > c_t/c_{t+1}$ is sufficient for $Q_{i,t} > 0$, which completes the proof of part (ii)b.

If instead either (1) $\partial\Pi_i/\partial x_{i,t}|_{X_t=0} < 0$ or (2) $\partial\Pi_i/\partial x_{i,t}|_{X_t=0} = 0$ and $\partial^2\Pi_i/\partial x_{i,t}^2|_{X_t=0} < 0$, then $Q_{i,t} = 0$ (part (ii)a).[50]

A.2 Proof of Proposition 2

Notice that, by assumption, $\gamma\left(\kappa\right) \in (0,1)$. If γ is strictly decreasing, using the inverse function of $\gamma\left(\kappa\right)$, we can define

$$\kappa_i^p := \gamma^{-1}\left(E\left(\Phi_j\left(\theta_i\right)\right)\right) \text{ and } \kappa_i^f := \gamma^{-1}\left(E\left(\theta_i\right)/\bar{\theta}\right).$$

First consider case (i), where $\kappa < \kappa_i^f$ and $\kappa \leq \kappa_i^p$. This implies that $c_t\left(\kappa\right)/c_{t+1}\left(\kappa\right) > E\left(\theta^i\right)/\bar{\theta}$ and $c_t\left(\kappa\right)/c_{t+1}\left(\kappa\right) \geq E\left(\Phi_j\left(\theta_i\right)\right)$. By Lemma 1(ii)a, country i strictly prefers a provision level of $Q_{i,t} = 0$ in period t.

Now consider case (ii) where $\kappa \geq \kappa_i^f$, which is equivalent to $c_t\left(\kappa\right)/c_{t+1}\left(\kappa\right) \leq E\left(\theta_i\right)/\bar{\theta}$. Using Lemma 1(i), country i prefers a full provision in period t.

[50] Similar as in part (i), if $\partial\Pi_i/\partial x_{i,t}|_{X_t=0} = 0$ and Assumption 1 holds with equality for $\theta \in \left[0, \theta'\right]$, $\theta' > 0$, then $\partial\Pi_i/\partial x_{i,t} = 0$ for all $X_t \in \left[0, Q_{i,t+1}\left(\theta'\right)\right]$, and i is indifferent between all period t *provision levels* $Q_{i,t} \in \left[0, Q_{i,t+1}\left(\theta'\right)\right]$. (Note that this does not necessarily imply that i is indifferent between all contributions $x_{i,t} \in \left[0, Q_{i,t+1}\left(\theta'\right)\right]$, but $x_{i,t} = 0$ is at least weakly preferred to all contributions $x_{i,t} > 0$.) To include this special case in part (ii), we assume that in this case $Q_{i,t} = 0$. If Assumption 1 holds with strict inequality, then $Q_{i,t} = 0$ if and only if (8) is fulfilled.

Finally, in case (iii), as γ is strictly decreasing, $\kappa_i^p < \kappa_i^f$ is equivalent to $E(\Phi_j(\theta_i)) > E(\theta_i)/\bar{\theta}$. Thus, for $\kappa \in (\kappa_i^p, \kappa_i^f)$, we have $E(\Phi_j(\theta_i)) > c_t(\kappa)/c_{t+1}(\kappa) > E(\theta_i)/\bar{\theta}$, and Lemma 1(ii)b holds. This means that country i prefers a partial provision with $0 < Q_{i,t} < (f')^{-1}(c_t/E(\theta_i))$. Notice that, as shown in Lemma 1, when $E(\Phi_j(\theta_i)) < E(\theta_i)/\bar{\theta}$ and consequently $\kappa_i^p > \kappa_i^f$, then $E(\Phi_j(\theta_i))$ does not influence the contribution decision, and country i prefers a full provision for all $\kappa \geq \kappa_i^f \Leftrightarrow c_t(\kappa)/c_{t+1}(\kappa) \leq E(\theta_i)/\bar{\theta}$.

A.3 Proof of Proposition 3

First of all, $\kappa > \min\{\kappa_i^p, \kappa_i^f\}$ implies that i prefers at least a partial provision in t (i.e., $Q_{i,t} > 0$), while $\kappa < \min\{\kappa_j^p, \kappa_j^f\}$ implies that $Q_{j,t} = 0$.[51] Since

$$\max\left\{E(\Phi_j(\theta_i)), \left(E(\theta_i)/\bar{\theta}\right)\right\} = \max\left\{\gamma(\kappa_i^p), \gamma\left(\kappa_i^f\right)\right\}$$

and since $\gamma(\kappa) = c_t(\kappa)/c_{t+1}(\kappa)$ is strictly decreasing, condition (13) is equivalent to

$$\min\left\{\kappa_i^p, \kappa_i^f\right\} < \min\left\{\kappa_j^p, \kappa_j^f\right\}.$$

Hence, there is a non-empty interval for κ where $x_{i,t}^* > 0$ ($i \in \{A, B\}$ is defined such that (13) holds).

