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Abstract

We introduce an international technology treaty ("Tech Treaty") that couples the funding of research for a more advanced abatement technology with an international emissions permit market. While each country decides on domestic permit issuance, a fraction of these permits is auctioned by an international agency. Auction revenues scale up license revenues for the innovators of abatement technologies. We show that such a treaty increases innovations and decreases emissions under plausible conditions compared to an emissions trading system without additional technology agreement. Finally, we discuss how a Tech Treaty may inspire next steps in existing technology programs.

JEL Classification: H23, Q54, O31

Keywords: Climate Change Mitigation - Technology Promotion - R&D - International Emissions Permit Markets - International Treaty - Externalities

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Technology Treaties and Climate Change*

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Abstract

We introduce an international technology treaty ('Tech Treaty') that couples the funding of research for a more advanced abatement technology with an international emissions permit market. While each country decides on domestic permit issuance, a fraction of these permits is auctioned by an international agency. Auction revenues scale up license revenues for the innovators of abatement technologies. We show that such a treaty increases innovations and decreases emissions under plausible conditions compared to an emissions trading system without additional technology agreement. Finally, we discuss how a Tech Treaty may inspire next steps in existing technology programs.

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1 Introduction

Motivation

Climate change is a global problem that ranks high on the agendas of international policy-makers.[1] It is difficult to solve, as climate protection is a global public good, and no institution exists that could enforce a global policy to avoid free-riding. Theoretical research suggests that an agreement on greenhouse gas emissions reductions between all countries can only be implemented if abatement targets are kept modest, a finding that goes back to some seminal papers in this area.[2] Modest abatement targets will not suffice to slow down climate change substantially (see e.g. estimations in IPCC (2014)). The 'Paris Agreement' is the first global agreement to limit greenhouse gas emissions, but the abatement targets the participating countries have committed to are insufficient to keep global warming below 2°C (European Commission, 2016b).

It is often argued that addressing climate change and slowing down global warming requires technological advances (see e.g. the discussion in Harstad (2016) or Schmidt (2014)). Potentially, technologies can indeed lead to emissions reduction (see e.g. International Energy Agency (2012)), and certain abatement targets may not be achievable without technological breakthroughs. It is well-known that only a small fraction of the gains from developing new technologies can be appropriated by the innovator, which is the operative factor behind the under-provision of R&D investments for such technologies (e.g. Barrett (2006) and Hoel and de Zeeuw (2010)). An additional challenge is to get developed abatement technologies onto the market. Many existing abatement technologies are not yet competitive (Benner et al. (2012); Croezen and Korteland (2010); UNFCCC (2009) and Table A1 in Appendix A), a fact that may be related to financing problems in general (UNFCCC, 2009) or to a lock-in in carbon-based technologies, as these carbon-based technologies benefit from investments made previously (Mazzucato, 2014).

In this paper we thus explore an approach to slowing down climate change that focusses on technological advances. All our approach requires is a set of rules fostering innovation in abatement technologies and the diffusion of such technologies in the context of an international permit market. We call the set of rules 'Tech Treaty'. We advance the idea to use revenues from permit trade to increase incentives to develop marketable abatement technologies that lower abatement costs. Lower abatement costs might then induce countries to tighten the issuance of emissions permits, especially in the longer run

[1] Paris Agreement; Goal 13 of the Sustainable Development Goals of the United Nations 2030 Agenda for Sustainable Development: "*Take urgent action to combat climate change and its impacts.*"

[2] E.g. Barrett (1994), Hoel (1992); also see discussion in Finus and Maus (2008).

when better technologies have been developed. Under plausible conditions, we show that Tech Treaties also induce countries to tighten permit issuance in the short run.[3] Overall, starting from a decentralized solution with inefficiently low R&D activities and excessively high emissions, we show that a Tech Treaty can help to move towards a socially more desirable situation with higher R&D activity and lower emissions. Our analysis suggests that a Tech Treaty that fosters the development of new technologies or the acceleration of technology diffusion is not detrimental to permit issuance.

The Tech Treaty is in the spirit of the NER300 program of the European Emissions Trading system. The NER300 program uses 2% of the permits to co-finance large demonstration projects that show how existing technologies can be used best (European Commission, 2017b). We focus on bridging the gap between technological development and commerzialisation by making support conditional on technology adoption by the market. The Tech Treaty incentivices development of technologies by private R&D firms and allows market forces to determine which technology will be supported.

Rules and implementation

A Tech Treaty consists of three main rules complementing a standard international emissions permit market. First, each country gives a pre-determined share of its issued permits to an international agency that sells these permits on the international permit market and administers the process. Second, the revenues from the sale of the permits are used to foster technological developments by scaling the license revenue for successful innovators. In this way, a Tech Treaty can foster investments in R&D to detect new abatement technologies, and it also avoids the situation where one 'winning' technology has to be selected by a planner or financed by the government. Third, revenues from auctioning permits are only paid to a successful innovator if the abatement technology is offered at a single price to all firms willing to buy it. The license fee thus will be equal to the willingness-to-pay for the advanced technology of the production firms in the country with the smallest gains from adopting the advanced technology. The requirement to make technology diffusion complete is part of the Tech Treaty.

Some remarks on the actual implementation of a Tech Treaty are in order. The Tech Treaty is aimed at those countries and firms that are in a position to adopt new production methods lowering carbon emissions. Croezen and Korteland (2010) give examples of such technological developments for the steel, cement, and paper industries. A selection of such technologies is listed in Table A2 in Appendix A. The focus on production techniques restricts the applicability of the Tech Treaty to industrialized and emerging countries,

[3]Without emissions permit markets, a treaty on technological cooperation may increase emissions (Strand, 2007).

including countries like China and India.[4] Still, this range of countries is responsible for the large part of emissions (World Bank (2018)). Also, carbon leakage[5]—the main concern if not all countries participate—is less menacing since there is no incentive for major dislocations of production sites to the remaining countries.

Model and results

To investigate whether the Tech Treaty fosters innovation and to establish how it affects permit issuance, we set-up a multi-country model of greenhouse gas emissions. The model is as follows: In each country, there is a representative production firm emitting pollutants, a representative R&D firm, and a local planner. An international emissions permit market is established, and the Tech Treaty is put in place. Then local planners issue permits. Subsequently, R&D firms decide whether to become active and to engage in research. The outcomes of R&D processes are stochastic and the chances to detect new abatement technologies increases the more R&D firms are active. Once an advanced technology materializes, one successful R&D firm becomes patent-holder and offers the advanced technology to the production firms at some license fee. The production firms decide whether to adopt it. Finally, the production firms decide on abatement, which simultaneously determines trading of permits.

Along these lines, we interpret the set-up of the model as a game with four stages with observed actions, i.e. in each stage, the actions of all agents in previous stages are common knowledge. The four stages are (1) permit issuance, (2) R&D activity, (3) technology diffusion, and (4) permit trade and abatement. We focus on the period when Tech Treaties are introduced and summarize what they imply for the future. In line with the focus on production techniques, we assume that countries differ in their baseline emissions as well as in the local damage they suffer from aggregate pollution, but that they have an identical ability to adopt technologies.

We explore the consequences of the Tech Treaty in two different environments. First we consider an environment with a given number of global emissions permits. We consider only the last three stages of the game and state conditions for a unique equilibrium with regard to R&D efforts, licensing fee, technology diffusion, and permit trade. We show that an increase in the share of permits auctioned by the international agency will increase the number of active R&D firms and the likelihood of inventing more advanced abatement technologies. A greater share of auctioned permits increases the prospect of larger license

[4] Most existing climate funds—like the Global Environment Facility (GEF) and the Green Climate Fund—focus on technology development and technology transfer to developing economies (compare (UNFCCC, 2014)).

[5] Carbon leakage refers to a situation in which the reduced carbon emissions of one country are (partially) offset by an increase in the carbon emissions of another country.

revenues, which in turn fosters innovation activity. For a given number of global emissions permits, a Tech Treaty thus increases the likelihood that a cheaper abatement technology is made available.

Second, we examine whether there might be adverse consequences arising from the incentives of countries to issue permits when a Teach Treaty is introduced. For this purpose, we examine the entire four-stage game and derive the conditions for an equilibrium involving permit issuance decisions, R&D efforts, technology diffusion, and permit trade. We introduce the notion of a 'difficult' research environment, characterized by large potential cost reductions in abating emissions but either low probabilities of innovation success or high research costs. This is arguably a characterization of technologies that can considerably lower the costs of emissions abatement. We show that with high research costs, countries will tighten emissions permit issuance when Tech Treaties are introduced, as long as the response of the permit price is inelastic. For quadratic abatement costs and many similar countries, this is fulfilled as soon as permit issuance falls slightly below business-as-usual emissions.

While we focus on Tech Treaties compared to the decentralized solution with only a permit market in the main body of the paper, two alternative benchmarks could be considered, namely the first-best solution, in which countries cooperate in both abatement and R&D, and the second-best solution, in which countries perfectly cooperate on R&D, but emissions limits remain decentralized. For Tech Treaties with only one instrument and decentralized abatement decisions, the relevant benchmark is the second-best solution. In Section 5 we discuss these benchmarks and provide a numerical example to illustrate how a Tech Treaty improves upon the decentralized solution and can move the economy close to the second-best outcome when the research environment is difficult. A Tech Treaty can also lead to lower emissions compared to the second-best setting for an appropriate choice of the share given to the international agency.

Organization of the paper

The paper is organized as follows: In the next section we show how our article relates to the literature. In Section 3 we set up the model. In Section 4 we solve for equilibria for a given Tech Treaty and a given global emissions limit, analyzing how changes in the Tech Treaty affect the innovation activity of the R&D firms. In the next section we endogenize the global emissions limit and consider the impact of a change in the Tech Treaty on the global emissions limit. How a Tech Treaty relates to the first-best, second-best and decentralized outcome is discussed in Section 6. In Section 7 we discuss the model and the results as well as participation in the Tech Treaty. Section 8 concludes. Appendix

A collects tables with additional information, e.g. with an overview of technologies with the potential for reducing carbon emissions. Appendix B contains the lengthier proofs, derivations and conditions, while Appendix C presents complementary examinations and further examples.

2 Related Literature

This paper relates to several strands of the literature. Our paper suggests a partial solution to the climate change problem by introducing technology clubs that come into being through rules defined in a treaty that relate to technological development.[6] Treaties focusing on grand solutions to the climate problem based on emissions targets with refunding in permit markets have been developed e.g. by Gersbach and Winkler (2011) and Gersbach and Oberpriller (2012).

Technology adoption in fostering cooperation and building a coalition to solve the climate change problem has been addressed repeatedly in the literature. As self-enforcing global environmental agreements will achieve very little (see e.g. Asheim et al. (2006)), some authors examine whether a focus on technology might improve outcomes and, in particular, how the prospect of developing new technologies can facilitate cooperation. Barrett (2006) and Hoel and de Zeeuw (2010) find that either breakthrough technologies with increasing returns or a focus on the research phase of breakthrough technologies can improve the potential for cooperation. Barrett (2012) finds that cooperation prospects also improve if a breakthrough technology with constant returns and a conventional technology can be used parallel to each other. Hong and Karp (2012) examine participation in a coalition when mixed strategies are allowed and an initial investment stage is added. If no breakthrough technologies are considered, but only technological improvements, participation in an agreement is low (El-Sayed and Rubio, 2014). Rubio (2016) finds potential for successful cooperation if the focus is on green technologies.

In this paper we adopt a complementary approach. We examine whether a Tech Treaty will increase innovation and whether in a given coalition higher R&D activities—promoted via a Tech Treaty—can help to lower emissions. We focus on R&D and follow the innovation literature discussion on the situation where many firms seek to obtain a patent for a new technology in a stochastic environment (see e.g. Acemoglu (2009) for an overview).[7]

[6] Nordhaus (2015) advocates climate clubs: The members of the climate club impose tariffs on non-participants, which theoretically might prompt all countries to participate. However, for larger emissions reductions, tariffs lose their power to induce participation. In Section 7.1, we discuss how Tech Clubs can be implemented by imposing high licensing fees for new technologies on outsiders.

[7] Denicolò and Franzoni (2010) find that in a broad set of circumstances a winner-takes-all system

Goeschl and Perino (2016) include a technology license fee setting for firms in international environmental agreements and show that intellectual property rights may create hold-up problems. They take innovation as given. Our paper is complementary as we focus on how scaling license income with revenues from auctioning permits can boost innovation. For an intriguing model of the interplay of environmental policy, technology adoption and R&D see e.g. Requate (2005). To our knowledge, we are the first to examine how a Tech Treaty impacts innovation and total emissions. Also, unlike many others, we work with a stochastic R&D sector.

We start from an existing international permit market. In his seminal paper, Helm (2003) showed the potential increase in emissions when moving from no-trade of permits to trading permits. We focus on how Tech Treaties can improve upon an existing permit market with non-cooperative permit issuance.

Finally, our paper also relates to the literature on the green paradox and especially the 'announcement effect'. An overview of different set-ups leading to a green paradox, including the announcement effect, is given in van der Werf and Di Maria (2012). The announcement effect refers to a situation with a time lag between the announcement and the implementation of a policy measure (see e.g. Di Maria et al. (2012); Riekhof and Bröcker (2017); Smulders et al. (2012)). During this time lag, emissions are higher than in absence of a policy. Strand (2007) shows that—when no emissions permit market exists—a treaty on technological cooperation may increase initial emissions. In this paper we identify situations in which the refunding of auctioned permit revenues to R&D firms provides incentives for countries to tighten permit issuance even if they expect abatement technologies to improve.

3 The Model

We consider a multi-country model of greenhouse gas emissions with $n \geq 2$ countries indexed by $i \in \{1, ..., n\}$.[8] In each country there is a representative production firm, a representative R&D firm and a local planner. We use the index i for both types of firm, and the local planner in country i. If necessary, we use j interchangeably with i.

Without abatement, the activity of the production firm in country i (henceforth production firm i) leads to baseline emissions $\bar{e}_i$, with $\bar{e}_i \geq 0$.[9] Production firm i can abate

is preferable, especially in highly innovative industries. Different ways of incentivizing innovation are explored in Fu et al. (2012).

[8] For the sake of simplicity, we assume that all countries can adopt advanced abatement technologies.

[9] Table A3 in Appendix A lists all symbols used.

its emissions. To keep the model as simple as possible, the output of the production firm is kept constant. If the production firm reduces the emissions by amount a_i with $a_i \geq 0$, it incurs costs $g_O(a_i)$. The function $g_O(\cdot)$ is continuous on $[0, \infty)$ and has the properties $g_O(0) = 0$, $g'_O(a_i) > 0$ and $g''_O(a_i) > 0$ for all $a_i > 0$.[10] So the cost function is strictly increasing and strictly convex. A quadratic abatement cost function fulfills these requirements and will be used for illustrative examples. The cost function is the same for all countries. The subscript '$_O$' stands for old technology. More advanced abatement technologies will be introduced later on.

Each R&D firm can decide to become active and look for an advanced abatement technology—henceforth advanced technology—that lowers abatement costs. Once such a technology is detected, one successful R&D firm becomes the patent-holder and licenses the advanced technology to the production firms at a fee that we will refer to as f, with $f \in \mathbb{R}_+$.[11] To distinguish between the two technology types, we denote this newly detected technology as the 'advanced' technology and mark it with the subscript '$_A$'. The abatement costs of production firm i for using the advanced technology are denoted by $g_A(a_i)$. The cost function is a continuous function on $[0, \infty)$ and satisfies $g_A(0) = 0$, $g'_A(a_i) > 0$, $g''_A(a_i) > 0$ and $g'_A(a_i) < g'_O(a_i)$ for all $a_i > 0$. The latter property implies $g_A(a_i) < g_O(a_i)$ for all $a_i > 0$.

Each country's local planner represents the local citizens and operates within the following context: Each country suffers damage from the total amount of greenhouse gases emitted by all countries. Let $E := \sum_{i=1}^{n} [\bar{e}_i - a_i]$ denote the total amount of greenhouse gases emitted in the world. Country i's damage is expressed by the function $d_i(E)$, where $d_i(\cdot)$ is twice continuously differentiable on $[0, \infty)$, $d'_i(E) > 0$, and $d''_i(E) > 0$ for all $E \geq 0$. One can think of the positive second derivative of the damage function as a representation of strongly increasing damages.

We next introduce an international emissions permit market and the Tech Treaty. The international emissions permit market operates via decentralized permit issuance. Each local planner issues an amount of permits ϵ_i, with $\bar{e}_i \geq \epsilon_i \geq 0$,[12] and each production firm has to hold permits for emissions. The Tech Treaty is an international agreement, denoted by $TT(\alpha)$ in which the parameter α termed 'Tech Treaty Share' is determined. The Tech Treaty is defined as follows:

[10] As usual, $g'(\cdot)$ and $g''(\cdot)$ denote the first and second derivative, respectively.

[11] We use $\mathbb{R}_+$ to refer to $\{x \in \mathbb{R} | x \geq 0\}$.

[12] The requirement that ϵ_i cannot exceed baseline emissions $\bar{e}_i$ is not a strong assumption, as industrialized countries usually aim at lower emissions compared to a baseline year (International Center for Climate Governance, 2016)

Definition 1 (Tech Treaty $TT(\alpha)$)

Under a Tech Treaty $TT(\alpha)$, with n participating countries, the following rules apply:

(i) A country i participates in the international emissions permit market, decides on the amount of permits to issue, and gives a fraction α ($0 \leq \alpha \leq 1$) of the permits issued ϵ_i to an international agency. The international agency sells $\alpha\epsilon_i$ on the international permit market. A fraction $[1-\alpha]\epsilon_i$ is given to the production firm i for free (grandfathering).

(ii) If a patent-holder of the advanced technology exists and $\alpha > 0$, the revenues of the international agency from selling permits are used to increase the license revenue of the patent-holder.

(iii) A firm holding a patent for an advanced technology will only receive the revenues from the international agency if it offers this superior technology to all production firms at the same license fee and if the advanced technology is used by them. If the technology is detected but the patent-holder does not qualify for revenues from the international agency, the revenue is distributed equally between countries.[13]

(iv) If no advanced technology is detected, the permits given to the international agency are returned to the countries, which grandfather them to the local production firms.

The first two rules are the core of the Tech Treaty. The third rule ensures that there is complete diffusion of technologies—one goal of the Tech Treaty—and it also simplifies the analysis. Variations of this rule or its absence are also conceivable. The last rule is there for practical reasons. It is a procedural rule for cases where nothing is paid to a patent-holder.

It is useful to introduce the following notation: Let $\mathcal{E} = \sum_{i=1}^{n} \epsilon_i$ denote the aggregate amount of permits, thus constituting the global limit on greenhouse gas emissions. Let p denote the prevailing permit price on the international permit market. The revenues of the international agency are thus $\alpha p \mathcal{E}$.

Several additional remarks are in order. First, the set of rules can be interpreted as burden-sharing agreement. While production firms only receive $[1-\alpha]\epsilon_i$ for free when an advanced technology is discovered, they receive the whole amount ϵ_i if it is *not* discovered. Receiving fewer permits when the technology is discovered make the production firms share the burden of financing R&D. Second, while the case $\alpha = 0$ is formally not equivalent

[13] This is to avoid adverse incentives of production firms not to adopt the advanced technology in order to increase the amount of grandfathered permits.

to the absence of a Tech Treaty, the outcome for R&D incentives and permit issuance for $\alpha = 0$ is however equivalent to the scenario without a Tech Treaty. Third, the number of participating countries is assumed to be given as e.g. in the European Emissions Trading System. We provide a sufficiency condition under which complying with the Tech Treaty is more profitable than not doing so in Section 4.2.

The sequence of decisions taken by the different agents is as follows: An international emissions permit market is established, and the Tech Treaty is drawn up. Local planners issue permits. Subsequently, R&D firms decide whether to become active and to engage in research. Once an advanced technology is detected, the patent-holder is determined. The patent-holder offers the advanced technology to the production firms for a license fee of some kind. The production firms decide whether to adopt it or not. Finally, the production firms decide on abatement and the trading of permits. Along these lines we interpret the set-up of the model as a four-stage game and observed actions, i.e. at each stage all actions by all agents in previous stages as well as parameters and functions such as $g_A(.)$ are common knowledge.

