CER-ETH – Center of Economic Research at ETH Zurich

Technology Treaties and Climate Change

H. Gersbach, M.-C. Riekhof

Working Paper 17/268
March 2017

Economics Working Paper Series

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Technology Treaties and Climate Change*

Hans Gersbach
CER-ETH – Center of Economic Research at ETH Zurich and CEPR
Zürichbergstrasse 18
8092 Zurich, Switzerland
hgersbach@ethz.ch

Marie-Catherine Riekhof
CER-ETH – Center of Economic Research at ETH Zurich
Zürichbergstrasse 18
8092 Zurich, Switzerland
mcriekhof@ethz.ch

This Version: March 2017

Abstract

We introduce an international technology treaty that couples the funding of research for a more advanced abatement technology with an international emissions permit market. Under the treaty, each country decides on the amount of permits for its domestic industries, but a fraction of these permits is auctioned on the permit market, and the revenues are used to scale up license revenues for the innovators of abatement technologies. We discuss the conditions under which such a technology treaty can slow down climate change through technological innovations and whether it creates complementary incentives for countries to tighten permit issuance. Finally, we discuss how participation in Tech Treaties can be fostered and how such treaties might be implemented.

Keywords: Climate change mitigation; Technology promotion; International permit markets; International treaty; Externalities

JEL Classification: H23; Q54; O31

*We would like to thank Scott Barrett, Clive Bell, Michael Finus, Tettje Halbertsma, Vincent Lohmann, Aurore Staes, and participants at the EAERE and SURED conferences 2016 for helpful comments.

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] But 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 (2013)), 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, the operative factor behind the under-provision of R&D investments for such technologies (e.g. Barrett (2006) and Hoel and 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 1 in the Appendix), 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 does not require an agreement on emissions reductions between all countries, which—as

[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), Carraro and Siniscalco (1993), Hoel (1992); also see discussion in Finus and Maus (2008).

we have seen—is extremely difficult if not impossible to reach if abatement targets are to be both binding and drastic. 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 focus on technologies in the form of new production methods that lower abatement costs. We call the set of rules 'Tech Treaty'. The idea behind it is to use revenues from permit trade to increase incentives to develop marketable abatement technologies that lower abatement costs. Lower abatement costs should induce countries to tighten the issuance of emissions permits.

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. Accordingly, a Tech Treaty includes a mechanism to raise rewards of successful innovators by auctioning permits to firms that emit greenhouse gases.[3] In this way, it 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 if the abatement technology is offered at a single price to all firms willing to buy it. This requirement to sell to all firms willing to buy makes technology diffusion part of the Tech Treaty.[4]

Three remarks on the actual implementation of a Tech Treaty are in order. First, auctioning a share of the permits is politically and administratively feasible, as is borne out by the example of the EU-ETS. Here, around 40% of the permits are auctioned (European Commission, 2016a). Moreover, under the NER300 programm, 5% of the permits of the EU-ETS are used to co-finance large demonstration projects (European Commission, 2013). Second, the Tech Treaty is angled at

[3]Nicolaï (2015) discusses the importance of firms supporting the environmental policy. In our approach, the payments the firms make are used to reduce their costs in the future, which make it likely that a Tech Treaty will gain their support.

[4]Bretschger et al. (2015) show that carbon-pricing policies should be complemented by R&D policy and discuss the importance of making technology diffusion part of R&D policy.

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 2 in the Appendix. The focus on production techniques restricts the applicability of the Tech Treaty to industrialized and emerging countries, including countries like China and India.[5] Still, this range of countries is responsible for the large part of emissions (World Bank (2016)). Also, carbon leakage[6]—the main concern if not all countries participate—is less menacing since the is no incentive for major dislocations of production sites to the remaining countries. Third, innovations fostered through the Tech Treaty make future emissions reduction less costly and thus easier to achieve. However, this prospect may increase current emissions. In the current trading period, the expectation of future cheaper abatement techniques and the requirement to provide a share of permits to the international agency under a Tech Treaty may induce the countries to increase permit issuance relative to standard international permit markets. We may thus encounter another situation in which well-intentioned environmental policies have negative side effects, in line with the potential undesirable supply-side effects popularly referred to as the 'green paradox' (see e.g. Sinn (2008)). We will address this problem in the course of our analysis.

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. 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 and on trading of permits.

[5]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)).

[6]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.

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. 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 three 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 share 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 revenues, which in turn fosters innovation activity. When international permit markets are used Tech Treaties thus yield lower expected emissions in all subsequent periods as abatement options become cheaper, which will induce countries to issue fewer permits.

Second, we consider an environment where a Tech Treaty can be complemented by some tightening of permit issuance in Stage 1. Typically, innovation incentives can be heightened further, although in special circumstances the opposite may also occur. For special cases with quadratic abatement costs, we show that tightening permit issuance will emcourage innovation effort and technology diffusion as long as the global emissions limit is close to baseline.

Third, 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 price elasticity of permits is not too large. For quadratic abatement costs and many similar countries, this is fulfilled as soon as permit issuance falls slightly below business-as-usual emissions. For linear abatement costs, tightening of permits issuance always occurs in difficult research environments.

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 Section 5 we discuss whether tightening global emissions will help the Tech Treaty to foster innovation. In Section 6 we endogenize the global emissions limit and consider the impact of a change in the Tech Treaty on the global emissions limit. In Section 7 we discuss participation in the Tech Treaty. The model and the results are discussed in Section 8. Section 9 concludes. In the Appendix we provide an overview of technologies with the potential for reducing carbon emissions. The Appendix also contains the lengthier proofs and further examples.

2 Related Literature

This paper relates to several strands of the literature. It suggests a partial solution to the climate change problem and focuses on rules defined in a treaty that relate to technological development. In its focus on a partial solution to the climate-change problem, it is related to the suggestion made by Nordhaus (2015) to focus on climate clubs instead of the grand coalition. In the approach proposed by Nordhaus (2015), the members of the climate club impose tariffs on non-participants, which theoretically might prompt all countries to participate. However, for larger emission reductions, tariffs lose their power to induce participation. 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).

Secondly, this paper relates to the literature on the role of technology adoption in fostering cooperation and building a coalition to solve the climate change problem. 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 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 the situation where many firms seek to obtain a patent for a new technology (see e.g. Acemoglu (2009) for an overview).[7] 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. Our paper is complementary as we focus on how scaling license income against auctioned permit revenues can boost innovation.

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 (2016); 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

[7] Denicolò and Franzoni (2010) find that in a broad set of circumstances a winner-takes-all system is preferable, especially in highly innovative industries. Different ways of incentivizing innovation are explored in Fu et al. (2012).

cooperation will 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 $i, j \in \{1, ..., n\}$.[8] In each country there is a representative production firm, a representative R&D firm and a local planner. We use the index i (j) for both types of firm, and the local planner in country i (j) as long as this causes no confusion.

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 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 e_i with $e_i \geq 0$, it incurs costs $g_O(e_i)$. The function $g_O(\cdot)$ is continuous on $[0, \infty)$ and has the properties $g_O(0) = 0$, $g'_O(e_i) > 0$ and $g''_O(e_i) > 0$ for all $e_i > 0$.[10] So the cost function is strictly increasing and strictly convex. The cost function is the same for all countries. The subscript '$_O$' stands for old technology. More advanced 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 $g_A(e_i)$. The cost function is a continuous function on $[0, \infty)$ and satisfies $g_A(0) = 0$, $g'_A(e_i) > 0$, $g''_A(e_i) > 0$ and

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

[9]A table that lists all symbols used can be found in Appendix A.7.

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

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

$g'_A(e_i) < g'_O(e_i)$ for all $e_i > 0$. The latter property implies $g_A(e_i) < g_O(e_i)$ for all $e_i > 0$.

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 $E := \sum_{i=1}^{n}[\bar{e}_i - e_i]$ 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 continuous on $[0, \infty)$ and $d'_i(E) > 0$ for all $E \geq 0$.

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 $\epsilon_i \geq 0$, and each production firm has to hold permits for emissions. The Tech Treaty is an international agreement and requires the countries to give a pre-determined share α of the emission permits issued to an international agency, with $0 \leq \alpha \leq 1$. The agency sells the permits on the international permit market and uses the revenue to augment the patent-holder's license income to incentivize research. The local planner gives the remaining permits $[1 - \alpha]\epsilon_i$ to the local production firm free of charge (so-called 'grandfathering'). A Tech Treaty is thus characterized by the parameter α and is denoted by $TT(\alpha)$. We will refer to α as the 'Tech Treaty's share'.

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 are common knowledge.

In the following we describe the sequential structure and all decision problems in more detail. We start with Stage '0', which represents the pre-game settings.

Stage '0': The Emissions Market and the Tech Treaty

In the initial stage, an international emissions permit market is established and a Tech Treaty $TT(\alpha)$ is drawn up. For the moment, we take these two institutions 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.

The international emissions permit market is standard. The local planner in country i, $i \in \{1, ...n\}$, issues an amount of permits denoted by ϵ_i. A special requirement is that ϵ_i cannot exceed baseline emissions $\bar{e}_i$, i.e. $\epsilon_i \leq \bar{e}_i$.[12] The Tech Treaty $TT(\alpha)$ is governed by the following set of rules:

Definition 1 (Tech Treaty $TT(\alpha)$)
Under a Tech Treaty $TT(\alpha)$, $\alpha \in [0, 1]$, *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 *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 in all countries.

(iv) If no advanced technology is detected or a patent-holder does not qualify for revenues from the international agency, the permits given to the international agency are returned to the countries, which grandfather them to the local production firms.

[12] This is not a strong assumption, as industrialized countries usually aim at lower emissions compared to a baseline year (International Center for Climate Governance, 2016).

The first three rules are the core of the Tech Treaty, while the last one 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 requirement that all production firms need to adopt the new technology for patent-holders to be eligible for additional revenues $\alpha p \mathcal{E}$ simplifies the analysis and ensures complete diffusion of the technology. Technology diffusion is an objective of the Tech Treaty. Second, formally the case $\alpha = 0$ is not equivalent to the absence of a Tech Treaty, since the rules still apply. In fact, however, the outcome for R&D incentives and permit issuance is equivalent to the scenario without a Tech Treaty. Third, for the remaining analysis we assume that the patent-holder sets the fee in such a way that all production firms will adopt it, i.e. license revenues are scaled through the Tech Treaty. We will discuss the significance of this assumption in more detail in Section 4.