A.4 Proof of Proposition 4

First note that $E(\theta_i) > E(\theta_j)$ is equivalent to $\kappa_i^f < \kappa_j^f$. Therefore, (14) requires that $\kappa_j^p < \kappa_0 < \min\{\kappa_i^p, \kappa_i^f\}$; at κ_0, j prefers a partial provision in t while i does not contribute.

Now consider an investment in technology $\kappa \in [\kappa_i^f, \infty)$. In this case, i prefers a full provision of the public good in period t. Furthermore, $Q_{i,t} > Q_{j,t}$ because of $E(\theta_i) > E(\theta_j)$; hence, $x_{i,t}^* > 0$ and $x_{j,t}^* = 0$. If $E(\theta_i)/\bar{\theta} \geq E(\Phi_j(\theta_i))$, then $\kappa_i^f \leq \kappa_i^p$, and i prefers a strictly positive period t provision if and only if $\kappa \geq \kappa_i^f$ (compare Proposition 2). This shows part (i). Otherwise, if $E(\theta_i)/\bar{\theta} < E(\Phi_j(\theta_i))$, then $\kappa_i^p < \kappa_i^f$, and i prefers a strictly positive period t provision for all $\kappa > \kappa_i^p$. This preferred quantity is increasing in κ and converges to $Q_{i,t} = (f')^{-1}(c_t/E(\theta_i))$ if κ approaches κ_i^f (from below). As $(f')^{-1}(c_t/E(\theta_i)) > (f')^{-1}(c_t/E(\theta_j)) \geq Q_{j,t}$, there exists $\delta > 0$ sufficiently small such that for all $\kappa \in (\kappa_i^f - \delta, \infty)$, $Q_{i,t} > Q_{j,t}$ and $x_{i,t}^* > 0$, that is, the investment in technology only needs to bring i's preferred provision level sufficiently close to a full provision in t.

[51] For simplicity, we omit the cases where κ is exactly equal to the thresholds κ_i^f and κ_i^p, respectively; the equilibrium contributions in these cases follow directly from the characterization in Proposition 2. The same comment applies to Proposition 4.

Finally, note that $E(\theta_i) > E(\theta_j)$ is sufficient but not necessary for obtaining the result on the "categorical" change in the equilibrium. If $\kappa_j^p < \kappa_0 < \kappa_i^p < \kappa_j^f < \kappa_i^f$, then $E(\theta_i) < E(\theta_j)$, and for $\kappa \in [\kappa_i^p, \kappa_j^f)$, both countries i and j prefer a partial provision of the public good in t. Even if $E(\theta_i) < E(\theta_j)$, condition (10) can, depending on the shape of the distribution functions, be positive at $X_t = Q_{j,t}$, in which case we get $Q_{i,t} > Q_{j,t}$ and $x_{i,t}^* = Q_{i,t} > 0$ for $\kappa \in [\kappa_i^p, \kappa_j^f)$.

A.5 Proof of Corollary 1

Total expected equilibrium contributions are $X_t^* + E_{\boldsymbol{\theta}}\left(X_{t+1}^* \mid X_t = X_t^*\right)$ where

$$\begin{aligned} E_{\boldsymbol{\theta}}\left(X_{t+1}^* \mid X_t = X_t^*\right) &= E_{\theta_A,\theta_B}\left[\max\left\{\max\left\{Q_{A,t+1}(\theta_A), Q_{B,t+1}(\theta_B)\right\} - X_t^*, 0\right\}\right] \\ &= \int_0^{\hat{\theta}} \int_{\hat{\theta}}^{\bar{\theta}} \left(Q_{B,t+1}(\theta_B) - X_t^*\right) d\Phi_B(\theta_B)\, d\Phi_A(\theta_A) \\ &\quad + \int_{\hat{\theta}}^{\bar{\theta}} \int_0^{\theta_A} \left(Q_{A,t+1}(\theta_A) - X_t^*\right) d\Phi_B(\theta_B)\, d\Phi_A(\theta_A) \\ &\quad + \int_{\hat{\theta}}^{\bar{\theta}} \int_{\theta_A}^{\bar{\theta}} \left(Q_{B,t+1}(\theta_B) - X_t^*\right) d\Phi_B(\theta_B)\, d\Phi_A(\theta_A). \end{aligned}$$

