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Originally published in:
Resource and Energy Economics 65, https://doi.org/10.1016/j.reseneeco.2021.101229

Resource and Energy Economics 65 (2021) 101229

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

Permit markets, carbon prices and the creation of innovation clusters☆

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ARTICLE INFO

Article history:
Received 7 April 2020
Received in revised form 5 November 2020
Accepted 27 January 2021
Available online 31 January 2021

JEL classification:
H23
Q54
O32

Keywords:
International permit markets
Carbon prices
Innovation clusters
Research infrastructure
Applied R&D
Climate change mitigation
Externalities

ABSTRACT

Innovation clusters combining public and private effort to develop breakthrough technologies promise greater technological advances to slow down climate change. We use a multi-country model with an emission trading system to examine whether and how international climate policy can incentivize countries to create such innovation clusters. We find that a minimal carbon price is needed to attract applied research firms, but countries may nevertheless fail to invest in complementary research infrastructure. We construct a mechanism that leads to innovation clusters when emissions targets are set before uncertainty surrounding technological developments is resolved. It is a combination of low permit endowments for the country with the lowest costs to build the needed infrastructure, compensation for this country by profits from permit trade, and maximal possible permit endowments for the remaining countries. We outline how the EU-ETS can be further refined according to this mechanism.

1. Introduction

Motivation. Most suggestions how to slow down climate change concern emissions reduction or technological advances. Technological advances could allow green(er) production or removal of CO_2 from the atmosphere. Ideally, the internalization of the externalities from carbon emissions with market-based policies—e.g. via permit markets or a carbon price—would both lower the emissions and foster the technological advances through R&D by private firms. While this may hold if small adjustments by private firms to existing technologies suffice, it is less clear for greater technological advances, which often require combining private and public effort (see e.g. Johnstone et al., 2010). Consider the development of wind energy as an example. In the 1970s, the Danish government financed the development of blueprints for one-megawatt wind plants, based on the expectation that private firms would conduct the commercialization.[1] The government also financed the construction

☆ We would like to thank Clive Bell, Sjak Smulders as well as participants at the Workshop "Environmental Regulation: Emission Trading Scheme and Market Power" in Zurich 2017, the SURED-Conference 2018, the WCERE 2018, the EEA 2018 and the VfS-Tagung 2018 for helpful comments.

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[1] The example is based on Mazzucato (2013, p. 185). The German and the US government also had similar programs at that time.

https://doi.org/10.1016/j.reseneeco.2021.101229

of prototypes, allowing private firms to gain experience with the new technology and with production. Another example is Carbon Capture and Storage (CCS). Only if its costs could be reduced substantially, CCS would become a viable technology option. To achieve that, a combination of university-based research and more applied trials leading to actual cost estimates looks promising (see e.g. *Economist*, June 9, 2018, p. 71/72). A showcase is the firm *Carbon Engineering*, whose acting chief scientist is also a climate physicist at Harvard University. The firm recently published cost estimates of US$ 94–233 for pulling 1 tonne of carbon dioxide from the atmosphere, down from US$ 600 some years ago (see Tollefson, 2018).

Combining public and private effort to create local spillovers for innovation and to make greater technological advances leading to breakthrough technologies[2] works particularly well in innovation clusters,[3] with prominent examples such as Silicon Valley and the Boston Area. In innovation clusters, an entire R&D infrastructure involving publicly financed institutions, like universities and research labs, typically provides ideas, methods, prototypes, skilled labor and laboratories, which private applied research firms can use to commercialize blueprints.[4] Without technological breakthroughs, e.g. in carbon capture and storage technologies or energy storage, keeping global warming below the 2-degree target with a certain probability may be impossible to achieve.[5] Accordingly, several political agencies now push for green innovation clusters.[6]

The major challenge in inducing innovation clusters for green technologies is the global public good property of slowing down climate change and the fact that costs of creating innovation clusters and technology development are borne at the local level. On the latter, we focus on the following problem: A country will only consider investing in a certain R&D infrastructure for an innovation cluster, e.g. in a science area for green technologies, if no other country has invested, because otherwise it can freeride on the other country's investment.[7] Creating the research infrastructure with positive spillovers to applied research attracts private R&D firms. If the new technology is detected, production firms in all countries can use the new technology by paying a license fee to a successful R&D firm. Since innovating firms are free to move to a country with R&D infrastructure, the world does not gain from more countries setting up identical R&D infrastructures for specific science areas to support green technologies—it only implies duplication of fixed costs. However, the country that sets up R&D infrastructure is less well off than the other countries as it also has to pay the set-up costs, and no country may set up R&D infrastructure, even if it is socially desirable that one country does so.

In this paper, we examine the impact of permit allocation within an emissions trading system (ETS) on the creation of innovation clusters. Our main focus is not on additional research subsidies, as they are likely to create political economy problems of their own and are probably infeasible in times of high public debt. We focus instead on a mechanism that internalizes the positive externalities a country generates within the ETS, when it invests in R&D infrastructure for green technologies. We introduce a mechanism that leads to an innovation cluster for one area of green technologies. It has to balance the desire to make it as attractive as possible for a country to set-up the R&D infrastructure and the incentives for other countries to participate in the ETS.

For the construction, we start from the idea that the country with the lowest cost of setting up the necessary R&D infrastructure should receive few emission permits. This country will then become a net buyer of permits on the permit market, and hence has relatively more to gain from a new cheaper abatement technology, since the technology will induce lower permit prices. The country is then compensated by the permit market regulator who gains income from auctioning a fraction of the available permits. Our analysis can be applied to any ETS and in particular to the European trading system, EU-ETS, as we will elaborate below.

Model and results. More specifically, we consider a multi-country model with an existing permit market administered by a trading agency. In each country, polluting production firms operate with an existing abatement technology. The detection of a new technology is only possible if an innovation cluster is in place. For an innovation cluster to form, two requirements have to be fulfilled. First, a country has to spend a fixed, country-specific amount to set up research infrastructure. This may mean spending on laboratories, skilled workforce or blueprints. Second, applied research firms become active and use the research infrastructure. Our set-up captures the positive spillovers between publicly financed research infrastructure and private research effort. The detection of new technologies is uncertain, and as more applied research firms become active in the cluster, the probability of a new abatement technology being detected increases.

We capture the degree of cooperation between the countries on reducing greenhouse gas emissions by a carbon price target instead of an emissions target.[8] We focus on the carbon price for the following four reasons. First, it is a simple

[2] "*Breakthrough*" means "*An important discovery or event that helps to improve a situation or provide an answer to a problem*" (based on https://dictionary.cambridge.org/dictionary/english/breakthrough, last accessed June 21, 2018). Accordingly, we define a breakthrough technology by the property that costs of greenhouse gas reductions decline substantially if it is used.

[3] Braunerhjelm and Feldman (2006), Kemp and Pontoglio (2011), Gersbach and Schneider (2015), Akcigit et al. (2021 and Baily and Montalbano (2018).

[4] Baily and Montalbano (2018) discuss several case studies and describe the role of public policy for the successful creation of innovation clusters.

[5] Many estimates of the transition path towards the 2-degree target rely heavily on carbon capture and storage.

[6] Such cluster policy is implemented in the European Union, for instance. See https://ec.europa.eu/growth/industry/policy/cluster_de, last accessed: November 13, 2017.

[7] Having only one country investing in an innovation cluster is a polar case. Typically, however, few countries focus on innovation clusters for the same technology and there are examples with only one to three innovation clusters. Examples are the initial phase of wind energy with three countries (Mazzucato, 2013, p. 185), nuclear fusion with only one country hosting the cluster in Europe or the Swiss ETH cluster on how sunlight and air can produce liquid hydrocarbon fuels at high temperature (Meier et al., 2019). Similar examples can be found in the US (Baily and Montalbano, 2018).

[8] However, our mechanisms to induce an innovation cluster can also be applied to permit markets in which countries agree on some aggregate emissions target.

way to parameterize cooperation from pure decentralization to perfect cooperation. Second, recent political initiatives from Chancellor Merkel and President Macron have focused on a carbon price target for the EU-ETS.[9] Third, a carbon price represents a focal point that may foster successful negotiations (Weitzman, 2014; Cramton et al., 2017). Fourth, the OECD focuses on a gradual approach to achieving uniform international carbon prices to realize some efficiency gains (OECD, 2016).[10] Our results may add insights on appropriate carbon price levels that take the creation of innovation clusters into account.

We note that a carbon price target in existing permit markets has to be implemented by an agreement on some aggregate emissions target, with a budget for the trading agency to ensure that the market price will not fall below the target. As part of our investigation, we will show how carbon price targets can be implemented by allowing a maximal permit endowment of countries, which local governments can then grandfather to local production firms.

While we also discuss how an innovation cluster can be induced in a first-best setting, we focus on the case in which institutional settings do not allow this. Especially, we focus on a situation inspired by the European Union where emissions reduction targets have already been set before uncertainty about technological developments has been resolved. In such a situation, if no other country creates an innovation cluster, a country's decision whether to create one for green technologies depends on the benefits from lower abatement costs, net research infrastructure costs (expected gains, e.g. in terms of tax revenues, minus costs), as well as on the impact of a new (green) technology on costs or revenues from permit trade. For net-buyers on the permit market, detecting the new technology will lower trading costs. For net-sellers, the opposite is true. Effective costs for creating the research infrastructure may thus be higher or lower than the cost for research infrastructure itself.

We obtain the following insights regarding the creation of innovation clusters. First, a minimal carbon price target is needed to incentivize applied research firms to become active and use a created research infrastructure. Second, compared to the global social optimum, countries may lack incentives to invest in research infrastructure and make one innovation cluster possible, even if the permit price target in the ETS is high. Moreover, even if some countries have an incentive to invest in research infrastructure, the country with the lowest research infrastructure costs may not be among them.

To overcome both potential inefficiencies *within* an ETS,[11] we introduce a mechanism—called "Innovation-cluster-generation" procedure—that works as follows: According to the mechanism, the country with the lowest costs for research infrastructure is only endowed with few permits. It is compensated with profits generated by the trading agency. The remaining countries are given maximal possible permit endowments. The intuition why the mechanism works is as follows. By giving only few free permits to the country with the lowest research infrastructure costs, this country's production firms become large net buyers of permits. Thus, this country has high incentives to invest in the research infrastructure and to attract applied research firms, such that an innovation cluster forms. This gives the chance to lower the abatement costs and the costs of buying large amounts of permits.

To motivate this country to participate, the mechanism compensates it by a payment from the trading agency. To generate sufficient profits for the trading agency, the permit endowments to the other countries have to be limited. This determines the maximal possible endowment of other countries. This mechanism does not only induce an innovation cluster, it also introduces a coordination on the country with the lowest research infrastructure costs.

Empirical studies on wind energy suggest that our mechanism also applies in other areas. First, interaction between applied research from private firms and public research matters (Ek and Söderholm, 2010; Lindman and Söderholm, 2016). Second, environmental policy—feed-in tariffs in the case of wind energy—positively impact technology development (Lindman and Söderholm, 2016). With our paper, we provide an analytical framework to examine several policy options to foster technological advances through innovation clusters.

