

Gersbach, Hans; Riekhof, Marie-Catherine

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Permit Markets, Carbon Prices and the Creation of Innovation Clusters

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Permit Markets, Carbon Prices and the Creation of Innovation Clusters*

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

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Abstract

Innovation clusters that combine public basic research and applied research performed by private firms may be needed for greater technological advances to slow down climate change. We use a multi-country model with emissions permit trade to examine how international climate policy can induce countries to create such clusters. We allow for a varying degree of cooperation between the countries, represented by different carbon price targets. We find that a minimal carbon price is needed to attract applied research firms, but countries may nevertheless fail to invest in basic research. We construct a mechanism that can overcome this barrier and that can induce the first-best creation of innovation clusters. The mechanism involves a combination of few permits given to the country with the lowest costs for basic research, fair burden-sharing and maximal grandfathering.

Keywords: International permit markets; Carbon prices; Innovation clusters; Basic research; Applied R&D; Climate change mitigation; Externalities

JEL Classification: H23; Q54; O32

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1 Introduction

Most suggestions how to slow down climate change concern emissions reduction or technological advances. Technological advances could allow green(er) production or taking CO_2 out of the atmosphere. The use of permit markets or carbon pricing, in particular, represent market-based policies for reducing emissions efficiently. Ideally, the internalization of the externalities from carbon emissions—e.g. via permit markets or a carbon price—would both lower emissions and foster technological advances. While this may hold when small adjustment to existing technologies by private firms suffice (Johnstone et al., 2010),¹ this is less clear for greater technological advances. In particular, advances related to breakthrough technologies need both basic research and applied R&D organized in innovation clusters (see e.g. Kemp and Pontoglio (2011)).

The importance of innovation clusters—such as ‘Silicon Valley’ and the Boston Area—combining both types of research and creating local spillovers for innovation has long been established (Braunerhjelm and Feldman, 2006)². Yet, the potential role of such clusters for developing green technologies has only received more attention recently. Indeed, basic research typically provides ideas, methods and prototypes, which private applied research firms can use to develop commercialized blueprints for new abatement or carbon storage technologies.³ Several political agencies now push for more green innovation clusters.

Such cluster policy is implemented in the European Union.⁴ Two major issues emerge as to the creation of innovation clusters to slow down climate change. First, applied research firms will only be attracted to an innovation cluster if basic research develops the knowledge base, and if carbon prices are sufficiently high, such that expected licensing revenues from selling newly detected technologies cover their costs. The level of the carbon price depends on the cooperation between countries. Second, governments may have insufficient incentives for investing in basic research to make innovation clusters viable, even if applied research firms can be attracted. The reason is that such investments have fixed costs, which cannot

¹For costlier energy technologies, more targeted subsidies are needed (Johnstone et al., 2010)

²See e.g. Akcigit et al. (2016), Gersbach and Schneider (2015) for recent contributions

³Baily and Montalbano (2017) discuss several case studies and carve out the role of public policy for the successful creation of innovation clusters.

⁴See https://ec.europa.eu/growth/industry/policy/cluster_de, last accessed: 13.11.2017

be recovered even if carbon prices are attractive. Local governments usually do not consider the positive spill-overs from sharing potential benefits internationally. Attempts to create innovation clusters via international agreements are complicated by two additional properties. First, cost considerations suggest focusing on few clusters, which requires international coordination. Second, basic research investments to create an innovation cluster are not contractible because it is difficult for one country to control to which extent basic research in another country is used for the development of new abatement technologies. Failure to detect an advanced technology may be due to lack of investment in basic research or simply to bad luck. Hence, the creation of innovation clusters has to rely solely on at least one country's incentives to make sufficient investments into basic research and become attractive for applied research firms to enter the innovation cluster.

Given these difficulties, we examine how innovation clusters for green technologies can be generated. We start from the condition that an international permit market exists or can be created. This implies some level of cooperation, which can be low or high. Our analysis can thus be applied to any emissions trading system and in particular to the European trading system, EU-ETS.

We consider a multi-country model with an existing permit market administered by an agency. In each country, polluting production firms operate with an existing abatement technology. The detection of the advanced technology is only possible if an innovation cluster is created. An innovation cluster is created if a country spends a fixed, country-specific amount on basic research and if applied research firms enter to detect the advanced technology. Since the detection of advanced technologies is uncertain, the probability that a new abatement technology is detected is higher if more applied research firms enter.

We capture the degree of cooperation on aggregate emissions reductions by a carbon price target instead. We focus on a carbon price, for the following three reasons. First, it is an easy way to parametrize cooperation between pure decentralization and perfect cooperation. Second, recent political initiatives—Chancellor Merkel and President Macron—have focused on a carbon price target for the EU-ETS. Third, a carbon price represents a focal point that may help successful negotiations (Weitzman (2014), Cramton et al. (2017)).

We note that a carbon price target in existing permit markets has to be imple-

mented by an agreement on some aggregate emissions target with a budget for the administrative agency to ensure that the market price will not fall below the target. As part of our investigation, we will outline how carbon price targets can be implemented. Indeed, a particular way to implement a carbon price target will be key to ensure the efficient creation of innovation clusters.

Our main insights are as follows. A minimum level of cooperation, i.e. a certain level of the carbon price, is needed for applied research firms to become active if an innovation cluster is created. Otherwise, investments into basic research will fail to attract applied research firms and an innovation cluster will not emerge. The incentives of local governments to invest in basic research are influenced by the level of cooperation and the amount of issued permits. An increase in cooperation or a reduction in the amount of grandfathered permits increases the incentives of a local government to invest in basic research. Still, efficiency may be improved by inducing the country with the lowest costs for basic research to create the innovation cluster. We show that climate policy that explicitly takes the role of innovation clusters into account can help to do so—and especially a combination of few permits grandfathered to the country with the lowest costs to create an innovation cluster, fair burden-sharing and the maximum amount of permits grandfathered possible. Our insights can also inform the discussion on carbon price levels initiated by the OECD, who discusses a gradual approach to achieve uniform carbon prices to realize some efficiency gains (OECD, 2016). Our insights can also inform the discussion initiated by the OECD (OECD, 2016) on a gradual approach to achieve uniform carbon prices for realizing some efficiency gains.

Our paper relates to the literature on environmental policy and innovation as well as on international carbon pricing. The literature on environmental policy and innovation focuses on applied research (see e.g. Vollebergh and Kemfert (2005) for a comprehensive overview). The importance for environmental policy to send the right price signals for applied research firms is established in Requate (2005), for instance. International carbon pricing is discussed in Weitzman (2014) and Cramton et al. (2017), among others⁵, but usually not in connection with an emissions trading system.⁶ To our knowledge, climate policy with innovation clusters has

⁵The discussion goes at least back to the famous paper of Weitzman (1974).

⁶There is a literature on how to combine price floors with emissions trading, see e.g. Wood and Jotzo (2011). The discussion of hybrid approaches under uncertainty, with both price floor

not been discussed so far.

In the next section, we outline the model. In Sections 3 to 5, we describe the different levels of the model in more detail and presents results. In Section 6, we discuss how an innovation cluster can be induced by international climate policy. We complete the paper with a discussion of the results and a conclusion in Section 7.