Hence, with $Q_{A,t+1}\left(\hat{\theta}\right) = Q_{B,t+1}\left(\hat{\theta}\right) = X_t^*$, we get

$$\begin{aligned} \left.\frac{\partial E\left(X_{t+1}^* \mid X_t\right)}{\partial X_t}\right|_{X_t = X_t^*} &= -\Phi_A\left(\hat{\theta}\right)\left(1 - \Phi_B\left(\hat{\theta}\right)\right) - \left(1 - \Phi_A\left(\hat{\theta}\right)\right) \\ &= -\left(1 - \Phi_A\left(\hat{\theta}\right)\Phi_B\left(\hat{\theta}\right)\right). \end{aligned}$$

Intuitively, when X_t^* is increased, $E\left(X_{t+1}^* \mid X_t = X_t^*\right)$ decreases by the same amount, except if θ_A and θ_B are both lower than the critical valuation $\hat{\theta}$ (in which case there is no contribution in period $t+1$ anyway). Hence, we get

$$\left.\frac{\partial}{\partial X_t}\left(X_t + E_{\boldsymbol{\theta}}\left(X_{t+1}^* \mid X_t\right)\right)\right|_{X_t = X_t^*} = \Phi_A\left(\hat{\theta}\right)\Phi_B\left(\hat{\theta}\right) \geq 0$$

with strict inequality for all $X_t^* > 0$.

A.6 Proof of Corollary 2

First of all note that

$$\left.\frac{\partial W}{\partial X_t}\right|_{X_t=X_t^*} = \Phi_A\left(\hat{\theta}\right)\Phi_B\left(\hat{\theta}\right)\left[\left(E\left(\theta_A \mid \theta_A \leq \hat{\theta}\right) + E\left(\theta_B \mid \theta_B \leq \hat{\theta}\right)\right) f'\left(X_t^*\right) - c_t\right] + \left(1 - \Phi_A\left(\hat{\theta}\right)\Phi_B\left(\hat{\theta}\right)\right)\left(c_{t+1} - c_t\right). \tag{18}$$

(Since $\partial W/\partial X_t|_{X_t=X_t^*} = \partial\Pi_i/\partial X_t|_{X_t=X_t^*} + \partial\Pi_j/\partial X_t|_{X_t=X_t^*}$, (18) is obtained, for instance, by adding (6) and j's marginal payoff in case i's period t contribution increases.) Intuitively, if both countries' valuations turn out to be lower than the critical valuation (the first term in (18)), then the welfare effect follows the standard cost-benefit considerations where benefits are evaluated with the sum of expected valuations conditional on being smaller than the critical valuation $\hat{\theta}$. If at least one country's valuation is higher than the critical valuation, there is a cost saving $c_{t+1} - c_t$ in case the early contribution is increased. (Compared to a single country's marginal payoff as in (6), the free-riding effect disappears.)

Case (i): $X_t^* = 0$. In this case, $\hat{\theta} = 0$ and $\partial W/\partial X_t|_{X_t=X_t^*} = c_{t+1} - c_t > 0$. (As in the one-country scenario analyzed in Section 4, there should always be a strictly positive early contribution from a welfare perspective.)

Case (ii): $X_t^* > 0$. Suppose without loss of generality that $x_{i,t}^* > 0$. Hence, $\partial\Pi_i/\partial x_{i,t}|_{X_t=x_{i,t}^*} =$ 0 and

$$\begin{aligned}\left.\frac{\partial W}{\partial X_t}\right|_{X_t=X_t^*} &= \left.\frac{\partial\Pi_i}{\partial x_{i,t}}\right|_{X_t=x_{i,t}^*} + \left.\frac{\partial\Pi_j}{\partial x_{i,t}}\right|_{X_t=x_{i,t}^*} \\ &= 0 + \int_0^{\hat{\theta}}\int_0^{\hat{\theta}} \theta_j f'\left(X_t^*\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right) + \int_0^{\bar{\theta}}\int_{\max\left\{\theta_i,\hat{\theta}\right\}}^{\bar{\theta}} c_{t+1} d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right)\end{aligned}$$

which is strictly positive. While the country i that increases X_t^* only takes into account its own marginal payoff, the other country j is made strictly better off.