Implementation. Four remarks are in order with regard to concerns about the implementation of green innovation clusters and our suggested mechanism. First, one might wonder why no simpler mechanism could engineer such innovation clusters. For instance, countries might agree on a tax and transfer scheme to provide incentives to the one chosen country that sets up the innovation cluster. However, it is difficult to contract on such investments, as the outcomes of basic and applied research are highly uncertain. If the innovation cluster does not emerge, the government of the chosen country could always claim that efforts to induce an innovation cluster turned out to be unsuccessful. Such a lack of verifiability may inhibit the use of a tax and transfer scheme. The proposed mechanism does not rely on verifiable investments in basic and applied research, as it is incentive-compatible for the chosen country to set up the innovation cluster.

Second, of course, implementing the proposed mechanism requires to achieve common knowledge about which country has the lowest R&D infrastructure costs. However, from a positive point of view, we observe that in those sectors in the EU in which the effort-sharing is in place, the rich countries have higher emissions reduction commitment than poor countries

[9] At the EU-ETS, a market stability reserve will operate, starting in January 2019 (https://ec.europa.eu/clima/policies/ets/reform_en, last accessed: July 25, 2018), which is expected to stabilize prices.

[10] Moreover, a carbon price prohibits strategic permit selling and buying to influence the carbon price level. Such type of behavior may prevent permit prices from equaling marginal abatement costs and may generate inefficiencies.

[11] In principle, many ways to mitigate the detected inefficiencies are possible. We focus on a solution that does not need additional institutions besides the ETS organization.

(European Commission, 2019).[12] Most likely, the rich countries have the lowest R&D infrastructure costs, since many ingredients, such as advanced basic research labs and institutions, are already available. Hence, modifying the permit allocation in the EU-ETS in the same direction as we observe for the sectors under effort-sharing approaches the mechanism we suggest to engineer a green innovation cluster. Third, the crowding-out of growth effects is a concern. While investing in green innovation clusters generates opportunity costs with respect to investments in other types of innovation activities, there is no reason to assume that a green innovation cluster is less growth-enhancing than other types of clusters. Fostering the internalization of environmental externalities may even be *more* growth-enhancing in the longer-run (see Bretschger et al., 2011; Bretschger, 2015; Riekhof et al., 2019). Another concern is the possible "picking technology winners" by governments. While governments select the general direction of research and technology development by investing in research infrastructure for clean technologies, politicians cannot pick "successful firms" or a specific technology in our model, as "picking" is replaced by patent races by private firms.

Fourth, we focus on setting-up an innovation cluster for one natural science area related to green technologies. One could argue that different innovation clusters are needed to tackle climate change, such as a cluster for carbon storage technologies and a cluster for renewable energy technologies, for instance. Our mechanism can readily be applied to the construction of more than one innovation cluster by granting fewer permits to several countries in order to motivate them to set-up different clusters.

Relation to literature. 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 of environmental policy to send the right price signals for applied research firms is established in Requate (2005), for instance. In line with our observation that climate agreements with high carbon prices are difficult to establish, some authors examine whether a focus on breakthrough technologies can improve outcomes in terms of cooperating on slowing down climate change (e.g. Barrett, 2006, 2012; Hoel and de Zeeuw, 2010). Our paper is complementary to this literature and our focus on the two-step process of basic and applied research is a new element in this literature. International carbon pricing is discussed e.g. in Weitzman (2014) and Cramton et al. (2017),[13] but generally not in connection with an emissions trading system. There is a strand of 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 and price ceiling, goes back to Roberts and Spence (1976). Finally, our model is best applied to industrial and high emission countries with existing R&D infrastructure, as only in those cases breakthrough technologies can be expected (Jaakkola and van der Ploeg, 2019).

Greaker and Hagem (2014) show that permit trade impacts strategic investment into abatement in a North-South model. In their model, permit trade always positively impacts investment, as only the North invests, who is a net-seller on the permit market per assumption. We build on Golombek and Hoel (2008) and De Cian and Tavoni (2012), who explore how climate policy (emissions quota or carbon price) influences R&D activity related to abatement technologies. Our set-up extends the existing analysis with respect to innovation clusters. We consider climate policy with innovation clusters—with both applied research and publicly funded research infrastructure—in a multi-country model. To our knowledge, this has not been discussed so far.

In the next section, we outline the details of our model. In Sections 3–5, we describe the different levels of the model in more detail and present results. In Section 6, we discuss how an innovation cluster can be induced by international climate policy and describe the innovation-cluster-generation procedure. 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. We focus on carbon emissions leading to global damages and neglect potential additional local impacts of greenhouse gases. Innovation clusters consist of publicly funded research infrastructures and applied research activities. Individual countries host the innovation clusters. Countries are indexed by $i \in \{1, \ldots, m\}$, and in each country, there is a local government and a polluting production firm, which may abate emissions.[14] Countries only differ in their firm's baseline emissions $\bar{e}_i$ and in their costs to set up research infrastructure F_i. If a country hosts an innovation cluster, there are also applied research firms in that country. Initially, only an old abatement technology is available, but in an innovation cluster, a new abatement technology may be detected. A patent holder can then license the new technology to the production firms.

An innovation cluster forms if two actions are taken. First, a country invests in research infrastructure. Second, applied research firms become active and use the research infrastructure. Thus, an innovation cluster is in place. As a shortcut for

[12] I.e. Commitments for reducing emissions in the sectors not regulated under the European ETS are higher for richer countries. In European Commission (2019) it is stated that "The national emission targets for 2020 range from a 20% reduction by 2020 (from 2005 levels) for the richest Member States to a 20% increase for the least wealthy one, Bulgaria."

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

[14] Table 1 in the Appendix lists all symbols used.

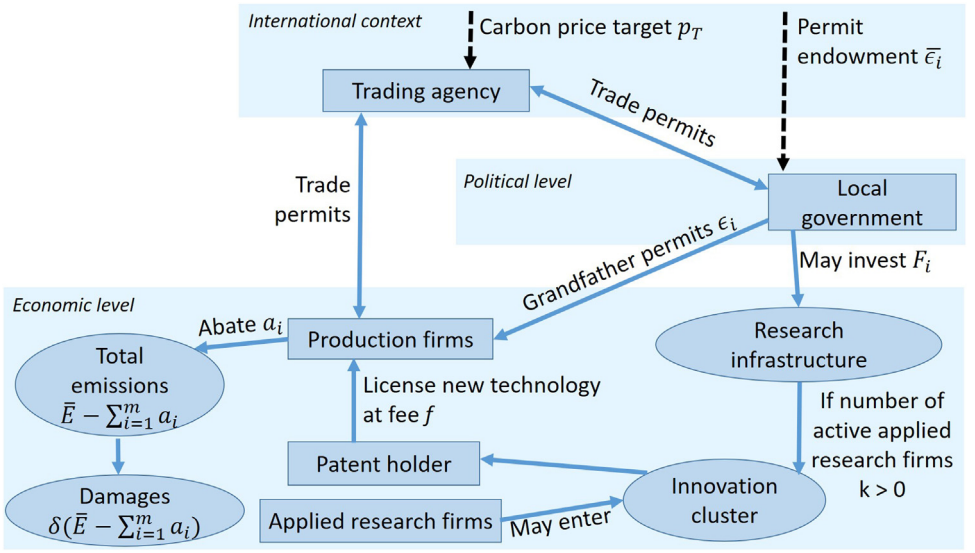

Fig. 1. The model.

both steps, we will say that research infrastructure investments of a country induce an innovation cluster. The idea is that a local government anticipates whether applied research firms will become active (see Condition (16) for details).

An emissions trading system with an emissions target exists and is administered by an international trading agency. The price target to achieve the emissions target is conditional on the technological level and denoted by p_T, with $T \in \{O, N\}$ standing for whether only the old (O) or, additionally, the new (N) technology is available in the economy. We directly focus on the price targets.

The model comprises two levels, namely a political and an economic level, embedded in an international context. The international context sets the organization of the emissions trading system and the strength of the climate policy. This includes a carbon price target and an initial amount of permits each country is endowed with. The political level consists of the decisions of the local government, who can decide about research infrastructure investments and on the number of permits to distribute freely to the local production firms. The economic level comprises the decisions taken by the local production firms and applied research firms.

Fig. 1 shows the different levels of the models—depicted by shaded areas—the different actors—depicted by squares—and their interaction—depicted by arrows. The exogenously given carbon price targets p_T and countries' permit endowments $\overline{\epsilon_i}$ are both depicted by dashed arrows.

In the following, we describe the model in more detail. We first describe and analyze the economic level of the model for given political decisions. Then, we describe the international context before we discuss the political level.

3. The economic level

In this section, we set up the model's economic level and contrast the market outcome with the global socially-optimal as well as with a second-best 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 $\bar{e}_i \geq 0$. To simplify notation, the production firm in country i is also denoted by i. Keeping output fixed, production firm i can reduce emissions by abating an amount $a_i \geq 0$ at costs $g_t(a_i)$. The lower case "t", $t \in \{o, n\}$, refers to the technology actually used by a production firm. The old technology, indicated by the subscript "o", is available for free. We assume quadratic abatement costs[15] of the form

$$g_o(a_i) = \frac{b_o}{2}(a_i)^2.$$

[15] A quadratic abatement cost function is strictly increasing and strictly convex and thus fulfills standard requirements for an abatement cost function (see e.g. Golombek and Hoel, 2008; Greaker and Hagem, 2014).

In an innovation cluster, the "new" abatement technology

$$g_n(a_i) = \frac{b_n}{2}(a_i)^2,$$

indicated by the subscript "n", may be detected. The new abatement technology—hence, "new technology"—lowers abatement costs, i.e. we assume $0 < b_n < b_o$. In the following, "T", $T \in \{O, N\}$, indicates the technology level available at the global scale, while "t", $t \in \{o, n\}$, refers to the technology actually used by a production firm.

One brief remark on the innovation process is in order. For simplicity, we assume that the abatement costs when using the new technology are known, but it is unknown whether such a technology will be detected. Another interpretation is that a breakthrough technology usually implies that a "significant" impact is made and accordingly, b_n can be interpreted as the minimal impact the new technology has to make.

The production firm is required to hold permits for the emissions it does not abate. It receives an amount of permits ϵ_i for free from the local government, and can buy additional (sell superfluous) permits at the prevailing carbon price p_T from (to) the agency.

Each country suffers damages caused by aggregate emissions. In monetary terms, damages are given by

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

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

To set up a research infrastructure, a country—represented by its local government—has to invest an amount F_i in monetary terms ($F_i > 0$). These costs consist of expenditures for research facilities, employment in these facilities and further costs for running them. We note that innovation clusters may generate benefits beyond developing new abatement technologies such as spillovers to other technologies or income generation. These benefits are deducted from the costs and thus F_i has to be interpreted as net costs.