2 The Levels of the Model

We consider a multi-country model with greenhouse gas emissions and innovation clusters. Innovation clusters consist of basic and applied research and are hosted by individual countries. Countries are indexed by $i, j \in \{1, \dots, n\}$ and in each country, there is a local government and a polluting production firm. If countries host an innovation cluster, there are also applied research firms in that country. Initially, only an old technology is available, but in an innovation cluster, an advanced technology may be detected. An emissions trading system with carbon targets conditional on the technological level exists and is administered by an international agency. The price target to achieve the carbon target is denoted by p_T , with $T \in O, A$ standing for the old (O) and advanced (A) technology.

The model comprises three levels, namely an international, a political and an economic level. At the international level, countries determine the organization of and cooperation in the emissions trading system. This includes setting the carbon price target and an initial amount of permits issued for each country. The political level involves the decision of the local government, who can decide on basic research investments—i.e. whether to create an innovation cluster—and on the number of permits to grandfather to the local production firms. The economic level comprises the decisions taken by the local production firms and the applied research firms.

We first describe and analyze the economic level of the model for given political and international decisions. Then, we describe the political and the international level.

and price ceiling goes back to Roberts and Spence (1976).

3 The Economic Level

In this section, we describe the set-up of the economic level of the model and present its solution. We contrast the market outcome with the socially optimal solution.

3.1 The Set-up of the Economic Level

In each country i , the local production firm i produces an output, which leads to emissions \bar{e}_i , with $\bar{e}_i \geq 0$. For ease of notation, the production firm in country i is also denoted by i . Production firm i can reduce emissions by abating an amount $e_i \geq 0$ at costs $g_t(e_i)$. The lower case ‘ t ’, $t \in \{o, a\}$, refers to the technology actually used by a production firm. The old technology, indicated by the superscript ‘ o ’, is available for free. We assume quadratic abatement costs of the form $g_o(e_i) = b_o/2(e_i)^2$. In an innovation cluster, the ‘advanced’ abatement technology $g_a(e_i) = b_a/2(e_i)^2$, indicated by the superscript ‘ a ’, may be detected. The advanced abatement technology lowers abatement costs, $b_a < b_o$.

The production firm is required to hold permits for the emissions not abated. It receives the amount of permits ϵ_i for free from the local government, and can buy additional or sell superfluous permits at the prevailing carbon price p_T . Note that ‘ T ’ indicates the technology level available at the global scale, while ‘ t ’ refers to the technology actually used by a production firm.

Damages from aggregate emissions in monetary terms for one country are

$$\delta \sum_{i=1}^n (\bar{e}_i - e_i) = \delta \left(\bar{E} - \sum_{i=1}^n e_i \right),$$

with aggregate baseline emissions $\bar{E} = \sum_{i=1}^n \bar{e}_i$ and marginal damages $\delta > 0$. Countries face identical damages, but differ in their baseline emissions. Identical damages allow for explicit solutions. The mechanism we propose can also be applied when damage functions differ across countries.

To form an innovation cluster, a country—represented by its local government—has to invest an amount F_i of basic research in monetary terms ($F_i > 0$). If a local government has invested F_i , applied research firms can enter the innovation cluster

and benefit from local spillovers. Specifically, if an applied research firm enters and invests the fixed amount x ($x > 0$) it can detect the advanced technology with probability π ($0 < \pi < 1$). If there is no basic research, the success probability of an applied research firm is zero.⁷ The innovation success is uncorrelated across applied research firms. If k applied research firms become active in the innovation cluster, the overall probability of detecting the advanced technology is

$$\Pi(k) = 1 - [1 - \pi]^k.$$

Some remarks on the interpretation of the set-up are in order. First, we assume that costs F_i are country-dependent, to reflect that some countries have already invested into basic research in the considered area or that some countries may be more productive in basic research, e.g. have a better university system. Once an innovation cluster is created, the success probability π is the same across clusters. This simplifies the analysis, but is not essential.⁸ Second, once the local government made the investment in basic research, applied research firms enter, benefiting from local spillovers. Without these spillovers, the success probability would be zero. Last, we assume that there is a large number of potential applied research firms that are mobile across countries. The idea is that a subset of individuals can turn into an innovator if conditions are sufficiently attractive.⁹

If at least one applied research firm (world-wide) is successful, a patent holder is determined by fair randomization between all successful applied research firms.¹⁰ The patent holder sets a licensing fee f ($f > 0$) and production firms decide whether to adopt the advanced technology at this fee. Production firms in all n countries have the same ability to adopt the advanced technology.

⁷This represents a stark assumption of local spillovers from basic research to applied research.

⁸Indeed if the country with the best basic research system can also produce the maximal success probability for applied research firms, no change of an analysis would be required for this scenario.

⁹We can assume that each country is populated by a set of agents and a subset of these agents can become entrepreneurs (see e.g. Gersbach et al. (2018)).

¹⁰The results are identical for joint patent holding of all successful firms and sharing of revenues.

3.2 The Market Solution

We next provide the solution for the economic level of the model. For this purpose, we assume that a carbon price target p_T , $T \in O, A$, has been set at the international level and will be enforced by the administrative agency. Moreover, production firms have received grandfathered permits ϵ_i . Finally, we assume that one country has invested in basic research. Then, the economic level of the model can be represented by a three stage game:

1. Research activity of applied research firms,
2. Licensing of new technology if detected,
3. Emissions abatement and permit trading of production firms.

We solve this three stage process backwards.

Stage 3: Emissions Abatement and Permit Trading of the Production Firms

Suppose that an advanced technology has been detected and that the production firm has chosen the technology g_t , $t \in \{o, a\}$. With grandfathered permits ϵ_i , production firms choose abatement level e_i by solving

$$\begin{aligned} \min_{e_i} \quad & g_t(e_i) + p_T[\bar{e}_i - \epsilon_i - e_i] \\ \text{FOC} \quad & p_T = g'_t(e_i) = b_t e_i, \end{aligned} \tag{1}$$

taking the permit price P_T , $T \in \{O, A\}$, as given.¹¹

For quadratic abatement costs, $e_i = \frac{p_T}{b_t}$. Production firms that use the same technology abate an identical amount of emissions. We therefore omit the index i and denote abatement decisions in the future by

$$e_{t,T} = \frac{p_T}{b_t}. \tag{2}$$

¹¹Global availability of the technology is depicted by T , $t = a$ is only possible if $T = A$, i.e. if the advanced technology is available. Otherwise, the problem of the production firm displayed in (1) is solved for $t = o$ and $T = O$.

We next turn to the license fee setting of the patent holder and the adoption of the advanced technology by the production firms.

Stage 2: License Fee Setting by the Patent Holder and Technology Adoption by Production Firms

Given the advanced technology is detected and $p_T = p_A$ prevails, production firm i 's maximal willingness to pay for the advanced technology, denoted by WTP_i , is

$$\begin{aligned} WTP_i &= g_o(e_{o,A}) + p_A[\bar{e}_i - \epsilon_i - e_{o,A}] - g_a(e_{a,A}) - p_A[\bar{e}_i - \epsilon_i - e_{a,A}] \\ &= g_o(e_{o,A}) - g_a(e_{a,A}) + p_A[e_{a,A} - e_{o,A}] =: WTP. \end{aligned} \quad (3)$$

The willingness to pay for the advanced technology is identical across production firms and independent of adoption decisions by other production firms. Hence, if the advanced technology is detected, the patent holder sets the license fee according to $f = WTP$ and all production firms adopt the advanced technology. Then, $e_i = e_{a,A}$ for all production firms. Using functional forms and (2), we can write the fee that equals (3) as a function of p_A . Proposition 1 summarizes the result.