A.7 Effect of technology on positive optimal contribution levels

While the main analysis of the effect of investments in cost-reducing technology κ has focused on "categorical changes" of a country's preferred provision level in t, this appendix considers the effect of a marginal change in κ on an initially positive contribution level. Obviously, if the irreversibility ratio c_t/c_{t+1} is close to one and the countries do not want to contribute in t, a marginal change in κ has no effect on the preferred period t provision. On the other hand, if there is a high degree of irreversibility (c_t/c_{t+1} is low) and the countries prefer a full provision of the public good in t, a marginal investment in technology simply marginally increases this preferred amount, since there still will be no contributions in period $t+1$. The only interesting case to consider is, hence, a situation where countries prefer a partial provision of the public good in t and contribute in $t+1$ with positive probability.

Remark 1 *Suppose that $Q_{i,t} \in (0, (f')^{-1}(c_t/E(\theta_i)))$. Then, $Q_{i,t}$ is strictly increasing in κ if and only if $|\frac{\partial c_t}{\partial \kappa}| > D|\frac{\partial c_{t+1}}{\partial \kappa}|$ where*

$$D := \int_0^{\hat{\theta}} \Phi_j'(\hat{\theta})\theta_i d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i) d\Phi_i(\theta_i) < 1.$$

Proof. $Q_{i,t}$ is determined by the condition

$$\int_0^{\hat{\theta}} \Phi_j(\hat{\theta})\theta_i f'(Q_{i,t}) d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i) c_{t+1} d\Phi_i(\theta_i) - c_t = 0,$$

where $\hat{\theta} = c_{t+1}/f'(Q_{i,t})$. Total differentiation yields

$$\frac{\partial Q_{i,t}}{\partial \kappa} = -\frac{\left(\int_0^{\hat{\theta}} \Phi_j'(\hat{\theta})\theta_i d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i) d\Phi_i(\theta_i)\right) \frac{\partial c_{t+1}}{\partial \kappa} - \frac{\partial c_t}{\partial \kappa}}{\pi_i''(Q_{i,t})},$$

hence, $\partial Q_{i,t}/\partial\kappa > 0$ if and only if $D(\partial c_{t+1}/\partial\kappa) - \partial c_t/\partial\kappa > 0$ or $|\partial c_t/\partial\kappa| > D|\partial c_{t+1}/\partial\kappa|$. It remains to show that $D < 1$. By Assumption 1, $\Phi_j'(\hat{\theta}) \leq \Phi_j(\hat{\theta})/\hat{\theta}$, and, hence,

$$\begin{aligned} D &\leq \int_0^{\hat{\theta}} \frac{\Phi_j(\hat{\theta})}{\hat{\theta}}\theta_i d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i) d\Phi_i(\theta_i) \\ &< \int_0^{\hat{\theta}} \Phi_j(\hat{\theta}) d\Phi_i(\theta_i) + \int_{\hat{\theta}}^{\bar{\theta}} \Phi_j(\theta_i) d\Phi_i(\theta_i) < 1. \end{aligned}$$

■

In line with the analysis of "categorical changes", as long as a marginal change in κ does not change c_{t+1} much stronger than c_t, a marginal investment in cost-reducing technology increases country i's preferred provision level in period t, in a situation where i prefers a partial provision in t and the probability of a contribution in $t+1$ is strictly positive.

With regard to this late contribution in period $t+1$, the effect of a marginal change in κ on the expected contributions in $t+1$ is ambiguous. Intuitively, a change in κ reduces c_{t+1}, which, keeping total contributions in t unchanged, increases a country's expected contribution in $t+1$. But the change in κ also reduces c_t, which, as shown, typically increases $Q_{A,t}$ and $Q_{B,t}$ and, hence, increases total contributions in t; higher early contributions, however, reduce a country's expected contribution in $t+1$. Mathematically,

$$E\left(x_{i,t+1}^{*}\right)=\int_{\hat{\theta}}^{\bar{\theta}}\Phi_{j}\left(\theta_{i}\right)\left(Q_{i,t+1}\left(\theta_{i}\right)-X_{t}\right)d\Phi_{i}\left(\theta_{i}\right)$$

and, hence,

$$\begin{aligned}\frac{\partial E\left(x_{i.t+1}^{*}\right)}{\partial\kappa} &= \int_{\hat{\theta}}^{\bar{\theta}}\Phi_{j}\left(\theta_{i}\right)\left(\frac{\partial Q_{i,t+1}\left(\theta_{i}\right)}{\partial\kappa}-\frac{\partial X_{t}}{\partial\kappa}\right)d\Phi_{i}\left(\theta_{i}\right)\\ &= \int_{\hat{\theta}}^{\bar{\theta}}\Phi_{j}\left(\theta_{i}\right)\left(\frac{1}{\theta^{i}f''\left(Q_{i,t+1}\left(\theta_{i}\right)\right)}\frac{\partial c_{t+1}}{\partial\kappa}-\frac{\partial X_{t}}{\partial\kappa}\right)d\Phi_{i}\left(\theta_{i}\right),\end{aligned}$$

where the first term in the integrand is positive (the direct effect on $Q_{i,t+1}$) and the second term is negative (the indirect effect through X_t); overall, whether a country's expected contribution in $t+1$ increases or decreases depends not only on the shape of f but also on how *both countries'* preferred provision levels in t change.