In the next stage, we describe permit issuance in more detail.

Stage 1: Permit Issuance

Given an international permit market and a Tech Treaty $TT(\alpha)$, the local planners decide simultaneously how many permits they want to issue. For their decision they consider both local damages from global emissions and the costs for the local firms. Both may differ from country to country.

If no advanced technology is detected, local production firms either have to abate $\bar{e}_i - \epsilon_i$ or buy additional permits on the market.[13] 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

[13] Due to the fourth rule of the Tech Treaty, the share α initially allocated to the international agency is returned to the countries.

in addition to abatement costs and costs (or revenues) from trading on the permit market.

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. 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 decide simultaneously on emissions reduction e_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.

We are looking for subgame perfect equilibria of the multi-stage game with observed actions covering Stages 1 to 4. In the next sections we specify the payoff functions of all agents involved and determine the equilibria. Here, we note that R&D firms aim to maximize expected profits, the production firms to minimize costs, and the local planners to minimize citizens' costs.

4 Equilibria for a Given Tech Treaty and Aggregate Emissions

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 e_i, $i \in \{1, ...n\}$ and on trade on the emissions permit market. 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 $g_A(e_q)$ and the index $m = l + 1, ..., n$ to refer to the production firms that still use the old technology and face abatement costs $g_O(e_m)$.

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.

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

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

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 are $c_A(\alpha, \epsilon_q, e_q) + f$. The license fee f is constant and independent of e_i. As $g_O(\cdot)$ and $g_A(\cdot)$ are assumed to be strictly convex and strictly increasing for $e_i > 0$, total costs are also convex. So, total costs are minimized where

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

which implies

$$p = g_A'(e_q) = g_O'(e_m), \quad q = 1, ..., l, \quad m = l+1, ..., n \tag{2}$$

for $e_q, e_m > 0$. 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 $e_A(p)$ and $e_O(p)$ denote the two abatement choices. As marginal abatement-cost functions are strictly increasing, the inverse functions exist, and the abatement choices are given by

$$g_A'^{-1}(p) = e_A(p), \quad g_O'^{-1}(p) = e_O(p). \tag{3}$$

We next summarize a standard property of permit-market equilibria.

Lemma 1
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, $e_A(p) > e_O(p)$.

Lemma 1 follows from the assumption

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

and the definition of the inverse,

$$g'_A(e_A(p)) = g'_A(g'^{-1}_A(p)) = p, \quad \text{and} \quad g'_O(e_O(p)) = g'_O(g'^{-1}_O(p)) = p.$$

Given property (4), we must therefore have $e_O(p) < e_A(p)$.

We next characterize the equilibrium on the permit market. The demand E is given by $E = \sum_{i=1}^n \bar{e}_i - e_i$. Equalizing it to supply $\mathcal{E}$ yields

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

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 $e_A(p)$ and $e_O(p)$ 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 2

(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 2. See A.2.1 in the Appendix. □

The properties established in Lemma 2 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. 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. We derive conditions under which this ensures that all production firms will license the advanced abatement technology—as required by the Tech Treaty—and that license revenues are maximized.

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

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

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

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

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 3
Assume that all production firms 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 3.
Production firm i's maximum willingness to pay when $n-1$ production firms have already adopted the advanced technology is

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

Since $p(\mathcal{E}, n-1) > p(\mathcal{E}, n)$ by Lemma 2, 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 3 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 3 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 4.

Lemma 4
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*

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

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's share, and the permits issued by country n, $f(\mathcal{E},\alpha,\epsilon_n)$

Setting the fee according to Lemma 4 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 4, 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. We assume $\frac{\partial f_i(l)}{\partial l} < 0$ for the remainder of the paper. The next Lemma states the conditions for which this is indeed the case.

Lemma 5

All production firms license the advanced technology at the fee

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

This is the case when either

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

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

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

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

Proof of Lemma 5. See A.2.2 in the Appendix. □

The condition $\bar{e}_i - [1-\alpha]\epsilon_i - e_A(p(\mathcal{E}, l+1)) \geq 0$ 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.

In the next corollary we state that Lemma 5 holds for standard abatement cost functions.

Corollary 1

For quadratic abatement costs,

$$\frac{\partial f_i(l)}{\partial l} < 0, l \in \{0, ..., n-1\} \qquad \textit{for plausible values of } b_0/b_A \textit{ and } n.$$

Corollary 1 is shown in Appendix A.5.4, where the entire model is solved explicitly for quadratic abatement cost functions.

Note that the production firm n is indifferent between buying and doing without the advanced technology. We assume that indifferent production firms will opt for the advanced technology. This could be rationalized by postulating an arbitrarily minor inclination on the part of the production firm to alleviate climate change in the case of indifference. The tie-breaking rule is not critical for our results. It merely avoids working with license fees that are higher 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 $f_n(n-1)n + \alpha p\mathcal{E} \geq \max f_l(l-1), l \in \{1, ..., n-1\}$. We will later discuss conditions under which this property holds.

Lemma 6 states how license fee f reacts to a change in α.

Lemma 6
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 $\mathcal{E} \geq 0$, $\alpha \in [0,1], \epsilon_n \geq 0$.

Proof of Lemma 6.
Equation (8) and Lemma 2 imply that $f'_\alpha = -\epsilon_n(p(\mathcal{E}, n) - p(\mathcal{E}, n-1)) > 0$, as e_o, e_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's share is intuitive. If it increases, all production firms, *ceteris paribus*, will receive fewer permits for free and will thus be willing to pay a higher license fee.

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. We assume perfect coordination among them.

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

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

with $f(\mathcal{E}, \alpha, \epsilon_n)$ set according to Equation (8).

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

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

where the nominator equals the overall probability of detecting the advanced technology when k R&D firms are active, $\Pi^T := 1 - [1 - \pi]^k$.[14] The superscript T indicates that the expressions refer to true probabilities. For analytic convenience, we approximate the probability $\tilde{\pi}(\pi, k)$ to

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

and use

$$\Pi(\pi, k^A) = k\tilde{\pi}^A(\pi, k) \quad \text{based on} \quad \Pi = k\tilde{\pi}.$$

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, the fit of the approximation, and a comparison of the main results under both probabilities are discussed in Appendix A.4. Most importantly, the approximation works well—especially for small π—and produces the same qualitative outcomes for major results.

[14] Assuming the other extreme—perfectly correlated innovation successes—yields $\tilde{\pi}(\pi, k) = \pi/k$.

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

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

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 $\Pi^A(k(\mathcal{E}, \alpha, \epsilon_n))$, respectively. Corner solutions with $k = 0$ arise when (9) produces a negative value. Throughout the paper we focus on interior solutions.

A remark on the interpretation of k is in order. Equation (9) only holds with equality if k is a continuous number, while the number of R&D firms can be expected to be a discrete number. One can also permit only a part of an R&D firm to be active if an R&D firm stands for an entire research cluster formed by investing x. Once the cluster is initiated, it may become clear which part has a chance of being successful. The other part will be closed down, and only part of the cluster will remain active.

A further remark concerns the case where $k(\mathcal{E}, \alpha, \epsilon_n)$ is larger than n. In such cases, we can allow countries to 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 paper we focus on scenarios with low success probabilities π or high research costs x, which leads to small numbers of R&D firms.

Lemma 7 states how the number of active R&D firms k affects the overall probability Π that an advanced technology will be detected.

Lemma 7
The overall probability that the advanced technology will be detected is increasing with the number of active R&D firms, i.e. $\Pi_k^{\prime A} > 0$.

Proof of Lemma 7.

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

□

Proposition 1 indicates how the Tech Treaty affects innovation by stating how the Tech Treaty's share α affects the number of active R&D firms.

Proposition 1

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

Proof of Proposition 1.

Equation (9) implies

$$k'_\alpha = \frac{nf'_\alpha(\mathcal{E}, \alpha) + p(\mathcal{E}, n)\mathcal{E}}{x} > 0,$$

as $f'_\alpha > 0$ by Lemma 6. □

For a given amount of aggregate permits $\mathcal{E}$, the impact of a change in the Tech Treaty's share α on the number of active R&D firms is intuitive. A larger share given to the international agency increases the expected income of an active R&D firm 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 revenues of the patent-holder and thus the number of active R&D firms.

The influence of the Tech Treaty's share on the number of active R&D firms can easily be seen for quadratic abatement costs, as demonstrated in Corollary 2.

Corollary 2

For quadratic abatement costs, the number of active R&D firms is

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

$$\textit{with} \quad f = \frac{[\bar{E}-\mathcal{E}]^2}{2}\left[-b_O\left[\frac{b_A}{b_O[n-1]+b_A}\right]^2 + \frac{b_A}{n^2}\right] + [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]b_A\frac{b_O - b_A}{n[b_O[n-1]+b_A]}.$$

Corollary 2 is shown in Appendix A.5.2.

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.

5 Tightening of Global Emissions

In this section we investigate whether a marginal tightening of the global emissions limit would help to foster innovation further under a Tech Treaty. The answer is not obvious, as crowding-out effects may occur.

We first indicate how 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 8 states conditions for which the 'normal' reaction—$f'_{\mathcal{E}} < 0$—holds.[15]

[15]Lemma 5 implies $f'_{\mathcal{E}} < 0$ for the conditions stated in Lemma 8.

Lemma 8
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 $\bar{e}_i - [1-\alpha]\epsilon_i - e_O(p(\mathcal{E}, n-1)) \geq 0$ *and*

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

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

Proof of Lemma 8.
See A.2.3. □

We note that the conditions are a special case of the conditions of Lemma 5, with $l = n-1$. In the next Corollary we state that for standard abatement cost functions $f'_{\mathcal{E}} < 0$ holds as well.

Corollary 3
If abatement costs functions are quadratic, $f'_{\mathcal{E}} < 0$*.*

Corollary 3 follows directly from Lemma 8, but we find it worthwhile to state it more explicitly. As already mentioned, in Appendix A.5 the entire model is solved explicitly for quadratic abatement cost functions. This allows a direct proof of $f'_{\mathcal{E}} < 0$.

Proposition 2 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

$$k'_{\mathcal{E}} = \frac{nf'_{\mathcal{E}}(\mathcal{E}, \alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E}, n)\mathcal{E} + p(\mathcal{E}, n)]}{x}. \tag{10}$$

This yields Proposition 2.