Proposition 1

All production firms adopt the advanced technology at the fee

$$\hat{f}(p_A) := p_A^2 \frac{b_o - b_a}{2b_a b_o}. \quad (4)$$

Next, we turn to the decision of the applied research firms.

Stage 1: Research Activity of Applied Research Firms

Given that one local government has invested into basic research, applied research firms decide whether to become active in this innovation cluster based on expected profits. An applied research firm only earns profits from licensing the advanced technology to all production firms if it is the patent holder. The probability for an applied research firm to detect an advanced abatement technology and to become patent-holder is

$$\frac{\Pi(k)}{k} \approx \frac{\pi}{1 + \pi(k - 1)}.$$

The approximation works well—especially for small π (see Gersbach and Riekhof (2017)), which is a plausible assumption for the development of breakthrough abatement technologies.

Applied research firms become active as long as expected profits are positive and thus the number of active applied research firms k is based on the expected zero profit condition,

$$nf \frac{\Pi(k)}{k} - x \approx nf \frac{\pi}{1 + \pi(k - 1)} - x = 0.$$

We can re-arrange the equation and write the number of active applied research firms as a function of p_A by using (4). The next proposition summarizes results.

Proposition 2

If one innovation cluster is created, \hat{k} applied research firms with

$$\hat{k}(p_A) = \frac{\pi - 1}{\pi} + \frac{nf(p_A)}{x} \tag{5}$$

become active in the cluster.

Since $\hat{k}(p_A)$ is a real number, it is convenient to treat it as a real number in the analysis. Of course, the number of applied research firms becoming active is equal to the largest natural number smaller than $\hat{k}(p_A)$.

An important remark is in order. As the success of applied research firms are stochastically independent, and applied research firms are mobile, the number of active applied research firms would be the same as given in (5) if more than one innovation clusters are created by basic research. Hence, from a welfare perspective one innovation cluster is sufficient to reap all possible benefits from innovation activities.¹²

We assemble some intuitive properties of $\hat{k}(p_A)$ in the following corollary.

¹²We will comment in Section 7 on extensions of the model in which more than one cluster could be beneficial.

Corollary 1

(i) An increase of the carbon price target when the advanced technology is detected increases the number of applied research firms,

$$\frac{\partial \hat{k}}{\partial p_A} > 0.$$

(ii) Innovation clusters are operating with at least one applied research firm if

$$\frac{n\hat{f}(p_A)}{x} \geq \frac{1}{\pi}.$$

(iii) An increase in the marginal abatement costs of the advanced technology for a given level of emissions reduces the number of applied research firms,

$$\frac{\partial \hat{k}}{\partial b_A} < 0.$$

The second property in Corollary 1 indicates that the number of applied research firms depends on the license income in relation to the research costs and the success probability. The license income, in turn, is related to the production firms' willingness to pay for the advanced technology, such that the number of applied research firms increases with the prevailing permit price and decreases with the prevailing abatement costs (Corollary 1 (i) and (iii)).

Next, we consider which abatement level and what kind of research activity is optimal from the perspective of a global social government.

3.3 The Socially Optimal Solution

Before we proceed with the political and international level, it is useful to introduce the socially optimal solution. We assume that a social planner can dictate abatement in all countries and that the social planner can determine in which countries basic research investment takes place as well as how many applied research firms become active. The social planner thus characterizes the optimal solution

if countries cooperate perfectly to maximize aggregate welfare.¹³ Let the superscript ‘*’ denote variables connected to the optimal solution. Then, Proposition 3 characterizes the socially optimal solution.

Proposition 3

The socially optimal abatement level of each production firm is

$$e^* = \frac{n\delta}{b_a} - \frac{1}{b_a} \left[\frac{[1 - \pi]2x[b_o - b_a]}{\pi n} \right]^{0.5}. \quad (6)$$

Suppose $\frac{xk + \min\{F_i\}}{\Pi(k)} \leq \frac{b_o - b_a}{2} \sum_{i=1}^n [e^]^2$. Then, the optimal solution is characterized by one innovation cluster with*

$$k^* = \frac{[\frac{\pi[1-\pi]n[b_o-b_a]}{2x}]^{0.5}n\delta - b_o[1-\pi]}{b_a\pi}$$

applied research firms, with the innovation cluster being created by country j with $F_j = \min\{F_i\}$.

Proof of Proposition 3.

See Appendix A. □

From a global perspective, it is optimal to create the innovation cluster in the country with the lowest costs for basic research, i.e. in country j with $F_j = \min\{F_i\}$. Still, it is only optimal to create an innovation cluster if total costs—i.e. costs for basic and applied research—are lower than the expected gains, i.e. if¹⁴

$$\underbrace{xk + \min\{F_i\}}_{\text{Total research costs}} \leq \underbrace{\Pi(k) \frac{b_o - b_a}{2} n [e^*]^2}_{\text{Expected gains}}. \quad (7)$$

In this paper, we examine under which conditions innovation clusters are (not) created, assuming the economy is in a situation in which it will be optimal to have an innovation cluster. Thus, we assume (7) holds for the rest of the paper.

¹³The same solution could be achieved when the social planner can only decide on how many permits are issued by each country instead of directly dictating abatement in all countries, see Proof of Proposition 4.

¹⁴For a derivation see Proof of Proposition 3.

Proposition 4 summarizes results on how the first-best abatement level can be induced in a market setting.

Proposition 4

The optimal abatement level e^ can be induced by setting carbon prices according to*

$$p_A^* = n\delta - \left[\frac{[1 - \pi]2x[b_o - b_a]}{\pi n} \right]^{0.5} \quad \text{and} \quad p_O^* = \frac{n\delta b_o}{b_a} - \frac{b_o}{b_a} \left[\frac{[1 - \pi]2x[b_o - b_a]}{\pi n} \right]^{0.5}, \quad (8)$$

depending on the detection of the advanced technology.

Proof of Proposition 4.

See Appendix A. □

The price menu p_A^*, p_O^* ensures the first-best abatement level in a setting without a global social planner, independent of the detection of the advanced technology. It is not the classical result that the permit price equals marginal damages. The reason for the difference relates to the inclusion of different, uncertain technologies.¹⁵

While p_T^* can ensure the optimal abatement level, the price menu can neither simultaneously ensure k^* nor that the innovation cluster is created in country j . Scaling the license fee can lead to $\hat{k} = k^*$, but we abstract from the potential non-optimal number of applied research firms to focus on the creation of innovation clusters. In Section 6, we present a mechanisms that induces country j to create the innovation cluster. This mechanism can easily be extended to include the scaling of the license fees to ensure $\hat{k} = k^*$. In the following, we describe the international institutions that define the decision space of the local government and the setting in which our mechanism has to be implemented.

4 The International Level

Given an emissions trading system exists, countries need to decide on carbon prices, on the initially distributed amount of permits as well as on burden-sharing.

¹⁵Either permit prices or permits issued have to be conditional on the technological level to achieve first-best emissions for a given technology level.

We assume that countries have agreed on equal burden-sharing and that the initial amount of distributed permits should be set to ensure the carbon price target without the need of additional expenditures by the countries. The countries' decision on the carbon price target reflects their willingness to cooperate in abatement. In the following, we will first present the carbon price as a measure of cooperation in abatement, before we discuss the practical implementation of the targeted price, taking equal burden-sharing and the restrictions on permit issuance to ensure no additional expenditures by the countries into account.