A.8 Details on the case of convex cost functions

Country i's payoff for a given contribution profile is given by

$$\pi_{i}\left(\mathbf{x}_{t},\mathbf{x}_{t+1}\right)=\theta_{i}f\left(\sum_{k=A,B}\sum_{\tau=t,t+1}x_{k,\tau}\right)-\frac{c_{t}}{2}x_{i,t}^{2}-\frac{c_{t+1}}{2}x_{i,t+1}^{2},\ i\in\{A,B\}.$$

Equilibrium contributions in period $t+1$. Consider first the equilibrium choices in the period $t+1$ subgame, for a given early contribution $X_t = x_{A,t} + x_{B,t}$ and a valuation pair $\boldsymbol{\theta} = (\theta_A, \theta_B)$. With the first order conditions

$$\begin{aligned}\theta_{A}f'\left(X_{t}+x_{A,t+1}+x_{B,t+1}\right)-c_{t+1}x_{A,t+1} &= 0,\\ \theta_{B}f'\left(X_{t}+x_{A,t+1}+x_{B,t+1}\right)-c_{t+1}x_{B,t+1} &= 0,\end{aligned}$$

equilibrium contributions in period $t+1$ have to fulfill

$$\frac{x_{A,t+1}^{*}}{x_{B,t+1}^{*}}=\frac{\theta_{A}}{\theta_{B}}. \tag{19}$$

Therefore, $X_{t+1}^{*} = (1+\theta_j/\theta_i)\,x_{i,t+1}^{*}$ where $x_{i,t+1}^{*}$ is the solution to

$$\theta_{i}f'\left(X_{t}+\left(1+\frac{\theta_{j}}{\theta_{i}}\right)x_{i,t+1}^{*}\right)-c_{t+1}x_{i,t+1}^{*}=0. \tag{20}$$

Before turning to the optimality condition for period t, note that $x^*_{i,t+1}$ is strictly decreasing in X_t, as total differentiation of (20) yields

$$\frac{\partial x^*_{i,t+1}}{\partial X_t} = -\frac{\theta_i f''\left(X_t + X^*_{t+t}\right)}{\left(\theta_i + \theta_j\right) f''\left(X_t + X^*_{t+t}\right) - c_{t+1}} \in (-1, 0)$$

A marginal increase in the total period t contribution X_t reduces i's equilibrium contribution in $t+1$, but by less than the increase in X_t. Note that $\left|\partial x^*_{i,t+1}/\partial X_t\right| > \left|\partial x^*_{j,t+1}/\partial X_t\right|$ if and only if $\theta_i > \theta_j$. Moreover,

$$\frac{\partial X^*_{t+1}}{\partial X_t} = \frac{\partial x^*_{i,t+1}}{\partial X_t} + \frac{\partial x^*_{j,t+1}}{\partial X_t} = -\frac{\left(\theta_i + \theta_j\right) f''\left(X_t + X^*_{t+t}\right)}{\left(\theta_i + \theta_j\right) f''\left(X_t + X^*_{t+t}\right) - c_{t+1}} \in (-1, 0).$$

Thus, if X_t is increased, period $t+1$ contributions X^*_{t+1} are reduced by less than the increase in X_t, such that total contributions $X_t + X^*_{t+1}$ go up.

Equilibrium contributions in period t. Consider now the countries' early contribution choice. In period t, anticipating the subgame equilibrium in $t+1$, country i maximizes

$$\Pi_i\left(x_{i,t}, x_{j,t}\right) = \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f\left(x_{i,t} + x_{j,t} + X^*_{t+1}\right) - \frac{c_t}{2} x^2_{i,t} - \frac{c_{t+1}}{2}\left(x^*_{i,t+1}\right)^2\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right),$$

where Π_i again denotes i's reduced form payoff given the subgame equilibrium in $t+1$. Thus, i's marginal payoff $\partial \Pi_i / \partial x_{i,t}$ from increasing $x_{i,t}$ (keeping $x_{j,t}$ fixed) is

$$\int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(x_{i,t} + x_{j,t} + X^*_{t+1}\right)\left(1 + \frac{\partial X^*_{t+1}}{\partial X_t}\right) - c_t x_{i,t} - c_{t+1} x^*_{i,t+1} \frac{\partial x^*_{i,t+1}}{\partial X_t}\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right).$$