Proposition 2
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 2.
Points (i) and (ii) from Proposition 2 follow directly from the general condition. Point (iii) follows from the complete solution of the model for quadratic abatement costs in Appendix A.5. □

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 2. 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 2 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.

We conclude this section with an extreme example in which only a Tech Treaty can spur innovation. Crowding-out occurs, and tightening the Tech Treaty can neutralize the effects of that phenomenon.

Proposition 3
Suppose that abatement costs are linear ($g_O(e_i) = b_O e_i$, $g_A(e_i) = b_A e_i$). 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) $k(\mathcal{E}, \alpha, \pi) = \frac{b_A \alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi}$.

Proof of Proposition 3.
The proof is given in Appendix A.6. □

The intuition for Proposition 3 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. Lowering $\mathcal{E}$ will reduce k, but it can be compensated for by an increase of α.

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.

6 The Tech Treaty and Decentralized Permit Issuance

In this section we first describe how given a Tech Treaty the local emission 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.

6.1 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 a fixed value of $\mathcal{E}$ (and ϵ_n). 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's 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 $V(\epsilon_i)$.

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

$$\begin{aligned} V(\epsilon_i) = & \\ & \Pi[[\overbrace{g_A(e_A(p(\mathcal{E},n)))}^{\text{abatement costs}} + \overbrace{p(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i]}^{\text{expenditures permit market}}] + \overbrace{f(\mathcal{E},\alpha,\epsilon_n)}^{\text{fee}} + \overbrace{d_i(\mathcal{E})}^{\text{damages}}] \\ & + (1-\Pi)[[\underbrace{g_O(e_O(p(\mathcal{E},0)))}_{\text{abatement costs}} + \underbrace{p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i]}_{\text{expenditures permit market}}] + \underbrace{d_i(\mathcal{E})}_{\text{damages}}. \qquad (11) \end{aligned}$$

For convenience, we re-arrange expression (11) 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

$$c(\alpha,\epsilon_i) := g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] \qquad (12)$$

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

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

Four remarks are in order. First, to save on notation and because results hold both for Π^A and Π^T (see Table 3), we write Π. Second, 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

$$e_A = e_O = \frac{\bar{E} - \mathcal{E}}{n}.$$

Third, 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.[16] Fourth, using (8), the cost reduction for the production firm in country n can be written as

$$\begin{aligned}\Delta c_n =& g_O(e_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n] \\ & - g_O(e_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n],\end{aligned} \tag{14}$$

as the licensing fee is set equal to the firm's willingness to pay for the advanced technology $f = f_n(n-1)$.[17]

As $E = \mathcal{E}$, we directly write $d_i(\mathcal{E})$.

[16]

$$\begin{aligned}\Delta c(\alpha,\epsilon_i) :=& \underbrace{g_A + p(\mathcal{E},n)][\bar{e}_i - e_A - [1-\alpha]\epsilon_i] + f - g_O - p(\mathcal{E},0)[\bar{e}_i - e_O - \epsilon_i] - p(\mathcal{E},0)\alpha\epsilon_i}_{\leq 0 \quad \text{follows from Lemma 4}} \\ & + p(\mathcal{E},0)\alpha\epsilon_i.\end{aligned} \tag{13}$$

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.

[17] All results for country n are given in Appendix A.3.

Then the local planner's problem in countries $i \in \{1, ..., n-1\}$ can be written as

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

$$\begin{aligned} V(\epsilon_i) = & \underbrace{[g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i]]}_{\text{costs } c} + \underbrace{d_i(\mathcal{E})}_{\text{local damages}} \\ & + \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{overall innovation probability}} \\ & \underbrace{\begin{aligned}&[g_A(e_A(p(\mathcal{E},n))) + p(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &+ f(\mathcal{E},\alpha,\epsilon_n) - [g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i]]]\end{aligned}}_{\text{cost change } \Delta c}. \end{aligned} \tag{15}$$

Without R&D activity, i.e. for $k = 0$ and $\Pi = 0$, the expression reduces to *cost* plus *local damages.*

We now turn to the solution of (15). As $\epsilon_i \in [0, \bar{e}_i]$, 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. We present the first-order optimality condition in the following and discuss the second-order condition in Appendix A.2.

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 out and the first order condition reads

$$\begin{aligned} V'_{\epsilon_i} = & \underbrace{p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] - p(\mathcal{E},0)}_{\text{marginal costs } c'_{\epsilon_i}} + \underbrace{d'_i(\mathcal{E})}_{\text{marginal damage}} \\ & + \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{Ov. Inno. Prob.}} \\ & \underbrace{\begin{aligned}&[p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &- p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] - [1-\alpha]p(\mathcal{E},n) + p(\mathcal{E},0) + f'_{\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)]\end{aligned}}_{\text{marginal cost change } \Delta c'_{\epsilon_i}} \\ & + \underbrace{\Pi'_k(k(\mathcal{E},\alpha,\epsilon_n))k'_{\mathcal{E}}(\mathcal{E},\alpha)}_{\text{marginal innovation}} \\ & \underbrace{\begin{aligned}&[g_A(e_A(p(\mathcal{E},n))) + p(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &- g_O(e_O(p(\mathcal{E},0))) - p(\mathcal{E},0)][\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] + f(\mathcal{E},\alpha,\epsilon_n)]\end{aligned}}_{\text{cost change } \Delta c} = 0. \end{aligned} \tag{16}$$

Equation (16) 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 2 and Equation (12). 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. Condition (16) 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. The condition is given in

Equation (26) in Appendix A.3. Then Condition (16) for $i \in \{1, ..., n-1\}$ and Condition (26) for $i = n$ give n equations for n unknowns ϵ_i, $i \in \{1, ..., n\}$.[18]

Proposition 4 states conditions under which such an equilibrium exists and is unique when countries $i \in \{1, ..., n-1\}$ are symmetric. It shows that an equilibrium is more likely to exist when the research environment is difficult.

Proposition 4
An equilibrium described by the first-order Condition (16) *for symmetric countries* $i \in \{1, ..., n-1\}$ *and Condition* (26) *for* $i = n$ *exists and is unique when*

(i) damages accelerate sufficiently fast and research costs x *are sufficiently large*

(ii) or innovation probability is sufficiently small, $p''_{\mathcal{E}\mathcal{E}} = 0$ *and* $-\partial e_O/\partial p p'_{\mathcal{E}} < 2$.

Proof of Proposition 4.
See A.2.4 in the Appendix. □

We note three things. First, quick acceleration of damages is in line with catastrophic damages after crossing a threshold. Second, there are circumstances in which an equilibrium does not involve any active R&D firms. Third, the logic of the proof can be extented to certain types of asymmetry, notably with respect to baseline emissions and an additive term to damages.

6.2 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.

[18] In such an equilibrium, 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.

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 first provide a proposition that shows that the permit price elasticity is one important condition for the Tech Treaty's impact on permit issuance.

Proposition 5

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's 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 5.
See A.2.5 in the Appendix. □

Here is an example to illustrate condition $\xi(l, \epsilon_i) > -1$ in Proposition 5. For quadratic abatement costs,

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

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 $\xi(l, \epsilon_i) > -1$ 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.

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 5 stated results for high research costs, Proposition 6 discusses the case of small π.

Proposition 6

Suppose abatement costs are quadratic and the number of countries is large. Then an increase in the Tech Treaty's 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 technology and the advanced technology is large,*

(iii) *damages accelerate sufficiently fast,*

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

(v) *and* ϵ_n *small.*

Proof of Proposition 6.
See A.5.5 in the Appendix. □

In a numerical example Figure 1 illustrates how global emissions and the number of R&D firms depend on the Tech Treaty's 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's share needs to be sufficiently high to achieve $k > 0$.

To obtain further insights, we again consider the case of linear abatement costs initially discussed in Section 5. Proposition 7 states results for linear abatement costs.

Proposition 7

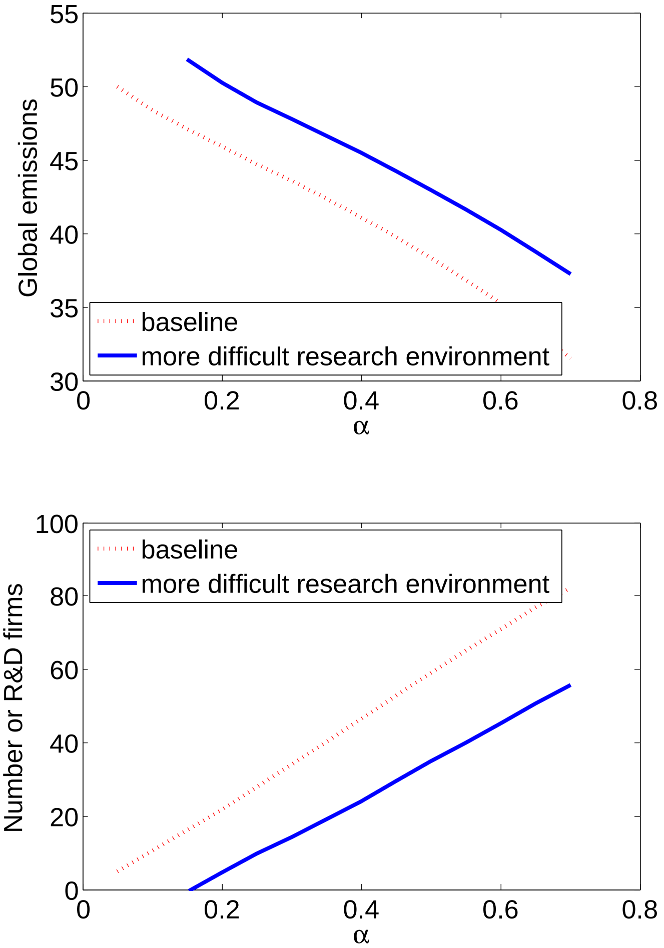
Suppose abatement costs are linear.

The increase in the Tech Treaty's 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 7.
See A.6.2 in the Appendix. □



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 7 considered the case of high research costs. In the following, we now consider low success probabilities of R&D success. Assuming countries are identical, low innovation probability[19] $\Pi \approx \pi k$ and a quadratic damage function allow a direct solution for ϵ_i. Proposition 8 summarizes the result we obtain.

Proposition 8
Suppose abatement costs are linear, damages are quadratic, innovation probabilities are low and lead to $\Pi \approx \pi k$, and countries are identical. Then,

(i)

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

and

(ii) an increase in the Tech Treaty's 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 8.
See A.6.3 in the Appendix. □

Proposition 8 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's share may not be sufficient to stimulate R&D, as illustrated by the numerical simulations.