In the following we describe the sequential structure and all decision problems in more detail. For the moment, we take emissions permit market and the Tech Treaty as given and analyze their consequences for innovations and global emissions. Later we will discuss the incentives for countries to participate in these international environmental agreements. We start with describing permit issuance in more detail.

Stage 1: Permit Issuance

Given an international permit market and a Tech Treaty $TT(\alpha)$, the local planner in country i, $i \in \{1, ...n\}$, decides simultaneously with the other local planners on an amount of permits denoted by ϵ_i she wants to issue. Local planners aim to minimize their citizen's costs. For their decision the local planners consider both local damages from global emissions and the costs for the local firms. Both may differ from country to country. The next stage describes in more detail how the R&D firms operate and how the advanced technology can be detected.

Stage 2: R&D Activity

In each country, the R&D firm i, $i \in \{1, ...n\}$, chooses whether or not to become active and to invest a fixed amount x ($x > 0$) in research. The decision is based on non-negative expected profits. A positive income can only be earned if the firm becomes the patent-holder. In the following we describe the patent-holder's income and the probability of becoming a patent-holder.

The income of the patent-holder is the license fee f times the number of production firms that buy the license. We use l to denote the number of firms that buy the license and use the advanced technology ($0 \leq l \leq n$). If a Tech Treaty is present, the patent-holder has to set the license fee in such a way that all production firms will adopt the advanced technology, i.e. $l = n$. In addition, the patent-holder obtains the additional income $\alpha p \mathcal{E}$. The patent-holder's total revenue thus becomes $nf + \alpha p \mathcal{E}$. The number of active R&D firms will be determined by comparing expected revenues with the costs of performing R&D.

The probability of becoming the patent-holder is a combination of the probability of the firm detecting the advanced technology and of this firm—of all the successful R&D firms—becoming the patent-holder. Let k denote the number of all active R&D firms. We assume that the investment x by one active R&D firm will lead to the detection of the advanced technology with a probability of π, $0 < \pi < 1$. Success probability π is stochastically independent across all active R&D firms. Let Π denote the overall probability that an advanced technology is discovered, i.e. that at least one R&D firm is successful.

If several active firms are successful, the patent-holder is determined by fair randomization in this group. Alternatively, all successful active R&D firms could share the revenues from licensing the technology equally. For risk-neutral firms, the results would be the same as with one patent-holder who obtains all licensing revenues, because expected revenues—which determine whether an R&D firm becomes active—are the same in both scenarios. The process of setting the license fee is described in more detail in the next stage.

Stage 3: The License Fee and Technology Diffusion

Stage 3 is only relevant if an advanced abatement technology has been detected. Suppose that this is the case. The successful R&D firm that becomes the patent-holder sets the fee f at which production firms can license the advanced technology. The production firms decide simultaneously about licensing.

A production firm chooses the technology type that minimizes total costs. Total costs consist of abatement costs and costs (or benefits) from trading on the permit market. If the advanced technology is used, total costs additionally include the payments of the licensing fee f.

If total costs are identical in both cases the production firm will be indifferent between licensing the advanced technology and using the old technology. Let $\bar{f}_i$ denote the fee that equalizes production firm i's total costs with both technology types. We refer to $\bar{f}_i$ as the production firm i's willingness to pay for the advanced technology. Typically, $\bar{f}_i$ depends on $\mathcal{E}$, the Tech Treaty $TT(\alpha)$, and the number of other production firms licensing the advanced technology.

Let us now turn to the patent-holder. To ensure $l = n$, the patent-holder has to set the fee in such a way that the firm with the lowest willingness to pay will still adopt it. The production firms' decision on abatement and on the trade of permits is considered in the next stage.

Stage 4: Permit Market Equilibrium

Each production firm i, $i \in \{1, ...n\}$, has received grandfathered permits from the local planner and has chosen the abatement technology it wants to use. The amount of permits received is $[1 - \alpha]\epsilon_i$ if an advanced technology has been detected and ϵ_i if no advanced technology has been detected.

All production firms aim to minimize costs and decide simultaneously on emissions reduction a_i, and the permit market clears. The global supply of permits $\mathcal{E}$ is given at this stage and the equilibrium permit price p prevails. Note that the international agency is a net-supplier in the market, while production firms may act as buyers or sellers. In the next sections we specify the payoff functions of all agents involved and determine the equilibria.

4 Equilibria for a Given Tech Treaty and Aggregate Emissions

We are looking for subgame perfect equilibria of the multi-stage game with observed actions covering Stages 1 to 4. We solve the model by backward induction, starting from Stage 4 and assuming that a Tech Treaty $TT(\alpha)$ has been drawn up and the international emissions permit market is in operation. For the moment, we assume that an international emissions limit has been set. This means that we only consider Stages 4, 3, and 2. We are then in a position to make statements on how the Tech Treaty affects the number of active R&D firms for a given global emissions limit.

4.1 Solution in Stage 4: Permit Market Equilibrium

In this last stage, aggregate permits $\mathcal{E}$ are given and uncertainty about the detection of an advanced technology has been resolved. The licensing fee f has also been set. Each production firm has decided which technology to use and is left to decide on its abatement effort a_i, $i \in \{1, ...n\}$. To cover their emissions, production firms have to hold emissions permits. Missing permits can be bought and superfluous permits sold in the market. Production firms act as price-takers on the permit market.[14] Market clearing will determine the permit price p.

For the solution of the first three stages it is useful to consider a situation in which both technologies may be used. This will ultimately only occur out of equilibrium. Both technologies are used if $0 < l < n$. We introduce the index $q = 1, ..., l$ to refer to the production firms using the advanced technology and facing abatement costs $g_A(a_q)$ and the index $m = l+1, ..., n$ to refer to the production firms that still use the old technology and face abatement costs $g_O(a)$.

Let c_A and c_O denote the sum of abatement costs and costs from trading on the emissions market when using the advanced or the old technology.

$$c_A(\alpha, \epsilon_q, a_q) := g_A(a_q) + p[\bar{e}_q - a_q - [1-\alpha]\epsilon_q], \tag{1a}$$

$$c_O(\alpha, \epsilon_m, a_m) := g_O(a_m) + p[\bar{e}_m - a_m - [1-\alpha]\epsilon_m]. \tag{1b}$$

Production firms in both groups only receive the amount $[1-\alpha]\epsilon_i$ of permits, as the advanced technology has been detected and $\alpha\epsilon_i$ is given to the international agency.

With the advanced technology, total costs of a production firm are $c_A(\alpha, \epsilon_q, a_q) + f$. The license fee f is constant and independent of a_i. As $g_O(\cdot)$ and $g_A(\cdot)$ are assumed to be strictly convex and strictly increasing for $a_i > 0$, total costs are also convex. So, total costs are minimized where

$$\frac{\partial c_A(\alpha, \epsilon_q, a_q)}{\partial a_q} = 0 \text{ and } \quad \frac{\partial c_O(\alpha, \epsilon_m, a_m)}{\partial a_m} = 0,$$

[14] Although we assume one production firm per country, this one production firm can stand for many production firms. For example, on the EU-ETS, more than three thousand firms trade, and the three biggest emitting firms represent each less than 8% of total emissions (RWE: 7.1%, E.ON: 4.7% and Vattenfall: 4.2%.) (Nicolaï, 2015). With many trading firms, an equilibrium approximates the competitive equilibrium (Lange, 2012). As an alternative explanation, one could consider the abatement technology in each country as the result of abatement efforts of a continuum of production firms which have the option to abate one unit of emissions at some costs. With a continuum of firms, we obtain price-taking behavior on the permit market.

which implies that the permit price equals marginal abatement costs

$$p = g'_A(a_q) = g'_O(a_m), \quad q = 1, ..., l, \quad m = l + 1, ..., n \tag{2}$$

for $a_q, a_m > 0$. In permit market equilibrium, the marginal abatement costs of all production firms are equal.

Equation (2) also implies that the firms with the same technology will choose identical abatement levels. Let $a_A(p)$ and $a_O(p)$ denote the two abatement choices. As marginal abatement-cost functions are strictly increasing, the inverse functions exist, and the abatement choices are given by

$$g'^{-1}_A(p) = a_A(p), \quad g'^{-1}_O(p) = a_O(p). \tag{3}$$

From the assumption

$$g'_A(a_i) < g'_O(a_i) \quad \text{for all} \quad a_i > 0 \tag{4}$$

and the definition of the inverse,

$$g'_A(a_A(p)) = g'_A(g'^{-1}_A(p)) = p, \quad \text{and} \quad g'_O(a_O(p)) = g'_O(g'^{-1}_O(p)) = p,$$

it follows that $a_O(p) < a_A(p)$. For any permit price $p > 0$, the production firms using the advanced abatement technology will abate more than the production firms using the old technology.

We next characterize the equilibrium on the permit market. The demand E is given by $E = \sum_{i=1}^{n} \bar{e}_i - a_i$ and supply is $\mathcal{E} = \sum_{i=1}^{n} \epsilon_i$. Market clearing yields

$$\begin{aligned} \mathcal{E} = \sum_{i=1}^{n} \epsilon_i = \sum_{i=1}^{n} \bar{e}_i - a_i = \sum_{i=1}^{n} \bar{e}_i - \sum_{q=1}^{l} [a_A(p)] - \sum_{m=l+1}^{n} [a_O(p)] \\ = \bar{E} - l a_A(p) - [n - l] a_O(p), \end{aligned} \tag{5}$$

where $\bar{E} := \sum_{i=1}^{n} \bar{e}_i$ denotes the aggregate amount of baseline emissions.

Equation (5) implicitly determines the equilibrium permit price as a function of the global emissions limit $\mathcal{E}$ and the number of production firms l that have adopted the advanced technology. All elements of Equation (5), except p, are known at the beginning of Stage 4. Since $a_A(p)$ and $a_O(p)$ are strictly increasing and continuous functions of p, we obtain a unique solution for the equilibrium price p, which we write as a function of total permit issuance $\mathcal{E}$ and the number of firms using the advanced technology, $p(\mathcal{E}, l)$.

In the next lemma we set out two properties of $p(\mathcal{E}, l)$. For this purpose, we treat l as a continuous real variable, since (5) can be solved for any real variable. Also, we introduce the following notation to denote partial derivatives of functions with several inputs:

$$p'_l := \frac{\partial p(\mathcal{E}, l)}{\partial l} \quad \text{and} \quad p'_{\mathcal{E}} := \frac{\partial p(\mathcal{E}, l)}{\partial \mathcal{E}}.$$

Lemma 1

(i) The permit price decreases with the number of production firms that have adopted the advanced technology, $p'_l < 0$.

(ii) The permit price decreases with the global emissions limit, $p'_{\mathcal{E}} < 0$.

Proof of Lemma 1. See B.1 in the Appendix. □

The properties established in Lemma 1 are intuitive. The permit price decreases when the global emissions limit increases, because emissions permits become more abundant. The same holds when more production firms adopt the advanced abatement technology because more firms have access to the cheaper abatement technology.

We note that initial permit ownership is irrelevant for the cost minimization effort of production firms in Stage 4 and for the equilibrium permit price. Similarly, the Tech Treaty—which implies that the share $\alpha\mathcal{E}$ is auctioned by the international agency—has no impact on the outcome in Stage 4 once technological development, diffusion of technologies, and $\mathcal{E}$ are determined. However, as we will see below, the Tech Treaty will influence the expected number of R&D firms and the overall supply of permits.

4.2 Solution in Stage 3: The License Fee and Technology Diffusion

We next consider Stage 3 and determine the license fee and technology choices given an aggregate amount of emission permits $\mathcal{E}$.

Suppose an advanced technology has been detected. Otherwise, as stated before, Stage 3 is redundant. Since $\mathcal{E}$ is given, prices and abatement efforts for any licensing constellations can be perfectly anticipated. Under the Tech Treaty, the patent-holder has to set the license fee in such a way that all production firms will adopt it, $l = n$. In the following we determine each individual production firm's highest willingness to pay for the advanced technology when it assumes that all other production firms will be licensing that technology. Based on this, the patent-holder sets a license fee that equals the lowest of these numbers. In the following, the optimal license fee and its characteristics are determined.

To find the license fee for which $l = n$ holds, consider the case where $l < n$ production firms adopt the advanced technology. Any production firm m is indifferent between using the old and the advanced technology if

$$c_A(\alpha, \epsilon_m, a_A) + f = c_O(\alpha, \epsilon_m, a_O), \tag{6}$$

with c_A and c_O defined in Equations (1a) and (1b). In other words, the production firm m is indifferent if the fee f satisfies

$$\begin{aligned} f = \bar{f}_m(l) :=& c_O(\alpha, \epsilon_m, a_O) - c_A(\alpha, \epsilon_m, a_A) \\ =& g_O(a_O(p(\mathcal{E}, l))) - g_A(a_A(p(\mathcal{E}, l+1))) \\ &+ p(\mathcal{E}, l)[\bar{e}_m - [1-\alpha]\epsilon_m - a_O(p(\mathcal{E}, l))] \\ &- p(\mathcal{E}, l+1)[\bar{e}_m - [1-\alpha]\epsilon_m - a_A(p(\mathcal{E}, l+1))]. \end{aligned} \tag{7}$$

The willingness to pay equals the abatement cost differences and the differences in buying (or selling) permits when either the old or the advanced technology is adopted. The latter difference depends on the differences between the permit prices and the differences between emission reductions under the two technologies.

The following lemma establishes how $\bar{e}_i - [1-\alpha]\epsilon_i$ influences the adoption of the advanced technology.

Lemma 2
Assume that all production firms j except firm i adopt the advanced technology. The remaining production firm's willingness to pay for use of the advanced abatement technology denoted by $\bar{f}_i(n-1)$ is increasing in $\bar{e}_i - [1-\alpha]\epsilon_i$.

Proof of Lemma 2.
Production firm i's maximum willingness to pay when $n-1$ production firms have already adopted the advanced technology is

$$\begin{aligned} \bar{f}_i(n-1) =& g_O(a_O(p(\mathcal{E}, n-1))) + p(\mathcal{E}, n-1)[\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E}, n-1))] \\ &- g_A(a_A(p(\mathcal{E}, n))) - p(\mathcal{E}, n)[\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, n))]. \end{aligned}$$

Since $p(\mathcal{E}, n-1) > p(\mathcal{E}, n)$ by Lemma 1, we observe that

$$f_i(n-1) > f_j(n-1) \Leftrightarrow \bar{e}_i - [1-\alpha]\epsilon_i > \bar{e}_j - [1-\alpha]\epsilon_j$$

since all other components are independent of the particular firm under consideration. □

Lemma 2 shows that the fewer permits firm i obtains relative to its baseline emissions, the greater is its willingness to pay for the advanced abatement technology. Lemma 2 also implies that

$$\text{argmax}_{i\in[1,n]}\bar{f}_i(n-1) = \text{argmax}_{i\in[1,n]}(\bar{e}_i - [1-\alpha]\epsilon_i).$$

Without loss of generality, we can now order $1, ..., n$ in such a way that

$$\bar{e}_1 - [1-\alpha]\epsilon_1 > \bar{e}_2 - [1-\alpha]\epsilon_2 > ... > \bar{e}_{n-1} - [1-\alpha]\epsilon_{n-1} > \bar{e}_n - [1-\alpha]\epsilon_n,$$

so that country n has the minimum willingness to pay, i.e.

$$f_n(n-1) = \min_{i\in[1,n]} f_i(n-1).$$

Then, we obtain Lemma 3.

Lemma 3
The license fee is determined by the production firm with the lowest $\bar{e}_i - [1-\alpha]\epsilon_i$*. In particular, the patent-holder sets the fee* f *according to*

$$\begin{aligned} f(\mathcal{E},\alpha,\epsilon_n) \equiv f_n(n-1) =& g_O(a_O(p(\mathcal{E},n-1))) - g_A(a_A(p(\mathcal{E},n))) \\ &+ p(\mathcal{E},n-1)[\bar{e}_n - [1-\alpha]\epsilon_n - a_O(p(\mathcal{E},n-1))] \\ &- p(\mathcal{E},n)[\bar{e}_n - [1-\alpha]\epsilon_n - a_A(p(\mathcal{E},n))]. \end{aligned} \tag{8}$$

and all production firms license the advanced technology.

In equilibrium, the license fee set by the patent-holder is a function of total emissions, the Tech Treaty Share, and the permits issued by country n, $f(\mathcal{E},\alpha,\epsilon_n)$. Setting the fee according to Lemma 3 will lead to a unique equilibrium in which all production firms will license the advanced technology if the production firm i's willingness to pay decreases with the number of production firms adopting the advanced technology l.

We assume $\frac{\partial f_i(l)}{\partial l} < 0$ for the remainder of the paper. Appendix B.2 discusses general conditions for $\frac{\partial f_i(l)}{\partial l} < 0$ to hold. This is the case e.g. when α is not too small and countries are sufficiently symmetric, or when abatement costs are quadratic and costs parameters and the number of countries are in a plausible range.[15] Appendix C.3 solves the model with quadratic abatement costs of the form $g_\tau = b_\tau a_i^2/2$.

Note that the production firm n is indifferent between buying the advanced technology and using the old technology. We assume that indifferent production firms will opt for the

[15]For abatement costs $g_\tau = b_\tau a_i^2/2$, with $\tau \in \{O, A\}$, the sufficient condition is $\frac{b_A}{[lb_0+b_A[n-l]]^3} < \frac{b_O}{[[l+1]b_0+b_A[n-l-1]]^3}$. More details are discussed in Appendix C.3, especially C.3.4.

advanced technology. This tie-breaking rule is not critical for our results. It merely avoids working with license fees that are lower than the one derived in (8) when this difference is arbitrarily small.

We also note that the rules of the Tech Treaty are not restrictive for the patent-holder if $f_n(n-1)n + \alpha p\mathcal{E} \geq \max f_l(l-1)l, l \in \{1, ..., n-1\}$. If α is not close to zero, revenues from the Tech Treaty are arguably higher than gains from discriminatory pricing. Lemma 4 states how license fee f reacts to a change in α.

Lemma 4
A higher share given to the international agency leads to a higher license fee f, $f'_\alpha(\mathcal{E}, \alpha, \epsilon_n) > 0$, for all $\mathcal{E} \geq 0$, $\alpha \in [0,1], \epsilon_n \geq 0$.

The property $f'_\alpha = -\epsilon_n(p(\mathcal{E}, n) - p(\mathcal{E}, n-1)) > 0$ in Lemma 4 follows from Equation (8) and Lemma 1, as a_O, a_A, $p(\mathcal{E}, n-1)$ and $p(\mathcal{E}, n)$ do not depend on α.

The property established in this Lemma with respect to the Tech Treaty Share is intuitive. If it increases, all production firms, *ceteris paribus*, will receive fewer permits for free, will either have to abate more or buy more permits and will thus be willing to pay a higher license fee to lower marginal costs. Next we consider the decision problem facing the R&D firms.

4.3 Solution in Stage 2: R&D Activity

In Stages 3 and 4 the availability of the advanced technology was taken for granted. Stage 2 describes the innovation process and shows how R&D firms decide whether they want to become active.

Given that $k-1$ other R&D firms are active the individual R&D firm will invest in research if the expected payoff is non-negative. Let $\tilde{\pi}(\pi, k)$ denote the probability of an active R&D firm becoming a patent-holder if k R&D firms are active in total and if the probability of detecting the advanced technology is π. Under Tech Treaty $TT(\alpha)$, this implies that an individual R&D firm will be interested in becoming active if

$$\tilde{\pi}(\pi, k)\left[nf(\mathcal{E}, \alpha, \epsilon_n) + p(\mathcal{E}, n)\alpha\mathcal{E}\right] - x \geq 0,$$

with $f(\mathcal{E}, \alpha, \epsilon_n)$ set according to Equation (8) as R&D firms anticipate that license fees will eventually be determined by this formula.

The number of successful R&D firms when k R&D firms are active is binomially distributed with parameters k and π. Accordingly, the expected number of successes is πk.