Using $\partial X^*_{t+1}/\partial X_t = \partial x^*_{i,t+1}/\partial X_t + \partial x^*_{j,t+1}/\partial X_t$ and the optimality condition (20) for the period $t+1$ contributions,

$$\begin{aligned} \frac{\partial \Pi_i}{\partial x_{i,t}} &= \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(x_{i,t} + x_{j,t} + X^*_{t+1}\right)\left(1 + \frac{\partial x^*_{j,t+1}}{\partial X_t}\right) - c_t x_{i,t}\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right) \\ &= \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(c_{t+1} x^*_{i,t+1}\left(1 + \frac{\partial x^*_{j,t+1}}{\partial X_t}\right) - c_t x_{i,t}\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right), \end{aligned} \tag{21}$$

In the period t equilibrium, both countries' first order conditions obtained from (21) have to hold simultaneously (and $x^*_{i,t+1}$ and $x^*_{j,t+1}$ are functions of both $x^*_{i,t}$ and $x^*_{j,t}$), and closed form solutions cannot be obtained. Comparative statics of the marginal payoff (21) offer, however, insights on the effect of technology investments for the countries' incentives to contribute early.

Effect of investments in technology on incentive to contribute early. To separate the effects of an improved technology κ, consider first the marginal benefit of contributing early, as given by the first term in the integrand of (21). Here,

$$\frac{\partial}{\partial \kappa}\left(c_{t+1}x^*_{i,t+1}\left(1+\frac{\partial x^*_{j,t+1}}{\partial X_t}\right)\right)$$
$$=\left[\left(x^*_{i,t+1}+c_{t+1}\frac{\partial x^*_{i,t+1}}{\partial c_{t+1}}\right)\left(1+\frac{\partial x^*_{j,t+1}}{\partial X_t}\right)+c_{t+1}x^*_{i,t+1}\frac{\partial^2 x^*_{j,t+1}}{\partial X_t \partial c_{t+1}}\right]\frac{\partial c_{t+1}}{\partial \kappa}$$

which is strictly negative for $\partial c_{t+1}/\partial \kappa < 0$ since

$$\begin{aligned} x^*_{i,t+1}+c_{t+1}\frac{\partial x^*_{i,t+1}}{\partial c_{t+1}} &= x^*_{i,t+1}+c_{t+1}\frac{x^*_{i,t+1}}{(\theta_i+\theta_j)\,f''\left(X_t+X^*_{t+t}\right)-c_{t+1}} \\ &= x^*_{i,t+1}\frac{(\theta_i+\theta_j)\,f''\left(X_t+X^*_{t+t}\right)}{(\theta_i+\theta_j)\,f''\left(X_t+X^*_{t+t}\right)-c_{t+1}}>0, \end{aligned}$$

$1+\partial x^*_{j,t+1}/\partial X_t>0$ (see above), and

$$\frac{\partial^2 x^*_{j,t+1}}{\partial X_t \partial c_{t+1}} = -\frac{\theta_j f''\left(X_t+X^*_{t+t}\right)}{\left[(\theta_i+\theta_j)\,f''\left(X_t+X^*_{t+t}\right)-c_{t+1}\right]^2}>0.$$

On the other hand, the marginal cost of contributing early in (21) changes by

$$\frac{\partial}{\partial \kappa}\left(c_t x_{i,t}\right)=\frac{\partial c_t}{\partial \kappa}x_{i,t}.$$

Hence, both the marginal cost and the marginal benefit of contributing early are reduced if κ is increased: It becomes less costly to increase $x_{i,t}$ but it also becomes less costly to wait until the uncertainty is resolved in $t+1$. The overall effect on the early contribution depends on the relation of $\partial c_t/\partial \kappa$ to $\partial c_{t+1}/\partial \kappa$. In the one extreme case where $\partial c_{t+1}/\partial \kappa \to 0$ and $\partial c_t/\partial \kappa < 0$ (that is, the technology is only useful for today's contribution), we get $\partial^2 \Pi_i/\partial x_{i,t}\partial \kappa > 0$. Hence, i's incentive to contribute early is increasing in κ, or in other words, i's best reply function to $x_{j,t}$ is shifted upwards. The opposite is true in the other extreme case where $\partial c_t/\partial \kappa \to 0$ and $\partial c_{t+1}/\partial \kappa < 0$ (the technology is only useful for future contributions); here we get $\partial^2 \Pi_i/\partial x_{i,t}\partial \kappa < 0$. In general, whether or not $x^*_{i,t}$ is increasing or decreasing in κ depends on how strongly c_t and c_{t+1} are affected by κ as well as on the strength of the reaction of the other country's early contribution $x^*_{j,t}$ to a change in κ (and, hence, also on the distribution functions Φ_A and Φ_B).