7 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

[19] The results are based on a Taylor Approximation of Π^T around $\pi \approx 0$.

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. If not all countries participate, one might from a global perspective be concerned about carbon leakage in situations when local planners tighten emissions and choose ϵ_i substantially smaller than $\bar{e}_i$. The danger of carbon leakage can be alleviated by granting free permits to industries in which carbon leakage is more likely to occur (see e.g. Martin et al. (2014)).

Gains from participating in the Tech Treaty come from positive externalities from innovation and—under certain conditions—also from an immediate global emissions reduction. Although there are clear gains from the Tech Treaty, there are also incentives to free-ride and to grandfather all permits to the local production firm instead of giving a share to the international agency. Behaving in this way means that a country does not finance innovation activities, but still benefits in several ways from higher innovation efforts by other countries: lower global emissions in the future, lower current permit prices if it is a net buyer, and possibly lower global emissions in the present. Moreover, once the advanced technology is detected, the country could try to license it at market fee f.

To reduce the incentives to free-ride, 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 the Tech Treaty. Consider the following two possibilities: First, countries that do not participate in the Tech Treaty are not allowed to license the advanced technology at all. One can enforce this by adding the following rule to the Tech Treaty: If the patent-holder sells the advanced technology to production firms outside the Tech Treaty, it will not obtain financial support from the Tech Treaty. This approach follows Barrett (2006) in the sense of setting that a threshold that punishes free-riding, which may ensure participation. A second possibility is to license the advanced abatement technology to non-Tech-Treaty countries at a higher fee 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 created from the start.

It will suffice for the industrial countries and large carbon emitters such as India, China and Brazil to participate in order to spur innovation activities as envisioned by the Tech Treaty while free-riding incentives exist. The reason is that these countries account for the vast share of greenhouse gas emissions and R&D efforts. Hence, if they form a 'Tech club', most of the gains from a Tech Treaty will be realized.

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.[20] The obvious solution is to form a Tech club—as discussed—and to allow developing countries to adopt the technologies nevertheless. In addition, one could implement technology transfers, possibly conditional on the developing countries' own efforts to reduce emissions. Some developing countries make their abatement efforts conditional on technology transfers (see International Center for Climate Governance (2016)).

8 Discussion

Based on a theoretical model, we have derived conditions under which the introduction of a Tech Treaty will spur innovation activities and lead to expected lower future emissions. The Tech Treaty may in addition incentivize countries to reduce emissions immediately. In the following, we discuss some of the model's assumptions and how they influence our results.

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. They could also be auctioned. One could include this 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—uses the revenues to support technological developments. Auctioning a larger share of permits increases incentives for production firms to use the advanced technology, which further spurs innovation activities.

[20]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—will still occur. Moreover, when the Tech Treaty's share α is not close to zero, the revenues from a Tech Treaty for R&D firms are plausibly higher than the gains from price discrimination in licensing technologies. 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, 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 is 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 (2016b) and XPRIZE Foundation (2016a)).

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.

9 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 introduce 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. 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, together with a Tech Treaty a reduction of the global emissions limit will also increase innovation as long as countries have not already tightened permit issuance significantly compared to business-as-usual. Finally, even in the currently observable situation with little research and without Tech Treaties, introducing such a treaty would reduce emissions.

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 Tech Treaty proposed here provides incentives for developing more advanced abatement technologies, possibly inducing countries to reduce emissions now and doing so more certainly in the future. Also, as tighter emissions limits are not necessarily sufficient to spur innovation, additional instruments like a Tech Treaty may well be needed.

References

Acemoglu, D. (2009). *Introduction to Modern Economic Growth*. Princeton University Press, Princeton, NJ.

Asheim, G. B., Froyn, C. B., Hovi, J., and Menz, F. C. (2006). Regional versus global cooperation for climate control. *Journal of Environmental Economics and Management*, 51(1):93–109.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46:878–894.

Barrett, S. (2006). Climate treaties and 'breakthrough' technologies. *American Economic Review*, 96(2):22–25.

Barrett, S. (2012). Climate treaties and backstop technologies. *CESifo Economic Studies*, 58(1):31–48.

Benner, J., van Lieshout, M., and Croezen, H. (2012). Identifying breakthrough technologies for the production of basic chemicals: A long term view on the sustainable production of ammonia, olefins and aromatics in the European region. http://www.cedelft.eu/?go=home.downloadPub&id=1221&file=CE_Delft_finalreport_1329899563.pdf [Accessed: 08.03.2016].

Bretschger, L. (2013). Climate policy and equity principles: Fair burden sharing in a dynamic world. *Environment and Development Economics*, 18(05):517–536.

Bretschger, L., Lechthaler, F., Rausch, S., and Zhang, L. (2015). Knowledge diffusion, endogenous growth, and the costs of global climate policy. CER-ETH Working Paper 15/226.

Bretschger, L. and Vinogradova, A. (2015). Equitable and effective climate policy: Integrating less developed countries into a global climate agreement. *International Economics and Economic Policy*, 12(4):437–467.

Carraro, C. and Siniscalco, D. (1993). Strategies for the international protection of the environment. *Journal of Public Economics*, 52(3):309–328.

ClimateTechWiki (2016). Industrial efficiency. http://www.climatetechwiki.org/category/service/industrial-efficiency[Accessed:11.04.2016].

Croezen, H. and Korteland, M. (2010). Technological developments in Europe: A long-term view of CO_2 efficient manufacturing in the European region. http://www.cedelft.eu/?go=home.downloadPub&id=1098&file=7207_finalreportMaKEV.pdf[Accessed:08.03.2016].

Denicolò, V. and Franzoni, L. A. (2010). On the winner-take-all principle in innovation races. *Journal of the European Economic Association*, 8(5):1133–1158.

Di Maria, C., Smulders, S., and van der Werf, E. (2012). Absolute abundance and relative scarcity: Environmental policy with implementation lags. *Ecological Economics*, 74:104–119.

El-Sayed, A. and Rubio, S. J. (2014). Sharing R&D investments in cleaner technologies to mitigate climate change. *Resource and Energy Economics*, 38:168–180.

European Commission (2013). *The EU Emissions Trading Scheme System (EU ETS), 2013 edition*. Publications Office, Luxembourg.

European Commission (2016a). Climate action: Auctioning. http://ec.europa.eu/clima/policies/ets/cap/auctioning/index_en.htm[Accessed: 09.02.2016].

European Commission (2016b). Climate action: Paris Agreement. http://ec.europa.eu/clima/policies/international/negotiations/paris/index\en.htm [Accessed: 20.01.2016].

Finus, M. and Maus, S. (2008). Modesty may pay! *Journal of Public Economic Theory*, 10(5):801–826.

Fu, Q., Lu, J., and Lu, Y. (2012). Incentivizing R&D: Prize or subsidies? *International Journal of Industrial Organization*, 30(1):67–79.

Gersbach, H. and Oberpriller, Q. (2012). Rules vs. targets: Climate treaties under uncertainty. CER-ETH Working Paper 12/159.

Gersbach, H. and Winkler, R. (2011). International emission permit markets with refunding. *European Economic Review*, 55(6):759–773.

Goeschl, T. and Perino, G. (2016). The climate policy hold-up: Green technologies, intellectual property rights, and the abatement incentives of international agreements. *Scandinavian Journal of Economics, Accepted Author Manuscript.*

Harstad, B. (2016). The dynamics of climate agreements. *Journal of the European Economic Association*, 14(3):719–752.

Hoel, M. (1992). International environment conventions: The case of uniform reductions of emissions. *Environmental and Resource Economics*, 2(2):141–159.

Hoel, M. and Zeeuw, A. d. (2010). Can a focus on breakthrough technologies improve the performance of international environmental agreements? *Environmental and Resource Economics*, 47(3):395–406.

Hong, F. and Karp, L. (2012). International environmental agreements with mixed strategies and investment. *Journal of Public Economics*, 96(9-10):685–697.

International Center for Climate Governance (2016). INDC (intended nationally determined contribution). http://climateobserver.org/open-and-shut/indc/ [Accessed: 07.03.2016].

International Energy Agency (2013). Technology roadmap: Low-carbon technology for the indian cement industry. http://www.iea.org/publications /freepublications/publication /technology-roadmap-low-carbon- for-the-indian-cement-industry- –foldout.html [Accessed: 24.02.2016].

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC, Geneva.

Martin, R., Muûls, M., de Preux, Laure B., and Wagner, U. J. (2014). On the empirical content of carbon leakage criteria in the EU emissions trading scheme. *Ecological Economics*, 105:78–88.

Mazzucato, M. (2014). *Das Kapital des Staates: Eine andere Geschichte von Innovation und Wachstum*. Kunstmann, München.

Nicolaï, J.-P. (2015). Emission reduction and profit-neutral permit allocations. CER-ETH Working Paper 15/224.

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, 105(4):1339–1370.

Riekhof, M.-C. and Bröcker, J. (2016). Does the adverse announcement effect of climate policy matter? – A dynamic general equilibrium analysis. CER-ETH Working Paper 16/256.

Rubio, S. J. (2016). Sharing R&D investments in breakthrough technologies to control climate change. FEEM Working Paper No. 002.2016.

Schmidt, R. C. (2014). A balanced-efforts approach for climate cooperation. *Nature Climate Change*, 5(1):10–12.

Sinn, H.-W. (2008). Public policies against global warming: A supply side approach. *International Tax and Public Finance*, 15(4):360–394.

Smulders, S., Tsur, Y., and Zemel, A. (2012). Announcing climate policy: Can a green paradox arise without scarcity? *Journal of Environmental Economics and Management*, 64(3):364–376.

Strand, J. (2007). Technology treaties and fossil-fuels extraction. *Energy Journal*, 28(4):129–141.

UNFCCC (2009). Recommendations on future financing options for enhancing the development, deployment, diffusion and transfer of technologies under the convention. http://unfccc.int/resource/docs/2009/sb/eng/02.pdf [Accessed: 21.01.2016].

UNFCCC (2014). Finance for technology. http://unfccc.int/ttclear/templates/render_cms_page?IMS_home [Accessed: 25.07.2016].

van der Werf, E. and Di Maria, C. (2012). Imperfect environmental policy and polluting emissions: The green paradox and beyond. *International Review of Environmental and Resource Economics*, 6(2):153–194.