There is a large number of applied research firms that are mobile across countries and that can become active in abatement technology research. If a local government has invested F_i, applied research firms decide whether to become active and use the research infrastructure to benefit from local spillovers. Specifically, if an applied research firm becomes active and invests the fixed amount x ($x > 0$), an innovation cluster is in place and the applied research firm can detect the new technology with probability π , independent from F_i . The innovation successes are stochastically independent across applied research firms. If there is no research infrastructure, the success probability of an applied research firm is zero.

If k applied research firms become active in the innovation cluster in one country, the overall probability of detecting the new technology is

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

We note that the new technology will not be detected if all applied firms are not successful, which occurs with probability $[1 - \pi]^k$. Several further remarks on the specification of our assumptions and the interpretation are in order. First, since we focus on the interaction between research infrastructure and applied research, we make the above stark assumption of local spillovers from research infrastructure to applied research. In addition, we could consider the interaction of many applied research firms through local spillovers via network effects, which would require that π ($0 < \pi < 1$) is an increasing function of k and research successes may be correlated. In the basic version, we neglect this second type of spillovers to obtain analytical solutions. The proposed solution developed in this paper, however, readily applies to the more general set-up.[16] Second, we assume that costs F_i are country-dependent, to reflect the fact that some countries have already invested into research infrastructure in the area considered or that some countries may be more productive in research infrastructure, e.g. have a university system that is better suited for developing new abatement technologies. Once an innovation cluster exists, the success probability π is the same across clusters. This simplifies the analysis, but is not essential.[17] Third, 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 start to innovate if conditions are sufficiently attractive.[18]

If at least one applied research firm is successful, a patent holder is determined by fair randomization among all successful applied research firms.[19] The patent holder sets a licensing fee f ($f > 0$) and production firms decide whether to adopt the new technology at this fee. Production firms in all m countries have the same ability to adopt the new technology.

[16] The conditions for a successful working of the innovation-cluster-generation procedure become much more involved, however.

[17] Indeed, if the country with the best research infrastructure system can also produce the maximal success probability for applied research firms, no change in the analysis is required for this scenario.

[18] We can assume that each country has a subset of these agents who can become entrepreneurs.

[19] The results are identical for joint patent holding of all successful applied research firms and profit sharing.

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 $p_T, T \in \{O, N\}$, has been set at the international level and will be enforced by the trading agency. Moreover, production firms have received grandfathered permits ϵ_i from their local government. Finally, we assume that one country has invested in research infrastructure.

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.

3.2.1. Stage 3: Emissions abatement and permit trading of the production firms

Suppose that a new technology has been detected and that each production firm has chosen the technology $g_t, t \in \{o, n\}$. With grandfathered permits ϵ_i, production firms choose abatement level a_i by solving[20]

$$\min_{a_i} \quad g_t(a_i) + p_T[\bar{e}_i - \epsilon_i - a_i],$$

which yields the first order condition

$$p_T = g_t'(a_i), \tag{2}$$

taking the permit price $p_T, T \in \{O, N\}$, as given.[21]

For quadratic abatement costs, $p_T = b_t a_i$. Since production firms that use the same technology abate an identical amount of emissions, we omit the index i and denote abatement decisions in the future by

$$a_{t,T} = \frac{p_T}{b_t}. \tag{3}$$

3.2.2. Stage 2: License fee setting by the patent holder and technology adoption by production firms

We next turn to the setting of the license fee and to the adoption of the new technology. Given the new technology is detected and $p_T = p_N$ prevails, production firm i's maximal willingness to pay for the new technology, denoted by WTP_i, is

$$\begin{aligned} WTP_i &= g_o(a_{o,N}) + p_N[\bar{e}_i - \epsilon_i - a_{o,N}] - g_n(a_{n,N}) - p_N[\bar{e}_i - \epsilon_i - a_{n,N}] \\ &= g_o(a_{o,N}) - g_n(a_{n,N}) + p_N[a_{n,N} - a_{o,N}] =: WTP. \end{aligned} \tag{4}$$

The willingness to pay for the new technology is identical across production firms, and is independent of adoption decisions by other production firms. Hence, if the new technology is detected, the patent holder sets the license fee according to $f = WTP$, and all production firms adopt the new technology. Then, $a_i = a_{n,N}$ for all production firms. Using Eq. (3), we can write the fee that equals (4) as a function of p_N. Lemma 1 summarizes the result.

Lemma 1. *Suppose that the new technology has been detected. Then, all production firms adopt it at the fee*

$$\hat{f}(p_N) := p_N^2 \frac{b_o - b_n}{2 b_n b_o}. \tag{5}$$

The proof is in Appendix C.

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

3.2.3. Stage 1: Research activity of applied research firms

Given that one local government has invested into research infrastructure, applied research firms decide whether to become active and use the created infrastructure, based on expected profits. An applied research firm only earns profits from licensing the new technology to all production firms if it is the patent holder. If several research firms have detected

[20] We assume price-taking behavior for the following reasons. In a country, every production firm can stand for many production firms. For example, on the EU-ETS, more than three thousand firms trade, and the three biggest emitting firms represent less than 8% of total emissions each (RWE: 7.1%, E.ON: 4.7% and Vattenfall: 4.2%.) (Nicolaï, 2015). With many trading firms, an equilibrium approximates the competitive equilibrium (Lange, 2012). In every country, the abatement technology could also be seen as the result of abatement efforts of a continuum of production firms. Each firm has the option to abate one unit of emissions at some costs. We also obtain price-taking behavior on the permit market when we consider a continuum of firms.

[21] Global availability of the technology is depicted by T. $t = n$ is thus only possible if $T = N$, i.e. if the new technology is available.

the new technology, the patent holder is determined by fair randomization. Then, using Eq. (1), the probability for an applied research firm to detect a new technology and to become patent-holder is given by

$$\frac{\Pi(k)}{k} = \frac{1-(1-\pi)^k}{k}.$$

The probability can be approximated by the probability to detect the new technology divided by one plus the expected number of other successful active R&D firms—which reflects the probability of a successful R&D firm to become patent holder,

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

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. It will be used in the subsequent analysis to calculate explicit formulas.

Applied research firms become active as long as expected profits are positive. Thus the number of active applied research firms k is based on the expected zero profit condition,[22]

$$m\hat{f}(p_N)\frac{\Pi(k)}{k} - x = 0,$$

or with the approximation

$$m\hat{f}(p_N)\frac{\pi}{1+\pi(k-1)} - x = 0.$$

We can re-arrange the equation and write the number of active applied research firms as a function of p_N by using (5). This yields the next result.

Lemma 2. *If one research infrastructure is created, $\hat{k}$ applied research firms with*

$$\hat{k}(p_N) := \frac{\pi-1}{\pi} + \frac{m\hat{f}(p_N)}{x} \tag{6}$$

become active and use the infrastructure such that an innovation cluster forms if $\hat{k}(p_N) > 0$.

It is convenient to treat $\hat{k}(p_N)$ 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 $\hat{k}(p_N)$.[23],[24]

An important remark is in order. The successes of applied research firms are stochastically independent, and applied research firms are mobile. Hence, the number of active applied research firms is the same as in (6) if more than one country invests in research infrastructure. Those research firms would be distributed over all created research infrastructures. Hence, from a welfare perspective, one innovation cluster is sufficient to reap all possible benefits from innovation activities.[25]

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

Corollary 1. *(i) Given a research infrastructure has been created, an innovation cluster is in place ($\hat{k}(p_N) > 0$), if*

$$m\hat{f}(p_N) > \frac{1-\pi}{\pi}x.$$

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

$$\frac{\partial \hat{k}(p_N)}{\partial p_N} > 0.$$

(iii) A reduction in the marginal abatement costs of the new technology for a given level of emissions and a given carbon price target increases the number of applied research firms,

$$\frac{\partial \hat{k}(p_N)}{\partial b_n} < 0.$$

[22] Here, we already assume that all m countries pay the license fee as long as the new technology is detected. License fee setting will ensure that this is indeed the case.

[23] In practice, one would require that $\hat{k}(p_N) \geq 1$ and thus it is ensured that at least one firm is present in the innovation cluster.

[24] In the given set-up, excessive entry of R&D firms could result. This scenario does not seem to be the most likely one given that observed carbon prices are low. At the end of Section 6.3, we discuss a subsidy to ensure firm entry that could be changed into a tax in case of excessive entry.

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

The first property of 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. If the licensing income increases due to a higher carbon price target p_N or to lower abatement costs b_n, the number of active applied research firms increases (Corollary 1(ii) and (iii)).

Proposition 1 characterizes the solution of the entire game when research firms become active and also when not.

Proposition 1. *If no research infrastructure is created and $\hat{k} = 0$, or if the new technology is not detected, all production firms use the old technology to abate*

$$a_{o,O} = \frac{p_O}{b_o}.$$

If one research infrastructure is created and p_N is sufficiently high, i.e.

$$\hat{k}(p_N) = \frac{\pi - 1}{\pi} + \frac{m\hat{f}(p_N)}{x} > 0$$

such that an innovation cluster forms. If the new technology is detected, the patent holder licenses it to all production firms at the fee

$$\hat{f}(p_N) := p_N^2 \frac{b_o - b_n}{2b_n b_o}$$

and all production firms use the new technology to abate

$$a_{n,N} = \frac{p_N}{b_n}.$$

We have assumed that both the probability that a firm innovates and the amount of resources invested in R&D are exogenous whereas the number of firms is endogenous. A suitable extension is to assume that the number of firms is given. Suppose there is only one firm, but the probability $\Pi(x)$ is a function of the investment x which can be arbitrarily chosen and will be chosen optimally by the firm. In such circumstances the endogenous amount of investment by the firm replaces the role of k. There is one difference. In the case of one research firm, the impact on the marginal probability to be successful is relevant for the decision how much to invest in research, while in the case with many research firms, the average probability matters (as the zero profit condition determines entry). So the outcome will not be the same quantitatively, but qualitatively it will. Next, we consider which abatement level and what kind of research activity are optimal from the perspective of a global social planner and in a second-best setting.

3.3. The global first-best and a second-best solution

Before we proceed with the political level and the international context, it is useful to introduce the socially-optimal solution at the global level. We assume that a social planner can dictate abatement in all countries and that he can determine in which countries research infrastructure 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 and if they can condition abatement on the availability of the new technology. Let the superscript ^{fb} denote variables describing the first-best solution. The following proposition characterizes the outcome:

Proposition 2. *Suppose*

$$\Pi(k^{fb})\left[\frac{m(m\delta)^2}{2}\frac{b_o - b_n}{b_n b_o}\right] - xk^{fb} \geq F_{ifb},$$

with k^{fb} and F_{ifb} characterized below.

Then, the first-best solution is characterized by

(i) One innovation cluster with

$$k^{fb} = \frac{\pi - 1}{\pi} + \frac{m\delta}{\pi}\sqrt{\frac{m}{2x}\pi(1-\pi)\frac{b_o - b_n}{b_o b_n}}$$

applied research firms. Country i^{fb} invests into the research infrastructure, where $F_{ifb} = \min_{i=1,\cdots,m}\{F_i\}$.