As all active R&D firms have the same chance of becoming patent-holders, we obtain

$$\tilde{\pi}(\pi, k) = \frac{1 - [1 - \pi]^k}{k},$$

where the nominator equals the overall probability of detecting the advanced technology when k R&D firms are active.

For analytic convenience, we approximate the probability $\tilde{\pi}(\pi, k)$ by

$$\tilde{\pi}^A(\pi, k) = \frac{\pi}{1 + \pi(k-1)}$$

and, accordingly, use

$$\Pi(\pi, k) = k\tilde{\pi}^A(\pi, k)$$

as the approximated probability that a new technology is detected.[16] The approximation of $\tilde{\pi}(\pi, k)$ consists of two parts. First, it entails the probability of the R&D firm under consideration detecting an advanced abatement technology. Second, it also entails the probability of becoming the patent-holder against all successful R&D firms. The first part is π and the second part is approximated by

$$\frac{1}{1 + \pi(k-1)},$$

i.e. with the inverse of one plus the expected number of other successful active R&D firms.

The derivation of the true probability and the fit of the approximation are discussed in Appendix C.1. The Appendix also shows that main results under both probabilities are qualitatively the same.

The number of active R&D firms k in an interior solution with $k > 0$ is determined by the expected zero profit condition,

$$\pi \frac{nf(\mathcal{E}, \alpha, \epsilon_n) + p(\mathcal{E}, n)\alpha\mathcal{E}}{1 + \pi(k-1)} - x = 0$$
$$\Leftrightarrow \quad k = \frac{nf(\mathcal{E}, \alpha, \epsilon_n) + p(\mathcal{E}, n)\alpha\mathcal{E}}{x} - \frac{1}{\pi} + 1. \quad (9)$$

An additional innovator would make the expected profits negative. The number of active R&D firms depends on global emissions $\mathcal{E}$, on α, and on ϵ_n, and we write $k(\mathcal{E}, \alpha, \epsilon_n)$ and $\Pi(k(\mathcal{E}, \alpha, \epsilon_n))$, respectively. Corner solutions with $k = 0$ arise when (9) produces a negative value. Throughout the theoretical analysis we focus on interior solutions.

A remark on the interpretation of k is in order. Equation (9) only holds with equality if

[16] We note that $\Pi(\pi, k) \leq 1$.

k is a continuous number, while the number of R&D firms is a natural number. Hence, the largest natural number below k will be the equilibrium number of R&D firms. For simplicity, we work directly with k.

A further remark concerns the case where $k(\mathcal{E}, \alpha, \epsilon_n)$ is larger than n. In such cases, countries host more than one R&D firm since there is no natural limit to the number of R&D firms in one country. However, in the theoretical analysis we focus on scenarios with low success probabilities π or high research costs x, which leads to small numbers of R&D firms.

Lemma 5 below states how the number of active R&D firms k affects the overall probability Π that an advanced technology will be detected. Proposition 1 below indicates how the Tech Treaty affects innovation by stating how the Tech Treaty Share α affects the number of active R&D firms.

Lemma 5

The overall probability that the advanced technology will be detected is increasing with the number of active R&D firms, i.e. $\Pi_k^{'} > 0$.

Lemma 5 follows from

$$\Pi_k^{'} = \frac{[1 + (k-1)\pi]\pi - k\pi^2}{[1 + (k-1)\pi]^2} = \frac{\pi - \pi^2}{[1 + (k-1)\pi]^2} > 0.$$

Proposition 1

Increasing the share of permits given to the international agency increases the number of active R&D firms, i.e. $k_\alpha' > 0$.

Proposition 1 follows from Equation (9), which implies

$$k_\alpha' = \frac{n f_\alpha'(\mathcal{E}, \alpha) + p(\mathcal{E}, n)\mathcal{E}}{x} > 0,$$

as $f_\alpha' > 0$ by Lemma 4.

For a given amount of aggregate permits $\mathcal{E}$, the impact of a change in the Tech Treaty Share α on the number of active R&D firms is intuitive. A larger share given to the international agency increases the patent holder's profits. The patent holder's profit increases through two channels. First, the production firm's willingness to pay for the advanced technology will increase, as it receives fewer permits for free. Second, the income due to the Tech Treaty will increase as well, as the international agency receives a higher share of the issued permits and as permit prices are not affected by the Tech Treaty parameter α. Both effects increase the expected profits of the patent-holder. Higher revenue perspectives for the patent holder attract more R&D firms. Entry of R&D firms will occur until the expected profit for an R&D firm is zero.

Overall, we find that a Tech Treaty increases innovation activities and the chances of success in finding a more efficient abatement technology for given permit issuance behavior of countries. Starting from $\alpha = 0$, increasing α pushes up license fees and the scaling up of these fees by the Tech Treaty. As a consequence, a Tech Treaty has an expected positive impact on all future periods in which abatement of emissions has to take place in the sense that expected abatement costs decrease. In this paper, we focus on the immediate effects and turn to comparative statics next.

4.4 Tightening of Global Emissions

Before we proceed to the solution of the entire game, it is useful to consider whether a marginal tightening of global emissions would help to foster innovation further under a Tech Treaty. For instance, one might imagine that the Paris Agreement (see European Commission (2016b)) succeeds in tightening emissions somewhat and a Tech Treaty, e.g. in Europe, would complement this agreement.

The answer how tightening emissions would affect R&D activities is not obvious, as crowding-out effects may occur. In Appendix C.2 the comparative statics are examined in detail. Essentially, we show that when aggregate emissions limits are not far away from baseline emissions, tightening aggregate emissions will increase the number of active R&D firms and spur innovation.

So far, the analysis does not take into account that the Tech Treaty itself may influence the global emissions limit as it affects the incentives of countries to issue permits. This we analyze in the next section.

5 The Tech Treaty and Decentralized Permit Issuance

In this section we first describe how—given a Tech Treaty—the local emissions limits are set in Stage 1. This implies solving the entire four-stage game. Then we discuss how the Tech Treaty impacts the global emissions limit. To explore whether a Tech Treaty is likely to initially increase or decrease global emissions, we define what we call a 'difficult research environment.' Otherwise there is no need for a Tech Treaty. The difficult research environment is characterized by low probabilities of innovation success or high research costs. Large potential cost reductions in abating or storing emissions are possible. This set-up leaves sufficient degrees of freedom for constellations with either few or many active R&D firms.

5.1 Solution in Stage 1: Permit issuance

We examine the choices of local planners in Stage 1, given the solutions in Stages 2, 3, and 4 as derived in Section 4 for fixed values of $\mathcal{E}$ and α (and ϵ_n). We note that α is the result of an international agreement and is determined before the game starts in Stage 1. Hence, it is given. A local planner chooses ϵ_i to minimize the costs for the local citizen, taking the permits issued by the other planners $\mathcal{E}_{-i}$ and the Tech Treaty Share α as given. Let $V(\epsilon_i)$ denote local citizens' costs as a function of the permits issued in that country. Local costs consist of damages and the local production firm's expenditures on abatement, on emissions permits, and on the license fee. Expected income for the local R&D firm is zero and does not enter $V(\epsilon_i)$. If no advanced technology is detected—e.g. because no R&D firm is active ($k = 0$)—, local production firms either have to abate $\bar{e}_i - \epsilon_i$ or buy additional permits on the market. If a production firm abates more than $\bar{e}_i - \epsilon_i$, it can sell permits. When an advanced technology is detected, local production firms only receive the amount $[1 - \alpha]\epsilon_i$ of permits, but they can choose to license the advanced technology. Then total costs include the license fee in addition to abatement costs and costs (or revenues) from trading on the permit market.

Since an advanced abatement technology may only be discovered with probability Π, the expected costs are[17]

$$V(\epsilon_i) = \Pi[[\overbrace{g_A(a_A(p(\mathcal{E},n)))}^{\text{abatement costs}} + \overbrace{p(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i]}^{\text{expenditures permit market}}] + \overbrace{f(\mathcal{E},\alpha,\epsilon_n)}^{\text{fee}} + \overbrace{d_i(\mathcal{E})}^{\text{damages}}] + (1-\Pi)[[\underbrace{g_O(a_O(p(\mathcal{E},0)))}_{\text{abatement costs}} + \underbrace{p(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i]}_{\text{expenditures permit market}} + \underbrace{d_i(\mathcal{E})}_{\text{damages}}]. \quad (10)$$

As $E = \mathcal{E}$, we directly write $d_i(\mathcal{E})$. The local planner's problem is

$$V^*(\alpha, \mathcal{E}_{-i}, \bar{e}_i) = \min_{\epsilon_i} V(\epsilon_i). \quad (11)$$

Because no analytical expression for ϵ_i can be derived, we present the first-order optimality

[17] In such a situation, countries $1, ..., n-1$ could have a strategic incentive to become country n by their choices of ϵ_i, as country n is in a position to influence f not only via $\mathcal{E}$ but also via ϵ_n. As production firm n's cost is independent of the licensing fee, there are few incentives for production firm n to change f via ϵ_n. Thus incentives to become country n to change f are small, and we neglect them accordingly.

condition in Appendix B.3. We find that the optimal number of permits a local planner issues is determined by several effects. Increasing the number of permits in a country will increase the local citizens' costs by increasing damages, can increase or decrease the production firms' marginal costs depending on whether it is a net-buyer or net-seller on the emissions permit market, and increases (decreases) innovation activities if $k'_{\mathcal{E}} > (<) 0$. For quadratic abatement costs, $k'_{\mathcal{E}} < 0$ if $\mathcal{E} > \bar{E}/2$, i.e. if the emissions limit is not too tight (see Appendix C.3, especially C.3.3).

Proposition 2 states conditions under which an equilibrium exists and is unique.

Proposition 2
An equilibrium exists and is unique when

(i) damage acceleration is identical across countries ($d''_i = d''$) and sufficiently fast, $p''_{\mathcal{E}\mathcal{E}} = 0$ and research costs x are sufficiently large

(ii) or countries are symmetric, innovation probability is sufficiently small, $p''_{\mathcal{E}\mathcal{E}} = 0$

$$\textit{and} \quad -\frac{\partial a_O}{\partial p} p'_{\mathcal{E}} < 2.$$

Proof of Proposition 2.
See B.4 in the Appendix. □

Note that $p''_{\mathcal{E}\mathcal{E}} = 0$ is fulfilled for quadratic abatement costs functions. When all countries are symmetric, the Condition $p''_{\mathcal{E}\mathcal{E}} = 0$ in [(i)] can be dropped.

5.2 The effect of the Tech Treaty on permit issuance

In the following, we explore whether a Tech Treaty is likely to initially increase or decrease global emissions when the research environment is difficult, i.e. when potential cost reductions for abating emissions are large, but when probabilities of innovation success are low or research costs are high.

To facilitate interpretation, let

$$\xi(l, \epsilon_i) := p'_{\mathcal{E}}(\mathcal{E}, l) \frac{\epsilon_i}{p(\mathcal{E}, l)}$$

display the elasticities of the permit price with respect to the permits issued by country i when l, $l = 1, ..., n$ production firms have adopted the advanced technology.

We next provide a proposition that shows that the permit price elasticity is one important condition for the Tech Treaty's impact on permit issuance.[18]

Proposition 3

Suppose that second derivatives $p''_{\mathcal{E},\mathcal{E}}(\mathcal{E}, l) \approx 0$*,* $f''_{\mathcal{E},\mathcal{E}} \approx 0$*,* $f''_{\mathcal{E},\alpha} \approx 0$ *are small, damages accelerate sufficiently fast and* x *is large with* Π'_k/x *small.*

Then an increase in the Tech Treaty Share will lower the number of permits issued by the local planner in country i *if* $\xi(l, \epsilon_i) > -1$*, with* $l = 1, ..., n$*.*

Proof of Proposition 3.
See B.5 in the Appendix. □

Here is an example to illustrate condition $\xi(l, \epsilon_i) > -1$ in Proposition 3. For quadratic abatement costs, we obtain

$$\xi(l, \epsilon_i) = -\frac{\epsilon_i}{\sum_{i=1}^{n} \bar{e}_i - \sum_{i=1}^{n} \epsilon_i}.$$

If all countries are identical and issue the same number of permits, we obtain

$$\xi(l, \epsilon) = -\frac{\epsilon}{n\bar{e} - n\epsilon}.$$

The condition $\xi(l, \epsilon_i) > -1$ or equivalently $|\xi(l, \epsilon_i)| < 1$ means a rather inelastic response of the permit price and implies $\epsilon < \bar{e}n/(n+1)$, with $\bar{e}n/(n+1)$ close to $\bar{e}$ when n is large. Hence, the elasticity condition is fulfilled as soon as permit issuance is slightly below business-as-usual emissions.[19]

With quadratic abatement costs, we obtain a direct condition on the underlying parameters and functions for the impact of the Tech Treaty on global emissions. While Proposition 3 stated results for high research costs, Proposition 4 discusses the case of a low innovation probability π.[20]

[18] Note that the Conditions stated in Proposition 3 imply a unique equilibrium when one additionally assumes that damage acceleration is identical across countries. Then, all conditions in Proposition 2(i) are fulfilled.

[19] When countries are not identical and quadratic abatement costs are assumed, the condition can be written as $\epsilon_i < \bar{E} - \mathcal{E}$, implying that a higher Tech Treaty Share α will lower permits issued in all countries when permit issuance is close to baseline emissions.

[20] Note that the conditions stated in Proposition 4 imply a unique equilibrium when countries are symmetric. Then, conditions in Proposition 2(ii) are fulfilled, as quadratic abatement costs imply $p''_{\mathcal{E},\mathcal{E}} = 0$, and $-\frac{\partial a_O}{\partial p} p'_{\mathcal{E}} = 1/n < 2$.

Proposition 4

Suppose abatement costs are quadratic and the number of countries is large. Then an increase in the Tech Treaty Share will lower the permits issued by the local planners, i.e. $\frac{\partial \epsilon_i}{\partial \alpha} < 0$, *if*

(i) *innovation probability is low,*

(ii) *the cost difference between the old and the advanced technology is large,*

(iii) *damages accelerate sufficiently fast,*

(iv) $\bar{E} - \epsilon_i > \mathcal{E} > \bar{E}/2$,

(v) ϵ_n *small,*

(vi) *and* α *sufficiently small.*

Proof of Proposition 4.
See Appendix C.3, especially C.3.5. □

In a numerical example Figure 1 illustrates for intermediate values of α how global emissions and the number of R&D firms depend on the Tech Treaty Share when abatement costs are quadratic. It shows that, without Tech Treaty, no R&D may take place. It also shows that the Tech Treaty Share needs to be sufficiently high to achieve $k > 0$.

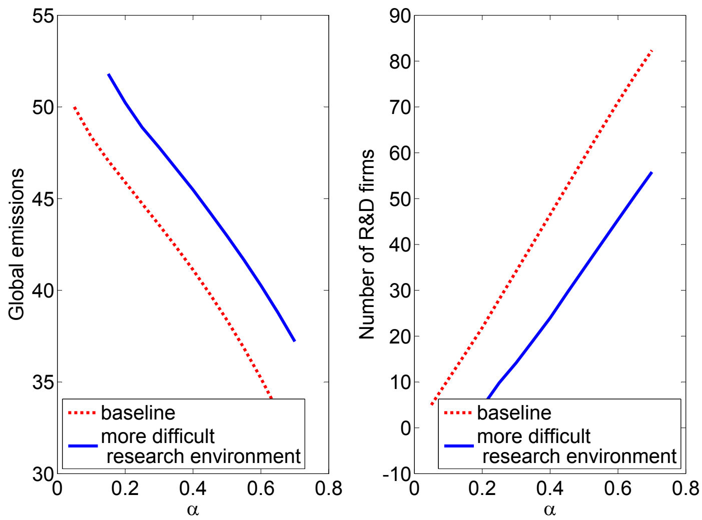
If research costs are too high compared to expected profits and no Tech Treaty exists, no R&D firm will become active. In such a situation, only a Tech Treaty can induce R&D firms to become active. This result is even more pronounced in the case of linear abatement costs. We discuss this case next.

5.3 Linear abatement costs

Linear abatement costs illustrate the benefits of Tech Treaties in stark terms since without such treaties no R&D activity will take place. Moreover, the linear case yields explicit solutions for licensing fees, number of R&D firms, and emissions levels. Linear abatement costs do not fulfil the assumption $g'' > 0$ in the general case, but since the solution can be directly calculated this violation is not critical.

For the present case, we allow abatement in the form of extracting carbon from the atmosphere. Thus, $a_i > \bar{e}_i$ is possible.[21] Proposition 5 characterizes the resulting equilibrium.

[21]Before, we did not make any specific assumptions on abatement, as $g'' > 0$ puts an indirect limit to the amount abated by any individual firm.



The parameter values chosen are as follows: $b_O = 590$, $b_A = 0.7b_O$, $\beta = 23.7667$, $n = 8$ and $\bar{e}_i, i \in 1, ..., 8 = [9.8330, 9.9443, 10.0557, 10.1670, 9.6104, 9.7217, 10.2783, 10.3896]$ for both scenarios; for the baseline: $\pi = 0.1$ and $x = 840.9869$, and for the more difficult research environment: $\pi = 0.05$ and $x = 1000$.

Figure 1: The influence of the Teach Treaty's share α on global emissions and on the number of R&D firms.

Proposition 5

Suppose that abatement costs are linear ($g_O(a_i) = b_O a_i$, $g_A(a_i) = b_A a_i$). Then,

(i) $p = b_O$ *if no technology is detected or no firm adopts an advanced technology,*

(ii) $p = b_A$ *if at least one firm adopts the advanced technology*

(iii) $f = 0$

(iv) $k(\mathcal{E}, \alpha, \pi) = \frac{b_A \alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi}$ *if* $\frac{b_A \alpha}{x}\mathcal{E} > 1 - \frac{1}{\pi}$, *otherwise* $k = 0$.

Proof of Proposition 5.
See Appendix C.4, especially C.4.1. □

The intuition for Proposition 5 is as follows: Suppose the fee is positive and at least one production firm buys the advanced technology, so the permit price becomes $p = b_A$. Then for the remaining production firms buying permits is more attractive than buying the license for the advanced technology. Actually, there can never be an equilibrium in which more than one firm will switch to the advanced technology when $f > 0$. R&D firms anticipate this and will not become active. This logic is independent of the rule of the

Tech Treaty. In such a situation, only a Tech Treaty can induce R&D firms to become active.

In the following, we consider identical countries, low innovation probability[22] $\Pi \approx \pi k$ and a quadratic damage function to directly solve for ϵ_i.[23] Proposition 6 summarizes the result we obtain.

Proposition 6
Suppose abatement costs are linear, damages are quadratic, innovation probabilities are very low, and countries are identical. Then,

(i)

$$\epsilon = \frac{b_O - \pi \frac{b_A \alpha}{x}[b_A - b_O]\bar{e} + [1-\pi]\,[b_O - [1-\alpha]b_A]}{\pi \frac{b_A \alpha}{x}[b_O - [1-\alpha]b_A][n+1] + \delta n} \qquad \text{and}$$

(ii) an increase in the Tech Treaty Share lowers the number of permits issued by the local planners ($\frac{\partial \epsilon_i}{\partial \alpha} < 0$) if the potential cost reduction $b_O - b_A$ is sufficiently large.

Proof of Proposition 6.
See Appendix C.4, especially C.4.3. □

Proposition 6 yields important insights on how emissions change when a Tech Treaty is introduced. As long as potential cost reductions are large and the research environment is difficult, then a Tech Treaty will provide additional incentives for local planners to tighten permit issuance. In line with our other results, it shows that introducing a Tech Treaty step by step with low values of α will not backfire into higher aggregate emissions when the research environment is difficult. However, a low value for the Tech Treaty Share may not be sufficient to stimulate R&D, as illustrated by the numerical simulations. A high value, in turn, may lead to an increase in emissions (see Propositions 4).