World Bank (2016). Data: CO_2 emissions (kt). http://data.worldbank.org/indicator/EN.ATM.CO2E.KT/countries?display=map [Accessed: 08.03.2016].

XPRIZE Foundation (2016a). Google lunar XPRIZE: Overview. http://lunar.xprize.org/about/overview [Accessed: 06.04.2016].

XPRIZE Foundation (2016b). What is an XPRIZE? http://www.xprize.org/about/what-is-an-xprize [Accessed: 06.04.2016].

A Appendix

A.1 Technologies

Table 1: 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 nanotechnology 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 as follows:

'*Research and development means that while the basic science is understood, the technology is at the stage of conceptual design or testing at the laboratory or at the bench scale. The unique barriers it faces relate to the proof of concept and to technological challenges. R&D typically occurs in only a few institutions globally for a given technology.*

Demonstration involves full-scale implementation of a limited number of installations by a small number of companies or research facilities. Demonstrations provide information on the capital and operating costs and performance of the technology at full scale. This information is used to improve the cost, performance or other characteristics to make the technology attractive to potential consumers.

A technology at the deployment stage is well understood and is available for selected *commercial applications but is more costly than the established technology, even taking into account a price for GHG emissions or equivalent policy. The buyers must pay a premium price, owners must accept a loss on each sale or governments must provide financial or other incentives for the technology. The experience gained from additional sales usually enables the cost of the technology to be reduced.*

At the diffusion stage the technology is competitive with the established technology if a price of greenhouse gases (GHG) emissions or equivalent policy is taken into account. However, the technology may still face barriers relating to the economic environment, social acceptance, cultural issues, or institutional arrangements, such as access to the grid for the sale of electricity generated or the adoption of appropriate safety standards.

A commercially mature technology is competitive with the established technology even if the price of GHG emissions is not considered, but may need to overcome market failures and specific transaction costs. The market failures faced by energy efficiency technologies are a typical example. Existing subsidies for fossil fuel and other GHG-emitting technologies are another example.' (UNFCCC, 2009, p. 9)

Table 2: 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)

A.2 Proofs for Sections 4-6

A.2.1 Proof of Lemma 2

Proof of Lemma 2.
Using implicit differentiation in (5) yields

$$\frac{\partial p}{\partial l} = \frac{-[e_A(p) - e_O(p)]}{l\frac{\partial e_A(p)}{\partial p} + [n-l]\frac{\partial e_O(p)}{\partial p}}. \tag{17}$$

From Lemma 1, $e_A(p) - e_O(p) > 0$. Equation (2) implies

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

and thus

$$\frac{\partial e_O(p)}{\partial p} > 0, \frac{\partial e_A(p)}{\partial p} > 0.$$

As $n \geq l$, the denominator of Equation(17) is positive and thus

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

Similarly, it follows that

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

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

A.2.2 Proof of Lemma 5

Proof of Lemma 5.
Equation (7) implies

$$\begin{aligned}\frac{\partial f_i(l)}{\partial l} =& p_l'(\mathcal{E}, l)[\bar{e}_i - [1-\alpha]\epsilon_i - e_O(p(\mathcal{E}, l))] \\ &- p_l'(\mathcal{E}, l+1)[\bar{e}_i - [1-\alpha]\epsilon_i - e_A(p(\mathcal{E}, l+1))],\end{aligned} \tag{18}$$

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), $e_A(p(\mathcal{E}, n)) = e_O(p(\mathcal{E}, 0))$ and since

$e_i(p(\mathcal{E},l))$ is decreasing in l,

$$e_A(p(\mathcal{E},l+1)) > e_O(p(\mathcal{E},l))$$

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

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

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

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

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

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

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

□

A.2.3 Proof of Lemma 8

Proof of Lemma 8.
Equation (8) implies

$$\begin{aligned}f_{\mathcal{E}}' =& p_{\mathcal{E}}'(\mathcal{E},n-1)[\bar{e}_n - [1-\alpha]\epsilon_n - e_O(p(\mathcal{E},n-1))] \\ &- p_{\mathcal{E}}'(\mathcal{E},n)[\bar{e}_n - [1-\alpha]\epsilon_n - e_A(p(\mathcal{E},n))],\end{aligned} \tag{19}$$

where $p_{\mathcal{E}}'(\mathcal{E},n) < 0$ by Lemma 2. 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 $p_{\mathcal{E},n}' \approx p_{\mathcal{E},n-1}'$,

$$f_{\mathcal{E}}' = p_{\mathcal{E}}'(\mathcal{E})[-e_O(p(\mathcal{E},n-1)) + e_A(p(\mathcal{E},n))] < 0 \tag{20}$$

with $e_A(p(\mathcal{E},n)) > e_O(p(\mathcal{E},n-1))$, as shown in the Proof of Lemma 5.

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

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

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

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

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

□

A.2.4 Proof of Proposition 4

Proof of Proposition 4.

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 (16),

$$
\begin{aligned}
V''_{\epsilon_i,\epsilon_i} =& p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] + p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial e_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 1\right] - p'_{\mathcal{E}}(\mathcal{E},0) \\
&+ \frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2} + 2\Pi'_k \frac{nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{x}\Delta c'_{\epsilon_i} \\
&+ \Pi\,[\; p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\
&\quad + p'_{\mathcal{E}}(\mathcal{E},n)[-\frac{\partial e_A(p(\mathcal{E},n))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n) - [1-\alpha]] \\
&\quad - p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] \\
&\quad - p'_{\mathcal{E}}(\mathcal{E},0)[-\frac{\partial e_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 1] - [1-\alpha]p'_{\mathcal{E}}(\mathcal{E},n) + p'_{\mathcal{E}}(\mathcal{E},0) \\
&\quad + f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)\;] \\
&+ [\;\Pi''_{kk}\left[\frac{nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha[p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E} + p(\mathcal{E},n)]}{x}\right]^2 \\
&\quad + \Pi'_k \frac{nf''_{\mathcal{E},\mathcal{E}} + \alpha[p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)\mathcal{E} + 2p'_{\mathcal{E}}(\mathcal{E},n)]}{x}\;]\,\Delta c,
\end{aligned} \tag{21}
$$

with

$$
\begin{aligned}
\Delta c'_{\epsilon_i} =& p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - \epsilon_i] - p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - [1-\alpha]\epsilon_i] \\
&- [1-\alpha]p(\mathcal{E},n) + p(\mathcal{E},0) + f'_{\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n) \\
f''_{\mathcal{E},\mathcal{E}} =& p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_n - (1-\alpha)\epsilon_n - e_O(p(\mathcal{E},n-1))] + p'_{\mathcal{E}}(\mathcal{E},n-1)[-\frac{\partial e_O}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n-1)] \\
&- p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},n)[\bar{e}_n - (1-\alpha)\epsilon_n - e_A(p(\mathcal{E},n))] - p'_{\mathcal{E}}(\mathcal{E},n)[-\frac{\partial e_A}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n)]
\end{aligned} \tag{22}
$$

and Δc defined in Equation (13).

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 $\pi \approx 0$ (see Table 3) and $-\frac{\partial e_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) < 2$ (i.e. Condition (ii) in this proposition), we have

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

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 for symmetric countries $i \in \{1, ..., n-1\}$. 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 (10)) 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). It is easy to verify then that this Hessian is positive-definite. The equilibrium corresponds to a global minimum. Hence Proposition 4 holds. □

A.2.5 Proof of Proposition 5

Proof of Proposition 5.

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

$$\frac{\partial \epsilon_i}{\partial \alpha} = \frac{-V^{*''}_{\epsilon_i,\alpha}}{V^{*''}_{\epsilon_i^2}}. \tag{23}$$

To keep the examination independent of choosing Π^A or Π^T, we define

$$Z := \frac{\Pi''_{kk}}{\Pi'_k} < 0$$

(see Table 3).

We start by discussing the sign of $V^{*''}_{\epsilon_i,\alpha}$:

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} =& \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{ov. inno. prob.}} \underbrace{[p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i + p(\mathcal{E},n) + f''_{\mathcal{E},\alpha}]}_{\text{cost-reduction effect},\Delta c''_{\epsilon_i,\alpha}} \\
&+ \underbrace{\frac{\Pi'_k}{x}\left[nf'_{\alpha}(\mathcal{E},\alpha) + p(\mathcal{E},n)\mathcal{E}\right]}_{\Pi'_k k'_{\alpha}>0} \\
&\underbrace{\begin{array}{l}[p'_{\mathcal{E}}(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] - p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},0)) - \epsilon_i] \\ +p(\mathcal{E},0) - [1-\alpha]p(\mathcal{E},n) + f'_{\mathcal{E}}(\mathcal{E},\alpha)]\end{array}}_{\text{marginal cost reduction, } \Delta c'_{\epsilon_i}} \\
&+ \underbrace{\frac{\Pi'_k}{x}\left[nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right]}_{\text{marginal innovation, } \Pi'_k k'_{\mathcal{E}}} \\
&\underbrace{[f'_{\alpha} + \epsilon_i p(\mathcal{E},n)]}_{\Delta c'_{\alpha}} \\
&\underbrace{\begin{array}{l}+\frac{\Pi'_k}{x}[\left[nf''_{\mathcal{E},\alpha} + p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right] \\ +Z\frac{nf'_{\alpha}(\mathcal{E},\alpha) + p(\mathcal{E},n)\mathcal{E}}{x}\left[nf'_{\mathcal{E}}(\mathcal{E},\alpha) + \alpha p(\mathcal{E},n)[\frac{p'_{\mathcal{E}}(\mathcal{E},n)\mathcal{E}}{p(\mathcal{E},n)} + 1]\right]]\end{array}}_{\text{innovation effect, } (\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{kk}k'_{\alpha}k'_{\mathcal{E}})} \\
&\underbrace{\begin{array}{l}[g_A(e_A(p(\mathcal{E},n))) - g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ -p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},n)) - \epsilon_i] + f]\end{array}}_{\text{cost reduction, } \Delta c_i}.
\end{aligned} \tag{24}
$$

Equation (24) shows that marginal damages do not influence the marginal effect of the Tech Treaty's 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 (24). 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's share α matters for the overall direction of a change in α.