4.1 Cooperation on Abatement

We depict the level of cooperation between countries by the agreed carbon price target relative to the carbon price needed to achieve the first-best level depicted in Proposition 4. We describe the set-up in more detail in the following.

Countries cooperate to set a menu of carbon prices $p_O = \lambda p_O^*$ and $p_A = \lambda p_A^*$ ($\underline{\lambda} \leq \lambda \leq 1$). The scalar λ measures the level of cooperation between the countries, with $\lambda = \underline{\lambda}$ denoting no cooperation, and $\lambda = 1$ full cooperation. The level $\underline{\lambda}$ corresponds to the permit price when countries individually decide on the amount of permits.¹⁶ Also, in this case, a positive permit price obtains. The optimal prices p_O^* and p_A^* (see Proposition 4) can only be obtained under full cooperation.

For this paper we take the level of cooperation on abatement as given and investigate how innovation clusters may emerge. There are many theories how a particular level of cooperation develops. A simple rationale is the likelihood of a complete breakdown of cooperation if one country withdraws itself from the agreement. If the likelihood is low (high), high (low) carbon price targets can be achieved.

A brief remark is in order on how different cooperation levels impact local production firms' abatement. Given p_A and p_O , abatement levels are the same under

¹⁶In our set-up, this solution is given by $\underline{\lambda} = \frac{\tilde{p}_T}{p_T^*}$, with $\tilde{p}_T = g'_t(e_{e,T}) = b_t \frac{\bar{E} - \tilde{E}}{n}$ and \tilde{E} denoting the total amount of permits when each country decides individually on local permits issuance (see Gersbach and Riekhof (2017)).

both scenarios, and we denote this level by $\hat{e}(\lambda)$ given by:¹⁷

$$\hat{e}(\lambda) := e_{a,A} = e_{o,O} = \lambda e^*. \quad (9)$$

We now turn to the discussion of implementing the carbon price.

4.2 Implementing Permit Issuance and a Carbon Price

Given a level of cooperation represented by $p_T = \lambda p_T^*$, we next discuss how such price targets are implemented in the permit market without additional funds from the local governments and how permit issuance works. We state initial permit allocation given countries agreed upon equal burden-sharing and describe the trading process.

Based on equal burden-sharing, we assume that countries agreed on some initial allocation of permits across countries, given by

$$\bar{\epsilon}_i = \alpha \bar{e}_i \quad (0 \leq \alpha < 1).$$

Permits are initially issued to the local governments. Local governments can buy additional permits or sell superfluous permits to grandfather an amount of ϵ_i to their local production firms. Both local governments as well as local production firms trade on the permit markets.

The administrative agency ensures that the carbon price target prevails in the permit market. The residual budget of the agency is equally distributed between all countries. The implementation of initial permit allocation is feasible if the residual budget of the agency is non-negative, i.e. if

$$\begin{aligned} & p_T \sum_{i=1}^n \left(\underbrace{\bar{e}_i - e_i - \epsilon_i}_{\text{bought by prod. firm } i} + \underbrace{\epsilon_i - \alpha \bar{e}_i}_{\text{bought by local government } i} \right) \geq 0, \\ \Leftrightarrow & p_T \sum_{i=1}^n ((1 - \alpha)\bar{e}_i - e_i) \geq 0, \quad T \in \{O, A\}. \end{aligned} \quad (10)$$

We obtain

¹⁷Based on Equation (2) and Proposition (4).

Lemma 1

Carbon price targets $p_T, T \in \{O, A\}$, are implementable if and only if

$$\alpha \leq \bar{\alpha}(\lambda) := 1 - \lambda \underbrace{\frac{ne^*}{\bar{E}}}_{<1}.$$

Proof of Lemma 1.

Based on (10) and using (9),

$$\lambda p_T^* [[1 - \alpha] \bar{E} - n\lambda e^*] \geq 0 \quad \Rightarrow \quad [1 - \alpha] \bar{E} \geq n\lambda e^* \quad \Leftrightarrow \quad 1 - \lambda \underbrace{\frac{ne^*}{\bar{E}}}_{<1} \geq \alpha,$$

which is fulfilled for any λ , $1 \geq \lambda \geq \underline{\lambda} > 0$, as there exists an α for which the condition holds when $\lambda = 1$. □

Some remarks are in order. First, the condition of a non-negative residual budget of the administrative agency gives an upper bound on α , i.e. on the amount initially agreed upon among countries. Second, for the budget of the agency it is irrelevant whether the local government buys more permits from the agency than $\alpha \bar{e}_i$ and grants them to their local production firms. The more the local government buys the more permits the corresponding production firm will sell in the permit market. Buying more permits by the local government simply redistributes revenues within a country without affecting the budget of the agency. Third, for every level of cooperation, there is an α that can ensure a non-negative budget. The level of cooperation and the share of grandfathered permits are inversely related: A high level of cooperation (high λ) means a high carbon price, and in order for the agency to ensure the price target without an additional budget, the grandfathered share α needs to be relatively low.

5 The Political Level

Next, we consider the decision problem of local governments. Local governments want to minimize local costs by deciding on basic research investment and on the

amounts of permits grandfathered to the local production firm. The local costs K_i are given as follows:

$$\begin{aligned}
K_i = & \Pi(k)[f(p_A) + g_A(p_A) + p_A[\bar{e}_i - \epsilon_i - e_{a,A}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{a,A}] + p_A[\epsilon_i - \bar{\epsilon}_i] \\
& + \frac{1}{n}[p_A \sum_{i=1}^n -[\bar{e}_i - \epsilon_i - e_{a,A}] - [\epsilon_i - \bar{\epsilon}_i]] \\
& + [1 - \Pi(k)][g_o(p_O) + p_O[\bar{e}_i - \epsilon_i - e_{o,O}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{o,O}] + p_O[\epsilon_i - \bar{\epsilon}_i] \\
& + \frac{1}{n}[p_O \sum_{i=1}^n -[\bar{e}_i - \epsilon_i - e_{o,O}] - [\epsilon_i - \bar{\epsilon}_i]] + F_i. \tag{11}
\end{aligned}$$

Local costs include the licensing fee—if relevant—, abatement costs, trading costs of the local production firm, damages, trading costs of the local government and possible redistribution of a positive budget of the administrative agency, all conditional on whether the advanced technology is detected or not. Costs for applied research do not have to be considered, as expected profits of applied research firms are zero. Costs for basic research have to be added if the local government decides to create an innovation cluster.

Given local costs, we first consider the amount of permits the local government grandfathers to the local production firm.

5.1 Grandfathering Permits to Local Production Firms

The local government's decision to grandfather ϵ_i to the local production firm may imply buying (or selling) $\epsilon_i - \alpha \bar{\epsilon}_i$ from (to) the administrative agency at the prevailing price. Lemma 2 summarizes the results on the choice of grandfathered permits ϵ_i to local production firm i .

Lemma 2

The amount grandfathered to the local production firm ϵ_i is indetermined.

Proof of Lemma 2.

See Appendix B. □

The reason for the result of Lemma 2 is that the local government considers *total* local costs. In such a set-up it does not matter for a country whether the costs are paid by the local government or by the local production firm. If a local government buys additional permits at the given carbon price, the administrative agency obtains revenues. As abatement is independent of the amount of grandfathered permits, the production firm will sell the additional permits at the given price. The agency uses the revenues obtained from selling to the local government to buy the permits. The process is neutral for the agency's budget.