6 Benchmarks

In the following, we discuss how the Tech Treaty relates to the decentralized solution, the first-best outcome and a second-best outcome. For the comparison, we use theoretical arguments as well as a numerical example with identical countries, linear damages and

[22] The results are based on a Taylor Approximation around $\pi \approx 0$.
[23] A more general result without an explicit solution for ϵ is given in Appendix C.4.2.

quadratic abatement. We show that even for linear damages—which we chose for analytical tractability of the first and second best solution—Tech Treaties can improve about the second best. We believe that the effect will be even higher for quadratic damages.

The first-best solution is achieved when countries frictionlessly cooperate over emissions and the number of active R&D firms, i.e. by the minimization of the aggregate expected costs with respect to these two variables. The second-best solution entails frictionless cooperation on R&D activity but decentralized permit issuance decisions. This means that countries coordinate on R&D (Stage 2) after each country individually has chosen how many permits to issue (Stage 1). As all countries cooperate on R&D, production firms can use advanced abatement technologies at no costs—if they are detected. Production firms decide on abatement and permit trading as before.

We do not consider the additional benchmark scenario with full cooperation on emissions reduction but without cooperation on R&D, because experience with the Kyoto Protocol and the Paris Agreement has shown that significant cooperation on emissions reduction is very difficult to achieve.

The decentralized solution is the solution without a Tech Treaty, i.e. the equilibria derived in the previous section for $\alpha = 0$.[24] It is well-known that the decentralized solution does not lead to the social optimum since two types of externalities are present in multi-country models of greenhouse gas emissions and R&D. First, each country only considers its individual marginal damage stemming from an additional unit of emissions and ignores the damages on other countries. As a result, countries emit too much greenhouse gases. Second, R&D firms cannot fully appropriate returns to innovations since the patent holder's income from licensing is lower than the total production firms' cost savings.[25] In addition, both externalities interact: The damage externality that leads to a global emissions limit that is too excessive from a global perspective reduces the incentives to engage in R&D activities.

We next report the results from a simple numerical example to illustrate that a Tech Treaty can improve over the decentralized and—if α is set sufficiently high—also over the second-best solution with perfect cooperation on R&D.[26] Table 1 gives the number of active R&D firms as well as the number of permits issued in the different settings. The

[24] We note that the patent holder licenses the advanced technology to all production firms at the same fee in this solution. More sophisticated license fee settings can be considered in the decentralized solution, such as excluding some countries from technology transfer or discriminatory license fees.

[25] In the current model, there may also be too much R&D activity in a second best setting—either with a Tech Treaty or with some other kind of second-best policy—compared to the social optimum, as the entry of R&D firms is determined by average expected and not marginal profits.

[26] Tech Treaties alone do not lead to first-best solutions. As usually—following the Tinbergen Rule—at least as many instruments as targets would be needed.

underlying equations are derived in Appendix C.3.6.

Table 1: An illustrative example with linear damages.

	First best	Second-best (full coop. on R&D)	Decentralized solution ($\alpha = 0$)	Tech Treaty ($\alpha = 0.05$)	Tech Treaty ($\alpha = 0.1$)
k	58.9	25.5	2.4	13.8	24.8
$\mathcal{E}$	0.6	15.1	15.6	15.3	14.9

For the calibration, we use $n = 30$, $b_O = 590$, $b_A = 0.7b_O$, $\pi = 0.008$, $\bar{E} = 80$, $x = 69$, $\delta = 40.24$. The underlying equations are derived in Appendix C.3.6.

In this illustrative example, there is R&D activity and quite some emissions reduction in all scenarios. Still, compared to the first best, there is too little R&D activity and too little abatement in all other scenarios. With cooperation on R&D, R&D activity is higher than in the decentralized solution and comes close to the first best. In comparison to the similarity in R&D activity, the emissions reduction with cooperation on R&D in comparison to the first best seems small. The introduction of a Tech Treaty with $\alpha = 0.05$ increases the number of active R&D firms and reduces emissions compared to the dezentralized solution. If α is increased, the Tech Treaty can further increase R&D activity and reduce emissions. The Tech Treaty improves over the dezentralized solution, and may even improve over the second best outcome, but it is not as good as the first best solution. Still, it may be easier—and thus sooner—implementable, also creating cheap abatement technologies for the future.

7 Discussion

In this section, we discuss several important aspects of Tech Treaties and their modelling. We first consider participation in the emissions permit market and in the Tech Treaty. Then, we discuss whether changing critical model assumptions would change the qualitative results of our analysis.

7.1 Participation

So far, we have taken either the emissions limit or the countries' participation in the emissions permit market and the Tech Treaty as given. In this section, we discuss the countries' incentives to participate in both the emissions permit market and the Tech Treaty.

Since the local planners in the different countries can always choose permits ϵ_i equal to baseline emissions $\bar{e}_i$, participating in the international permit market does not make a country worse off than autarky, and in general, there are efficiency gains, as global abatement costs are minimized for a given aggregate level of emissions.

To increase incentives to participate in the Tech Treaty, one can add a rule to the Teach Treaty that specifies the terms of use of the advanced technology for countries that are not part of it. One could license the advanced abatement technology to non-Tech-Treaty countries at a fee higher than for the participating countries, so that the R&D expenditures of the participating countries are partly recovered and an incentive to participate in the Tech Treaty is given from the start, especially as the permit share allocated to the international agency is returned to the countries if no R&D firm was successful. If industrial countries and large carbon emitters such as India, China and Brazil participate in the Tech Treaty despite free-riding incentives, i.e. if they form a 'Tech club', most of the gains from a Tech Treaty will be realized.[27] The reason is that these countries account for the vast share of greenhouse gas emissions and R&D efforts.

Moreover, developing countries may lack the ability to adopt advanced technologies. This will lower their incentives to participate in the Tech Treaty, as they would be financing R&D in industrialized and emerging countries, which violates the fairness criteria.[28] The obvious solution is to form a Tech club—as discussed—and to allow developing countries to adopt the technologies nevertheless.

7.2 Model assumptions and possible extensions

In this section, we discuss some of the model's critical assumptions and how they could be relaxed. We also consider possible extensions of the model.

First, in the present set-up, the Tech Treaty states that all permits that are not given to the international agency are grandfathered to the production firms. This does not have to be the case as they could also be auctioned. One could include this feature explicitly in the model by splitting up the share of permits auctioned into two parts. One part would be returned to the countries, as is currently the case under the EU ETS (European Commission, 2016a). The other part would be given to the international agency, which—as under the presented Tech Treaty—would use the revenues to support technological developments. Auctioning a larger share of permits would increase incentives for production firms to use the advanced technology, which further spurs innovation activities.

[27] Emissions trading could remain at the global level.

[28] See e.g. the discussion in Bretschger (2013) or Bretschger and Vinogradova (2015).

Second, in order to increase revenues from licensing, an R&D firm may want to price-differentiate licensing fees among production firms, depending on their willingness to pay. This option is always available, but such an R&D firm will lose the rescaling of license fees by the Tech Treaty. If an R&D firm decides not to be subject to the rules of the Tech Treaty, this is of no concern for the Tech Treaty itself, as innovation efforts—the aim of the Tech Treaty—would still occur. Moreover, if the Tech Treaty Share α is not close to zero, the revenues from a Tech Treaty for R&D firms will be plausibly higher than the gains from price discrimination in licensing technologies. Thus, especially for difficult research environments—for which Tech Treaties are designed—the assumption that the patent holder prefers licensing to all firms without price discrimination to obtain the additional revenues from the Tech Treaty is not strong. Of course, since in practice many production firms operate in one country, the requirement to license to all firms in all participating countries would have to be made practical by requiring that a significant fraction of the production firms adopt the new technology.

Third, while an increase in the Tech Treaty Share α unambiguously increases innovation activity, it may increase R&D above the socially desirable point, and it may lead countries to increase permit issuance. These aspects speak in favor of a Tech Treaty Share that is well below one. With a low Tech Treaty Share, they are less of a concern, especially in a difficult research environment, which is the focus of this paper.

Fourth, if one interprets the Tech Treaty as a subsidy for patent purchases, one may ask why the government does not buy the patents directly, or at least gain partial ownership. One reason for this is the existence of informational constraints. It is difficult for a government to determine what patents to buy and what price to pay. Additionally, making support dependent on existing licensing revenues ensures that the developed technology is commercialized. Support via the Tech Treaty is like an additional prize for the success of innovation efforts. This kind of incentive in targeting private-sector research is currently being used by Google to spur private innovations in the space sector (see XPRIZE Foundation (2018b) and XPRIZE Foundation (2018a)).

Finally, the present set-up of the model focuses on technology licensing, i.e. on reducing emissions in the production process. One could also focus on supporting the development of products that emit less carbon when used. Then the sales price would have to be considered, instead of the licensing fee. In principle, Tech Treaties can be used for such scenarios as well. We leave detailed analysis to future research.

Of course, numerous other extensions can and likely should be pursued in the future research on this matter. One challenging issue is under which circumstances countries will participate in a Tech Treaty. The aim of this paper was to examine whether a Tech Treaty is worth attempting in the first place. Potentially, the Tech Treaty Share α could be endogenized. One natural way is to set α at a level that induces participation of all or at least a sufficiently large number of countries. The role of uncertainty and learning of new technological opportunities could be incorporated following the lead of Finus and Pintassilgo (2013). Incorporating international trade would provide future insights into the participation problem. Allowing for delays in diffusion of technologies and dynamic versions of the model following Greaker and Midttømme (2016) would help to delineate plausible time frames in which Tech Treaties display their full force.

8 Conclusion

As it is extremely difficult, if not impossible, to design global climate treaties with binding and drastic abatement targets, we have examined a different approach to see if it can slow down climate change. We introduced an international technology treaty, a 'Tech Treaty', that couples the funding of research for detecting a more advanced abatement technology with an international emissions permit market. While each country is free to issue as many permits as it likes, under the Teach Treaty a fraction of these permits is auctioned in the permit market, and the revenues are used to reward innovations in abatement technologies. This set-up is inspired by the existing NER300 program of the EU-ETS (see European Commission (2017b) for details), but differs in its focus on production techniques and by the way eligible technologies are determined. Still, our analysis may provide useful insights for the next steps of the NER300 program in future trading periods, especially for its successor, the 'Innovation Fund'.[29]

Our results suggest the following: First, for a given global emissions limit, a Tech Treaty will increase innovation activity, furthering the development of new abatement technologies, which will lower future emissions. Second, even in the currently observable situation with little research and without Tech Treaties, introducing such a treaty would reduce emissions. This is also good news for the NER300 program and the Innovation Fund, as our results suggest that it is unlikely that they lead to an increase in emissions in the respective trading periods.

The proposed design only partially solves the climate change problem, since even with better abatement technologies, too many permits might still be issued by countries. But, given that a grand coalition like the one initiated by the Paris Agreement now exists, the

[29] See European Commission (2017a) for details.

Tech Treaty we propose here provides incentives for developing more advanced abatement technologies, inducing countries to reduce emissions possibly already now, but certainly in the future. What is more, as tighter emissions limits are not necessarily sufficient to spur innovation, additional instruments like a Tech Treaty may well be needed.

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Appendices

A Tables

Table A1: Maturity of technologies in the area of renewable energy based on UNFCCC (2009).

Stage of maturity	Technology applications
R&D	Biomass fuel cell and CCS power generation; Power storage; Solar nano-technology photovoltaic
Demonstration	Ocean power (saline gradient (osmosis), thermal gradient (OTEC), wave); Offshore wind (floating); Geothermal–enhanced geothermal systems; Concentrated solar power/solar thermal
Deployment	Offshore wind (fixed); Biomass integration gasification combined cycle, gasification and pyrolysis; Biogas; Solar photovoltaic; Concentrated solar power / solar thermal (barrier, steam); Tidal (barrier, stream)
Diffusion	Onshore wind; Run of river hydropower; Geothermal–conventional
Commercial	Hydropower (dam); Biomass co-firing

The different stages are defined in UNFCCC (2009, p. 9).

Table A2: Technologies to increase industrial efficiency in saving carbon emissions.

Sector	Technology	Source
Iron and steel	Advanced wet quenching	ClimateTechWiki (2016)
Iron and steel	Coke dry quenching	ClimateTechWiki (2016)
Paper and pulp	Black liquor gasifier	ClimateTechWiki (2016); Croezen and Korteland (2010)
(Petro-)Chemical	Biopolymer production	ClimateTechWiki (2016)
Cement	Blast furnace slag granulation	ClimateTechWiki (2016)
Cement	Clinker substitute (slag, natural or synthetic pozzolans)	ClimateTechWiki (2016)
Steel	Electrolysis	Croezen and Korteland (2010)
Steel	Coke-free steelmaking, with or without CCS (HIsarna)	Croezen and Korteland (2010)
Cement	Magnesium based clinker (Novacem)	Croezen and Korteland (2010)
Paper and pulp	Paper drying innovations	Croezen and Korteland (2010)

Table A3: List of Notation.

Symbol	Description
n	number of countries
i, j	country index
m	index production firms using old technology
q	index production firms using advanced technology
l	number of production firms licensing the new technology
k	number of active R&D firms
a_i	abated emissions of production firm i
$a_O(p)$	emissions abated using the old technology
$a_A(p)$	emissions abated using the advanced technology
$\bar{e}_i$	baseline emissions of production firm i
$\bar{E}$	sum of baseline emissions over all production firms
x	innovation efforts / research costs
$g_O(a_i)$	abatement costs, old technology
$g_A(a_i)$	abatement costs, advanced technology
b_O	coefficient abatement costs, old technology
b_A	coefficient abatement costs, advanced technology
f	license fee to use g_A
$\bar{f}_i(l)$	production firm i's willingness to pay to use g_A given l other production firms already using it
E	total emissions
ϵ_i	permits issued in country i
$\mathcal{E}$	global emissions limit
TT	Tech Treaty
α	Tech Treaty Share, i.e share of permits allocated to international agency
$d_i(E)$	damages in country i because of total emissions
δ_i	coefficient damages in country i
π	probability of a successful innovation per firm
$\Pi(k)$	overall probability of detection of the advanced technology given k R&D firms are active
p	permit price
ξ	elasticity of the permit price with respect to emissions permits
c_i	cost when no advanced technology is discovered
Δc_i	cost change when advanced technology is discovered compared to no discovery

B Derivations, Proofs, and Conditions for Sections 4-5

B.1 Proof of Lemma 1

Proof of Lemma 1.
Using implicit differentiation in (5) yields

$$\frac{\partial p}{\partial l} = \frac{-[a_A(p) - a_O(p)]}{l\frac{\partial a_A(p)}{\partial p} + [n-l]\frac{\partial a_O(p)}{\partial p}}. \tag{12}$$

As stated in the text, $a_A(p) - a_O(p) > 0$. Equation (2) implies

$$\frac{\partial e_j}{\partial p} = \left[\frac{\partial g_O^2}{\partial e_j^2}\right]^{-1} > 0, \quad \frac{\partial a_i}{\partial p} = \left[\frac{\partial g_A^2}{\partial a_i^2}\right]^{-1} > 0, \quad i = 1, ..., l, \quad j = l+1, ..., n,$$

and thus

$$\frac{\partial a_O(p)}{\partial p} > 0, \frac{\partial a_A(p)}{\partial p} > 0.$$

As $n \geq l$, the denominator of Equation(12) is positive and thus

$$\frac{\partial p}{\partial l} < 0.$$

Similarly, it follows that

$$\frac{\partial p}{\partial \mathcal{E}} = \frac{-1}{l\frac{\partial a_A(p)}{\partial p} + [n-l]\frac{\partial a_O(p)}{\partial p}} < 0$$

for all $\mathcal{E} \geq 0$, $l \in [0, n]$. □

B.2 Conditions for $\partial f_i(l)/\partial l < 0$

Setting the fee according to Lemma 3 will lead to a unique equilibrium in which all production firms will license the advanced technology if the production firm i's willingness to pay decreases with the number of production firms adopting the advanced technology l. Then $f_i(n-1)$ corresponds to this production firm's lowest willingness to pay. As $f_n(n-1) < f_i(n-1)$ by Lemma 3, it is always profitable for production firm i to switch, independently of the actual realization of l. As this holds for all production firms, $l = n$ results. The next Lemma states the conditions for which this is indeed the case.

Lemma 6

All production firms license the advanced technology at the fee

$$f(\mathcal{E},\alpha,\epsilon_n) = f_n(n-1) \quad \text{if} \quad \frac{\partial f_i(l)}{\partial l} < 0, l \in \{0,...,n-1\}.$$

This is the case when either

(i) $p_l'(\mathcal{E},l) \approx p_l'(\mathcal{E},l+1)$;

(ii) or $\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},l)) \geq 0$ *and*

  (I) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},l+1)) < 0$

  (II) or $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},l+1)) > 0$
  and in addition $|p_l'(\mathcal{E},l)| \geq |p_l'(\mathcal{E},l+1)|$.

Proof of Lemma 6.
Equation (7) implies

$$\begin{aligned}\frac{\partial f_i(l)}{\partial l} =& p_l'(\mathcal{E},l)[\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},l))] \\ &- p_l'(\mathcal{E},l+1)[\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},l+1))],\end{aligned} \tag{13}$$

where other terms in the expression for $\partial f_i(l)/\partial l$ cancel out, as prices equal marginal abatement costs (Equation (2)). By Equation (5), $a_A(p(\mathcal{E},n)) = a_O(p(\mathcal{E},0))$ and since $a_i(p(\mathcal{E},l))$ is decreasing in l,

$$a_A(p(\mathcal{E},l+1)) > a_O(p(\mathcal{E},l))$$

for $l = 1,...,n-1$. Then, under Condition (i),

$$\frac{\partial f_i(l)}{\partial l} \approx p_l'(\mathcal{E},l)[a_A(p(\mathcal{E},l+1)) - a_O(p(\mathcal{E},l))] < 0.$$

Under conditions stated in (ii), we have $\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},l)) \geq 0$ and the two cases:

(I) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},l+1)) < 0$:

$$\begin{aligned}\frac{\partial f_i(l)}{\partial l} =& \overbrace{p_l'(\mathcal{E},l)[\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},l))]}^{\leq 0} \\ &- \underbrace{p_l'(\mathcal{E},l+1)[\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},l+1))]}_{>0} < 0,\end{aligned}$$

(II) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, l+1)) > 0$:

$$\frac{\partial f_i(l)}{\partial l} < 0 \Leftrightarrow \overbrace{\frac{p_l'(\mathcal{E}, l)}{p_l'(\mathcal{E}, l+1)}}^{\geq 1} \overbrace{\frac{\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E}, l))}{\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, l+1))}}^{>1} > 1.$$

□

The condition $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, l+1)) \geq 0$ means that all production firms are buyers on the permit market. Note that this is the case when α is sufficiently large and countries are sufficiently symmetric.