Incentive for technology transfer. Now turn to a country i's incentive to implement a technology transfer mechanism. For this purpose, consider i's expected equilibrium payoff

$$\Pi_i^*\left(x_{i,t}^*, x_{j,t}^*\right) = \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f\left(x_{A,t}^* + x_{B,t}^* + X_{t+1}^*\right) - \frac{c_t}{2}\left(x_{i,t}^*\right)^2 - \frac{c_{t+1}}{2}\left(x_{i,t+1}^*\right)^2\right) d\Phi_j\left(\theta_j\right) d\Phi_i\left(\theta_i\right).$$

A marginal change in κ changes Π_i^* by

$$\begin{aligned}\frac{\partial \Pi_i^*}{\partial \kappa} = & \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(X_t^* + X_{t+1}^*\right)\left(1 + \frac{\partial X_{t+1}^*}{\partial X_t}\right) - c_t x_{i,t}^* - c_{t+1} x_{i,t+1}^* \frac{\partial x_{i,t+1}^*}{\partial X_t}\right) \frac{\partial x_{i,t}^*}{\partial \kappa} d\Phi_j d\Phi_i \\ & + \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(X_t^* + X_{t+1}^*\right)\left(1 + \frac{\partial X_{t+1}^*}{\partial X_t}\right) - c_{t+1} x_{i,t+1}^* \frac{\partial x_{i,t+1}^*}{\partial X_t}\right) \frac{\partial x_{j,t}^*}{\partial \kappa} d\Phi_j d\Phi_i \\ & - \frac{1}{2}\frac{\partial c_t}{\partial \kappa}\left(x_{i,t}^*\right)^2 - \frac{1}{2}\frac{\partial c_{t+1}}{\partial \kappa}\left(x_{i,t+1}^*\right)^2.\end{aligned}$$

Here, the first line contains the effect on Π_i^* caused by the effect of κ on $x_{i,t}^*$: This effect is zero since $x_{i,t} = x_{i,t}^*$ is chosen optimally.[52] The second line represents the effect on Π_i^* caused by the effect of κ on the other country's contribution $x_{j,t}^*$. The two terms in the third line are equal to the direct effect of κ on the contribution cost; for the case of a cost-reducing technology with $\partial c_t/\partial\kappa \leq 0$ and $\partial c_{t+1}/\partial\kappa \leq 0$, these two terms are positive. Using again (20),

$$\begin{aligned}\frac{\partial \Pi_i^*}{\partial \kappa} = & \int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \theta_i f'\left(X_t^* + X_{t+1}^*\right)\left(1 + \frac{\partial x_{j,t+1}^*}{\partial X_t}\right) \frac{\partial x_{j,t}^*}{\partial \kappa} d\Phi_j d\Phi_i \\ & - \frac{1}{2}\frac{\partial c_t}{\partial \kappa}\left(x_{i,t}^*\right)^2 - \frac{1}{2}\frac{\partial c_{t+1}}{\partial \kappa}\left(x_{i,t+1}^*\right)^2. \end{aligned} \tag{22}$$

Due to $\partial x_{j,t+1}^*/\partial X_t \in (-1, 0)$, the integral in (22) is positive if and only if $\partial x_{j,t}^*/\partial\kappa > 0$. Thus, there is a direct effect of a marginal increase in κ which makes the own contributions cheaper by reducing c_t and c_{t+1}. And there is an indirect effect on Π_i^* which works through the change in $x_{j,t}^*$. For types of technologies that reduce future contribution costs relatively more strongly, this indirect effect is negative (whenever $\partial x_{j,t}^*/\partial\kappa < 0$). But the indirect effect is positive when sharing types of technologies that have a strong impact on today's contribution cost and cause $\partial x_{j,t}^*/\partial\kappa > 0$. Therefore, there is a strategic benefit of technology transfer mechanisms whenever technology sharing increases the other country's early contribution.