(ii) An abatement level of each production firm depending on whether the new technology has been detected

$$a_{i,n}^{fb} = a_n^{fb} = \frac{m\delta}{b_n}, \quad a_{i,o}^{fb} = a_o^{fb} = \frac{m\delta}{b_o}.$$

The proof is in Appendix A.

The next step is to think about how this optimal solution can be decentralized, especially related to emissions, the focus of this paper. Looking at existing institutions like the EU-ETS: adapting abatement targets after the detection of a new technology may not be feasible. In the case of the EU-ETS, participating countries agreed to reduce emissions by 40% in 2030 relative to the baseline. A reserve of certificates is there to react to unforeseen developments. Accordingly, we also consider a related second-best set-up in which abatement targets have to be set before uncertainty surrounding technological change is resolved, i.e. taking an 'ex-ante' perspective.

Let the superscript * denote variables describing the second-best solution when research infrastructure is created and applied research firms become active such that an innovation cluster forms. Let Country i^* denote the country with the lowest costs to create an innovation cluster, $F_{i^*} = \min_{i=1,\dots,m} \{F_i\}$. Then, Proposition 3 characterizes the second-best solution.

Proposition 3. *Suppose*

$$xk^* + F_{i^*} \leq m\left(-\frac{m^2\delta^2}{2b_o} + m\delta a^* - \frac{[a^*]^2}{2}\left[\Pi(k^*)b_n + [1-\Pi(k^*)]b_o\right]\right),$$

with k^* and a^* given in (i) and (ii) below.

Then, the second-best solution is characterized by

(i) One innovation cluster with

$$k^* = \frac{Bm\delta}{\pi b_n} + \frac{b_o(\pi-1)}{\pi b_n}$$

applied research firms, with

$$B = \sqrt{\frac{\pi(1-\pi)(b_o-b_n)m}{2x}}. \tag{7}$$

Country i^* invests into the research infrastructure.

(ii) An abatement level of each production firm

$$a^* = \frac{m\delta}{b_n} + \frac{(1-\pi)(b_n-b_o)}{Bb_n}, \tag{8}$$

with B as in (i).

The proof is in Appendix B.

From a global perspective, it is optimal to establish an innovation cluster in the country with the lowest costs for research infrastructure, i.e. in Country i^* with $F_{i^*} = \min_{i=1,\dots,m} \{F_i\}$. Still, it is only optimal to create an innovation cluster if total costs—i.e. costs for research infrastructure and applied research—are lower than the expected gains, i.e. if

$$\underbrace{xk^* + F_{i^*}}_{\text{Total research costs}} \underbrace{\leq \Pi(k^*)\left[m\frac{b_o-b_n}{2}[a^*]^2\right] - \frac{mb_o}{2}\left[\frac{\pi k^*(b_o-b_n)}{b_o B}\right]^2}_{\text{Expected gains}}. \tag{9}$$

Expected gains consist of two terms. The first term depicts the lower expected abatement costs from new abatement levels. The second term corresponds to the net effect of lower expected damages and more ambitious abatement. The formula follows from the proof of Proposition 3, using the binomial formula and partly plugging in for a^*.

We examine under which conditions innovation clusters are (not) created, assuming the economy is in a situation in which it would be optimal from a global perspective to create an innovation cluster. Thus, we assume (9) holds for the remainder of the paper. The condition includes that $k^* > 0$.[26]

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

Proposition 4. *The second-best abatement level a^* can be induced by setting carbon prices according to*

$$p_N^* = m\delta + \frac{(1-\pi)(b_n-b_o)}{B} \quad \text{and} \tag{10}$$

$$p_O^* = \frac{b_o m\delta}{b_n} + \frac{b_o(1-\pi)(b_n-b_o)}{Bb_n} \quad \text{with} \quad B = \sqrt{\frac{\pi(1-\pi)(b_o-b_n)m}{2x}}, \tag{11}$$

depending on the detection of the new technology.

The proof is in Appendix B.

[26] Thus, based on Proposition 3, $k^* > 0 \leftrightarrow Bm\delta > (1-\pi)b_o$.

The price menu p_N^*, p_O^* ensures the second-best abatement level in a setting without a global social planner, independent from the detection of the new technology. This is not the classical result of the permit price being equal to marginal damages under certainty, as for the first-best outcome $p_T^{fb} = m\delta$. The reason is that aggregate abatement levels (or aggregate permits) have to be chosen before technologies are realized.

4. The international context

We assume that there exists an emissions trading system which is administered by a trading agency. Its role is to administer emissions trading in order to minimize global costs. The context for the agency is given as follows. First, similar to the EU-ETS set-up, we assume that aggregate abatement levels are chosen before uncertainty about technologies is resolved. Typically, it takes a long time to negotiate emission targets and therefore, renegotiations of emissions targets when new information about technologies arrives take time.[27]

Second, the strength of the policy enacted by the international agency may be constrained by the willingness of its members to cooperate. For this paper we take the level of cooperation on abatement as a parameter related to the agency's ability to enforce the prices it aimed for 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 from the agreement. If the likelihood is low (high), low (high) carbon price targets can be achieved.[28]

The system has the following additional characteristics: First, countries face proportional burden-sharing, implying that each country can issue permits as a given fraction of its baseline emissions. Second, the sum of the initial amount of permits countries are endowed with should be set to guarantee a non-negative profit of the trading agency, i.e. the agency should be in a position to guarantee the carbon price target without needing additional funds from the countries. Third, the residual budget of the trading agency, i.e. the budget that may remain after all trading took place especially if the new technology was not detected, is equally distributed among all countries.

We now first present the carbon price as a measure of cooperation in abatement. We then discuss permit endowment and feasibility of the targeted price, taking the assumptions above into account.

4.1. Cooperation on abatement

We measure the level of cooperation between the countries by a scalar λ that describes the agreed carbon price target relative to the carbon price needed to achieve the second-best level. Countries cooperate to set a menu of carbon prices $p_O = \lambda p_O^*$ and $p_N = \lambda p_N^*$ ($0 < \underline{\lambda} \leq \lambda \leq 1$), with $\lambda = \underline{\lambda}$ denoting no cooperation, and $\lambda = 1$ denoting full cooperation. The level $\underline{\lambda}$ corresponds to the permit price when countries non-cooperatively decide about the amount of permits as best responses to each other, which results in the lowest possible but still positive carbon price.

One remark is in order on how different cooperation levels impact local production firms' abatement. Given p_N and p_O from Eq. (3), and Eqs. (10) and (11) from Proposition 4, we observe that abatement levels are the same under both scenarios, and we denote this level by $\hat{a}(\lambda)$. It is given by

$$\hat{a}(\lambda) := a_{n,N} = a_{o,O} = \lambda a^*. \tag{12}$$

While we have already assumed that parameters are such that an innovation cluster is socially optimal, we now make the following additional assumption. When research infrastructure is created under full cooperation, applied research firms will enter, i.e. $\hat{k}(p_N^*) > 0$. We make this assumption to focus on incentives for investing in research infrastructure. If applied research firms did not even become active under full cooperation, one would have to focus more on incentivizing applied research to become active and not on the incentives for local governments to invest in research infrastructure. Later, we will discuss how applied research could be incentivized even if $\hat{k}(p_N^*) = 0$.

We now address initial permit endowment in relation to the feasibility of the carbon price target.

4.2. Initial permit endowment and a carbon price

For a given level of cooperation represented by $p_T = \lambda p_T^*$, we determine feasible initial permit endowments and describe the trading process. We also state how initial permit endowments determine the feasibility of a carbon price target under a non-negative profit of the trading agency.

[27] Moreover, the socially optimal solution may also prevail ex-post when the society faces a tipping point problem. In particular, when sticking to emission targets is dictated by avoiding a tipping point in terms of damages, a socially optimal solution requires to keep global warming below a certain level. Indeed, suppose we reformulate the damage function as a tipping point problem in which marginal damage jumps from δ to very high levels if aggregate emissions exceed ma^*. In such cases, the optimal solution ex-ante is also optimal ex-post.

[28] One possible way to endogenize carbon prices works as follows: There exists a lower bound on the carbon price targets, at which innovation clusters just become viable. At such prices, no country wants to reject the corresponding emission targets as it would destroy the innovation cluster and R&D for new technologies and make a defecting country (and all other countries) worse off. A further way to endogenize carbon prices would be to assume the standard approach that coalitions have to be internally and externally stable.

With the initial allocation of permit endowments $\overline{\epsilon}_i$ across countries determined by proportional burden sharing and at least a minimal amount of emissions reduction, we have

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

The parameter α represents the tightness of initial permit endowments. Local governments can buy additional permits or sell superfluous permits. Ultimately, they will grandfather an amount of ϵ_i to their local production firms. Local governments and local production firms trade on the permit market.

The implementation of the initial permit endowment is feasible if the profit of the trading agency,

$$p_T \sum_{i=1}^{m} \Bigg(\underbrace{\overline{e}_i - a_i - \varepsilon_i}_{\text{bought by prod. firm i}} + \underbrace{\varepsilon_i - \alpha \overline{e}_i}_{\text{bought by local government i}} \Bigg) = p_T \sum_{i=1}^{m} ((1-\alpha)\overline{e}_i - a_i) \geq 0; T \in \{O, N\}. \tag{13}$$

Lemma 3 characterizes a feasibility constraint on initial permit endowments related to an upper bound on α denoted by $\overline{\alpha}$.

Lemma 3. *Carbon price targets $p_T = \lambda p_T^*, T \in \{O, N\}$, are feasible for given initial permit endowments represented by α if and only if*

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

The proof is in Appendix C.

Some interpretations are in order. First, the condition of a non-negative residual budget of the trading agency determines an upper bound on α, i.e. on the initial permit endowments of the countries relative to their baseline emissions. Second, for the profit of the agency, it is irrelevant whether the local government buys more permits from the agency than $\alpha \overline{e}_i$ and grants them to their local production firms. The more the local government buys, the more permits the corresponding production firm will sell on the permit market. If a local government buys more permits, it simply redistributes revenues within the country, i.e. from the government to local production firms, without affecting the profit of the agency. Third, for every level of cooperation, there is an α that can guarantee a non-negative profit. The level of cooperation and the share of permit endowments relative to baseline emissions are inversely related: A high level of cooperation (high λ) means a high carbon price. For the trading agency to ensure the price target without an additional budget, the share α of permits needs to be relatively low. This is reflected in the property

$$\frac{\partial \overline{\alpha}(\lambda)}{\partial \lambda} < 0.$$

An example is illustrated in Fig. 2.