For sufficiently high research costs x (as required in Proposition 5),

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

The other terms of (24) are close to zero. If $f''_{\mathcal{E},\alpha} \approx 0$ (Proposition 5), then $V^{*\prime\prime}_{\epsilon_i,\alpha} > 0$ for $\frac{p'_{\mathcal{E}}(\mathcal{E},n)\epsilon_i}{p(\mathcal{E},n)} + 1 > 0$, as stated in Proposition 5 in terms of the elasticity $\xi(l,\epsilon_i)$.

We now turn to the sign of $V''_{\epsilon_i,\epsilon_i}$. Equation (21) gives its general expression. For $\Pi'_k/x \approx 0$ and $p''_{\mathcal{E},\mathcal{E}}(\mathcal{E},l) = 0$ (both required in Proposition 5), Equation (21) reduces to

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

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 5), we obtain $V''_{\epsilon_i,\epsilon_i} > 0$. □

A.3 Country n

$$\begin{aligned} V(\epsilon_n) =& [g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n]] + d_n(\mathcal{E}) \\ &+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[-g_O(e_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] \\ &+ g_O(e_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]], \end{aligned} \quad (25)$$

with

$$\begin{aligned} V'_{\epsilon_n} =& \left[p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] - p(\mathcal{E},0)\right] + d'_{\mathcal{E}} \\ &+\Pi'_k k'_{\mathcal{E}}(\mathcal{E},\alpha)[-g_O(e_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] \\ &+ g_O(e_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]] \\ &+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[-p'_{\mathcal{E}}(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] + p(\mathcal{E},0) \\ &+ p'_{\mathcal{E}}(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n] - [1-\alpha]p(\mathcal{E},n-1)] \end{aligned} \quad (26)$$

and

$$
\begin{aligned}
&V''_{\epsilon_n,\alpha} = (\Pi''_{kk}k'_\alpha k'_\mathcal{E}(\mathcal{E},\alpha) + \Pi'_k k''_{\mathcal{E},\alpha}(\mathcal{E},\alpha)) \\
&[-g_O(e_O(p(\mathcal{E},0))) - p(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] \\
&\quad + g_O(e_O(p(\mathcal{E},n-1))) + p(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n]] \\
&+\Pi'_k k'_\mathcal{E}(\mathcal{E},\alpha)[p(\mathcal{E},n-1)\epsilon_n] \\
&+\Pi'_k k'_\alpha[-p'_\mathcal{E}(\mathcal{E},0)[\bar{e}_n - e_O(p(\mathcal{E},0)) - \epsilon_n] + p(\mathcal{E},0) \\
&\quad + p'_\mathcal{E}(\mathcal{E},n-1)[\bar{e}_n - e_O(p(\mathcal{E},n-1)) - [1-\alpha]\epsilon_n] - [1-\alpha]p(\mathcal{E},n-1)] \\
&+\Pi(k(\mathcal{E},\alpha,\epsilon_n))[p'_\mathcal{E}(\mathcal{E},n-1)\epsilon_n + p(\mathcal{E},n-1)]. \qquad (27)
\end{aligned}
$$

As stated in footnote 14, we neglegt possible additional strategic effects that would lead to differences between $k'_\mathcal{E}$ and k'_{ϵ_n}, among others.

A.4 Comparison Between True and Approximated $\tilde{\Pi}$

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 $\mathbb{P}^A_k[i = P] = \tilde{\pi}^T$ 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,

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

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

$$\Pi^T(k) = 1-[1-\pi]^k. \tag{28}$$

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 3 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 3 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.

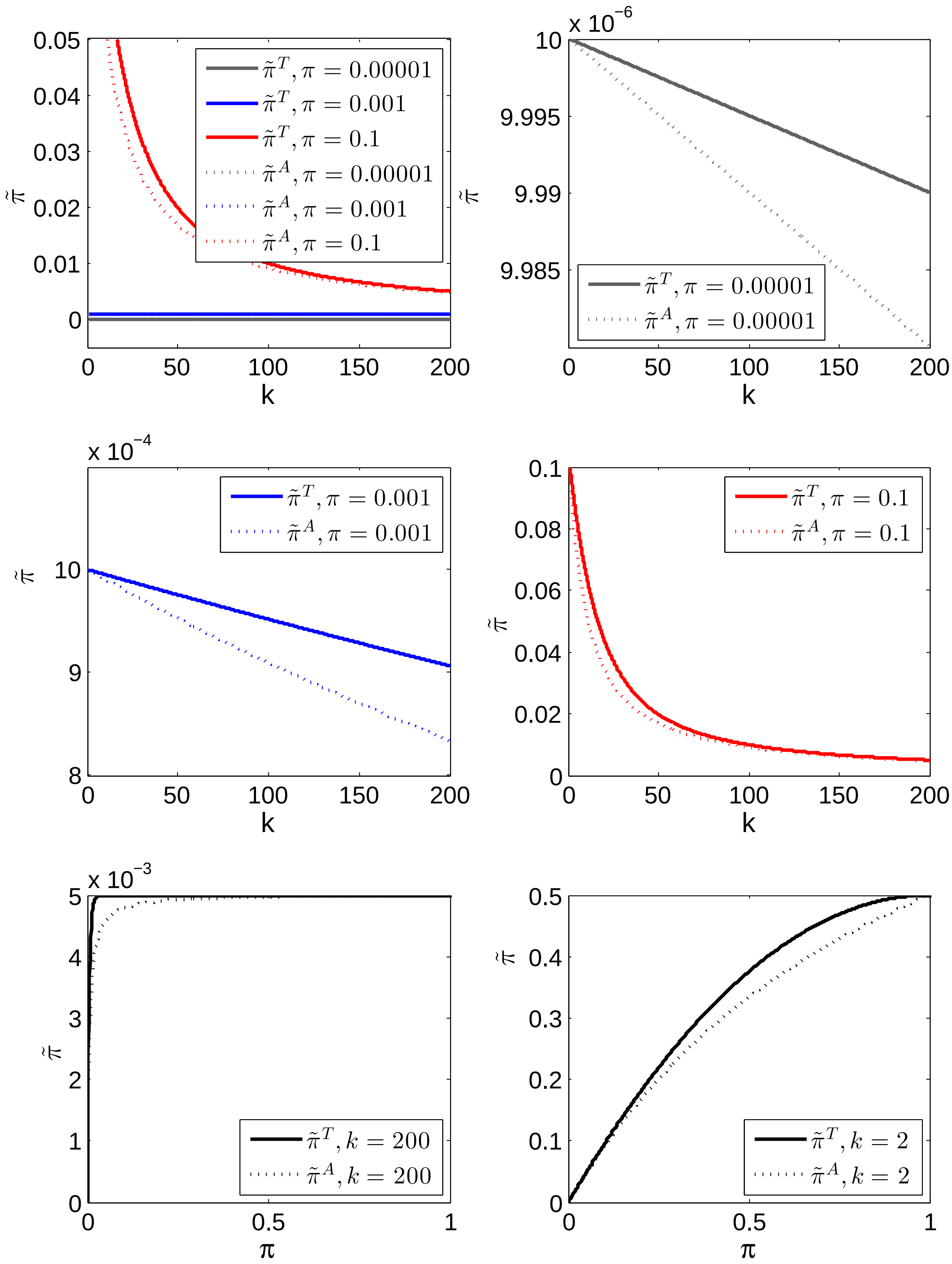


Figure 2: Comparison of true probability $\tilde{\pi}^T$ and approximated probability $\tilde{\pi}^A$ for different values of k and π.

Table 3: 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 following, we show that results for k_α' and $k_\mathcal{E}'$ from Propositions 1 and 2 also hold under $\tilde{\Pi}^T$. If we take $\tilde{\Pi}^T$, we cannot solve for k in zero-profit Condition (9)

$$\frac{1}{k}[1-[1-\pi]^k][nf(\mathcal{E},\alpha,\epsilon_n)+p(\mathcal{E},n)\alpha\mathcal{E}] - x = 0, \tag{29}$$

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 (29). The reason is as follows: For $k=1$, $\tilde{\Pi}^T = \pi$ and

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

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 $k \geq 0$.

Using the implicit function theorem, we can derive k_α' and $k_\mathcal{E}'$.

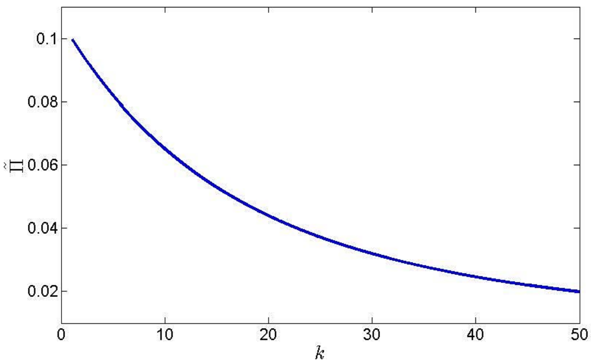


Figure 3: Illustration of $\tilde{\pi}^T$ for $\pi = 0.1$.

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

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 2. 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 6 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 3).

A.5 Example I: Quadratic Abatement Costs

A.5.1 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

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

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

Equations (2) and (3) become

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

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

$$\mathcal{E} = \bar{E} - l\frac{p}{b_A} - [n-l]\frac{p}{b_O} \Leftrightarrow p = \frac{\bar{E} - \mathcal{E}}{\frac{l}{b_A} + \frac{n-l}{b_O}} = \frac{b_A b_O[\bar{E} - \mathcal{E}]}{l b_0 + b_A[n-l]}.$$

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,

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

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.