Note that besides the production firms' optimal abatement $\hat{e}(\lambda)$, the license fee $\hat{f}(\lambda p_A^*)$ and the number of active applied research firms $\hat{k}(\lambda p_A^*)$ are also independent of permit issuance decisions of governments, but of course all depend on the level of cooperation between countries. Furthermore, the sum of issued permits does not tell anything about aggregate emissions. What matters is the carbon price target which determines how many permits will ultimately be used to cover emissions.

Next, we consider the local government's decision on basic research.

5.2 Deciding on Basic Research Investments

To consider the local government's decision on basic research, it is useful to define total costs denoted by K_i^{IC} when some other country invested into basic research to create an innovation cluster. As the choice of ϵ_i does not matter, and with $\bar{\mathcal{E}} := \sum_{i=1}^n \bar{\epsilon}_i$, these total costs are given by

$$K_i^{IC} = \Pi(k)[f(p_A) + g_A(p_A) + p_A[\bar{e}_i - \bar{\epsilon}_i - e_{a,A}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{a,A}] - \frac{p_A}{n}[\bar{E} - \bar{\mathcal{E}}] - p_A e_{a,A}] \\ + [1 - \Pi(k)][g_o(p_O) + p_O[\bar{e}_i - \bar{\epsilon}_i - e_{o,O}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{o,O}] - \frac{p_O}{n}[\bar{E} - \bar{\mathcal{E}}] - p_O e_{o,O}].$$

If no local government invests in basic research and no innovation cluster is created, only the old technology is available and total costs, denoted by K_i^{NIC} , are given by

$$K_i^{NIC} = g_o(p_O) + p_O[\bar{e}_i - \bar{\epsilon}_i - e_{o,O}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{o,O}] + \frac{1}{n}[p_O \sum_{i=1}^n -[\bar{e}_i - \bar{\epsilon}_i - e_{o,O}]].$$

A local government invests in basic research and creates an innovation cluster if and only if no other country undertakes these investments and

$$K_i^{IC} + F_i \leq K_i^{NIC}. \quad (12)$$

Lemma 3 summarizes how—building on Condition (12)—the incentives of a local government to create an innovation cluster depend on the level of cooperation λ and grandfathered permits, reflected by α .

Lemma 3

The local government in country i invests in basic research if no other country invests and

$$\underbrace{F_i - \Pi(\hat{k}(\lambda p_A^*))}_{\text{Effective costs}} \underbrace{\lambda [p_O^* - p_A^*] [1 - \alpha] \left[\bar{e}_i - \frac{\bar{E}}{n} \right]}_{\text{Price change effect}} \leq \underbrace{\Pi(\hat{k}(\lambda p_A^*)) \hat{f}(\lambda p_A^*) \frac{b_o - b_a}{b_a}}_{\text{Expected gains}}. \quad (13)$$

Proof of Lemma 3.

See Appendix B. □

Condition (13) can be interpreted as follows. Country-unspecific expected gains from detecting the advanced technology, depicted on the right hand side (RHS), have to be at least as high as country-specific effective costs to induce an innovation cluster, depicted on the left hand side (LHS). In the following, we discuss both terms in more detail.

The expected gains depicted on the RHS are the license fee weighted by the reduction in marginal abatement costs with the advanced technology relative to the marginal abatement costs with the advanced technology, multiplied with the overall probability of detecting the advanced technology. As the licensing fee equals the production firms' willingness to pay to adopt the advanced technology, the RHS can be interpreted as gains from the advanced technology.

On the left hand side (LHS), we collect the country-specific terms. The first term depicts the investment costs for basic research. The second term depicts the change in costs or revenues from permit trading due to the detection of the advanced

technology, net of the redistribution of the administrative agency’s budget (see Equation (20) in the Appendix for details). It is driven by changes in the prevailing permit price due to the detection of the advanced technology. Accordingly, we term it the ‘Price-change effect’.

It can be positive or negative, depending on the country’s baseline emissions \bar{e}_i . In principle, one can classify the countries into three groups, namely countries with above-average baseline emissions $\bar{e}_i > \bar{E}/n$, with average baseline emissions $\bar{e}_i = \bar{E}/n$, and with below-average baseline emissions $\bar{e}_i < \bar{E}/n$. Countries with above-average baseline emissions—‘high-emissions’ countries—gain from the detection of the advanced technology, as the price to buy additional permits on the permit market is decreased. They face a negative price-change effect and their effective costs to induce an innovation cluster are reduced. Countries with below-average baseline emissions—‘low-emissions’ countries—lose from the detection of the advanced technology, as the price to sell superfluous permits on the permit market is decreased. They face a positive price-change effect and effective costs to induce an innovation cluster are increased. Countries with average baseline emissions are not affected.

Some further remarks are in order. First, although all countries initially receive an amount of permits that is in relation to their baseline emissions, $\bar{e}_i = \alpha \bar{e}_i$, the re-distribution of the remaining administrative agency’s budget by giving equal shares to all countries leads to the separation of the countries into groups with above or below average emissions. Second, if Condition (13) is fulfilled for several countries, local governments need to coordinate on who invests in basic research. Local governments decide simultaneously such that a coordination problem arises, with many possible solutions. A focal point¹⁸ in this coordination game may be the following: The local government in the country with the lowest effective costs (LHS in Equation (13)) invests, because that country gains the most from the detection of the advanced technology. This country may not be country j —the country with the lowest basic research costs—, because of the price-change effect. Another country with $F_i > F_j$, but with a negative price change effect may face the lowest effective costs to induce an innovation cluster. Second, if Condition (13) is not fulfilled for any country, all countries may still benefit from jointly

¹⁸In game theory, a focal point (also called a ‘Schelling point’) refers to a solution that all players are likely to choose in the absence of communication.

financing basic research investment in one country. In such a situation, additional mechanisms are needed, as basic research is not contractible.

As the creation of an innovation cluster depends on α and λ , we will consider how the setting of these parameters influence the creation of an innovation cluster in the following. We then present a mechanism that solves the coordination and commitment problem and can thus help to create an innovation cluster even in difficult situations.

6 Inducing Innovation Clusters

In this section, we explore three different ways in which the international community may induce an innovation cluster when Condition (13) is initially not fulfilled for any country. First, we discuss the impact of cooperation. Then, we consider the amount of initially grandfathered permits. Last, we suggest a procedure with maximal grandfathering and fair burden-sharing. This mechanism also serves as coordination device for inducing the innovation cluster in country j .

Consider a low level of cooperation and a situation in which no country faces incentives to create an innovation cluster. Proposition 5 states how changes in cooperation on the international level can induce the creation of an innovation cluster.

Proposition 5

Suppose $\underline{\lambda} \leq \lambda^\circ < \check{\lambda} \leq 1$, with $\check{\lambda} = \min\{\check{\lambda}_i\}$ and $\check{\lambda}_i$ implicitly defined by

$$\frac{F_i}{\Pi(\hat{k}(\check{\lambda}_i p_A^*))} - \check{\lambda}_i [p_O^* - p_A^*] [1 - \alpha] \left[\bar{e}_i - \frac{\bar{E}}{n} \right] = \hat{f}(\check{\lambda}_i p_A^*) \frac{b_o - b_a}{b_a}, \quad i = 1, \dots, n, \quad (14)$$

based on (13).

Then, increasing the level of cooperation from λ° to λ with $1 \geq \lambda \geq \check{\lambda}$ leads to the creation of an innovation cluster.

Proof of Proposition 5.