5. The political level

Next, we consider the decision problem of local governments. Local governments want to minimize local expected costs when deciding about research infrastructure investments and on the amounts of permits grandfathered to the local production firms. As abatement levels depend on carbon price targets, we write abatement costs directly as functions of

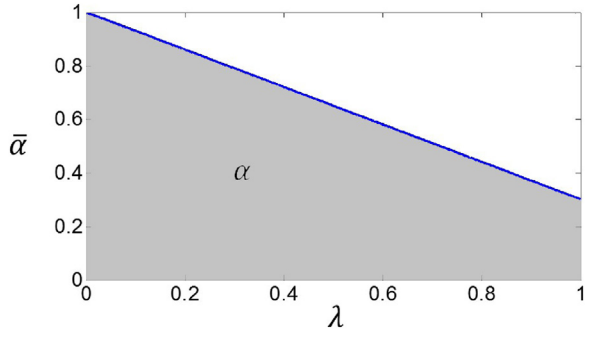

Fig. 2. Illustration of Lemma 3 for the ratio $\frac{ma^*}{\overline{E}} = 0.7$.

the respective price, i.e. $g_n(p_N)$ and $g_o(p_O)$. When needed, we will use j as index instead of i. The local expected costs K_i of country i are given as follows:[29]

$$K_i = \Pi\left(\hat{k}(p_N)\right)\left[\hat{f}(p_N) + g_n(p_N) + \overbrace{p_N[\bar{e}_i - \epsilon_i - a_{n,N}]}^{\text{trading costs firm}} + \overbrace{\delta\sum_{j=1}^{m}[\bar{e}_j - a_{n,N}]}^{\text{damages}} + \overbrace{p_N[\epsilon_i - \bar{\epsilon}_i]}^{\text{trading costs gov}} + \overbrace{\frac{1}{m}\left[P_N\sum_{j=1}^{m} - [\bar{e}_j - \epsilon_j - a_{n,N}] - [\epsilon_j - \bar{\epsilon}_j]\right]}^{\text{refunding}}\right]$$
$$+ \left[1 - \Pi\left(\hat{k}(p_N)\right)\right]\left[g_o(p_O) + \overbrace{p_O[\bar{e}_i - \epsilon_i - a_{o,O}]}^{\text{trading costs firm}} + \overbrace{\delta\sum_{j=1}^{m}[\bar{e}_j - a_{o,O}]}^{\text{damages}} + \overbrace{p_O[\epsilon_i - \bar{\epsilon}_i]}^{\text{trading costs gov}} + \overbrace{\frac{1}{m}\left[p_O\sum_{j=1}^{m} - [\bar{e}_j - \epsilon_j - a_{o,O}] - [\epsilon_j - \bar{\epsilon}_j]\right]}^{\text{refunding}}\right] \quad (14)$$

Local expected costs include the licensing fee $\hat{f}(p_N)$—if relevant, abatement costs $g_n(p_N)$ or $g_o(p_O)$, permit trading costs (or revenues) of the local production firm, damages, trading costs (or revenues) of the local government "trading costs gov", and refunding of the trading agency's profit, conditional on whether the new technology is detected or not. Local expected costs also include costs for research infrastructure F_i—if the local government decides to make the investment. Costs for applied research do not need to be considered, as expected profits of applied research firms are zero.

In the following, we 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) $\epsilon_i - \alpha\bar{e}_i$ from (to) the trading agency at the prevailing price. Lemma 4 shows that the grandfathering decision has no impact on total costs of a local government.

Lemma 4. *The amount of permits grandfathered to the local production firm ϵ_i is undetermined.*

The proof is in Appendix C.

The reason for the result of Lemma 4 is that the local government considers *total* local expected 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 trading agency obtains revenues. As abatement $\hat{a}(\lambda)$ is independent of the amount of grandfathered permits, the production firm will sell the additional permits at the given price. The trading agency uses the revenues obtained from selling to the local government to buy the permits. The process is neutral for the agency's profit (see also Section 4.2).

5.2. Research infrastructure investments

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

To consider the local government's decision on research infrastructure, it is useful to define total expected costs, denoted by K_i^{IC} ("IC" stands for "innovation cluster"), when some other country invested into research infrastructure to induce an innovation cluster, as well as to define total costs, denoted by K_i^{NIC} ("NIC" stands for "no innovation cluster"), when no country invested in research infrastructure and only the old technology is available.[30] Both expressions build on K_i (Eq. (14))

[29] We neglect revenues from license fees as they cancel out with the cost of doing applied research.
[30] Note that the permit prices are set at the international level and are taken as given for this decision.

with "trading costs gov" merged with "trading costs firm". As the choice of ϵ_i does not influence the total costs considered by the local planner, and with $\overline{\varepsilon}:=\sum_{i=1}^{m}\overline{\epsilon}_i$, these total costs are given by

$$\begin{aligned} K_i^{IC} &= \Pi(\hat{k}(p_N))[\hat{f}(p_N)+g_n(p_N)+p_N[\overline{e}_i-\overline{\epsilon}_i-a_{n,N}]+\delta\sum_{j=1}^{m}[\overline{e}_j-a_{n,N}]-\frac{p_N[\overline{E}-\overline{\varepsilon}]}{m} \\ &\quad + p_N a_{n,N}] \\ &\quad + [1-\Pi(\hat{k}(p_N))][g_o(p_O)+p_O[\overline{e}_i-\overline{\epsilon}_i-a_{o,O}]+\delta\sum_{j=1}^{m}[\overline{e}_j-a_{o,O}]-\frac{p_O[\overline{E}-\overline{\varepsilon}]}{m} \\ &\quad + p_O a_{o,O}], \\ K_i^{NIC} &= g_o(p_O)+p_O[\overline{e}_i-\overline{\epsilon}_i-a_{o,O}]+\delta\sum_{j=1}^{m}[\overline{e}_j-a_{o,O}]-\frac{p_O[\overline{E}-\overline{\varepsilon}]}{m}+p_O a_{o,O}. \end{aligned}$$

If a country has invested in research infrastructure, it is not profitable for a second country to invest, as this would only add costs without adding benefits. Hence, a local government invests in research infrastructure if and only if no other country has undertaken these investments and if

$$K_i^{IC}+F_i \le K_i^{NIC}. \tag{15}$$

Building on Condition (15), Lemma 5 summarizes how the incentives of a local government to invest in research infrastructure depend on the level of cooperation λ and on permit endowments reflected by α. Indirectly, the incentive also depends on whether applied research firms will become active and use the infrastructure, i.e. on $k>0$.

Lemma 5. *The local government in country i invests in research infrastructure if no other country invests and if*

$$\overbrace{F_i-\Pi(\hat{k}(\lambda p_N^*))\underbrace{\lambda[p_O^*-p_N^*][1-\alpha]\left[\overline{e}_i-\frac{\overline{E}}{m}\right]}_{\text{Price-change effect}}}^{\text{Effective costs}} \le \overbrace{\Pi(\hat{k}(\lambda p_N^*))\hat{f}(\lambda p_N^*)\frac{b_o-b_n}{b_n}}^{\text{Expected gains}}. \tag{16}$$

The proof is in Appendix C.

Condition (16) can be interpreted as follows. Expected gains from detecting the new 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). Let us discuss both terms in more detail.

The expected gains depicted on the RHS are the same for each country and consist of the license fee weighted by the relative reduction in marginal abatement costs with the new technology, multiplied with the overall probability of detecting the new technology. As the licensing fee equals the production firms' willingness to pay to adopt the new technology, the RHS can be interpreted as the country's expected gains from the new technology, mainly in the form of reduced abatement costs. On the LHS, we have the country-specific terms. The first term depicts the investment costs for research infrastructure. The second term depicts the change in costs or revenues from permit trading due to the detection of the new technology, net of the refunding of the trading agency's profit (see Eq. (25) in Appendix C for details). The second term is driven by changes in the prevailing permit price, due to the detection of the new technology. Accordingly, we term it the "price-change effect".

The price-change effect can be positive or negative, depending on whether the country is a net-seller or a net-buyer on the permit market. In principle, one can classify the countries into three groups, namely net-buyers with above-average baseline emissions $\overline{e}_i > \overline{E}/m$, countries with average baseline emissions $\overline{e}_i = \overline{E}/m$, and net-sellers with below-average baseline emissions $\overline{e}_i < \overline{E}/m$. Net-buyers gain from the detection of the new technology, as the price to buy additional permits on the permit market declines. They face a negative price-change effect and their effective costs to create an innovation cluster are reduced. Net-sellers lose from the detection of the new technology, as the selling price for superfluous permits on the permit market decreases. They face a positive price-change effect, and effective costs to create an innovation cluster are increased. Countries with average baseline emissions are not affected.

Without loss of generality, we order the countries according to their baseline emissions $\overline{e}_i$, from lowest to highest. Let $i=1,\ldots,m_s$ denote the net-sellers and $i=m_b,\ldots,m$ the net-buyers, with $m_s \le m_b-1$, depending on the number of countries with $\overline{e}_i=\overline{E}/m$.

Four points are important. First, although all countries initially receive a permit amount relative to their baseline emissions, $\overline{\epsilon}_i=\alpha\overline{e}_i$, the refunding of the trading agency's profits leads to the separation of the countries into groups with above-average or below-average emissions. Second, if Condition (16) is fulfilled for several countries, local governments need to coordinate on who will invest in research infrastructure. Yet, local governments decide simultaneously, such that a

coordination problem arises, with many possible solutions. A focal point[31] in this coordination game may be the following: The local government in the country with the lowest effective costs (LHS in Equation (16)) invests, because it will gain most from the detection of the new technology. This country may not be Country i^*—the country with the lowest research infrastructure costs—because of the price-change effect. Another country with $F_i > F_{i^*}$, but with a negative price-change effect, may face the lowest effective costs to create an innovation cluster. As a result of permit trade, countries may not coordinate on the socially optimal Country i^* to create an innovation cluster.[32] Third, if Condition (16) is not fulfilled for any country, all countries may still benefit from jointly financing research infrastructure investment in one country. In such a situation, additional mechanisms are needed. Here, permit trade may create opportunities for adding such mechanisms. We will develop one below. Fourth, Eq. (16) cannot be fulfilled if $k = 0$. If upon investment in a research infrastructure, no applied firms are expected to enter—and $\Pi(k = 0) = 0$, a local government would not invest in it in the first place.

We focus on how innovation clusters can be induced. We first discuss the impact of the level of cooperation and permit endowments on the emergence of innovation clusters. We then present a mechanism that solves the coordination and commitment problem and can thus help to create an innovation cluster, even in difficult settings.

6. Inducing innovation clusters

In this section, we explore different ways how the international community may induce an innovation cluster when Condition (16) is not fulfilled for any country. In principle, many ways to incentivize an innovation cluster can be imagined. One possibility is to create a fund to which all countries contribute. Then, to be cost-effective, the money would be given to the country with the lowest costs to create the research infrastructure. A possible difficulty is that one cannot control to which extent this money will indeed be used for the development of new abatement technologies. Failure to detect a new technology may be due to lack of investment into research infrastructure or simply to bad luck. Hence, inducing innovation clusters has to rely on either additional costly monitoring devices, which will remain imperfect and require additional institutions, or on additional incentives for a country to invest in research infrastructure. We focus on another approach and stay within the given institutional set-up of a permit market, i.e. no further institutions are considered. As it will turn out, none are needed.