B.3 First-order condition local planner's decision

For convenience, we re-arrange expression (10) into three parts: the costs if no advanced technology is discovered, the cost change that occurs if it is discovered, and damages. Let the costs that occur if the advanced technology is not discovered be denoted by

$$c(\alpha, \epsilon_i) := g_O(a_O(p(\mathcal{E}, 0))) + p(\mathcal{E}, 0)[\bar{e}_i - a_O(p(\mathcal{E}, 0)) - \epsilon_i] \tag{14}$$

and let the cost change when the advanced technology is discovered be expressed as

$$\begin{aligned}\Delta c(\alpha, \epsilon_i) := & g_A(a_A(p(\mathcal{E}, n))) + p(\mathcal{E}, n)][\bar{e}_i - a_A(p(\mathcal{E}, n)) - [1-\alpha]\epsilon_i] + f \\ & - g_O(a_O(p(\mathcal{E}, 0))) - p(\mathcal{E}, 0)[\bar{e}_i - a_O(p(\mathcal{E}, 0)) - \epsilon_i].\end{aligned}$$

Three remarks are in order. First, abated emissions will be the same under both technologies. The emissions limit is the same with both technologies, and all production firms use the same technology in equilibrium, such that

$$a_A = a_O = \frac{\bar{E} - \mathcal{E}}{n}.$$

Second, if no advanced technology is discovered the permit share initially allocated to the international agency is returned to the countries and grandfathered to the production firms (Rule 4). For this reason, total costs for some production firms may be lower when no advanced technology is discovered compared to when it is discovered.[30]

[30]

$$\begin{aligned}\Delta c(\alpha, \epsilon_i) := & \underbrace{g_A + p(\mathcal{E}, n)][\bar{e}_i - a_A - [1-\alpha]\epsilon_i] + f - g_O - p(\mathcal{E}, 0)[\bar{e}_i - a_O - \epsilon_i] - p(\mathcal{E}, 0)\alpha\epsilon_i}_{\leq 0 \quad \text{follows from Lemma 3}} \\ & + p(\mathcal{E}, 0)\alpha\epsilon_i.\end{aligned} \tag{15}$$

Third, using (8), the cost reduction for the production firm in country n can be written as

$$\begin{aligned}\Delta c_n =& g_O(a_O(p(\mathcal{E}, n-1))) + p(\mathcal{E}, n-1)[\bar{e}_n - a_O(p(\mathcal{E}, n-1)) - [1-\alpha]\epsilon_n] \\ & - g_O(a_O(p(\mathcal{E}, 0))) - p(\mathcal{E}, 0)[\bar{e}_n - a_O(p(\mathcal{E}, 0)) - \epsilon_n],\end{aligned} \quad (16)$$

as the licensing fee is set equal to the firm's willingness to pay for the advanced technology $f = f_n(n-1)$.[31]

As $E = \mathcal{E}$, we directly write $d_i(\mathcal{E})$. Then the local planner's problem in countries $i \in \{1, ..., n-1\}$ can be written as (11) with

$$\begin{aligned}V(\epsilon_i) =& \underbrace{[g_O(a_O(p(\mathcal{E}, 0))) + p(\mathcal{E}, 0)[\bar{e}_i - a_O(p(\mathcal{E}, 0)) - \epsilon_i]]}_{\text{costs } c} + \underbrace{d_i(\mathcal{E})}_{\text{local damages}} \\ & + \underbrace{\Pi(k(\mathcal{E}, \alpha, \epsilon_n))}_{\text{overall innovation probability}} \\ & \underbrace{\begin{aligned}&[g_A(a_A(p(\mathcal{E}, n))) + p(\mathcal{E}, n)[\bar{e}_i - a_A(p(\mathcal{E}, n)) - [1-\alpha]\epsilon_i] \\ &+ f(\mathcal{E}, \alpha, \epsilon_n) - [g_O(a_O(p(\mathcal{E}, 0))) + p(\mathcal{E}, 0)[\bar{e}_i - a_O(p(\mathcal{E}, 0)) - \epsilon_i]]]\end{aligned}}_{\text{cost change } \Delta c}.\end{aligned} \quad (17)$$

To simplify notation and as $\mathcal{E} = \sum_{j \neq i}^{n} \epsilon_j + \epsilon_i$, we directly use $\partial\mathcal{E}/\partial\epsilon_i = 1$. Given the fact that the permit price equals marginal abatement costs (Equation (2)), some terms cancel

The case $\Delta c(\alpha, \epsilon_i) > 0$ is more likely to occur when α is large and the gain from the advanced technology is low. Once the advanced technology is discovered, it is always profitable—given our assumptions—to adopt it.

[31] All results for country n—with f plugged in—are given in Equations (19)-(21) below.

out and the first order condition reads

$$
\begin{aligned}
V'_{\epsilon_i} = &\underbrace{p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] - p(\mathcal{E},0)}_{\text{marginal costs } c'_{\epsilon_i}} + \underbrace{d'_i(\mathcal{E})}_{\text{marginal damage}} \\
&+ \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{Ov. Inno. Prob.}} \\
&\underbrace{\begin{aligned}&[p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &- p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] - [1-\alpha]p(\mathcal{E},n) + p(\mathcal{E},0) + f'_{\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)]\end{aligned}}_{\text{marginal cost change } \Delta c'_{\epsilon_i}} \\
&+ \underbrace{\Pi'_k(k(\mathcal{E},\alpha,\epsilon_n))k'_{\mathcal{E}}(\mathcal{E},\alpha)}_{\text{marginal innovation}} \\
&\underbrace{\begin{aligned}&[g_A(a_A(p(\mathcal{E},n))) + p(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &- g_O(a_O(p(\mathcal{E},0))) - p(\mathcal{E},0)][\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] + f(\mathcal{E},\alpha,\epsilon_n)]\end{aligned}}_{\text{cost change } \Delta c} = 0. \qquad (18)
\end{aligned}
$$

Equation (18) reveals that the optimal number of permits a local planner issues is determined by

(i) 'marginal costs', i.e. the marginal effect of a change in permits issued on the production firm's costs without the advanced technology,

(ii) 'marginal damage', i.e. the marginal effect of a change in permits issued on damages,

(iii) 'marginal cost change', i.e. the marginal effect of a change in permits issued on the production firm's cost change when the advanced technology is discovered,

(iv) 'marginal innovation', i.e. the marginal effect of a change in permits issued on the overall probability of detecting an advanced technology.

We next discuss the direction of these effects. Increasing the number of permits in a country will

(i) decrease or increase the production firms' marginal costs when no advanced technology is discovered (c'_{ϵ_i}). This follows directly from property $p'_{\mathcal{E}} < 0$ in Lemma 1 and Equation (14). When the production firm is a buyer on the international permit market, marginal costs are decreased;

(ii) increase the local citizens' costs by increasing damages ($d'_i > 0$);

(iii) can increase or decrease the marginal cost change. For instance, when $|p'_{\mathcal{E}}(\mathcal{E}, l-1)| > |p'_{\mathcal{E}}(\mathcal{E}, l)|$, the marginal cost change increases if the production firm is a buyer on the international permit market and if $f'_{\mathcal{E}}$ is small;

(iv) increase (decrease) innovation activities if $k'_{\mathcal{E}} > (<) 0$.

Let us consider a potential equilibrium with interior solution. We will focus on an interior solution, as extreme parameter constellations for corner solutions $\epsilon_i = 0$ or $\epsilon_i = \bar{e}_i$ are implausible and of no interest. Condition (18) can be seen as a best response by each local planner in country $i, j \in \{1, ..., n-1\}$ to the actions of the other local planners. For the local planner in country n, the condition is slightly different, as the fee f is set in such a way as to make country n indifferent between adopting and not adopting the advanced technology. Some terms cancel. The condition is given in Equation (20) below. Then Condition (18) for $i \in \{1, ..., n-1\}$ and Condition (20) for $i = n$ give n equations for n unknowns ϵ_i, $i \in \{1, ..., n\}$.

For country n, $f = \bar{f}_n(n-1)$ and some terms cancel. Then,

$$\begin{aligned} V(\epsilon_n) &= [g_O(a_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n]] + d_n(\mathcal{E}) \\ &+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[-g_O(a_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] \\ &\quad + g_O(a_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - a_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]], \end{aligned} \tag{19}$$

with

$$\begin{aligned} V'_{\epsilon_n} &= [p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] - p(\mathcal{E},0)] + d'_{\mathcal{E}} \\ &+\Pi'_k k'_{\mathcal{E}}(\mathcal{E},\alpha)[-g_O(a_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] \\ &\quad + g_O(a_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - a_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]] \\ &+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[-p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] + p(\mathcal{E},0) \\ &\quad + p'_{\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_n - a_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n] - [1-\alpha]p(\mathcal{E},n-1)] \end{aligned} \tag{20}$$

and

$$\begin{aligned} V''_{\epsilon_n,\alpha} &= (\Pi''_{kk}k'_\alpha k'_{\mathcal{E}}(\mathcal{E},\alpha) + \Pi'_k k''_{\mathcal{E},\alpha}(\mathcal{E},\alpha)) \\ &[-g_O(a_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] \\ &\quad + g_O(a_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - a_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]] \\ &+\Pi'_k k'_{\mathcal{E}}(\mathcal{E},\alpha)[p(\mathcal{E},n-1)\epsilon_n] \\ &+\Pi'_k k'_\alpha[-p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_n - a_O(p(\mathcal{E},0)) - \epsilon_n] + p(\mathcal{E},0) \\ &\quad + p'_{\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_n - a_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n] - [1-\alpha]p(\mathcal{E},n-1)] \\ &+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[p'_{\mathcal{E}}(\mathcal{E},n-1)\epsilon_n + p(\mathcal{E},n-1)]. \end{aligned} \tag{21}$$

As stated in footnote 16, we neglect possible additional strategic effects that would lead to differences between $k'_{\mathcal{E}}$ and k'_{ϵ_n}, among others.

B.4 Proof of Proposition 2

Proof of Proposition 2.

For inner solutions with $\epsilon_i \in [0, \bar{e}_i]$, we derive conditions under which the solution of the local planner's problem exists and is unique. Moreover, we examine whether an equilibrium regarding permit issuance for all local planners exists and is unique.

The solution of the local planner's problem exists and is unique when the minimization problem is convex. This is the case when the second order condition holds, i.e. when $V''_{\epsilon_i,\epsilon_i} > 0$.

Based on (18), we obtain

$$
\begin{aligned}
V''_{\epsilon_i,\epsilon_i} =& p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] + p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 1\right] - p'_{\mathcal{E}}(\mathcal{E},0) \\
&+ \frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2} + 2\Pi'_k \frac{n f'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{x}\Delta c'_{\epsilon_i} \\
&+ \Pi\,[\, p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\
&\quad + p'_{\mathcal{E}}(\mathcal{E},n)[-\frac{\partial a_A(p(\mathcal{E},n))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n) - [1-\alpha]] \\
&\quad - p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] \\
&\quad - p'_{\mathcal{E}}(\mathcal{E},0)[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 1] - [1-\alpha]p'_{\mathcal{E}}(\mathcal{E},n) + p'_{\mathcal{E}}(\mathcal{E},0) \\
&\quad + f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)\,] \\
&+ [\,\Pi''_{kk}\left[\frac{n f'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{x}\right]^2 \\
&\quad + \Pi'_k \frac{n f''_{\mathcal{E},\mathcal{E}} + \alpha[p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)\mathcal{E} + 2p'_{\mathcal{E}}(\mathcal{E},n)]}{x}\,]\,\Delta c,
\end{aligned} \tag{22}
$$

with

$$
\begin{aligned}
\Delta c'_{\epsilon_i} =& p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - \epsilon_i] - p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - [1-\alpha]\epsilon_i] \\
&- [1-\alpha]p(\mathcal{E},n) + p(\mathcal{E},0) + f'_{\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n) \\
f''_{\mathcal{E},\mathcal{E}} =& p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_n - (1-\alpha)\epsilon_n - a_O(p(\mathcal{E},n-1))] + p'_{\mathcal{E}}(\mathcal{E},n-1)[-\frac{\partial a_O}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n-1)] \\
&- p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)[\bar{e}_n - (1-\alpha)\epsilon_n - a_A(p(\mathcal{E},n))] - p'_{\mathcal{E}}(\mathcal{E},n)[-\frac{\partial a_A}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n)]
\end{aligned} \tag{23}
$$

If damages accelerate sufficiently fast—i.e. if $\frac{\partial^2 d_i}{\partial \mathcal{E}^2}$ is sufficiently large—(i.e. Condition (i) in this proposition), $V''_{\epsilon_i,\epsilon_i} > 0$. This also holds for the case $k = 0$. Hence, we have established that for an individual local planner—keeping the permits issued by all other local planners constant—the decision problem is convex and thus the solution unique. If $p''_{\mathcal{E}\mathcal{E}}=0$, $\Pi=\Pi'_k=\Pi''_{kk}=0$ because $\pi\approx 0$ and $-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0)<2$ (i.e. Condition (ii) in this proposition), we have

$$V''_{\epsilon_i,\epsilon_i}=p'_{\mathcal{E}}(\mathcal{E},0)[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0)-2]+\frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2}>0.$$

Again, for an individual local planner—keeping the permits issued by all other local planners constant—the decision problem is convex and thus the solution unique.

We now discuss an equilibrium with permit issuance for all local planners when either damage acceleration across countries is identical (Condition (i) in the Proposition) or countries $i\in\{1,...,n-1\}$ are symmetric (Condition (ii) in the Proposition). The equilibrium is unique when it corresponds to a global minimum. We therefore examine the properties of the Hessian matrix

$$H=\begin{bmatrix} V''_{\epsilon_1,\epsilon_1} & V''_{\epsilon_1,\epsilon_2} & V''_{\epsilon_1,\epsilon_3} & \dots & V''_{\epsilon_1,\epsilon_n}\\ V''_{\epsilon_2,\epsilon_1} & V''_{\epsilon_2,\epsilon_2} & V''_{\epsilon_2,\epsilon_3} & \dots & V''_{\epsilon_2,\epsilon_n}\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ V''_{\epsilon_n,\epsilon_1} & V''_{\epsilon_n,\epsilon_2} & V''_{\epsilon_n,\epsilon_3} & \dots & V''_{\epsilon_n,\epsilon_n}\end{bmatrix}.$$

The difference between $V''_{\epsilon_i,\epsilon_i}$ and $V''_{\epsilon_i,\epsilon_j}$ stems from the impact of ϵ_i. When a derivative with respect to ϵ_i is taken, the term appears in $V''_{\epsilon_i,\epsilon_i}$ but not in $V''_{\epsilon_i,\epsilon_j}$. One can write

$$V''_{\epsilon_i,\epsilon_i}=V''_{\epsilon_i,\epsilon_j}+X$$

with

$$X=-\underbrace{[[1-\Pi]p'_{\mathcal{E}}(\mathcal{E},0)+[1-\alpha]\Pi[p'_{\mathcal{E}}(\mathcal{E},n)]}_{<0}+k'_{\mathcal{E}}\underbrace{\Pi'_k[[1-\alpha]p(\mathcal{E},n)-p(\mathcal{E},0)]}_{<0}.$$

Plugging in for $k'_{\mathcal{E}}$ (given in Equation (30)) yields

$$\begin{aligned}X=&-[[1-\Pi]p'_{\mathcal{E}}(\mathcal{E},0)+[1-\alpha]\Pi[p'_{\mathcal{E}}(\mathcal{E},n)]\\&+\left[\frac{nf'_{\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)+\alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}+p(\mathcal{E},n)]}{x}\right]\Pi'_k[[1-\alpha]p(\mathcal{E},n)-p(\mathcal{E},0)].\end{aligned}$$

In the case of country n, $V''_{\epsilon_n,\epsilon_n}=V''_{\epsilon_n,\epsilon_j}+X$ only holds when the impact of ϵ_n on f, and thereby on k and its derivatives, can be neglected. It can be neglected when x is high or

π small. Then the Hessian can be written as

$$\begin{bmatrix} V''_{\epsilon_1,\epsilon_1} & V''_{\epsilon_1,\epsilon_2} & V''_{\epsilon_1,\epsilon_3} & \dots & V''_{\epsilon_1,\epsilon_n} \\ V''_{\epsilon_2,\epsilon_1} & V''_{\epsilon_2,\epsilon_2} & V''_{\epsilon_2,\epsilon_3} & \dots & V''_{\epsilon_2,\epsilon_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ V''_{\epsilon_n,\epsilon_1} & V''_{\epsilon_n,\epsilon_2} & V''_{\epsilon_n,\epsilon_3} & \dots & V''_{\epsilon_n,\epsilon_n} \end{bmatrix} = \begin{bmatrix} A+X & A & A & \dots & \bar{A} \\ A & A+X & A & \dots & \bar{A} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \bar{A} & \bar{A} & \bar{A} & \dots & \bar{A}+\bar{X} \end{bmatrix}$$

with $A = V''_{\epsilon_i,\epsilon_j}$, $\bar{A} = V''_{\epsilon_i,\epsilon_n}$, $A+X = V''_{\epsilon_i,\epsilon_i}$, and $\bar{A}+\bar{X} = V''_{\epsilon_n,\epsilon_n}$, and $A, X > 0$ for a large x (i.e. Condition (i) in this proposition) or a small π (i.e. Condition (ii) in this proposition). Note that terms for countries $i = 1, ..., n-1$ are either identical or cancel out. It is easy to verify then that this Hessian is positive-definite. The equilibrium corresponds to a global minimum. Hence Proposition 2 holds. □

B.5 Proof of Proposition 3

Proof of Proposition 3.

To determine the reactions of the local planners to changes in the Tech Treaty, we consider the sign of

$$\frac{\partial \mathcal{E}}{\partial \alpha} = \sum_{i=1}^{n} \frac{\partial \epsilon_i}{\partial \alpha},$$

by implicit differentiation with

$$\frac{\partial \epsilon_i}{\partial \alpha} = \frac{-V^{*''}_{\epsilon_i,\alpha}}{V^{*''}_{\epsilon_i^2}} \tag{24}$$

when V^* is given in (17).

We start by discussing the sign of $V^{*''}_{\epsilon_i,\alpha}$. The expression is stated in Equation (25). It shows that marginal damages do not influence the marginal effect of the Tech Treaty Share α on the permits issued ϵ_i. The marginal effect of an additional research firm on the overall success probability per x (Π'_k/x), the effects on the licensing fee ($f'_{\mathcal{E}}$, f'_α, $f''_{\mathcal{E},\alpha}$) and the reaction of the permit price play an important role for the determination of the sign of Equation (25). The reaction of the permit price works through four different channels, i.e. through the elasticities of the permit price with respect to the global emissions limit and with respect to country i's permit issuance, the difference in permit prices, and the differences in the marginal effects of the global emissions limit on the permit prices. In terms of exogenous parameters, the effects can be traced back to research costs x, innovation probability π, and to the difference in abatement costs between using the old and the advanced technology. Also, the level of the Tech Treaty Share α matters for the overall direction of a change in α.

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} =& \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{ov. inno. prob.}} \underbrace{[p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i + p(\mathcal{E},n) + f''_{\mathcal{E},\alpha}]}_{\text{cost-reduction effect},\Delta c''_{\epsilon_i,\alpha}} \\
&+ \underbrace{\frac{\Pi'_k}{x}[nf'_\alpha(\mathcal{E},\alpha) + p(\mathcal{E},n)\mathcal{E}]}_{\Pi'_k k'_\alpha > 0} \\
&\underbrace{\begin{aligned}&[p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] - p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i] \\ &+p(\mathcal{E},0) - [1-\alpha]p(\mathcal{E},n) + f'_{\mathcal{E}}(\mathcal{E},\alpha)]\end{aligned}}_{\text{marginal cost reduction, }\Delta c'_{\epsilon_i}} \\
&+ \underbrace{\frac{\Pi'_k}{x}\left[nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right]}_{\text{marginal innovation, }\Pi'_k k'_{\mathcal{E}}} \\
&\underbrace{[f'_\alpha + \epsilon_i p(\mathcal{E},n)]}_{\Delta c'_\alpha} \\
&\underbrace{\begin{aligned}&+\frac{\Pi'_k}{x}[\left[nf''_{\mathcal{E},\alpha} + p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right] \\ &+\frac{\Pi''_{kk}}{\Pi'_k}\frac{nf'_\alpha(\mathcal{E},\alpha) + p(\mathcal{E},n)\mathcal{E}}{x}\left[nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right]]\end{aligned}}_{\text{innovation effect, }(\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{kk}k'_\alpha k'_{\mathcal{E}})} \\
&\underbrace{\begin{aligned}&[g_A(a_A(p(\mathcal{E},n))) - g_O(a_O(p(\mathcal{E},0))) + p(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &-p(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},n)) - \epsilon_i] + f]\end{aligned}}_{\text{cost reduction, }\Delta c_i}. \qquad (25)
\end{aligned}
$$

For sufficiently high research costs x (as required in Proposition 3),

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} =& \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{ov. inno. prob.}} \underbrace{[[p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i + p(\mathcal{E},n) + f''_{\mathcal{E},\alpha}]]}_{\text{cost reduction effect},\Delta c''_{\epsilon_i,\alpha}} \\
=& \Pi(k(\mathcal{E},\alpha,\epsilon_n))[[p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i}{p(\mathcal{E},n)} + 1] + f''_{\mathcal{E},\alpha}]].
\end{aligned}
$$

The other terms of (25) are close to zero. If $f''_{\mathcal{E},\alpha} \approx 0$ (Proposition 3), then $V^{*''}_{\epsilon_i,\alpha} > 0$ for $\frac{p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i}{p(\mathcal{E},n)} + 1 > 0$, as stated in Proposition 3 in terms of the elasticity $\xi(l,\epsilon_i)$.