See Appendix B. □

The intuition is as follows. Higher cooperation increases carbon prices and makes

the advanced technology more attractive for production firms. Their willingness to pay to adopt the advanced technology increases, and so does the licensing fee. The gains from an innovation cluster increase (e.g. RHS in Equation (14)). With the higher licensing fee, more applied research firms are attracted by the higher expected profits, increasing the overall probability to detect the advanced technology. For high-emissions countries, the price-change effect increases and decreases effective costs for basic research.

Note that for low-emissions countries, the price-change effect goes in the opposite direction than for high-emissions countries. In principal, the effect could determine the overall outcome, implying that also a lower level of cooperation may induce an innovation cluster. Still, if cooperation is so low that

$$\frac{n(\lambda p_A^*)^{2\frac{b_o-b_a}{2b_a b_o}}}{x} > \frac{1-\pi}{\pi}$$

does not hold, Condition (13) is never fulfilled and an increase in cooperation is a prerequisite for any further discussion on innovation clusters (see also Corollary 1, (ii)).

Proposition 6 summarizes the impact of changes in the amount of initially grandfathered permits on incentives to create an innovation cluster. To do so, it is useful to introduce the index $h = 1, \dots, \bar{h}$ for the ‘high-emissions’ countries with above-average baseline emissions $\bar{e}_i > \frac{\bar{E}}{n}$.

Proposition 6

Suppose $0 \leq \tilde{\alpha} < \alpha^\circ \leq \bar{\alpha}$, with

$$\tilde{\alpha} = \max \left\{ 1 - \frac{\frac{F_h}{\Pi(k(\lambda p_A^*))} - \hat{f}(\lambda p_A^*)^{\frac{b_o-b_a}{b_a}}}{\lambda[p_O^* - p_A^*] \left[\bar{e}_h - \frac{\bar{E}}{n} \right]}, \quad h = 1, \dots, \bar{h} \right\} \quad (15)$$

based on (13).

Then, decreasing the share of grandfathered permits from α° to α with $0 \leq \alpha \leq \tilde{\alpha}$ leads to the creation of an innovation cluster.

Proof of Proposition 6.

See Appendix B. □

The intuition is as follows. If the share of grandfathered permits is too high, there is no incentives for high-emissions countries to invest in an innovation cluster.¹⁹ If α is lower, high-emissions countries want to buy more permits. Creating an innovation cluster to detect the advanced technology becomes more attractive.

Still, inducing innovation via increased cooperation (λ) or reduced grandfathering (α) faces several problems. First, there is a coordination problem and countries are unlikely to coordinate on country j to create the innovation cluster. Second, α may have to be comparatively low if F_i s are large. Last, if the country that creates the innovation cluster is a high-emissions country, it faces a double burden: It must buy a large amount of permits (to have incentive to create an innovation cluster), and it bears costs F_i to create the innovation cluster.

To face these problems, we formulate three desiderata for an approach to induce an innovation cluster. First, country j should invest. Second, there should be a fair sharing of the overall burden. Third, there should be maximal grandfathering for the given cooperation level.

We present the ‘InCG procedure’ (Innovation-Cluster-Grandfathering procedure), which fulfils all described desiderata. The procedure is as follows:

- Country j receives permits $\tilde{\epsilon}$ from the administrative agency (to ensure that an innovation cluster is created),
- Countries $i \neq j$ receive permits $\tilde{\alpha}\tilde{e}_i$ (to ensure a non-negative budget of the administrative agency),
- Country j receives $\tilde{\pi}$ (equally well-off condition).

A few additional remarks are in order before we present the results in Proposition 7. First, country j receives no share from the residual budget of the agency. Second, to have maximal grandfathering, but still ensuring a non-negative budget of the agency, we assume a zero budget in case of the lower carbon price (p_A). Last, the equally well-off condition requires that country j is equally well-off when it creates an innovation cluster compared to the situation when another country does so. We assume that this other country is identical to j to simplify the analysis.

¹⁹For low-emissions countries, an increase in α would make an innovation cluster more likely, but one would expect $\alpha = \bar{\alpha}$, as local governments often use grandfathering to gain the support from industry. Accordingly, we do not examine this case in more detail.

Proposition 7

There exists a uniquely determined combination of $\tilde{\alpha}, \tilde{\epsilon}, \tilde{\pi}$ defined by

- the incentive constraint to create an innovation cluster in country j

$$\frac{F_j}{\Pi(\hat{k}(p_A))} - [p_O - p_A][\bar{e}_j - \tilde{\epsilon}_j - \hat{e}(\lambda)] \leq \hat{f}(\lambda p_A^*) \frac{b_o - b_a}{b_a}, \quad (16)$$

- the budget constraint of the administrative agency

$$p_A[\bar{E} - n\hat{e} - \alpha\bar{E} + \alpha\bar{e}_j - \tilde{\epsilon}] = \tilde{\pi}, \quad (17)$$

- and the equally well-off condition

$$\begin{aligned} & \Pi(k)[-p_A\bar{e}_j\alpha] + [1 - \Pi(k)][-p_O\bar{e}_j\alpha] \\ & + \frac{1 - \Pi(k)}{n - 1}[p_O[[1 - \alpha]\bar{E} - n\hat{e} + \alpha\bar{e}_j - \tilde{\epsilon}] - \tilde{\pi}] \\ & = \Pi(k)[-p_A\tilde{\epsilon}] + [1 - \Pi(k)][-p_O\tilde{\epsilon}] + F_j - \tilde{\pi}, \end{aligned} \quad (18)$$

which characterizes the InCG-procedure and implements one innovation cluster in country j .

Proof of Proposition 7. See Appendix B. □

The intuition is as follows. For $\tilde{\epsilon}$ rather small, country j faces a strong negative price-change effect such that effective costs for basic research are low. The incentive constraint (16) for country j is satisfied. The share α is set at the level that generates the positive budget for the administrative agency to compensate country j via $\tilde{\pi}$ (equally well-off condition). Figure 1 in Appendix C illustrates the outcome.

Several remarks are in order. In principal, $\tilde{\epsilon} < 0$ is possible, but difficult to enforce. Although $\tilde{\pi} < 0$ is theoretically also possible, it is not likely to occur. It means that country j has to pay the other countries to be equally well-off compared to a situation without creating the innovation cluster. In this situation, the international community can induce country j to create an innovation cluster without using the InCG-procedure. A more binding constraint is that $0 \leq \alpha \leq 1$. If $\alpha > 1$, the countries initially receive a negative amount of permits. This

is similar to $\tilde{\epsilon} < 0$, and thus possible, but difficult to enforce. With $\alpha < 0$, the countries would receive more permits than their initial baseline emissions, an unlikely situation. Last, besides being a way to ensure an innovation cluster, the InCG-procedure is also a way for countries to coordinate on country j to create the innovation cluster and thus to increase efficiency.

7 Discussion and Conclusion

Innovation clusters appear to be crucial for technological solutions to slow down climate change. We discuss whether international cooperation on climate policy can induce innovation clusters. Innovation clusters are created by local governments through investments into basic research. Building on the knowledge from basic research, applied research firms search for an advanced abatement technology. Innovation clusters for green technologies are not contractible on an international level, interact with climate policy, and thus require sophisticated procedures to be initiated.