6.1. The impact of cooperation

When the level of cooperation is low, represented by a low value of λ, no local government may have incentives to invest in research infrastructure when endowed with $\alpha\bar{e}_i$. This may be because no applied research firms would become active to use this infrastructure, or because costs to create this research infrastructure outweigh country-specific gains. It is useful to introduce the cooperation threshold λ_i°, implicitly, based on Equation (16), defined by

$$\frac{F_i}{\Pi(\hat{k}(\lambda_i^\circ p_N^*))\lambda_i^\circ} - [p_O^* - p_N^*][1 - \overline{\alpha}(\lambda^\circ)][\bar{e}_i - \frac{\bar{E}}{m}] = \lambda_i^\circ \frac{(p_N^*)^2(b_o - b_n)}{2b_n b_o} \frac{b_o - b_n}{b_n}, \tag{17}$$

with λ° defined as as the minimal level of cooperation at which a first country is willing to create the research infrastructure if all countries are endowed with $\alpha(\lambda^\circ)$, $\lambda^\circ = \min_{i=1,\ldots,m} \{\lambda_i^\circ\}$. We note that λ_i° is uniquely determined and describes the level of cooperation at which country i is willing to invest in research infrastructure when countries are endowed with $\overline{\alpha}(\lambda_i^\circ)$ permits. We note that a particular value of λ_i° may not be in $[\underline{\lambda}, 1]$ and hence no level of cooperation can induce an innovation cluster in country i. Moreover, $\lambda_b^\circ = \min_{i=m_b,\ldots,m} \{\lambda_i^\circ\}$ describes the minimal level of cooperation at which a first country that is a net-buyer on the permit market is willing to create the research infrastructure.

Proposition 5 states how changes in cooperation at the international level can induce the creation of an innovation cluster, with a special focus on net-buyers.

[31] A focal point (also called a "Schelling Point") refers to a solution in games that all players are likely to choose in the absence of communication.

[32] Without permit trade, a local planner would consider

$$\Pi(\hat{k}(p_N))[\hat{f}(p_N) + g_n(p_N) + \delta\sum_{i=1}^{m}[\bar{e}_i - a_{n,N}]] + [1 - \Pi(\hat{k}(p_N))][g_o(p_O) + \delta\sum_{i=1}^{m}[\bar{e}_i - a_{o,O}] + F_i$$
$$\leq g_o(p_O) + \delta\sum_{i=1}^{m}[\bar{e}_i - a_{o,O}]].$$

Based on (25), we can write $F_i \leq \Pi(\hat{k}(p_N))[-\hat{f}(p_N) - g_n(p_N) + g_o(p_O)] = \Pi(\hat{k}(p_N))\hat{f}(p_N)\frac{b_o - b_n}{b_n}$.

Proposition 5. *(i) Suppose that $\lambda < \lambda^\circ < 1$ and $\alpha = \overline{\alpha}(\lambda^\circ)$. Then, an increase in the level of cooperation from λ to λ° induces an innovation cluster.*

(ii) Consider countries $i = m_b, .., m$ that are net-buyers on the permit market. Suppose $\lambda < \lambda_b^\circ < 1$ and $\alpha = \overline{\alpha}(\lambda)$. Then, an increase in cooperation from λ to λ_b° and a decrease of α to $\overline{\alpha}(\lambda_b^\circ)$ induces an innovation cluster.

The proof is in Appendix C.

The relation between the cooperation level λ and incentives to invest in research infrastructure is as follows. First, higher carbon prices due to a higher level of cooperation increase the gains from detecting the new technology. Second, higher prices increase the license income of the patent holder, as production firms' willingness to pay to adopt the new technology increases. The higher license income attracts more applied research firms and the overall probability to detect the new technology increases. Thus, higher gains that will be obtained with a higher probability increase the local government's incentives to invest in research infrastructure. Moreover, only the higher income for the patent-holder may be sufficient to make applied research firms use the created research infrastructure, such that an innovation cluster will be in place.

If the share of permit endowments relative to baseline emissions α has to be lowered to ensure the feasibility of the carbon price targets at the higher cooperation level λ°, a potential countervailing force may arise. If $\alpha < \overline{\alpha}(\lambda^\circ)$, one can increase λ to λ°, assuming $\lambda^\circ < 1$, without the need to change α. Next, we examine the impact of changes in α for the creation of an innovation cluster in more detail.

6.2. The impact of countries' permit endowments

The next proposition summarizes how the incentives to create an innovation cluster depend on the initial permit endowment.

Proposition 6. *(i) Consider countries $i = m_b, \ldots, m$ that are net-buyers on the permit market. Suppose $\alpha \in [0, 1]$ and $\alpha > \alpha^\circ$, with*

$$\alpha^\circ = \max_{i=m_b,\ldots,m} \left\{ 1 - \frac{\frac{F_i}{\Pi(\hat{k}(\lambda p_N^*))} - \hat{f}(\lambda p_N^*)\frac{b_O - b_n}{b_n}}{\lambda[p_O^* - p_N^*]\left[\overline{e}_i - \frac{\overline{E}}{m}\right]} \right\} \tag{18}$$

and $\hat{k}(\lambda p_N^*) > 0$, and no country faces incentives to induce an innovation cluster.

Then, decreasing the share of grandfathered permits from α to α° for a given level of λ induces an innovation cluster in a country that is a net-buyer on the permit market.

(ii) Consider countries $i = 1, \ldots, m_s$ that are net-sellers on the permit market.

Suppose $\alpha < \alpha^\circ \leq \overline{\alpha}(\lambda)$, with

$$\alpha^\circ = \min_{i=1,\ldots,m_s} \left\{ 1 - \frac{\frac{F_i}{\Pi(\hat{k}(\lambda p_N^*))} - \hat{f}(\lambda p_N^*)\frac{b_O - b_n}{b_n}}{\lambda[p_O^* - p_N^*]\left[\overline{e}_i - \frac{\overline{E}}{m}\right]} \right\} \tag{19}$$

and $\hat{k}(\lambda p_N^*) > 0$, and no country faces incentives to induce an innovation cluster.

The proof is in Appendix C.

The intuition is as follows. If the share of issued permits is too high, there are no incentives for net-buyers to invest in an innovation cluster. If α is lowered, net-buyers need to buy more permits. Therefore, inducing an innovation cluster to detect the new technology becomes more attractive. Net-sellers have the opposite incentives. An increase in α would make an innovation cluster more likely, as the gains from selling permits relative to lower abatement costs decrease. Scope for increasing permit issuance at a given cooperation level is only possible if $\alpha \leq \overline{\alpha}(\lambda)$.[33]

Overall, inducing innovation clusters via increased cooperation (λ) or smaller permit endowments (α) entails several problems. First, countries are unlikely to coordinate on Country i^*, which has the lowest costs to invest in research infrastructure. Second, α—and thus the permit endowments—may have to be comparatively low if costs to create research infrastructure F_i are large. Lastly and most importantly, an innovation cluster may simply not be viable, since no country faces sufficient incentives. This is particularly obvious for high-emissions countries, as they face a double burden: They must buy a large amount of permits (to have incentives to create an innovation cluster), and they bear costs to invest in research infrastructure. Low-emissions countries may simply not expect sufficient gains from innovation clusters.

Next, we suggest how to solve these problems.

[33] Political-economic considerations suggest that α is close to $\overline{\alpha}$, since local governments often use grandfathering to gain the support from industry.

6.3. The innovation-cluster-generation procedure

We formulate three desiderata for inducing an innovation cluster. First, Country i^* should invest in research infrastructure. Second, there should be a fair sharing of the overall burden. Third, countries should have maximal permit endowments for the given cooperation level. The justification for these three requirements is as follows. The first desideratum is the efficiency requirement with respect to investments in research infrastructure. With the second requirement, we capture the fairness requirement. A country that bears the cost of generating the innovation cluster should not fare worse than the other countries. Besides fairness as a requirement per se, this should help to foster cooperation on sufficiently high carbon price targets. The third requirement aims at easing political-economic constraints at the local level.

We next present the Innovation-cluster-generation procedure (henceforth "ICG-Procedure"), which can fulfill all described desiderata as best as possible. The procedure consists of the following three elements:

- Country i^*'s permit endowment is $\tilde{\epsilon}$.
- Countries $i \neq i^*$' permit endowments are $\tilde{\alpha}\bar{e}_i$.
- Country i^* receives the payment $\tilde{\pi}$ from the trading agency.

The procedure implements the desiderata in the following way. Permits $\tilde{\epsilon}$ are set to ensure that Country i^* has incentives to invest in research infrastructure. We call this the "Incentive Constraint". By investing in research infrastructure, Country i^* faces expenditures the other countries do not have to bear. In addition, Country i^* will only be endowed with relatively few permits, as $\tilde{\epsilon}$ is set to incentivize research investments. To ensure overall fair sharing of the burden, Country i^* is compensated by the payment $\tilde{\pi}$ from the trading agency. We term this the "Equally Well-off Condition" and explain it in more detail below. The remaining countries are endowed with $\tilde{\alpha}\bar{e}_i$ permits, with $\tilde{\alpha}$ set to ensure that the trading agency can finance $\tilde{\pi}$ and ensure that the targeted carbon price p_T prevails. We term this the "Feasibility Constraint".

We interpret the Equally Well-off Condition as follows. Country i^* should be indifferent between two situations: It creates the innovation cluster, is endowed with $\tilde{\epsilon}$ permits and receives the payment $\tilde{\pi}$; another country takes the role of creating the innovation cluster, is endowed with $\tilde{\epsilon}$ permits and receives $\tilde{\pi}$. In the latter situation, Country i^* would be endowed with $\tilde{\alpha}\bar{e}_i$ permits.

We make two additional assumptions that simplify the analysis. First, we assume that the hypothetical other country that creates the innovation cluster instead of Country i^* has the same characteristics as Country i^*, i.e. it has $F_i = F_{i^*}$ and $\bar{e}_i = \bar{e}_i^*$. Second, to ensure a non-negative profit for the trading agency in all circumstances and maximal permit endowment of the countries, we assume zero profit of the agency after paying $\tilde{\pi}$ if the lower carbon price (p_N) prevails, i.e. if the new technology is detected. If the new technology is not detected, the agency's profit is equally distributed among all countries except country i^*, influencing the Equally Well-off Condition.

Proposition 7 presents the results of the ICG-Procedure when $\tilde{\alpha}, \tilde{\epsilon}, \tilde{\pi}$ are determined according to the above criteria and using $p_N = \lambda p_N^*$ as well as $p_O = \lambda p_O^*$.