A.5.2 The value of the fee and the number of active R&D firms

The fee is

$$
\begin{aligned}
f =& \frac{b_O}{2}\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}\left[\bar{e}_n - [1-\alpha]\epsilon_n - \frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right] \\
& - \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 - \frac{b_A[\bar{E}-\mathcal{E}]}{n}\left[\bar{e}_n - [1-\alpha]\epsilon_n - \frac{\bar{E}-\mathcal{E}}{n}\right] \\
=& \left[\frac{b_O}{2} - b_O\right]\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}[\bar{e}_n - [1-\alpha]\epsilon_n] \\
& - \left[\frac{b_A}{2} - b_A\right]\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 - \frac{b_A[\bar{E}-\mathcal{E}]}{n}[\bar{e}_n - [1-\alpha]\epsilon_n] \\
=& \left[\frac{b_O}{2} - b_O\right]\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 - \left[\frac{b_A}{2} - b_A\right]\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
& + [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]\left(\frac{1}{\frac{n-1}{b_A}+\frac{1}{b_O}} - \frac{b_A}{n}\right) \\
=& -\frac{b_O}{2}\left[\frac{\frac{\bar{E}-\mathcal{E}}{\frac{n-1}{b_A}+\frac{1}{b_O}}}{b_O}\right]^2 + \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
& + [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]\left[\frac{nb_Ab_O}{n[b_O[n-1]+b_A]} - \frac{b_Ab_On - b_Ab_O + b_A^2}{n[b_O[n-1]+b_A]}\right] \\
=& -\frac{b_O}{2}\left[\frac{b_Ab_O[\bar{E}-\mathcal{E}]}{b_O(n-1)+b_A}\frac{1}{b_O}\right]^2 + \frac{b_A}{2}\left[\frac{\bar{E}-\mathcal{E}}{n}\right]^2 \\
& + [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]b_A\frac{b_O - b_A}{n[b_O[n-1]+b_A]} \\
=& \frac{[\bar{E}-\mathcal{E}]^2}{2}\left[-b_O\left[\frac{b_A}{b_O(n-1)+b_A}\right]^2 + \frac{b_A}{n^2}\right] \\
& + [\bar{E}-\mathcal{E}][\bar{e}_n - [1-\alpha]\epsilon_n]b_A\frac{b_O - b_A}{n[b_O[n-1]+b_A]}
\end{aligned}
\tag{30}
$$

and the number of active R&D firms is

$$
k = \frac{nf + \alpha\mathcal{E}\frac{b_A[\bar{E}-\mathcal{E}]}{n}}{x} + 1 - \frac{1}{\pi}, \tag{31}
$$

based on Equation (9). Hence, this shows Corollary 2.

A.5.3 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 (19),

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

Using

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

gives

$$\begin{aligned} f''_{\mathcal{E},\alpha} &= \epsilon_n \left[\frac{b_A}{n} - \frac{b_A b_O}{b_O[n-1] + b_A} \right] = \epsilon_n \left[\frac{-n b_A b_O + b_A b_O(n-1) + b_A^2}{n[b_O[n-1] + b_A]} \right] \\ &= \epsilon_n \left[\frac{b_A [b_A - b_O]}{n[b_O[n-1] + b_A]} \right] < 0, \end{aligned} \tag{32}$$

and

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

with

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

because $n \geq 2$ in a multi-country world. This proves Corollary 3.

Also,

$$\begin{aligned}
f''_{\mathcal{E},\mathcal{E}} &= -p'_{\mathcal{E}}(\mathcal{E}, n-1)^2 \frac{\partial e_O}{\partial p} + p'_{\mathcal{E}}(\mathcal{E}, n)^2 \frac{\partial e_A}{\partial p} \\
&= \frac{-b_A^2 b_O^2}{[b_O[n-1]+b_A]^2} + \frac{b_A}{n^2} = b_A \left[\frac{-b_A b_O n^2 + [b_O[n-1]+b_A]^2}{[b_O[n-1]+b_A]^2 n^2} \right] > 0. \qquad (34)
\end{aligned}$$

Based on (31), we can derive

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

with $k'_{\mathcal{E}} < 0$ when $\mathcal{E} > \bar{E}/2$, as $f'_{\mathcal{E}} < 0$ for quadratic abatement costs (Corollary 3). This proves Proposition 2, (iii).

From (10) we obtain

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

A.5.4 The sign of $\partial f_i / \partial l$

Based on Equation (18),

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

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. This shows Corollary 1.

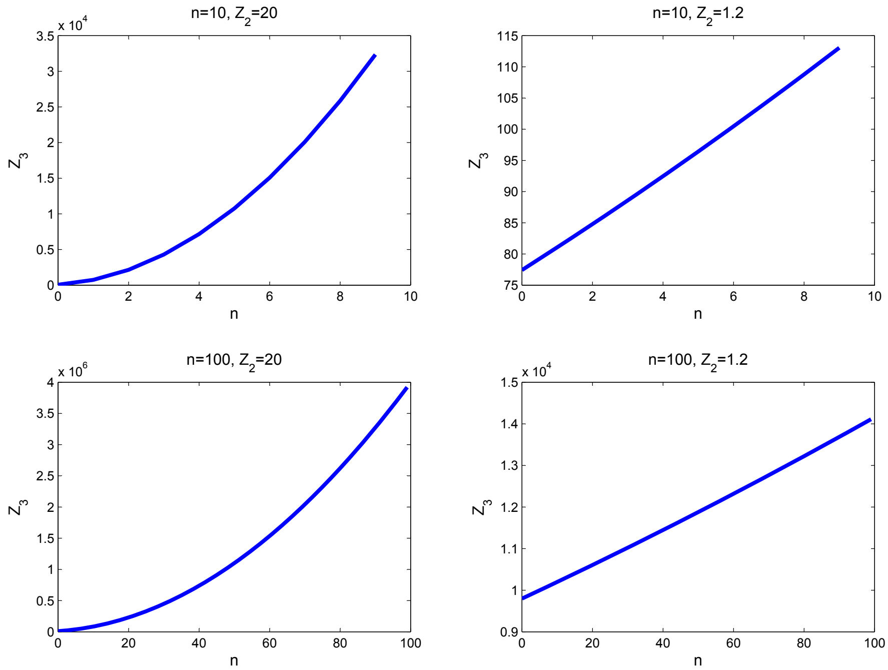


Figure 4: Simulation of Z_3 for different values of n and Z_2.

A.5.5 Proof of Proposition 6

Again based on Equation (23), we need to determine the signs of $V^{*''}_{\epsilon_i,\epsilon_i}$ and $V^{*''}_{\epsilon_i,\alpha}$. For quadratic abatement costs, Equation (24) becomes

$$V^{*''}_{\epsilon_i,\alpha} = \underbrace{\Pi}_{\text{ov. inno. prob.}} \underbrace{\left[\frac{b_A}{n}\left[\bar{E} - \mathcal{E} - \epsilon_i\right] + \epsilon_n \overbrace{\left[\frac{b_A[b_A - b_O]}{n[[n-1]b_O + b_A]}\right]}^{f''_{\mathcal{E}\alpha}<0} \right]}_{\text{cost-change effect,}\Delta c''_{\epsilon_i,\alpha}}$$
$$+ \underbrace{\frac{\Pi'_k}{x}\left[n \frac{\overbrace{\epsilon_n b_A[b_O - b_A][\bar{E} - \mathcal{E}]}^{f'_\alpha>0}}{n[b_O[n-1] + b_A]} + \frac{b_A[\bar{E} - \mathcal{E}]}{n}\mathcal{E} \right]}_{\Pi'_k k'_\alpha>0}$$
$$\underbrace{\left[\frac{b_O}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - \epsilon_i] - \frac{b_A}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - [1-\alpha]\epsilon_i] + [b_O - [1-\alpha]b_A]\frac{[\bar{E} - \mathcal{E}]}{n} + f'_{\mathcal{E}}(\mathcal{E},\alpha)\right]}_{\text{marginal cost change, }\Delta c'_{\epsilon_i}}$$
$$+ \underbrace{\frac{\Pi'_k}{x}\left[n f'_{\mathcal{E}}(\mathcal{E},\alpha) - \alpha\frac{b_A}{n}[2\mathcal{E} - \bar{E}]\right]}_{\text{marginal innovation, }\Pi'_k k'_{\mathcal{E}}<0}$$
$$\underbrace{\left[\frac{\overbrace{\epsilon_n b_A[b_O - b_A][\bar{E} - \mathcal{E}]}^{f'_\alpha>0}}{n[b_O[n-1] + b_A]} + \epsilon_i b_A \frac{[\bar{E} - \mathcal{E}]}{n} \right]}_{\Delta c'_\alpha>0}$$
$$\underbrace{+\frac{\Pi'_k}{x}[\left[n f''_{\mathcal{E},\alpha} - \frac{b_A}{n}[2\mathcal{E} - \bar{E}]\right] + Z\frac{n f'_\alpha + \frac{b_A[\bar{E}-\mathcal{E}]}{n}\mathcal{E}}{x}\left[n f'_{\mathcal{E}} + \alpha\left[\frac{b_A[\bar{E} - \mathcal{E}]}{n} - \frac{b_A}{n}\right]\right]]}_{\text{innovation effect, }\left[\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{k,k}, k'_\alpha, k'_{\mathcal{E}}\right]}$$
$$\underbrace{\left[\frac{b_A - b_O}{2}\left[\frac{\bar{E} - \mathcal{E}}{n}\right]^2 + \left[b_A\frac{\bar{E} - \mathcal{E}}{n}\right][\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - [1-\alpha]\epsilon_i] - b_O\frac{\bar{E} - \mathcal{E}}{n}[\bar{e}_i - \frac{\bar{E} - \mathcal{E}}{n} - \epsilon_i] + f\right]}_{\text{cost change, }\Delta c_i}, \tag{35}$$

with f, f'_α, $f'_{\mathcal{E}}$, and $f''_{\mathcal{E},\alpha}$ from Section A.5.3.

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 (32)).

2. $f'_\alpha > 0$ from Section A.5.3 and Π'_k from Table 3. 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 (33)) is weighted by $\bar{e}_n - [1-\alpha]\epsilon_n$, which according to Lemma 4 is small.