We consider the case of an international emissions trading system, with the level of international cooperation reflected in a carbon price target. We find that when carbon prices are set too low, applied research firms have no incentives to use the knowledge created from basic research to search for advanced abatement technologies. The increase of carbon prices, in turn, has repercussions on incentives of local governments to invest in basic research in the first place. At the level of the local government, the repercussions can, in principle, either increase or decrease the incentives to create an innovation cluster. These results suggest that only an integrated approach that considers the interlinkages between the creation of an innovation cluster and climate policy can result in technological advances to slow down climate change.

We suggest an approach that we call ‘Innovation-Cluster-Grandfathering’ (InCG) procedure that combines initial permit allocation with fair burden-sharing as a promising way to induce a successful innovation cluster in an efficient way, even under adverse conditions. Our InCG-procedure aims for maximal grandfathering, while auctioning some permits to use the revenues to financially support the country that builds the innovation cluster. The idea is that the country that creates

the innovation cluster should be made equally well-off in expectation compared to a situation in which another, identical country would resume the role of the innovation cluster creator.

Of course, one could solve the given problems differently: e.g. with full auctioning of permits and the use of the revenues to finance an innovation cluster. Still, countries prefer grandfathering to reduce opposition from industry, and our InCG-procedure combines grandfathering with the idea to use permit auctioning revenues to support the creation of an innovation cluster. If no advanced technology is detected, the country that created the innovation cluster has to buy relatively many emissions permits at a high price. Instead of putting all the risk on one country, one may consider an ex-post condition instead. As the creation of an innovation cluster is not contractible, a trade-off between incentives and insurance exists. The same may hold when creating joint basic research projects. The risk is shared, but incentives may be reduced.

Our model could be extended in different ways. One could explicitly model asymmetric information or include transaction costs of setting up the administrative agency. Also, one could introduce several clusters that focus on different technologies. If all technologies are equally good, some applied research firms would focus on one technology, others on another technology, and final revenues from licensing would be shared. The outcome would be very similar to the results presented. In a situation with different technologies, our proposed InCG-procedure could be extended to serve as a coordination device that reduces the doubling of research effort.

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A Proofs: Optimal solution

Proof of Proposition 3.

The global social optimum is characterized by

$$\min_{k, e_i} \Pi(k) \left[\sum_{i=1}^n \frac{b_a}{2} e_i^2 \right] + n\delta \sum [\bar{e}_i - e_i] + [1 - \Pi(k)] \left[\sum_{i=1}^n \frac{b_o}{2} e_i^2 \right] + xk,$$

with first order conditions

$$\begin{aligned} \Pi(k)[b_a e_i] + [1 - \Pi(k)][b_o e_i] - n\delta &= 0 \\ \Pi(k)'_k \left[\sum_{i=1}^n \frac{b_a}{2} e_i^2 - \sum_{i=1}^n \frac{b_o}{2} e_i^2 \right] + x &= 0, \end{aligned}$$

leading to

$$\begin{aligned} k^* &= \frac{\pi - 1}{\pi} + \frac{e^*}{\pi} \left[\frac{\pi[1 - \pi]n[b_o - b_a]}{2x} \right]^{0.5} = \frac{[\frac{\pi[1 - \pi]n[b_o - b_a]}{2x}]^{0.5} n\delta - b_o[1 - \pi]}{b_a \pi} \\ e^* &= \frac{n\delta}{b_a} - \frac{1}{b_a} \left[\frac{[1 - \pi]2x[b_o - b_a]}{\pi n} \right]^{0.5}. \end{aligned}$$

An innovation cluster is optimal if

$$\begin{aligned} &\Pi(k) \left[\sum_{i=1}^n \frac{b_a}{2} [\bar{e}_i - \epsilon_i]^2 \right] + [1 - \Pi(k)] \left[\sum_{i=1}^n \frac{b_o}{2} [\bar{e}_i - \epsilon_i]^2 \right] + xk + \min\{F_i\} \\ &\leq \sum_{i=1}^n \frac{b_o}{2} [\bar{e}_i - \epsilon_i]^2 \\ &\Leftrightarrow \frac{xk + \min\{F_i\}}{\Pi(k)} \leq \frac{b_o - b_a}{2} \sum_{i=1}^n [\bar{e}_i - \epsilon_i]^2. \end{aligned}$$

Obviously, costs from a global perspective are minimized when the country with

the lowest costs for basic research makes the investment. \square

Proof of Proposition 4.

Production firms' abatement is according to $e_{t,T} = p_T/b_t$ (see Stage 4). With p_T^* , $e^* = p_T^*/b_t$, such that $p_T^* = b_t e^*$ implements socially optimal abatement levels.

Note that, as $e_i = \bar{e}_i - \epsilon_i$, an initial allocation of permits according to $\epsilon_i^* = \bar{e}_i - e^*$ can also implement the socially optimal solution in terms of abatement. \square

B Further Proofs

Proof of Lemma 2.

We assume that some other country invested into basic research. Then, the costs considered by local government i given in (11) (with $F_i = 0$) can be written as

$$\begin{aligned} & \Pi(k)[f(p_A) + g_A(p_A) + p_A[\bar{e}_i - \bar{\epsilon}_i - e_{a,A}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{a,A}] \\ & \quad - \frac{p_A}{n}[\bar{E} - \bar{\mathcal{E}}] - p_A e_{a,A}] \\ & + [1 - \Pi(k)][g_o(p_O) + p_O[\bar{e}_i - \bar{\epsilon}_i - e_{o,O}] + \delta \sum_{i=1}^n [\bar{e}_i - e_{o,O}] \\ & \quad - \frac{p_O}{n}[\bar{E} - \bar{\mathcal{E}}] - p_O e_{o,O}], \end{aligned}$$

with $\bar{\mathcal{E}} := \sum_{i=1}^n \bar{\epsilon}_i$. It shows that the variable ϵ_i cancels out. \square

Proof of Lemma 3.

If we subtract K_i from both sides of (12), subtract F_i and divide by $\Pi(k)$ we obtain

$$\begin{aligned} -F_i/\Pi(k) & \geq [f(p_A) + g_A(p_A) - g_o(p_O) + p_A[\bar{e}_i - \bar{\epsilon}_i - e_{a,A}] - p_O[\bar{e}_i - \bar{\epsilon}_i - e_{o,O}] \\ & \quad + \delta n[e_{o,O} - e_{a,A}] + \frac{1}{n}[-p_A[\bar{E} - \bar{\mathcal{E}} - n e_{a,A}]] - \frac{1}{n}[-p_O[\bar{E} - \bar{\mathcal{E}} - n e_{o,O}]]]. \end{aligned} \tag{19}$$

Now, multiplying with -1 , insert for p_T and for $\bar{\epsilon}_i$, using that $e_{a,A} = e_{o,O} = \hat{e}$ and

isolating country-specific terms gives

$$\frac{F_i}{\Pi(\hat{k})} \overbrace{-[p_O - p_A] [[1 - \alpha]\bar{e}_i - \hat{e}]}^{\text{Impact from permit trade}} + \overbrace{\frac{[p_O - p_A]}{n} [[1 - \alpha]\bar{E} - n\hat{e}]}^{\text{Impact from redistribution of budget}} \leq B(\lambda p_A^*) \quad (20)$$

with $B(\lambda p_A^*) = g_o(p_O) - g_a(p_A) - \hat{f}(p_A) = \hat{f} \frac{b_o - b_a}{b_a} > 0$. This leads to (13). \square

Proof of Proposition 5.