We now turn to the sign of $V''_{\epsilon_i,\epsilon_i}$. Equation (22) gives its general expression. For $\Pi'_k/x \approx 0$ and $p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},l) = 0$ (both required in Proposition 3), Equation (22) reduces to

$$
\begin{aligned}
V''_{\epsilon_i,\epsilon_i} =&(1-\Pi)p'_{\mathcal{E}}(\mathcal{E},0)[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 2] + \frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2} \\
&+ \Pi p'_{\mathcal{E}}(\mathcal{E},n)[-\frac{\partial a_A(p(\mathcal{E},n))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n) - 2[1-\alpha]] + \Pi f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n).
\end{aligned}
$$

For $f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n) > 0$ or small and damages accelerating sufficiently fast—$\partial^2 d_i(\mathcal{E})/\partial\mathcal{E}^2$ large— (both required in Proposition 3), we obtain $V''_{\epsilon_i,\epsilon_i} > 0$. □

C Supplementary Material

C.1 Comparison Between True and Approximated $\tilde{\Pi}$

To be able to clearly distinguish the true and the approximated probabilities, we denote the former with superscript T and the latter with superscript A. Then, we have $\tilde{\pi}^T$ and Π^T, as well as $\tilde{\pi}^A$ and Π^A.

Derivation $\tilde{\pi}^T$ and discussion of Π^T

We are interested in the probability of R&D firm i obtaining the patent, given that R&D firm i is active and that there is a total of k active firms. Let P denote the patent-holder, A the set of active R&D firms, $S \subseteq A$ the set of successful R&D firms, and $\mathbb{P}_k^A[i = P] = \tilde{\pi}^T$ the probability that R&D firm i will obtain the patent, given that R&D firm i is active and there is a total of k active firms. Also let m denote $m = j - 1$. Then,

$$\begin{aligned}
\mathbb{P}_k^A[i = P] &= \mathbb{P}_k^A[i = P | i \in S] \cdot \underbrace{\mathbb{P}_k^A[i \in S]}_{=\pi} + \underbrace{\mathbb{P}_k^A[i = P | i \notin S] \cdot \mathbb{P}_k^A[i \notin S]}_{=0} \\
&= \pi \, \mathbb{P}_k^A[i = P | i \in S] \\
&= \pi \sum_{m=0}^{k-1} \underbrace{\mathbb{P}_k^A[i = P || S \backslash \{i\}_{i \in S}| = m]}_{=\frac{1}{m+1}} \cdot \underbrace{\mathbb{P}_k^A[|S \backslash \{i\}| = m+1]}_{=\pi^m [1-\pi]^{k-1-m} \binom{k-1}{m}} \\
&= \pi \sum_{m=0}^{k-1} \frac{1}{m+1} \binom{k-1}{m} \pi^m [1-\pi]^{k-1-m} \\
&= \pi \sum_{j=1}^{k} \frac{1}{j} \binom{k-1}{j-1} \pi^{j-1} [1-\pi]^{k-1-j+1} \\
&= \sum_{j=1}^{k} \frac{k}{k} \frac{1}{j} \binom{k-1}{j-1} \pi^j [1-\pi]^{k-j} = \sum_{j=1}^{k} \frac{1}{k} \binom{k}{j} \pi^j [1-\pi]^{k-j} \\
&= \frac{1}{k} \mathbb{P}(\text{Bin}(k,\pi) \geq 1) = \frac{1}{k} [1 - \mathbb{P}(\text{Bin}(k,\pi) = 0)] = \frac{1}{k} [1 - [1-\pi]^k]
\end{aligned}$$

and $\mathbb{P}_k^A[i = P | i \notin S] = 0$, as an R&D firm cannot be a patent-holder without success.

If k R&D firms are active, the overall probability that the new technology will be discovered is given by

$$\Pi^T(k) = 1 - [1 - \pi]^k. \tag{26}$$

The probability that all k firms will not be successful is $[1 - \pi]^k$, thus the probability that at least one firm will be successful is $1-[1-\pi]^k$. If only one R&D firm is active, $\Pi=\pi$.

Approximation and comparison

Table C1 compares the true probability to the approximation. The plots in Figure 2 compare $\tilde{\pi}^T$ and $\tilde{\pi}^A$ for different values of k and π. Table C1 shows that the true probability and the approximation have the same qualitative properties. Taking the scaling of the axis into account, Figure 2 shows that the differences between the two functions are small. Especially when it comes to second-order derivatives the small deviation from the true value is a low price to pay for gaining a lot in terms of tractability.

Table C1: Comparison of probabilities.

	True	Approximation
$\tilde{\pi}(k,\pi)$	$\tilde{\pi}^T=\frac{1}{k}[1-[1-\pi]^k]$	$\tilde{\pi}^A=\frac{\pi}{1+\pi(k-1)}$
$\Pi(k)$	$\Pi(k)^T=1-[1-\pi]^k$	$\Pi^A=k\tilde{\pi}^A$
$\Pi_k^{'}$	$\Pi_k^{'T}=-[1-\pi]^k\log[1-\pi]>0$	$\Pi_k^{'A}=\frac{\pi-\pi^2}{[1+[k-1]\pi]^2}>0$
$\Pi_{kk}^{''}$	$\Pi_{k,k}^{''T}=-(1-\pi)^k\log[1-\pi]^2<0$	$\Pi_{k,k}^{''A}=\frac{-[\pi-\pi^2]2[1+[k-1]\pi]\pi}{[1+[k-1]\pi]^4}<0$
$Z:=\frac{\Pi''kk}{\Pi_k'}$	$Z^T:=\log[1-\pi]<0$	$Z^A:=\frac{-2\pi}{k[1+\pi[k-1]]}<0$
k_α'	$k_\alpha'=-\frac{\Pi}{\Pi_k'-\frac{\Pi}{k}}\frac{nf_\alpha(\mathcal{E},\alpha,\epsilon_n)+p(\mathcal{E},n)\mathcal{E}}{f(\mathcal{E},\alpha,\epsilon_n)n+\alpha p(\mathcal{E},n)\mathcal{E}}>0$	$k_\alpha'=\frac{nf_\alpha'(\mathcal{E},\alpha)+p(\mathcal{E},n)\mathcal{E}}{x}>0$
$k_\mathcal{E}'$	$k_\mathcal{E}'=-\frac{\Pi}{\Pi_k'-\frac{\Pi}{k}}\frac{nf_\mathcal{E}'(\mathcal{E},\alpha,\epsilon_n)+\alpha[p_\mathcal{E}'(\mathcal{E},n)\mathcal{E}+p(\mathcal{E},n)]}{nf(\mathcal{E},\alpha,\epsilon_n)+\alpha p(\mathcal{E},n)\mathcal{E}}$	$k_\mathcal{E}'=\frac{nf_\mathcal{E}'(\mathcal{E},\alpha)+\alpha[p_\mathcal{E}'(\mathcal{E},n)\mathcal{E}+p(\mathcal{E},n)]}{x}$

In the table, the 'true' values are indicated by superscript 'T', while the approximated values are indicated by superscript 'A'. Z is introduced in the Proof of Proposition 3.

In the following, we show that results for k_α' and $k_\mathcal{E}'$ from Propositions 1 and 7 also hold under $\tilde{\Pi}^T$. If we take $\tilde{\Pi}^T$, we cannot solve for k in zero-profit Condition (9)

$$\frac{1}{k}[1-[1-\pi]^k][nf(\mathcal{E},\alpha,\epsilon_n)+p(\mathcal{E},n)\alpha\mathcal{E}]-x=0, \tag{27}$$

but this equation still defines a unique k under fairly mild conditions. When

$$\frac{x}{nf(\mathcal{E},\alpha,\epsilon_n)+p(\mathcal{E},n)\alpha\mathcal{E}}\in(0,\pi]$$

and $\pi\in[0,1)$, there exists a unique k that solves Equation (27). The reason is as follows: For $k=1$, $\tilde{\Pi}^T=\pi$ and

$$\begin{aligned}\frac{\partial\tilde{\Pi}^T}{\partial k}&=\frac{-1}{k^2}[1-[1-\pi]^k]+\frac{1}{k}[-[1-\pi]^k\log[1-\pi]]\\&=\frac{[1-\pi]^k[1-\log[[1-\pi]^k]]-1}{k^2}\leq 0,\end{aligned}$$

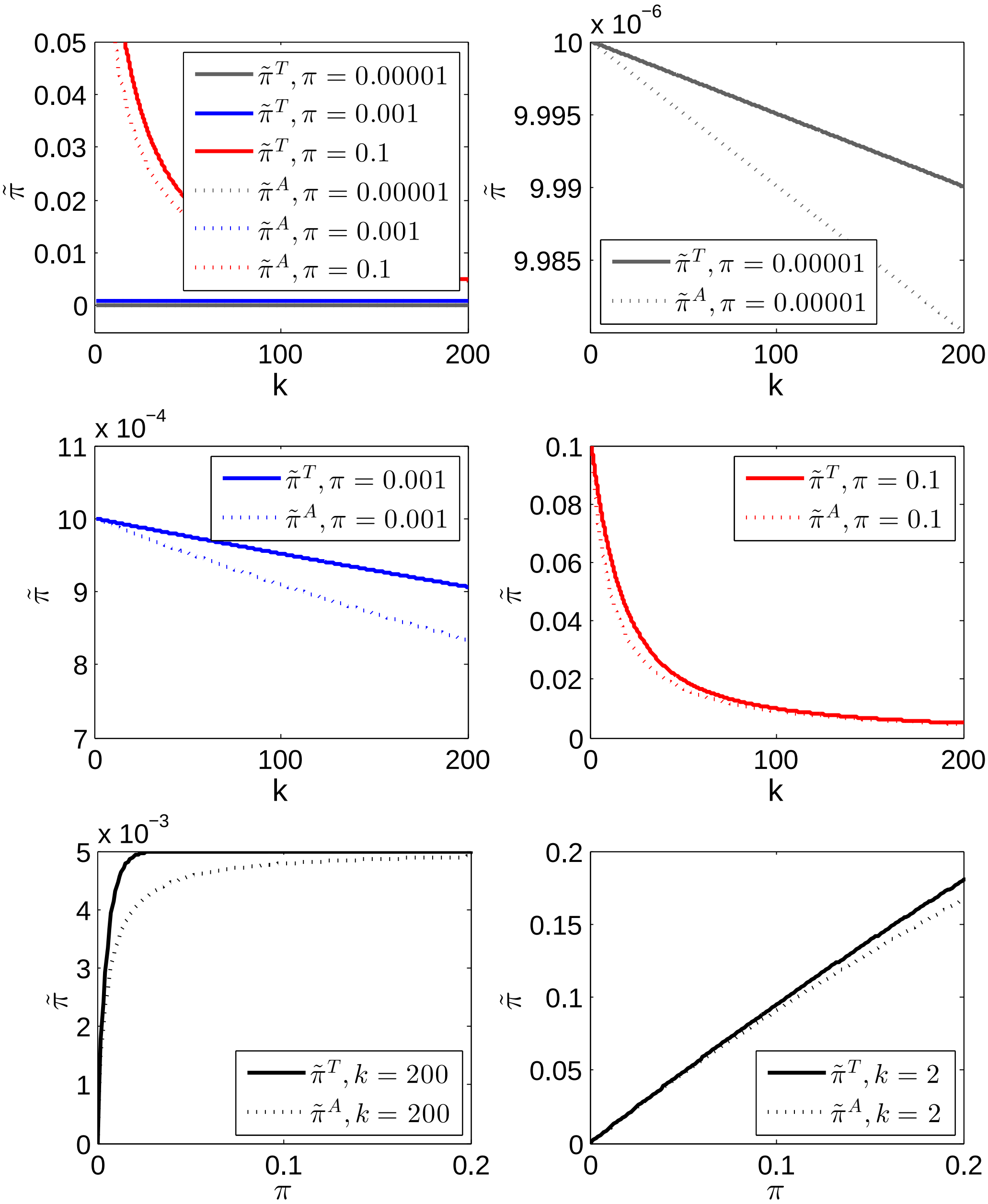

Figure 2: Comparison of true probability $\tilde{\pi}^T$ and approximated probability $\tilde{\pi}^A$ for different values of k and π.

as $[1-\pi]^k[1-\log[[1-\pi]^k]] \leq 1$ because of the following relationships:

$$\forall x \in (0,1], e \cdot \frac{1}{x} \leq e^{\frac{1}{x}} \rightarrow 1+\log[\frac{1}{x}] \leq \log[e^{\frac{1}{x}}] \rightarrow 1-\log[x] \leq \frac{1}{x}$$

and

$$\forall x \in (0,1], \frac{1}{x} \leq \frac{1}{x^k}.$$

Figure 3 illustrates the relationship. It is strictly decreasing for $k \geq 0$.

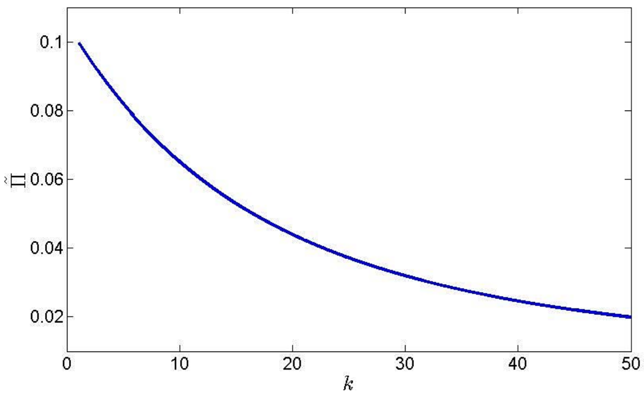

Figure 3: Illustration of $\tilde{\pi}^T$ for $\pi = 0.1$.

Using the implicit function theorem, we can derive k'_α and $k'_\mathcal{E}$.

$$k'_\alpha = -\frac{\Pi}{\Pi'_k - \frac{\Pi}{k}} \frac{nf_\alpha(\mathcal{E},\alpha,\epsilon_n) + p(\mathcal{E},n)\mathcal{E}}{f(\mathcal{E},\alpha,\epsilon_n)n + \alpha p(\mathcal{E},n)\mathcal{E}} > 0$$

$$k'_\mathcal{E} = -\frac{\Pi}{\Pi'_k - \frac{\Pi}{k}} \frac{nf'_\mathcal{E}(\mathcal{E},\alpha,\epsilon_n) + \alpha[p'_\mathcal{E}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{nf(\mathcal{E},\alpha,\epsilon_n) + \alpha p(\mathcal{E},n)\mathcal{E}},$$

with

$$k\Pi'_k - \Pi = -k(1-\pi)^k \log[1-\pi] - 1 + [1-\pi]^k = [1-\pi]^k[\log[[1-\pi]^{-k}] + 1 - [1-\pi]^{-k}] < 0,$$

as $\log[z] + 1 < z$ for $z > 1$, and $[1-\pi]^{-k} > 1$. The calculations show that the results for k'_α and $k'_\mathcal{E}$ are determined by the same expressions as in the Propositions 1 and 7. The results with both probabilities are identical in the sense that the signs of the effects are the same. The magnitudes of the effects may differ.

Results derived in Section 5 are also qualitatively the same for Π^T and Π^A, as the results for k'_α, $k'_\mathcal{E}$, Π, Π'_k, and Π''_{kk} are qualitatively the same for Π^T and Π^A (see Table C1).

C.2 More on 'Tightening of Global Emissions (Section 4.4)'

We first indicate how the license fee f will respond to a change in the global emissions limit for a given Tech Treaty. Then we consider the reaction of the number of active R&D firms k to a change in the global emissions limit for a given Tech Treaty. Finally, we discuss whether a tighter global emissions limit will help the Tech Treaty to foster innovation.

A reduction in the global emissions limit—which implies an increase in overall abatement—will increase the permit price when either the old or the new abatement technology is used. The impact of tightening aggregate emissions on the license fee as given by (8) is not straightforward. It depends on whether production firm n abates more with the advanced technology and whether the price increase is larger when $n-1$ or all n production firms use the advanced technology. These two factors determine production firm n's willingness to pay for the advanced technology and the sign of $f'_\mathcal{E}$. Lemma 7 states conditions for which the 'normal' reaction—$f'_\mathcal{E} < 0$—holds.

Lemma 7
A tighter limit on global emissions will increase the license fee, $f'_\mathcal{E} < 0$, if one of the two following conditions hold:

(i) $p'_{\mathcal{E},n} \approx p'_{\mathcal{E},n-1}$*;*

(ii) or $\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E}, n-1)) \geq 0$ *and*

(I) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, n)) < 0$

(II) or $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E}, n)) > 0$
and in addition $|p'_l(\mathcal{E}, n-1)| \geq |p'_l(\mathcal{E}, n)|$.

Proof of Lemma 7.
Equation (8) implies

$$f'_\mathcal{E} = p'_\mathcal{E}(\mathcal{E}, n-1)[\bar{e}_n - [1-\alpha]\epsilon_n - a_O(p(\mathcal{E}, n-1))] \\ - p'_\mathcal{E}(\mathcal{E}, n)[\bar{e}_n - [1-\alpha]\epsilon_n - a_A(p(\mathcal{E}, n))], \quad (28)$$

where $p'_\mathcal{E}(\mathcal{E}, n) < 0$ by Lemma 1. Other terms in the expression for $f'_\mathcal{E}$ cancel out, as prices equal marginal abatement costs (Equation (2)).

In the case of (i) with $p'_{\mathcal{E},n} \approx p'_{\mathcal{E},n-1}$,

$$f'_{\mathcal{E}} \approx p'_{\mathcal{E}}(\mathcal{E})[-a_O(p(\mathcal{E},n-1)) + a_A(p(\mathcal{E},n))] \tag{29}$$

with $a_A(p(\mathcal{E},n)) > a_O(p(\mathcal{E},n-1))$, as shown in the Proof of Lemma 6. Hence, $f'_{\mathcal{E}} < 0$.

Under conditions stated in (ii), we have the two cases.

(I) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},n-1)) < 0$:

$$\begin{aligned} f'_{\mathcal{E}} = &\overbrace{p'_{\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},n-1))]}^{\leq 0} \\ &- \underbrace{p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},n))]}_{>0} < 0, \end{aligned}$$

(II) $\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},n-1)) > 0$:

$$f'_{\mathcal{E}} < 0 \Leftrightarrow \overbrace{\frac{p'_{\mathcal{E}}(\mathcal{E},n-1)}{p'_{\mathcal{E}}(\mathcal{E},n)}}^{>1} \overbrace{\frac{\bar{e}_i - [1-\alpha]\epsilon_i - a_O(p(\mathcal{E},n-1))}{\bar{e}_i - [1-\alpha]\epsilon_i - a_A(p(\mathcal{E},n))}}^{>1} > 1.$$

□

We note that the conditions are a special case of the conditions of Lemma 6, with $l = n-1$. For quadratic abatement cost functions $f'_{\mathcal{E}} < 0$ holds as well. This follows directly from Lemma 7. As already mentioned, in Appendix C.3 the entire model is solved explicitly for quadratic abatement cost functions. This allows a direct proof of $f'_{\mathcal{E}} < 0$.

Proposition 7 summarizes how the global emissions limit $\mathcal{E}$ affects the number of active R&D firms. For this purpose, we use the fact that the zero profit condition (9) implies that

$$k'_{\mathcal{E}} = \frac{n f'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{x}. \tag{30}$$

This yields Proposition 7.