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 3). 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 (21) becomes

$$\begin{aligned} V''_{\epsilon_i,\epsilon_i} =& p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial e_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 2\right] + \frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2} + 2\Pi'_k k'_{\mathcal{E}}\Delta c'_{\epsilon_i} \\ &+\Pi[p'_{\mathcal{E}}(\mathcal{E},n)\left[-\frac{\partial e_A(p(\mathcal{E},n))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},n) - 2[1-\alpha]\right] \\ &- p'_{\mathcal{E}}(\mathcal{E},0)\left[-\frac{\partial e_O(p(\mathcal{E},0))}{\partial p}p'_{\mathcal{E}}(\mathcal{E},0) - 2\right] + f''_{\mathcal{E},\mathcal{E}}(\mathcal{E},\alpha,\epsilon_n)] \\ &+[\Pi''_{kk}(k'_{\mathcal{E}})^2 + \Pi'_k k''_{\mathcal{E},\mathcal{E}}]\Delta c. \end{aligned} \tag{36}$$

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

$$\begin{aligned}
V''_{\epsilon_i,\epsilon_i} = & \underbrace{[1-\Pi]p'_{\mathcal{E}}(\mathcal{E},0)\left[\frac{1}{n}-2\right] + \Pi p'_{\mathcal{E}}(\mathcal{E},n)\left[\frac{1}{n}-2[1-\alpha]\right]}_{>0 \quad \text{for} \quad \alpha<\frac{2n-1}{2n}} \\
& + \underbrace{\frac{\partial^2 d_i(\mathcal{E})}{\partial \mathcal{E}^2}}_{>0} \\
& + \underbrace{\Pi\left[-\frac{p'_{\mathcal{E}}(\mathcal{E},n-1)^2}{b_O} + \frac{p'_{\mathcal{E}}(\mathcal{E},n)^2}{b_A}\right]}_{>0} \\
& + \underbrace{2\Pi'_k k'_{\mathcal{E}} \Delta c'_{\epsilon_i}}_{<0} \\
& + [\underbrace{\Pi''_{kk}\left[k'_{\mathcal{E}}\right]^2}_{<0} + \underbrace{\Pi'_k}_{>0} k''_{\mathcal{E},\mathcal{E}}] \underbrace{\Delta c}_{<0}.
\end{aligned} \tag{37}$$

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 $V''_{\epsilon_i,\epsilon_i} > 0$.

A.6 Example II: Linear Abatement Costs

A.6.1 The set-up

We assume linear abatement costs, $g_O(e_i) = b_O e_i$ and $g_A(e_i) = b_A e_i$ 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.[21] 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

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

prices $p = b_A$, and choosing $e_i = 0$

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

than by paying the fee and abating with the new technology

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

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,

$$k = \frac{b_A \alpha}{x}\mathcal{E} + 1 - \frac{1}{\pi},$$

based on Equation (9). This proves Proposition 3.

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.

A.6.2 Proof of Proposition 7

Proof of Proposition 7.

For linear abatement costs, Equation (24) reduces to[22]

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} = & \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))}_{\text{ov. inno. prob.}} \quad \underbrace{p(\mathcal{E},n)}_{\text{cost-change effect, } \Delta c''_{\epsilon_i,\alpha}} \\
& + \underbrace{\frac{\Pi'_k}{x}\,[p(\mathcal{E},n)\mathcal{E}]}_{\Pi'_k k'_\alpha > 0} \underbrace{[p(\mathcal{E},0)-[1-\alpha]p(\mathcal{E},n)]}_{\text{marginal cost change, } \Delta c'_{\epsilon_i}} + \underbrace{\frac{\Pi'_k}{x}\,[\alpha p(\mathcal{E},n)]}_{\text{marginal innovation, } \Pi'_k k'_{\mathcal{E}}} \quad \underbrace{[\epsilon_i p(\mathcal{E},n)]}_{\Delta c'_\alpha} \\
& + \underbrace{\frac{\Pi'_k}{x}[p(\mathcal{E},n) + Z\frac{p(\mathcal{E},n)\mathcal{E}}{x}\alpha p(\mathcal{E},n)]}_{\text{innovation effect, } (\Pi'_k k''_{\epsilon_i,\alpha} + \Pi''_{kk} k'_\alpha k'_{\mathcal{E}})} \\
& \underbrace{\begin{aligned}&[g_A(e_A(p(\mathcal{E},n))) - g_O(e_O(p(\mathcal{E},0))) + p(\mathcal{E},n)[\bar{e}_i - e_A(p(\mathcal{E},n)) - [1-\alpha]\epsilon_i] \\ &-p(\mathcal{E},0)[\bar{e}_i - e_O(p(\mathcal{E},n)) - \epsilon_i]]\end{aligned}}_{\text{cost change, } \Delta c_i}. \qquad (38)
\end{aligned}
$$

Re-arranging and plugging in functional forms[23] leads to

$$
\begin{aligned}
V^{*''}_{\epsilon_i,\alpha} = & \underbrace{\Pi(k(\mathcal{E},\alpha,\epsilon_n))b_A + \frac{\Pi'_k}{x} b_A\,[\mathcal{E}[b_O - [1-\alpha]b_A] + \alpha b_A \epsilon_i]}_{>0} \\
& + \frac{\Pi'_k}{x}[b_A + \underbrace{Z\frac{b_A\mathcal{E}}{x}\alpha b_A}_{<0}][b_A[\bar{e}_i - [1-\alpha]\epsilon_i] - b_O[\bar{e}_i - \epsilon_i]]. \qquad (39)
\end{aligned}
$$

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, $V^{*''}_{\epsilon_i,\alpha} > 0$. □

[22]For linear abatement costs, $g'' = 0$ and $p'_{\mathcal{E}} = 0$ and $f = f'_{\mathcal{E}} = f'_\alpha = f''_{\mathcal{E},\alpha} = 0$.
[23]$p(\mathcal{E},0) = b_O$, $p(\mathcal{E},n) = b_A$, $g_O(e_i) = b_O e_i$ and $g_A(e_i) = b_A e_i$.

A.6.3 Proof of Proposition 8

Proof of Proposition 8.
We now additionally assume a quadratic damage function and $\Pi \approx \pi k$. Then the decision problem of the local planner becomes

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

Plugging in functional forms[24] 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

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

Then,

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

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

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.

□

A.7 Overview Notations

Table 4: 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
e_i	abated emissions of production firm i
$e_O(p)$	emissions abated using the old technology
$e_A(p)$	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
$g_O(e_i)$	abatement costs, old technology
$g_A(e_i)$	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's 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

Working Papers of the Center of Economic Research at ETH Zurich

(PDF-files of the Working Papers can be downloaded at www.cer.ethz.ch/research/working-papers.html).

17/268 H. Gersbach, M.-C. Riekhof
Technology Treaties and Climate Change

17/267 Christos Karydas
The inter-temporal dimension to knowledge spillovers: any non-environmental reason to support clean innovation?

17/266 Christos Karydas, Lin Zhang
Green tax reform, endogenous innovation and the growth dividend

17/265 Daniel Harenberg, Stefano Marelli, Bruno Sudret, Viktor Winschel
Uncertainty Quantification and Global Sensitivity Analysis for Economic Models

16/264 Marie-Catherine Riekhof
The Insurance Premium in the Interest Rates of Interlinked Loans in a Small-scale Fishery

16/263 Julie Ing
Adverse selection, commitment and exhaustible resource taxation

16/262 Jan Abrell, Sebastian Rausch, and Giacomo A. Schwarz
Social Equity Concerns and Differentiated Environmental Taxes

16/261 D. Ilic, J.C. Mollet
Voluntary Corporate Climate Initiatives and Regulatory Loom: Batten Down the Hatches

16/260 L. Bretschger
Is the Environment Compatible with Growth? Adopting an Integrated Framework

16/259 V. Grossmann, A. Schaefer, T. Steger, and B. Fuchs
Reversal of Migration Flows: A Fresh Look at the German Reunification

16/258 V. Britz, H. Gersbach, and H. Haller
Deposit Insurance in General Equilibrium

16/257 A. Alberini, M. Bareit, M. Filippini, and A. Martinez-Cruz
The Impact of Emissions-Based Taxes on the Retirement of Used and Inefficient Vehicles: The Case of Switzerland

16/256 H. Gersbach
Co-voting Democracy

16/255 H. Gersbach and O. Tejada
A Reform Dilemma in Polarized Democracies

16/254 M.-C. Riekhof and J. Broecker
Does the Adverse Announcement Effect of Climate Policy Matter? - A Dynamic General Equilibrium Analysis

16/253 A. Martinez-Cruz
Handling excess zeros in count models for recreation demand analysis without apology

16/252 M.-C. Riekhof and F. Noack
Informal Credit Markets, Common-pool Resources and Education

16/251 M. Filippini, T. Geissmann, and W. Greene
Persistent and Transient Cost Efficiency - An Application to the Swiss Hydropower Sector

16/250 L. Bretschger and A. Schaefer
Dirty history versus clean expectations: Can energy policies provide momentum for growth?

16/249 J. Blasch, M. Filippini, and N. Kumar
Boundedly rational consumers, energy and investment literacy, and the display of information on household appliances

16/248 V. Britz
Destroying Surplus and Buying Time in Unanimity Bargaining

16/247 N. Boogen, S. Datta, and M. Filippini
Demand-side management by electric utilities in Switzerland: Analyzing its impact on residential electricity demand

16/246 L. Bretschger
Equity and the Convergence of Nationally Determined Climate Policies

16/245 A. Alberini and M. Bareit
The Effect of Registration Taxes on New Car Sales and Emissions: Evidence from Switzerland

16/244 J. Daubanes and J. C. Rochet
The Rise of NGO Activism

16/243 J. Abrell, Sebastian Rausch, and H. Yonezawa
Higher Price, Lower Costs? Minimum Prices in the EU Emissions Trading Scheme

16/242 M. Glachant, J. Ing, and J.P. Nicolai
The incentives to North-South transfer of climate-mitigation technologies with trade in polluting goods

16/241 A. Schaefer
Survival to Adulthood and the Growth Drag of Pollution

16/240 K. Prettner and A. Schaefer
Higher education and the fall and rise of inequality

16/239 L. Bretschger and S. Valente
Productivity Gaps and Tax Policies Under Asymmetric Trade

16/238 J. Abrell and H. Weigt
Combining Energy Networks

16/237 J. Abrell and H. Weigt
Investments in a Combined Energy Network Model: Substitution between Natural Gas and Electricity?

16/236 R. van Nieuwkoop, K. Axhausen and T. Rutherford
A traffic equilibrium model with paid-parking search

16/235 E. Balistreri, D. Kaffine, and H. Yonezawa
Optimal environmental border adjustments under the General Agreement on Tariffs and Trade

16/234 C. Boehringer, N. Rivers, H. Yonezawa
Vertical fiscal externalities and the environment

16/233 J. Abrell and S. Rausch
Combining Price and Quantity Controls under Partitioned Environmental Regulation

16/232 L. Bretschger and A. Vinogradova
Preservation of Agricultural Soils with Endogenous Stochastic Degradation

16/231 F. Lechthaler and A. Vinogradova
The Climate Challenge for Agriculture and the Value of Climate Services: Application to Coffee-Farming in Peru

16/230 S. Rausch and G. Schwarz
Household heterogeneity, aggregation, and the distributional impacts of environmental taxes

16/229 J. Abrell and S. Rausch
Cross-Country Electricity Trade, Renewable Energy and European Transmission Infrastructure Policy