Consider (14). The RHS increases in λ (see Equation (4)). The first term on the LHS decreases in λ , as the denominator increases with λ ,

$$\frac{\partial \Pi}{\partial \hat{k}} > 0 \text{ and } \frac{\partial \hat{k}}{\partial \lambda} > 0 \quad (\text{cp. Corollary 1, (i)}).$$

The second term on the LHS—the price-change effect—increases in λ for high-emissions countries, such that a larger amount is subtracted, leading to an overall lower LHS. Accordingly, increasing λ can lead to a situation in which Condition (13) is fulfilled at least for one country.

Note that an increase in λ may lead to a decrease in α to ensure that the carbon price target remains implementable (see Lemma 1), but that the change in α reinforces the impact of an increase in λ .

\square

Proof of Proposition 6.

No country invests if

$$\frac{F_i}{\Pi(\hat{k}(\lambda p_A^*))} - \lambda [p_O^* - p_A^*] [1 - \alpha] \left[\bar{e}_i - \frac{\bar{E}}{n} \right] > \hat{f}(\lambda p_A^*) \frac{b_o - b_a}{b_a} \text{ for } i = 1, \dots, n,$$

based on (13). Accordingly, the prevailing α is too high (low) for high (low)

emissions countries,

$$\begin{aligned} \text{for } \bar{e}_i > \frac{\bar{E}}{n}, \quad \alpha > 1 - \frac{\frac{F_i}{\Pi(\hat{k}(\lambda p_A^*))} - \hat{f}(\lambda p_A^*) \frac{b_o - b_a}{b_a}}{\lambda[p_O^* - p_A^*] \left[\bar{e}_i - \frac{\bar{E}}{n} \right]}, \\ \text{for } \bar{e}_i < \frac{\bar{E}}{n}, \quad \alpha < 1 - \frac{\frac{F_i}{\Pi(\hat{k}(\lambda p_A^*))} - \hat{f}(\lambda p_A^*) \frac{b_o - b_a}{b_a}}{\lambda[p_O^* - p_A^*] \left[\bar{e}_i - \frac{\bar{E}}{n} \right]}, \end{aligned}$$

and for Condition (13) to hold, it needs to be lowered (increased) for high (low) emissions countries. The critical value is depicted in Equation (15) for high-emissions countries. \square

Proof of Proposition 7.

Based on (19), with \tilde{e}_j instead of $\alpha \bar{e}_j$ and no share from the residual budget of the administrative agency, the Incentive constraint to create an innovation cluster for country j is

$$\frac{F_j}{\Pi(\hat{k}(p_A))} - [p_O - p_A][\bar{e}_j - \tilde{e}_j - \hat{e}(\lambda)] \leq \underbrace{g_O(p_O) - f(p_A) - g_A(p_A)}_{\hat{f}(\lambda p_A^*)(b_o - b_a)/b_a}. \quad (21)$$

It determines \tilde{e}_j . The zero budget of agency in case of the lower carbon price (p_A) to ensure a non-negative budget in both cases is

$$p_A[\bar{E} - n\hat{e} - \alpha\bar{E} + \alpha\bar{e}_j - \tilde{\epsilon}] = \tilde{\pi}. \quad (22)$$

When we take into account that the agency's budget is zero when $T = A$, the equally well-off condition requires

$$\begin{aligned} & \Pi(k)[\hat{f}(p_A) + g_a(p_A) + p_A[\bar{e}_j[1 - \alpha] - \hat{e}]] + [1 - \Pi(k)][g_o(p_O) + p_O[\bar{e}_j[1 - \alpha] - \hat{e}]] \\ & + \delta[\bar{E} - n\hat{e}] + \frac{1 - \Pi(k)}{n - 1}[p_O[[1 - \alpha]\bar{E} - n\hat{e} + \alpha\bar{e}_j - \tilde{\epsilon}] - \tilde{\pi}] \\ = & \Pi(k)[\hat{f}(p_A) + g_a(p_A) + p_A[\bar{e}_j - \tilde{\epsilon} - \hat{e}]] + [1 - \Pi(k)][g_o(p_O) + p_O[\bar{e}_j - \tilde{\epsilon} - \hat{e}]] \\ & + \delta[\bar{E} - n\hat{e}] + F_j - \tilde{\pi}, \end{aligned} \quad (23)$$

which can be reduced to (24)

Equation (21) uniquely determines \tilde{e}_j , independently from α and $\tilde{\pi}$. So we can

take its value as given.

Equation (23) reduces to

$$\underbrace{[\Pi(k)p_A + [1 - \Pi(k)]p_O]}_{:=\bar{P}}[\tilde{\epsilon} - \alpha\bar{e}_j] + \underbrace{\left[\frac{1 - \Pi(k)}{n - 1} \left[\frac{p_O}{p_A} - 1\right] + 1\right]}_{:=T}\tilde{\pi} = F_j. \quad (24)$$

Re-arrange (22) to obtain

$$\alpha = \frac{\tilde{\pi}}{p_A[\bar{e}_j - \bar{E}]} + \underbrace{\frac{n\hat{e} + \tilde{\epsilon} - \bar{E}}{\bar{e}_j - \bar{E}}}_{:=V} \quad (25)$$

and combine it with (23)

$$\begin{aligned} \bar{P} \left[\tilde{\epsilon} - \left[\frac{\tilde{\pi}}{p_A[\bar{e}_j - \bar{E}]} + V \right] \bar{e}_j \right] + T\tilde{\pi} &= \bar{P}\tilde{\epsilon} - \bar{P} \frac{\tilde{\pi}}{p_A[\bar{e}_j - \bar{E}]} \bar{e}_j - \bar{P}V\bar{e}_j + T\tilde{\pi} = F_j \\ \tilde{\pi} &= \frac{F_j - \bar{P}\tilde{\epsilon} + \bar{P}V\bar{e}_j}{T - \frac{\bar{P}\bar{e}_j}{p_A[\bar{e}_j - \bar{E}]}}. \end{aligned}$$

Plugging this back into (25) gives α . □

C Graphical illustration

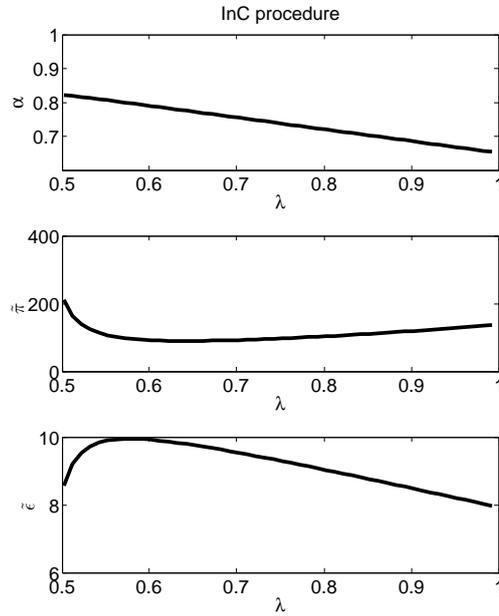


Figure 1: InCG procedure – Illustration

$14 = \bar{e}_j < \bar{E}/n = 20$; $n = 20$, $\delta = 6$, $\pi = 0.02$, $x = 10$, $b_O = 21$, $b_A = 0.7b_O$, $F_j = 5$, $\bar{E} = 400$;

Remark 1: For $\lambda < 0.5$, $k = 0$. Remark 2: $4.83 = \hat{e} \leq \bar{e}_i \approx \frac{\bar{E} - \bar{e}_j}{n-1} = 20.32$.