Proposition 7
A tighter global emissions limit will increase the number of active R&D firms, i.e. $k'_{\mathcal{E}} < 0$, if

$$p(\mathcal{E},n) < \frac{-f'_{\mathcal{E}}(\mathcal{E})n}{\alpha} - p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}.$$

In particular, $k'_{\mathcal{E}} < 0$ if one of the following conditions hold:

(i) $f'_{\mathcal{E}} < 0$ and $p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}/p < -1$,

(ii) $f'_{\mathcal{E}} < 0$*, and* α *is sufficiently small,*

(iii) the abatement cost functions are quadratic, and $\mathcal{E} > \bar{E}/2$*.*

Proof of Proposition 7.
Points (i) and (ii) from Proposition 7 follow directly from the general condition. Point (iii) follows from the complete solution of the model for quadratic abatement costs in Appendix C.3. □

The effect on the number of active R&D firms of a change in the global emissions limit depends on the effect of the global emissions limit on the license fee f and on the elasticity that describes the reaction of the permit price to a change in the global emissions limit. This elasticity is $p'_{\mathcal{E}}(\mathcal{E}, n)\mathcal{E}/p$, as described in case (i) of Proposition 7. The influence of this elasticity stems from the scaling of the patent-holder's income through the Tech Treaty. The international agency's budget for scaling the patent-holder's revenues is $\alpha p\mathcal{E}$. If fewer permits are issued, the permit price has to increase to compensate for the lower number of permits and ensure that $\alpha p\mathcal{E}$ does not decline.

We are now in a position to judge whether a tighter global emissions limit will support the Tech Treaty in fostering innovation. In a setting characterized by emissions limit $\mathcal{E}$ close to baseline emissions $\bar{E}$ and a low permit price p, tightening of the emissions limit will help the Tech Treaty to foster innovation. The general condition in Proposition 7 shows the interrelation. For a low permit price, a tightening in the global emissions limit increases the number of active R&D firms. When the global emissions limit is already low, crowding-out may occur in the sense that the number of active R&D firms will decline. However, potential crowding-out when overall emissions are marginally reduced can be compensated for by strengthening the Tech Treaty. This follows from Proposition 1.

C.3 Example I: Quadratic Abatement Costs

C.3.1 The set-up

In this section we illustrate the results with an example. We assume that the abatement cost functions take quadratic forms, i.e. we set

$$g_O(a_i) = \frac{b_O}{2}a_i^2 \quad \text{and} \quad g_A(a_i) = \frac{b_A}{2}a_i^2,$$

with $b_A, b_O > 0$, and $b_A < b_O$. Then, $g'_O(a_i) = b_O a_i$ and $g'_A(a_i) = b_A a_i$.

Equations (2) and (3) become

$$p(\mathcal{E},l) = b_O a_O = b_A a_A,$$
$$a_O(p(\mathcal{E},l)) = \frac{p(\mathcal{E},l)}{b_O} \quad \text{and} \quad a_A(p(\mathcal{E},l)) = \frac{p(\mathcal{E},l)}{b_A}.$$

A market equilibrium on the permit market implies that supply equals demand, as denoted in Equation (5):

$$\mathcal{E} = \bar{E} - l\frac{p}{b_A} - [n-l]\frac{p}{b_O} \Leftrightarrow p = \frac{\bar{E}-\mathcal{E}}{\frac{l}{b_A} + \frac{n-l}{b_O}} = \frac{b_A b_O[\bar{E}-\mathcal{E}]}{lb_0 + b_A[n-l]}.$$

The permit price $p(\mathcal{E},l)$ in the market equilibrium depends on $\mathcal{E}$ and l.

For $l = 0$, we have

$$p(\mathcal{E},0) = \frac{b_O[\bar{E}-\mathcal{E}]}{n},$$

and for $l = n$,

$$p(\mathcal{E},n) = \frac{b_A[\bar{E}-\mathcal{E}]}{n}.$$

Furthermore,

$$a_A(p(\mathcal{E},n)) = \frac{\bar{E}-\mathcal{E}}{n} = a_O(p(\mathcal{E},0)).$$

In both scenarios, emissions are the same. Once the global emissions limit is set and because all production firms use the same technology, the amount each production firm abates will be the same in both scenarios.

C.3.2 The value of the fee and the number of active R&D firms

The fee is

$$
\begin{aligned}
f =& \frac{b_O}{2}\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}\left[\bar{e}_n - [1-\alpha]\epsilon_n - \frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right] \\
&- \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 - \frac{b_A[\bar{E}-\mathcal{E}]}{n}\left[\bar{e}_n - [1-\alpha]\epsilon_n - \frac{\bar{E}-\mathcal{E}}{n}\right] \\
=& \left[\frac{b_O}{2} - b_O\right]\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}[\bar{e}_n - [1-\alpha]\epsilon_n] \\
&- \left[\frac{b_A}{2} - b_A\right]\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 - \frac{b_A[\bar{E}-\mathcal{E}]}{n}[\bar{e}_n - [1-\alpha]\epsilon_n] \\
=& \left[\frac{b_O}{2} - b_O\right]\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 - \left[\frac{b_A}{2} - b_A\right]\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
&+ [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n](\frac{1}{\frac{n-1}{b_A}+\frac{1}{b_O}} - \frac{b_A}{n}) \\
=& -\frac{b_O}{2}\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
&+ [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]\left[\frac{nb_Ab_O}{n[b_O[n-1]+b_A]} - \frac{b_Ab_On - b_Ab_O + b_A^2}{n[b_O[n-1]+b_A]}\right] \\
=& -\frac{b_O}{2}\left[\frac{b_Ab_O[\bar{E}-\mathcal{E}]}{b_O(n-1)+b_A}\frac{1}{b_O}\right]^2 + \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
&+ [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]b_A\frac{b_O-b_A}{n[b_O[n-1]+b_A]} \\
=& \frac{[\bar{E}-\mathcal{E}]^2}{2}\left[-b_O\left[\frac{b_A}{b_O(n-1)+b_A}\right]^2 + \frac{b_A}{n^2}\right] \\
&+ [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]b_A\frac{b_O-b_A}{n[b_O[n-1]+b_A]}
\end{aligned} \tag{31}
$$

and the number of active R&D firms is

$$
k = \frac{nf + \alpha\mathcal{E}\frac{b_A[\bar{E}-\mathcal{E}]}{n}}{x} + 1 - \frac{1}{\pi}, \tag{32}
$$

based on Equation (9).

C.3.3 The signs of $f'_{\mathcal{E}}$, $f''_{\mathcal{E},\alpha}$, $f''_{\mathcal{E},\mathcal{E}}$, $k'_{\mathcal{E}}$ and $k''_{\mathcal{E},\mathcal{E}}$

In the following, we derive $f'_{\mathcal{E}}$ and $f''_{\mathcal{E},\alpha}$ using quadratic abatement cost functions. For the sake of clarity, we derive $f''_{\mathcal{E},\alpha}$ in functional forms before we derive $f'_{\mathcal{E}}$. Based on Equation (28),

$$f''_{\mathcal{E},\alpha} = \epsilon_n [p'_{\mathcal{E}}(\mathcal{E}, n-1) - p'_{\mathcal{E}}(\mathcal{E}, n)].$$

Using

$$\begin{aligned} p(\mathcal{E}, n-1) &= \frac{b_A b_O [\bar{E} - \mathcal{E}]}{b_O[n-1] + b_A}, \\ p'_{\mathcal{E}}(\mathcal{E}, n-1) &= \frac{-b_A b_O}{b_O[n-1] + b_A}, \\ a_O(p(\mathcal{E}, n-1)) &= \frac{b_A [\bar{E} - \mathcal{E}]}{b_O[n-1] + b_A}, \end{aligned}$$

gives

$$\begin{aligned} f''_{\mathcal{E},\alpha} =& \epsilon_n \left[\frac{b_A}{n} - \frac{b_A b_O}{b_O[n-1] + b_A} \right] = \epsilon_n \left[\frac{-n b_A b_O + b_A b_O (n-1) + b_A^2}{n[b_O[n-1] + b_A]} \right] \\ =& \epsilon_n \left[\frac{b_A [b_A - b_O]}{n[b_O[n-1] + b_A]} \right] < 0, \end{aligned} \tag{33}$$

and

$$\begin{aligned} f'_{\mathcal{E}} =& - \frac{b_A}{n} \frac{\bar{E} - \mathcal{E}}{n} + \frac{b_A^2 b_O [\bar{E} - \mathcal{E}]}{[b_O[n-1] + b_A]^2} \\ & - [p'_{\mathcal{E}}(\mathcal{E}, n) - p'_{\mathcal{E}}(\mathcal{E}, n-1)][\bar{e}_n - [1-\alpha]\epsilon_n], \\ =& - b_A [\bar{E} - \mathcal{E}] \left[\frac{1}{n^2} - \frac{b_O b_A}{[b_O[n-1] + b_A]^2} \right] + \left[\frac{f''_{\mathcal{E},\alpha}}{\epsilon_n} \right] [\bar{e}_n - [1-\alpha]\epsilon_n], \\ =& - b_A [\bar{E} - \mathcal{E}] \left[\frac{[b_O[n-1] + b_A]^2 - n^2 b_O b_A}{n^2 [b_O[n-1] + b_A]^2} \right] \\ & - \frac{b_A [b_O - b_A]}{n[b_O[n-1] + b_A]} [\bar{e}_n - [1-\alpha]\epsilon_n] < 0 \end{aligned} \tag{34}$$

with

$$\begin{aligned}[b_O[n-1]+b_A]^2-n^2b_Ob_A &= b_O^2[n-1]^2+b_A^2+2b_O[n-1]b_A-n^2b_Ob_A\\ &= b_O^2[n-1]^2+b_A^2-b_Ob_A[n^2+2[1-n]]\\ &= b_O^2[n-1]^2+b_A^2-b_Ob_A[[n-1]^2+1]]\\ &= b_O[n-1]^2[b_O-b_A]-b_A[-b_A+b_O]\\ &= [b_O[n-1]^2-b_A][b_O-b_A]>0,\end{aligned}$$

because $n \geq 2$ in a multi-country world.

Also, based on (34),

$$f''_{\mathcal{E},\mathcal{E}} = b_A\left[\frac{-b_Ab_On^2+[b_O[n-1]+b_A]^2}{[b_O[n-1]+b_A]^2n^2}\right]>0. \tag{35}$$

Based on (32), we can derive

$$k'_{\mathcal{E}} = \frac{nf'_{\mathcal{E}}+\alpha\frac{b_A[\bar{E}-2\mathcal{E}]}{n}}{x},$$

with $k'_{\mathcal{E}} < 0$ when $\mathcal{E} > \bar{E}/2$, as $f'_{\mathcal{E}} < 0$ for quadratic abatement costs (Equation (34)). This proves Proposition 7, (iii).

From (30) we obtain

$$k''_{\mathcal{E},\mathcal{E}} = \frac{nf''_{\mathcal{E},\mathcal{E}}-\alpha 2b_A/n}{x}.$$

C.3.4 The sign of $\partial f_i/\partial l$

Based on Equation (13),

$$\begin{aligned}\frac{\partial f_i(l)}{\partial l} =& -\frac{b_Ab_O[\bar{E}-\mathcal{E}][b_0-b_A]}{[lb_0+b_A[n-l]]^2}\left[\bar{e}_i-[1-\alpha]\epsilon_i-\frac{b_A[\bar{E}-\mathcal{E}]}{lb_0+b_A[n-l]}\right]\\ &+\frac{b_Ab_O[\bar{E}-\mathcal{E}][b_0-b_A]}{[[l+1]b_0+b_A[n-l-1]]^2}\left[\bar{e}_i-[1-\alpha]\epsilon_i-\frac{b_O[\bar{E}-\mathcal{E}]}{[l+1]b_0+b_A[n-l-1]}\right]\\ =& b_Ab_O[\bar{E}-\mathcal{E}][b_0-b_A]\left[-\frac{\bar{e}_i-[1-\alpha]\epsilon_i}{[lb_0+b_A[n-l]]^2}+\frac{b_A[\bar{E}-\mathcal{E}]}{[lb_0+b_A[n-l]]^3}\right.\\ &\left.+\frac{\bar{e}_i-[1-\alpha]\epsilon_i}{[[l+1]b_0+b_A[n-l-1]]^2}-\frac{b_O[\bar{E}-\mathcal{E}]}{[[l+1]b_0+b_A[n-l-1]]^3}\right].\end{aligned}$$

The expression is negative when

$$
\begin{aligned}
&-\frac{1}{[lb_0 + b_A[n-l]]^2} + \frac{1}{[[l+1]b_0 + b_A[n-l-1]]^2} < 0 \\
\text{and} \quad &\frac{b_A}{[lb_0 + b_A[n-l]]^3} - \frac{b_O}{[[l+1]b_0 + b_A[n-l-1]]^3} < 0.
\end{aligned}
$$

The former is clear as $lb_0 + b_A[n-l] < [l+1]b_0 + b_A[n-l-1]$. For the latter, we need $\frac{b_A}{[lb_0+b_A[n-l]]^3} < \frac{b_O}{[[l+1]b_0+b_A[n-l-1]]^3}$. Define $Z_1 \equiv lb_0 + b_A[n-l-1]$. Then

$$
\begin{aligned}
&b_A[b_0 + Z_1]^3 - b_O[Z_1 + b_A]^3 \\
=&b_A[b_O^3 + 3Z_1b_0^2 + 3b_OZ_1^2 + Z_1^3] - b_O[b_A^3 + 3Z_1b_A^2 + 3b_AZ_1^2 + Z_1^3] \\
=&[b_A - b_O]Z_1^3 + b_Ab_O[b_O^2 + 3Z_1b_0 - b_A^2 - 3Z_1b_A] \\
=&[b_A - b_O]Z_1^3 + b_Ab_O[[b_O + b_A][b_O - b_A] + 3Z_1[b_0 - b_A]] \\
=&[b_A - b_O][Z_1^3 - b_Ab_O[b_O + b_A + 3Z_1]].
\end{aligned}
$$

Now define $Z_2 \equiv b_O/b_A$.

$$
\begin{aligned}
&[b_A - Z_2b_A][b_A^3[Z_2l + n - l + 1]^3 - b_AZ_2b_A[Z_2b_A + b_A + 3b_A[Z_2l + n - l + 1]]] \\
=&\underbrace{b_A^4[1 - Z_2]}_{<0}\underbrace{[[Z_2l + n - l + 1]^3 - Z_2[Z_2 + 1 + 3[Z_2l + n - l + 1]]]}_{\equiv Z_3}.
\end{aligned}
$$

The expression is negative if $Z_3 > 0$. Figure 4 shows that $Z_3 > 0$ for plausible values of n and Z_2.

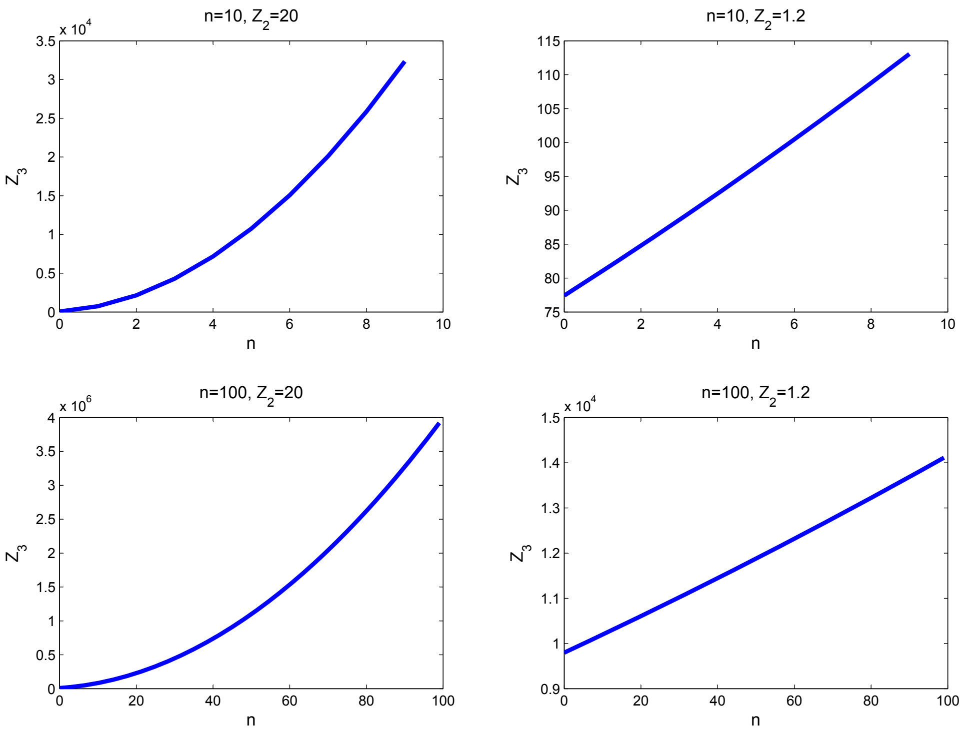

Figure 4: Simulation of Z_3 for different values of n and Z_2.

C.3.5 Proof of Proposition 4

Again based on Equation (24), we need to determine the signs of $V^{*''}_{\epsilon_i,\epsilon_i}$ and $V^{*''}_{\epsilon_i,\alpha}$. For quadratic abatement costs, Equation (25) becomes

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} = & \underbrace{\Pi}_{\text{ov. inno. prob.}} \underbrace{\left[\frac{b_A}{n}\left[\bar{E} - \mathcal{E} - \epsilon_i\right] + \overbrace{\epsilon_n \left[\frac{b_A[b_A - b_O]}{n[[n-1]b_O + b_A]}\right]}^{f''_{\mathcal{E}\alpha}<0} \right]}_{\text{cost-change effect,}\Delta c''_{\epsilon_i,\alpha}} \\
& \underbrace{+ \frac{\Pi'_k}{x}\left[n \overbrace{\frac{\epsilon_n b_A[b_O - b_A][\bar{E} - \mathcal{E}]}{n[b_O[n-1] + b_A]}}^{f'_\alpha>0} + \frac{b_A[\bar{E} - \mathcal{E}]}{n}\mathcal{E} \right]}_{\Pi'_k k'_\alpha>0} \\
& \underbrace{\left[\frac{b_O}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - \epsilon_i] - \frac{b_A}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - [1-\alpha]\epsilon_i] + [b_O - [1-\alpha]b_A]\frac{[\bar{E} - \mathcal{E}]}{n} + f'_{\mathcal{E}}(\mathcal{E},\alpha) \right]}_{\text{marginal cost change, } \Delta c'_{\epsilon_i}} \\
& \underbrace{+ \frac{\Pi'_k}{x}\left[n f'_{\mathcal{E}}(\mathcal{E},\alpha) - \alpha\frac{b_A}{n}[2\mathcal{E} - \bar{E}] \right]}_{\text{marginal innovation, } \Pi'_k k'_{\mathcal{E}}<0} \\
& \underbrace{\left[\overbrace{\frac{\epsilon_n b_A[b_O - b_A][\bar{E} - \mathcal{E}]}{n[b_O[n-1] + b_A]}}^{f'_\alpha>0} + \epsilon_i b_A \frac{[\bar{E} - \mathcal{E}]}{n} \right]}_{\Delta c'_\alpha>0} \\
& \underbrace{\begin{aligned} &+ \frac{\Pi'_k}{x}[\left[n f''_{\mathcal{E},\alpha} - \frac{b_A}{n}[2\mathcal{E} - \bar{E}] \right] \\ &+ Z\frac{n f'_\alpha + \frac{b_A[\bar{E} - \mathcal{E}]}{n}\mathcal{E}}{x}\left[n f'_{\mathcal{E}} + \alpha\left[\frac{b_A[\bar{E} - \mathcal{E}]}{n} - \frac{b_A}{n}\right]\right]] \end{aligned}}_{\text{innovation effect, } \left[\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{k,k}, k'_\alpha, k'_{\mathcal{E}}\right]} \\
& \underbrace{\left[\frac{b_A - b_O}{2}\left[\frac{\bar{E} - \mathcal{E}}{n}\right]^2 + \left[b_A \frac{\bar{E} - \mathcal{E}}{n}\right][\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - [1-\alpha]\epsilon_i] - b_O\frac{\bar{E} - \mathcal{E}}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - \epsilon_i] + f \right]}_{\text{cost change, } \Delta c_i},
\end{aligned}
\tag{36}
$$

with f, f'_α, $f'_{\mathcal{E}}$, and $f''_{\mathcal{E},\alpha}$ from Appendix C.3.3.