Proposition 7. *Suppose $\hat{k}(p_N) > 0$ if investments into research infrastructure are made. Then, there exists a uniquely-determined combination of $\tilde{\alpha}, \tilde{\epsilon}, \tilde{\pi}$ defined by the following three conditions:*

- *the Incentive Constraint to create an innovation cluster in Country i^*,*

$$\frac{F_{i^*}}{\Pi(\hat{k}(p_N))} - [p_O - p_N][\bar{e}_{i^*} - \tilde{\epsilon} - \hat{a}(\lambda)] = \hat{f}(p_N)\frac{b_o - b_n}{b_n}, \tag{20}$$

- *the Feasibility Constraint of the trading agency,*

$$p_N[\bar{E} - m\hat{a} - \tilde{\alpha}\bar{E} + \tilde{\alpha}\bar{e}_{i^*} - \tilde{\epsilon}] - \tilde{\pi} = 0, \tag{21}$$

- *and the Equally Well-off Condition*

$$\begin{aligned} &\Pi(\hat{k}(p_N))[-p_N\bar{e}_{i^*}\tilde{\alpha}] + [1 - \Pi(\hat{k}(p_N))][-p_O\bar{e}_{i^*}\tilde{\alpha}] \\ &\quad + \frac{1 - \Pi(\hat{k}(p_N))}{m - 1}[p_O[[1 - \tilde{\alpha}]\bar{E} - m\hat{a} + \tilde{\alpha}\bar{e}_{i^*} - \tilde{\epsilon}] - \tilde{\pi}] \\ &\quad = \Pi(\hat{k}(p_N))[-p_N\tilde{\epsilon}] + [1 - \Pi(\hat{k}(p_N))][-p_O\tilde{\epsilon}] + F_{i^*} - \tilde{\pi}, \end{aligned} \tag{22}$$

which characterize the ICG-Procedure and induce an innovation cluster in Country i^*.

The proof is in Appendix C.

Several remarks are in order. First, of course, if $\tilde{\pi} < 0$ were a solution, then the ICG-Procedure would be superfluous. We focus on constellations in which innovation clusters will not be created without the ICG-Procedure. Second, a binding constraint is that $0 \leq \tilde{\alpha} \leq 1$. If $\tilde{\alpha} < 0$, or if $\tilde{\epsilon} < 0$, countries are endowed with a negative amount of permits. Both $\tilde{\alpha} < 0$ or $\tilde{\epsilon} < 0$ are possible, but difficult to enforce. The case $\tilde{\alpha} > 1$ implies that countries obtain an amount of permit that is larger

than their baseline emissions. With our focus on innovation and thus on more industrialized countries, this case is not really relevant. Lastly, besides being a way to ensure an innovation cluster, the ICG-Procedure is also a way for countries to coordinate on Country i^* to invest in research infrastructure, and thus to increase social efficiency.

We now briefly discuss how the ICG-Procedure can be extended to include the case that $\hat{k}(p_N) = 0$. Lower research costs are one way to incentivize the applied research firms to become active and use research infrastructure even when the carbon price is low. One could lower research costs x through subsidizing by the factor $1 - \beta$, with $0 < \beta < 1$, i.e. firms only have to pay βx. This research subsidy could be financed by adding the amount to the research infrastructure costs of a country, $F_{i*} + k(1 - \beta)x$. To ensure $\hat{k}(p_N) > 0$, the scalar has to be sufficiently small, i.e.

$$\beta < {p_N}^2 \frac{\pi m(b_o - b_n)}{(1-\pi)x2b_n b_o},$$

which is derived from Eq. (6). Then, the ICG-Procedure could be implemented based on the modified costs for research infrastructure

$$F_{i*} + k(1 - \beta)x.$$

We provide an illustration in the working paper version (Gersbach and Riekhof, 2018). In the working paper, we also show how the carbon price levels impact the type of research infrastructure created. We also note that the ICG-Procedure could be adapted to induce innovation clusters for more efficient new technologies.

6.4. Implementing the first-best solution

Our ICG procedure can be readily adapted for the implementation of innovation clusters when optimal aggregate emissions can be made dependent on the available technology. The following lemma states how first-best abatement levels can be induced in a market setting and which license fee will result.

Lemma 6. *The first-best abatement levels a_o^{fb} and a_n^{fb} can be induced by setting the carbon price equal to $p_T^{fb} = m\delta$. The willingness-to-pay of production firms and, accordingly, the license fee is $f^{fb}(p_N) = p_N^2 \frac{b_o - b_n}{2b_n b_o}$ with $p_N = \lambda p_N^{fb}$.*

The proof is in Appendix C.

To ensure the carbon price, the total amounts of emission permits differ between the case with and without the detection of the new technology. Let ε^o and ε^n denote aggregate permits without and with the detection of the new technology. The creation of an innovation cluster by Country i^{fb} can be achieved by the permit distribution presented in the next proposition.

Proposition 8. *In the case of no technology detection, all countries receive permits ϵ_i^o related to their baseline emission $\overline{e}_i$,*

$$\epsilon_i^o = \frac{\overline{e}_i}{\overline{E}} \mathcal{E}^o.$$

In the case of technology detection,

$$\epsilon_i^n = \begin{cases} \hat{\epsilon}_i, & i = i^{fb} \\ \frac{\overline{e}_i}{\overline{E}}(\mathcal{E}^n - \hat{\epsilon}_i), & i \neq i^{fb} \end{cases}$$

with

$$\hat{\epsilon}_i = \frac{p_N(p_N - \delta m)}{\delta m} \frac{b_o - b_n}{b_n b_o} + [\overline{\epsilon}_i^o + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] + \frac{F_i}{\Pi(\hat{k}(p_N))\delta m}.$$

The proof is in Appendix C.

This way of distributing the permits fulfills the three desiderata for inducing an innovation cluster: First, Country i^{fb} (the country with the lowest costs to set-up a research infrastructure) invests in research infrastructure. The permit endowment for country i^{fb} in case the new technology is detected is chosen such that in expected terms, the country is indifferent between investing in research infrastructure and not doing so. We assume that in this case, the country will invest. Second, there is a fair sharing of the overall burden, as Country i^{fb} receives additional permits in case of technology detection that it can sell on the permit market as compensation for setting up the research infrastructure. Third, countries have maximal permit endowments for the given cooperation level. In the following, we will briefly compare our ICG-procedure for the first-best and the second-best setting. The condition for Country i^{fb} to invest in research infrastructure is (see proof of Proposition 8)

$$\epsilon^n_{ifb} \geq \hat{\epsilon}_i fb.$$

In the proposition, the permit amount is set equal to fulfill the desideratum that especially the other countries can have maximal permit endowments, assuming that an indifferent country will invest in research infrastructure. This shows that while in the second-best setting, relatively few permits incentivize research infrastructure investments of a country, in the first-best setting, a minimum amount of permits has to be promised to a country for the case of successful innovation to invest in research infrastructure. The difference comes from the policy instruments available to the agency in the different settings: In the first-best setting, the permit price is independent from technology detection. Permit issuance cannot only be adapted in general, but also at the individual level. Thus, allocating relatively many permits in the case of the detection of the new technology to the country that creates the research infrastructure serves both as an incentive to create the research infrastructure and as a compensation for the related costs. In the second-best setting, permits are issued before uncertainty surrounding technological progress is resolved. Permit prices are conditional on the technology available, but they hold for all agents. To create country-specific incentives, few permits are given to a country in combination with some kind of refunding to compensate for the costs.

7. Discussion and conclusion

Innovation clusters appear to be crucial for technological advances to slow down climate change. Innovation clusters need research infrastructure, typically financed by the government—e.g. laboratories, skilled workforce, and blueprints—and applied research firms to detect a new technology and commercialize it. Public spending on research infrastructure is rationalized by positive spillovers to applied research. We discussed whether and how international cooperation on climate policy with carbon pricing and emissions trading systems can induce such innovation clusters. Based on the observation that richer countries have higher commitments for reducing emissions in the sectors not regulated under the European emissions trading system, we analyze how such an approach *within* an emissions trading system would impact the creation of innovation clusters and whether it could be used to increase the prospects of creating innovation clusters.

Our analysis generates three major insights. First, the impact of carbon price targets goes beyond the pure internalization of externalities of emissions. We find that the level of carbon price targets influences whether and for which type of abatement technology research infrastructure is created, whether applied research firms become active and use the infrastructure such that an innovation cluster forms, and how high the overall probability to detect a new technology is. Second, permit trade impacts the creation of innovation clusters. This impact may increase the overall incentives to create an innovation cluster in a decentralized setting, but it may lead to the creation of an innovation cluster in a country with relatively high research infrastructure costs. Third, international climate policy can help to induce the creation of innovation clusters for green technologies, even under adverse conditions. The innovation-cluster-generation procedure we suggested combines the allocation of initial permit endowments with fair burden-sharing. Initial permit endowment ensures that the country with the lowest costs creates an innovation cluster. In addition, the ICG-Procedure aims for maximal permit endowment for the remaining countries, given that some revenues from permit trading are generated to financially support the country that invests in research infrastructure and creates the innovation cluster. While high carbon prices make the creation of an innovation cluster more likely, the ICG-Procedure can even induce the creation of an innovation cluster when carbon prices, relative to the costs to create the corresponding research infrastructure, are low.

Our model could be extended in different ways. One could explicitly model asymmetric information regarding abatement costs or damages, or include transaction costs of setting up the trading agency. Other variants of the ICG-Procedure are also conceivable. In the versions explored in this paper, the country that invests in research infrastructure is equally well-off in expected terms than other countries. However, if no technology is detected, it is ex-post worse-off, since it has to buy a large number of permits at a high price. Allowing for an additional insurance scheme among countries, based on the detection of new technologies, could mitigate this. Also, one could introduce several clusters operating simultaneously, which focus on different technologies. In such a situation, our proposed ICG-Procedure could be extended to serve as a coordination device that reduces duplication of research effort. Several countries may receive few permits and share the revenues from the trading agency. In a next step, dynamic incentives could also be considered explicitly.

Conflict of interest

None declared.

Appendix A. Proofs: first-best solution

Table 1
List of principal notation.

Symbol	Description
m	Number of countries
i, j	Country index
$1, \ldots, i_s$	Country index for net-sellers
$i_b, \ldots, m$	Country index for net-buyers
T	Index for technology level available in economy, with "O" for old and "N" for new
t	Index for technology used by a production firm, with "o" for old and "n" for new
p_T	Price target conditional on the technology level
$\overline{e}_i$	Baseline emissions of production firm i
$\overline{E}$	Sum of baseline emissions over all production firms
a_i	Abated emissions of production firm i
$g_o(a_i)$	Abatement costs, old technology
$g_n(a_i)$	Abatement costs, new technology
b_o	Coefficient abatement costs, old technology
b_n	Coefficient abatement costs, new technology
ϵ_i	Permits issued in country i
δ	Coefficient damages in a country
F_i	Research infrastructure costs of country i
x	Research investment of applied research firm
π	Probability of a successful innovation per active applied research firm
k	Number of active applied research firms
f	License fee to use g_n
$\Pi(k)$	Overall probability of detection of the new technology
$a_{o,O}$	Emissions abated using the old technology
$a_{n,N}$	Emissions abated using the new technology
a^*	Second-best emissions abated by firm i
$F_{i^*}; F_{i^{fb}}$	Lowest research infrastructure costs
$i^*; i^{fb}$	Country with lowest research infrastructure costs
λ	Scalar to reflect cooperation level
p_T^*	Price target to reach second-best abatement level
α	Grandfathered permits over baseline emissions
$\overline{\alpha}$	Upper bound on α to ensure feasibility of carbon price
$\overline{\varepsilon}$	Total amount of grandfathered permits
K_i^{IC}	Total expected costs when some other country invested into research infrastructure
K_i^{NIC}	Total costs when no other country invested into research infrastructure
$\tilde{\epsilon}$	Amount of grandfathered permits to Country i^* under ICG-Procedure
$\tilde{\alpha}$	Permits grandfathered over baseline emissions for countries $i \neq i^*$ under ICG-Procedure
$\tilde{\pi}$	Compensating amount under ICG-Procedure
f_b	Superscript to denote first-best outcome
*	Superscript to denote second-best outcome
$\hat{f}$	License fee in market solution
$\hat{k}$	Number of applied research firms in market solution
$\overline{\varepsilon}_i$	Permit endowment country i