[52] This holds due to the envelope theorem, with $\theta_i f'\left(X_t^* + X_{t+1}^*\right) - c_{t+1} x_{i,t+1}^* = 0$ ($x_{i,t+1}$ is chosen optimally) and $\int_0^{\bar{\theta}} \int_0^{\bar{\theta}} \left(\theta_i f'\left(X_t^* + X_{t+1}^*\right)\left(1 + \partial x_{j,t+1}^*/\partial X_t\right) - c_t x_{i,t}^*\right) d\Phi_j d\Phi_i = 0$ ($x_{i,t}$ is chosen optimally). For simplicity, the expressions for the derivatives omit that they must be evaluated at $X_t = X_t^*$.

An example. Closed form solutions can be obtained only for very simplified examples. Let the production function of the public good be given by

$$f(X) = -\frac{1}{2}(1-x)^2.$$

Then, with $f'(X) = 1 - x$ and (20), country i's equilibrium contribution in the period $t+1$ subgame is equal to

$$x^*_{i,t+1} = \frac{\theta_i (1 - X_t)}{\theta_i + \theta_j + c_{t+1}}.$$

Inserting $x^*_{i,t+1}$ into (21) we obtain the two countries' first order conditions for their equilibrium contribution in t, which can be solved explicitly only under further restrictive assumptions on the probability distributions Φ_A and Φ_B.

A special case which captures different types of uncertainty in a very stylized manner is a situation in which θ_B is known ex ante with certainty and θ_A follows a binary distribution: $\theta_A \in \{0, \theta_h\}$ where $\theta_h > \theta_B > 0$ and $\Pr(\theta_A = \theta_h) = p_A$. Since $\theta_A = 0$ with probability $1 - p_A$, country A's first order condition becomes

$$p_A \theta_h c_{t+1} \frac{1 - x_{A,t} - x_{B,t}}{\theta_h + \theta_B + c_{t+1}} \frac{\theta_h + c_{t+1}}{\theta_h + \theta_B + c_{t+1}} - c_t x_{A,t} = 0,$$

while B's first order condition, taking into account the two possible contributions of A in period $t+1$, is equal to

$$(1-p_A)\theta_B c_{t+1} \frac{1 - x_{A,t} - x_{B,t}}{0 + \theta_B + c_{t+1}} \frac{\theta_B + c_{t+1}}{0 + \theta_B + c_{t+1}} + p_A \theta_B c_{t+1} \frac{1 - x_{A,t} - x_{B,t}}{\theta_h + \theta_B + c_{t+1}} \frac{\theta_B + c_{t+1}}{\theta_h + \theta_B + c_{t+1}} - c_t x_{B,t} = 0.$$

Solving these two equations for $(x_{A,t}, x_{B,t})$ yields, after some manipulations,

$$x^*_{A,t} = \frac{p_A \theta_h c_{t+1} (\theta_h + c_{t+1})(\theta_B + c_{t+1})}{\theta_B c_{t+1} \left[(1-p_A) B^2 + p_A (\theta_B + c_{t+1})^2\right] + (\theta_B + c_{t+1}) \left[p_A \theta_h c_{t+1} (\theta_h + c_{t+1}) + c_t B^2\right]},$$

$$x^*_{B,t} = \frac{\theta_B c_{t+1} \left[(1-p_A) B^2 + p_A (\theta_B + c_{t+1})^2\right]}{\theta_B c_{t+1} \left[(1-p_A) B^2 + p_A (\theta_B + c_{t+1})^2\right] + (\theta_B + c_{t+1}) \left[p_A \theta_h c_{t+1} (\theta_h + c_{t+1}) + c_t B^2\right]},$$

where $B := \theta_h + \theta_B + c_{t+1}$. Comparing $x^*_{A,t}$ and $x^*_{B,t}$, we obtain that $x^*_{A,t} > x^*_{B,t}$ if and only if

$$p_A > \frac{\theta_B (\theta_h + \theta_B + c_{t+1})}{\theta_h (2\theta_B + c_{t+1})} =: \bar{p}_A.$$

Interestingly, there is a non-empty interval $(\theta_B/\theta_h, \bar{p}_A)$ such that for all $p_A \in (\theta_B/\theta_h, \bar{p}_A)$, country A has the higher expected valuation ($E(\theta_A) > \theta_B$) but country B chooses the higher early contribution in equilibrium ($x^*_{B,t} > x^*_{A,t}$). The same condition on p_A determines whether $\partial x^*_{A,t}/\partial c_t > \partial x^*_{B,t}/\partial c_t$. Thus, considering the limit case of an investment in technology which only reduces today's contribution cost, country B's early contribution increases more strongly than country A's early contribution for all $p_A < \bar{p}_A$ (even though A may have the higher expected valuation). The relative advantage of providing the cost-reducing technology depends, thus, on whether p_A is high or low.

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