The signs of the components of $V^{*''}_{\epsilon_i,\alpha}$ are discussed in the following:

1. The *cost-change effect* is positive because $[\bar{E} - \mathcal{E} - \epsilon_i] > 0$ (i.e. Condition (iv) in this

proposition) and $f''_{\mathcal{E},\alpha}$ is small because of small ϵ_n (i.e. Condition (v) in this proposition) (see Equation (33)).

2. $f'_\alpha > 0$ from Appendix C.3.3 and Π'_k from Table C1. The *marginal cost change* is positive for large differences between the old and the advanced technology (i.e. Condition (ii) in this proposition) and $f'_{\mathcal{E}}$ is relatively small, which is arguably the case, as the part of $f'_{\mathcal{E}}$ that depends on the cost difference (see Equation (34)) is weighted by $\bar{e}_n - [1-\alpha]\epsilon_n$, which according to Lemma 3 is small. This holds as long as α is sufficiently small, which we require in Condition (vi) in this proposition.

3. The product of *marginal innovation* and $\Delta c'_\alpha$ is positive. The effect is relatively small, as ϵ_n is small (Conditions (v) in this proposition) and $f'_{\mathcal{E}}$ is also small (see previous point). Multiplied by $\Pi'_k k'_{\mathcal{E}}$, the overall effect is negative. As the impact is relatively small, $V^{*''}_{\epsilon_i,\alpha} > 0$.

4. For low probability π (Condition (i) in this proposition), the part of the *innovation effect* that is weighted by Z is relatively smaller than the other part as $Z \approx 0$ (see Table C1). The *innovation effect* is negative. The *cost change* is negative for large cost differences (Condition (ii) in this proposition). The product of both effects is positive.

We now examine the conditions under which $V''_{\epsilon_i,\epsilon_i} > 0$. Quadratic abatement costs lead to $p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},l) = 0$. Then Expression (22) becomes

$$\begin{aligned}
V''_{\epsilon_i,\epsilon_i} =& p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 2\right] + \frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2} + 2\Pi'_k k'_{\mathcal{E}}\Delta c'_{\epsilon_i} \\
&+\Pi[p'_{\mathcal{E}}(\mathcal{E},n)\left[-\frac{\partial a_A(p(\mathcal{E},n))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n) - 2[1-\alpha]\right] \\
&- p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial a_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 2\right] + f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)] \\
&+[\Pi''_{kk}(k'_{\mathcal{E}})^2 + \Pi'_k k''_{\mathcal{E},\mathcal{E}}]\Delta c. \qquad (37)
\end{aligned}$$

Using $\frac{\partial a_A(p(\mathcal{E},n))}{\partial p} p'_{\mathcal{E}}(\mathcal{E},n) = \frac{\partial a_O(p(\mathcal{E},0))}{\partial p} p'_{\mathcal{E}}(\mathcal{E},0) = -1/n$ and re-arranging yields

$$\begin{aligned} V''_{\epsilon_i,\epsilon_i} = & \underbrace{[1-\Pi]p'_{\mathcal{E}}(\mathcal{E},0)\left[\frac{1}{n}-2\right] + \Pi p'_{\mathcal{E}}(\mathcal{E},n)\left[\frac{1}{n}-2[1-\alpha]\right]}_{>0 \quad \text{for} \quad \alpha<\frac{2n-1}{2n}} \\ & + \underbrace{\frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2}}_{>0} \\ & + \underbrace{\Pi\left[-\frac{p'_{\mathcal{E}}(\mathcal{E},n-1)^2}{b_O} + \frac{p'_{\mathcal{E}}(\mathcal{E},n)^2}{b_A}\right]}_{>0} \\ & + \underbrace{2\Pi'_k k'_{\mathcal{E}} \Delta c'_{\epsilon_i}}_{<0} \\ & + [\underbrace{\Pi''_{kk}\left[k'_{\mathcal{E}}\right]^2}_{<0} + \underbrace{\Pi'_k}_{>0} k''_{\mathcal{E},\mathcal{E}}] \underbrace{\Delta c}_{<0}. \end{aligned} \tag{38}$$

Overall, as the expression in the second-to-last line is negative, the impact of the second derivative of damages has to be sufficiently large (Condition (iii) in this proposition) to have $V''_{\epsilon_i,\epsilon_i} > 0$.

C.3.6 Calculation of first and second best

We focus on identical countries with a linear damage function with the parameter δ and quadratic abatement functions.

First best solution of a global planner

The global social planner minimizes the global costs by choosing the number of active R&D firms k and the amount of permits, taking the riskiness of innovation into account.

$$\min_{\epsilon,k} [1-\Pi(k)]n\frac{b_O}{2}[\bar{e}_i - \epsilon_i]^2 + \Pi(k)n\frac{b_A}{2}[\bar{e}-\epsilon]^2 + n^2\delta\epsilon + kx.$$

The first order conditions are

$$-[1-\Pi(k)]b_O[\bar{e}-\epsilon] - \Pi(k)b_A[\bar{e}-\epsilon] + n\delta = 0$$

$$\Leftrightarrow [\bar{e}-\epsilon]\left[b_O + [b_A - b_O]\overbrace{\frac{k\pi}{1+\pi(k-1)}}^{\Pi(k)}\right] = n\delta \tag{39}$$

$$\underbrace{\frac{\pi[1-\pi]}{(1+[k-1]\pi)^2}}_{\Pi'_k}\frac{b_O - b_A}{2}n[\bar{e}-\epsilon]^2 = x. \tag{40}$$

Isolate $\bar{e} - \epsilon$ in (39)and plug it into (39) to obtain

$$k^{opt} = \left[\frac{\pi[1-\pi]}{2x} n[b_O - b_A]\right]^{0.5} n^2\delta - \frac{b_O[1-\pi]}{bA\pi}$$
$$\mathcal{E}^{opt} = n[\bar{e} - [\frac{n^2\delta}{b_O + [b_A - b_O]k^{opt}\frac{\pi}{1+\pi[k^{opt}-1]}}]].$$

Second best solution with cooperation on R&D
We assume that countries coordinate on R&D (Stage 2) after each country has chosen how many permits to issue (Stage 1). As all countries cooperate on R&D, production firms can use advanced abatement technologies—if detected—without paying any additional fee. Production firms decide on abatement and permit trading as before. Thus, solving the model backwards, we obtain the following:

Results of the fourth stage are as before,

$$g_e' = p.$$

Stage 3—the fee setting and technology adoption—becomes irrelevant. In stage 2, the cooperation on R&D effort takes place and countries consider—taking the global emissions limit as given—

$$\min_k \quad \Pi(k)n[g_A(a_A) + p_A[\bar{e} - a_A - \epsilon]]$$
$$+[1-\Pi(k)]n[g_O(a_O) + p_O[\bar{e} - a_O - \epsilon]]$$
$$+n^2\delta\epsilon + xk.$$

The first order condition is

$$\Pi_k' \left[n[g_A(a_A) + p_A[\bar{e} - a_A - \epsilon]] - n[g_O(a_O) + p_O[\bar{e} - a_O - \epsilon]]\right] + x = 0.$$

With quadratic abatement functions, we obtain

$$\frac{\pi[1-\pi]}{[1+[k-1]\pi]^2} n \frac{b_A - b_O}{2} [\bar{e} - \epsilon]^2 = -x \tag{41}$$
$$\frac{\pi[1-\pi][b_O - b_A]n}{2x} [\bar{e} - \epsilon]^2 = [1 + [k-1]\pi]^2 \tag{42}$$
$$\frac{1}{\pi}\left[\frac{\pi[1-\pi][b_O - b_A]n}{2x}\right]^{0.5} [\bar{e} - \epsilon] - \frac{1}{\pi} + 1 = k.$$

In the first stage, the individual countries determine how many permits to issue, taking into account that they will cooperate on k later.

$$\begin{aligned}\min_{\epsilon} \quad & \Pi(k(\mathcal{E}))\,[g_A(a_A) + p_A[\bar{e} - a_A - \epsilon]] \\ & + [1 - \Pi(k(\mathcal{E}))]\,[g_O(a_O) + p_O[\bar{e} - a_O - \epsilon]] \\ & + \delta n \mathcal{E} + \frac{xk(\mathcal{E})}{n}.\end{aligned}$$

This yields the first order condition

$$\begin{aligned}& \Pi'_k k'_{\mathcal{E}}\,[g_A(a_A) - g_O(a_O) + p_A[\bar{e} - a_A - \epsilon] - p_O[\bar{e} - a_O - \epsilon]] \\ & + \Pi(k(\mathcal{E}))\,\left[p'_A[\bar{e} - a_A - \epsilon] - p_A\right] \\ & + [1 - \Pi(k(\mathcal{E}))]\,\left[p'_O[\bar{e} - a_O - \epsilon] - p_O\right] \\ & + \delta'_i(\mathcal{E}) + \frac{x}{n}k'_{\mathcal{E}} = 0.\end{aligned}$$

Using the functional forms as well as $\Pi'_k[b_A - b_O]/2[\bar{e} - \epsilon]^2 = -x/n$, based on (41), we obtain

$$\Pi(k(\mathcal{E}))\,[-b_A[\bar{e} - \epsilon]] + [1 - \Pi(k(\mathcal{E}))]\,[-b_O[\bar{e} - \epsilon]] + \delta = 0. \tag{43}$$

Isolating $\bar{e} - \epsilon$ in (42), plugging it into (43) and applying some transformations, we obtain

$$\begin{aligned}k^{2nd} &= \frac{b_O}{b_A}\frac{\pi - 1}{\pi} + \delta \frac{n}{b_A}\left[\frac{[1 - \pi][b_O - b_A]}{2\pi x n}\right]^{0.5} \\ \mathcal{E}^{2nd} &= \bar{E} - \frac{k^{2nd} - \frac{\pi - 1}{\pi}}{\left[\frac{[1-\pi][b_O - b_A]}{2\pi x * n}\right]^{0.5}}.\end{aligned}$$

C.4 Example II: Linear Abatement Costs

C.4.1 The set-up

We assume linear abatement costs, $g_O(a_i) = b_O a_i$ and $g_A(a_i) = b_A a_i$ with $b_O > b_A$, and a non-linear damage function. Marginal abatement costs are constant, $g'_O = b_O$ and $g'_A = b_A$. Linear abatement costs are a polar case and can be dealt with by explicit calculations.[32] With linear abatement costs, $f = 0$. The reason is as follows: Cost minimization implies that the marginal abatement cost equals the permit price. Only one technology will be used at a time. Suppose that some firms have switched to the advanced technology—so $p = b_A$—and that f is positive. Then a production firm is better off using the old technology, buying permits at prices $p = b_A$, and choosing $a_i = 0$

$$\text{(yielding costs } c_O = b_O 0 + b_A[\bar{e}_i - [1 - \alpha]\epsilon_i] = b_A[\bar{e}_i - [1 - \alpha]\epsilon_i]\text{)}$$

[32] The assumption in the general case involves strict convexity of cost functions to ensure interior solutions.

than by paying the fee and abating with the new technology

$$\text{(yielding costs } c_A + f = b_A a_i + b_A[\bar{e}_i - a_i - [1-\alpha]\epsilon_i] + f = b_A[\bar{e}_i - [1-\alpha]\epsilon_i] + f).$$

Hence, all production firms will only switch to the advanced technology if $f = 0$. R&D firms anticipate this and will not become active.

With a Tech Treaty, a patent-holder receives revenues, but only from the Tech Treaty. Accordingly,

$$k = \frac{b_A \alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi} \quad \text{if} \frac{b_A \alpha}{x}\mathcal{E} > 1 - \frac{1}{\pi}, \quad \text{and } k = 0 \quad \text{otherwise}$$

based on Equation (9). This proves Proposition 5.

Two further remarks are in order. First, the Tech Treaty leads to a unique equilibrium with respect to the adoption of the advanced technology. Second, for $\alpha > 0$, it generates some trade on the emissions permit market and a positive permit price that equals marginal abatement costs. Without the Tech Treaty and with linear abatement costs, no trade in emissions permits will take place. With a share of the permits given to the international agency, there are permits supplied to the market. In equilibrium, the permit price equals marginal abatement costs, so permits are bought by production firms.

C.4.2 Linear abatement costs and high research costs

Proposition 8 states how a change in the Tech Treaty Share impacts permit issuance for linear abatement costs and high research costs.

Proposition 8

Suppose abatement costs are linear.

The increase in the Tech Treaty Share will lower the permits issued by the local planners, i.e. $\frac{\partial \epsilon_i}{\partial \alpha} < 0$, *if*

(i) research costs are high,

(ii) or if α *is small.*

Proof of Proposition 8.

For linear abatement costs, Equation (25) reduces to[33]

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} =& \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{ov. inno. prob.}} \quad \underbrace{p(\mathcal{E},n)}_{\text{cost-change effect, } \Delta c''_{\epsilon_i,\alpha}} \\
&+ \underbrace{\frac{\Pi'_k}{x}\left[p(\mathcal{E},n)\mathcal{E}\right]}_{\Pi'_k k'_\alpha > 0} \underbrace{\left[p(\mathcal{E},0) - [1-\alpha]p(\mathcal{E},n)\right]}_{\text{marginal cost change, } \Delta c'_{\epsilon_i}} + \underbrace{\frac{\Pi'_k}{x}\left[\alpha p(\mathcal{E},n)\right]}_{\text{marginal innovation, } \Pi'_k k'_{\mathcal{E}}} \quad \underbrace{\left[\epsilon_i p(\mathcal{E},n)\right]}_{\Delta c'_\alpha} \\
&+ \underbrace{\frac{\Pi'_k}{x}\left[p(\mathcal{E},n) + Z\frac{p(\mathcal{E},n)\mathcal{E}}{x}\alpha p(\mathcal{E},n)\right]}_{\text{innovation effect, } (\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{kk} k'_\alpha k'_{\mathcal{E}})} \\
&\underbrace{\begin{array}{l}[g_A(a_A(p(\mathcal{E},n))) - g_O(a_O(p(\mathcal{E},0))) + p(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ -p(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},n)) - \epsilon_i]]\end{array}}_{\text{cost change, } \Delta c_i}.
\end{aligned} \tag{44}
$$

Re-arranging and plugging in functional forms[34] leads to

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} =& \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))b_A + \frac{\Pi'_k}{x} b_A \left[\mathcal{E}[b_O - [1-\alpha]b_A] + \alpha b_A \epsilon_i\right]}_{>0} \\
&+ \frac{\Pi'_k}{x}[b_A + \underbrace{Z\frac{b_A\mathcal{E}}{x}\alpha b_A}_{<0}][b_A[\bar{e}_i - [1-\alpha]\epsilon_i] - b_O[\bar{e}_i - \epsilon_i]].
\end{aligned} \tag{45}
$$

For large research costs x (Condition (i) in this proposition), $V^{*''}_{\epsilon_i,\alpha} = \Pi(k(\mathcal{E},\alpha,\epsilon_n))b_A > 0$.

For $\alpha \approx 0$ (Condition (ii) in this proposition), the expression reduces to

$$
V^{*''}_{\epsilon_i,\alpha} = \Pi b_A + \frac{\Pi'_k}{x} b_A [b_O - b_A][\mathcal{E} - \bar{e}_i + \epsilon_i].
$$

For $\bar{e} < \mathcal{E}_i + \epsilon_i$—which is fulfilled when n is not too small—and α close enough to 0, $V^{*''}_{\epsilon_i,\alpha} > 0$. □

[33]For linear abatement costs, $g'' = 0$ and $p'_{\mathcal{E}} = 0$ and $f = f'_{\mathcal{E}} = f'_\alpha = f''_{\mathcal{E},\alpha} = 0$.

[34]$p(\mathcal{E},0) = b_O$, $p(\mathcal{E},n) = b_A$, $g_O(a_i) = b_O a_i$ and $g_A(a_i) = b_A a_i$.

C.4.3 Proof of Proposition 6

Proof of Proposition 6.
We now additionally assume a quadratic damage function and $\Pi \approx \pi k$. Then the decision problem of the local planner becomes

$$
\begin{aligned}
V^*(\alpha, \mathcal{E}_{-i}, \bar{e}_i) &= \min_{\epsilon_i} V(\epsilon_i), \quad \text{with} \\
V(\epsilon_i) &= \underbrace{[g_O(a_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i]]}_{\text{cost}=c} \\
&+ \underbrace{\pi k(\mathcal{E},\alpha,\epsilon_n)}_{\text{Ov. Inno. Prob.}} \; [g_A(a_A(p(\mathcal{E},n))) + p(\mathcal{E},n)[\bar{e}_i - a_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\
&\underbrace{- [g_O(a_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_i - a_O(p(\mathcal{E},0)) - \epsilon_i]]]}_{\text{cost reduction}=\Delta c} + \underbrace{d_i(\mathcal{E})}_{\text{local damages}} .
\end{aligned}
$$

Plugging in functional forms[35] leads to

$$
V(\epsilon_i) = [b_O[\bar{e}_i - \epsilon_i]] + \pi \underbrace{\left[\frac{b_A\alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi}\right]}_{k} [b_A[\bar{e}_i - [1-\alpha]\epsilon_i] - b_O[\bar{e}_i - \epsilon_i]] + \frac{\delta_i}{2}\mathcal{E}^2
$$

and the first order condition is

$$
\begin{aligned}
V'_{\epsilon_i}(\epsilon_i) &= -b_O + \pi\frac{b_A\alpha}{x}[b_A[\bar{e}_i - [1-\alpha]\epsilon_i] - b_O[\bar{e}_i - \epsilon_i]] \\
&+ \pi\left[\frac{b_A\alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi}\right][-[1-\alpha]b_A + b_O] + \delta_i\mathcal{E} = 0.
\end{aligned}
$$

Assuming identical countries, $\mathcal{E} = n\epsilon$, we can solve for ϵ

$$
\epsilon = \frac{b_O - \pi\frac{b_A\alpha}{x}[b_A - b_O]\bar{e} + [1-\pi]\,[b_O - [1-\alpha]b_A]}{\pi\frac{b_A\alpha}{x}[b_O - [1-\alpha]b_A][n+1] + \delta n}.
$$

Then,

$$
\begin{aligned}
\frac{\partial\epsilon}{\partial\alpha} &= \frac{\left[\frac{\pi b_A\alpha}{x}[b_O - [1-\alpha]b_A][n+1] + \delta n\right]\left[-\frac{\pi b_A}{x}\bar{e}[b_A - b_O] + [1-\pi]b_A\right]}{\left[\pi\frac{b_A\alpha}{x}[b_O - [1-\alpha]b_A][n+1] + \delta n\right]^2} \\
&- \frac{\left[b_O - \pi\frac{b_A\alpha}{x}[b_A - b_O]\bar{e} + [1-\pi]\,[b_O - [1-\alpha]b_A]\right]\left[[1+n]\frac{\pi b_A}{x}[b_O - [1-\alpha]b_A + \alpha b_A]\right]}{\left[\pi\frac{b_A\alpha}{x}[b_O - [1-\alpha]b_A][n+1] + \delta n\right]^2}.
\end{aligned}
$$

[35] $p(\mathcal{E},0) = b_O$, $p(\mathcal{E},n) = b_A$, $g_O(a_i) = b_O a_i$ and $g_A(a_i) = b_A a_i$

The denominator is positive, so that the sign of $\partial\epsilon/\partial\alpha$ depends only on the nominator. Define $B := \frac{\pi b_A}{x}$ and $C := b_O - [1-\alpha]b_A$. Then the nominator can be re-arranged to

$$\begin{aligned}
&[b_O - b_A][\delta n B \bar{e} - b_O[1+n]B - [1-\pi]C[1+n]B] \\
&+b_A[\delta n[1-\pi] - 2b_O[1+n]B\alpha - \alpha[1-\pi]C[1+n]B] \\
&-\alpha^2 B[b_O - b_A]\bar{e}[1+n]Bb_A.
\end{aligned}$$

The expression is negative for large $b_0 - b_A$ (i.e. Condition (ii) in this proposition). Large $b_0 - b_A$ also implies large C. □