Proof Proposition 2. The global first-best solution with an innovation cluster is characterized by

$$\min_{k,a_{i,n},a_{i,o}} \quad \Pi(k)[\sum_{i=1}^{m}\frac{b_n}{2}a_{i,n}^2 + m\delta\sum_{i=1}^{m}[\overline{e}_i - a_{i,n}]] + [1-\Pi(k)][\sum_{i=1}^{m}\frac{b_o}{2}a_{i,o}^2 + m\delta\sum_{i=1}^{m}[\overline{e}_i - a_{i,o}]] + xk + F_i,$$

with first-order conditions

$$\Pi(k)[b_n a_{i,n} - m\delta] = 0,$$
$$(1-\Pi(k))[b_o a_{i,o} - m\delta] = 0,$$
$$\Pi'(\mathrm{k})[\sum_{i=1}^{m}(\frac{b_n}{2}a_{i,n}^2 - \frac{b_o}{2}a_{i,o}^2) + m\delta\sum_{i=1}^{m}(a_{i,o} - a_{i,n})] + x = 0$$

leading to

$$a_{i,n}^{fb} = a_n^{fb} = \frac{m\delta}{b_n}, \quad a_{i,o}^{fb} = a_o^{fb} = \frac{m\delta}{b_o},$$

as well as

$$\Pi'(k)\left[\sum_{i=1}^{m}\left(\frac{b_n}{2}a_{i,n}^2-\frac{b_o}{2}a_{i,o}^2\right)+m\delta\sum_{i=1}^{m}(a_{i,o}-a_{i,n})\right]+x=0$$
$$\frac{\pi(1-\pi)}{(1+\pi(k-1))^2}\left[m(m\delta)^2\frac{b_n-b_o}{2b_nb_o}\right]+x=0.$$

Hence,

$$\frac{1}{(1+\pi(k-1))^2}=\frac{2xb_nb_o}{m(m\delta)^2\pi(1-\pi)(b_o-b_n)}$$
$$k^{fb}=\frac{\pi-1}{\pi}+\frac{m\delta}{\pi}\sqrt{\frac{m\pi(1-\pi)(b_o-b_n)}{2xb_nb_o}}.$$

$$\Pi(k^{fb})[\sum_{i=1}^{m}\frac{b_n}{2}(a_n^{fb})^2+m\delta\sum_{i=1}^{m}[\bar{e}_i-a_n^{fb}]]+[1-\Pi(k^{fb})][\sum_{i=1}^{m}\frac{b_o}{2}(a_o^{fb})^2+m\delta\sum_{i=1}^{m}[\bar{e}_i-a_o^{fb}]]+xk^{fb}+F_{ifb}$$
$$\leq\sum_{i=1}^{m}\frac{b_o}{2}(a_o^{fb})^2+m\delta\sum_{i=1}^{m}[\bar{e}_i-a_o^{fb}]$$
$$\Leftrightarrow\Pi(k^{fb})[\frac{m(m\delta)^2}{2}\frac{b_o-b_n}{b_nb_o}]-xk^{fb}\geq F_{ifb}.$$

From a global perspective, costs are obviously minimized when the country with the lowest costs for research infrastructure makes the investment. □

Appendix B. Proofs: second-best solution

Proof Proposition 3. The global social optimum with an innovation cluster is characterized by

$$\min_{k,a_i}\quad\Pi(k)[\sum_{i=1}^{m}\frac{b_n}{2}a_i^2]+m\delta\sum_{i=1}^{m}[\bar{e}_i-a_i]+[1-\Pi(k)][\sum_{i=1}^{m}\frac{b_o}{2}a_i^2]+xk+F_{i^*},$$

with first-order conditions

$$\Pi(k)[b_na_i]+[1-\Pi(k)][b_oa_i]-m\delta=0,$$
$$\Pi'(k)\left[\sum_{i=1}^{m}\frac{b_n}{2}a_i^2-\sum_{i=1}^{m}\frac{b_o}{2}a_i^2\right]+x=0. \tag{23}$$

The first condition gives:

$$a_i^*=\frac{m\delta}{\Pi(k^*)b_n+(1-\Pi(k^*))b_o}=\frac{m\delta(1+\pi(k^*-1))}{k^*\pi b_n+(1-\pi)b_o}.$$

The second condition gives:

$$\frac{\pi(1-\pi)}{(1+\pi\times(k^*-1))^2}a_i^{*2}\frac{m(b_n-b_o)}{2}+x=0$$
$$\frac{\pi(1-\pi)m^2\delta^2}{(k^*\pi b_n+(1-\pi)b_o)^2}\frac{m(b_n-b_o)}{2}+x=0$$
$$\frac{1}{(k^*\pi b_n+(1-\pi)b_o)^2}=\frac{2x}{m(b_o-b_n)\pi(1-\pi)m^2\delta^2}$$
$$k^*\pi b_n+(1-\pi)b_o=Bm\delta$$
$$k^*=\frac{Bm\delta}{\pi b_n}+\frac{(\pi-1)b_o}{\pi b_n},\quad with$$
$$B=\sqrt{\frac{\pi(1-\pi)(b_o-b_n)m}{2x}}.$$

Finally, we obtain:

$$a_i^* = \frac{m\delta(1-\pi)+\pi m\delta k^*}{Bm\delta},$$
$$= \frac{(1-\pi)(b_n-b_o)}{Bb_n}+\frac{m\delta}{b_n}.$$

Collecting results,

$$k^* = \frac{Bm\delta}{\pi b_n}+\frac{b_o(\pi-1)}{\pi b_n},$$
$$a^* = \frac{m\delta}{b_n}+\frac{(1-\pi)(b_n-b_o)}{Bb_n}.$$

Note that Eq. (23) implies that $a_i = a^*$ for all i. The second-order conditions for a minimum $f(x,y)$ are $f_{xx}>0$, $f_{yy}>0$ and $f_{xx}f_{yy}>f_{yx}^2$. As a preparation for the calculations, consider first the derivatives of the approximation of the probability,

$$\frac{\partial \frac{\pi k}{1+\pi(k-1)}}{\partial k} = \frac{\pi(1-\pi)}{(1+\pi(k-1))^2} > 0 \quad \text{and} \quad \frac{\partial^2 \frac{\pi k}{1+\pi(k-1)}}{\partial k^2} = \frac{-2\pi^2(1-\pi)}{(1+\pi(k-1))^3} < 0.$$

Note that also $\Pi'(k)>0$ and $\Pi''(k)<0$. All three conditions are fulfilled:

$$\Pi(k)b_n+(1-\Pi(k))b_o > 0$$
$$\underbrace{\Pi''_{kk}(k)}_{<0}\underbrace{\Big[\sum\nolimits_{i=1}^{m}\frac{b_n}{2}a_i^2-\sum\nolimits_{i=1}^{m}\frac{b_o}{2}a_i^2\Big]}_{<0} > 0$$
$$(\Pi(k)b_n+(1-\Pi(k))b_o)\Pi''_{kk}(k)[\sum_{i=1}^{m}\frac{b_n}{2}a_i^2-\sum_{i=1}^{m}\frac{b_o}{2}a_i^2] > (\Pi'_k(k))^2[b_n-b_o]^2a_i^2$$
$$\Leftrightarrow \frac{\pi k b_n+(1-\pi)b_o}{1+\pi(k-1)}\frac{-2\pi^2(1-\pi)}{(1+\pi(k-1))^3}\frac{b_n-b_o}{2}[\sum_{i=1}^{m}a_i^2] > \frac{\pi^2(1-\pi)^2}{(1+\pi(k-1))^4}[b_n-b_o]^2a_i^2$$
$$\Leftrightarrow (\pi k b_n+(1-\pi)b_o)[\sum_{i=1}^{m}a_i^2] > (1-\pi)[b_o-b_n]a_i^2.$$

The global social optimum without an innovation cluster is characterized by

$$\min_{a_i} \quad m\delta\sum_{i=1}^{m}[\bar{e}_i-a_i]+\left[\sum_{i=1}^{m}\frac{b_o}{2}a_i^2\right],$$

with first-order conditions

$$[b_o a_i]-m\delta = 0,$$

leading to

$$a^{**} = \frac{m\delta}{b_o},$$

with the superscript ** denoting variables describing the second-best solution without an innovation cluster. Below, we consider under which conditions optimal abatement in a situation without an innovation cluster is lower than in a situation with an innovation cluster:

$$a^{**} = \frac{m\delta}{b_o} < a^* = \frac{m\delta}{b_n}+\frac{(1-\pi)(b_n-b_o)}{Bb_n},$$
$$\frac{m\delta}{b_o} < \frac{m\delta}{b_n}+\frac{(1-\pi)(b_n-b_o)}{Bb_n},$$
$$b_n m\delta < b_o m\delta+\frac{b_o(1-\pi)(b_n-b_o)}{B},$$
$$m\delta(b_n-b_o) < \frac{b_o(1-\pi)(b_n-b_o)}{B},$$
$$m\delta > \frac{b_o(1-\pi)}{B}.$$

An innovation cluster is optimal if

$$\begin{aligned}
&\Pi(k^*)\left[\sum_{i=1}^{m}\frac{b_n}{2}[a^*]^2\right]+[1-\Pi(k^*)]\left[\sum_{i=1}^{m}\frac{b_o}{2}[a^*]^2\right]+m\delta\sum_{i=1}^{m}[\bar{e}_i-a^*]+xk^*+F_{i^*}\\
&\leq\sum_{i=1}^{m}\frac{b_o}{2}[a^{**}]^2+m\delta\sum_{i=1}^{m}[\bar{e}_i-a^{**}]\\
&\Leftrightarrow\ \Pi(k^*)\left[m\frac{b_n}{2}[a^*]^2\right]+[1-\Pi(k^*)]\left[m\frac{b_o}{2}[a^*]^2\right]-m^2\delta a^*+xk^*+F_{i^*}\\
&\leq m\frac{b_o}{2}[a^{**}]^2-m^2\delta a^{**}\\
&\Leftrightarrow\ xk^*+F_{i^*}\leq m\frac{b_o}{2}[a^{**}]^2+m^2\delta(a^*-a^{**})-\Pi(k^*)\left[m\frac{b_n}{2}[a^*]^2\right]-[1-\Pi(k^*)]\left[m\frac{b_o}{2}[a^*]^2\right]\\
&\Leftrightarrow\ xk^*+F_{i^*}\leq m\left(-\frac{m^2\delta^2}{2b_o}+m\delta a^*-\frac{[a^*]^2}{2}\left[\Pi(k^*)b_n+[1-\Pi(k^*)]b_o\right]\right).
\end{aligned}$$

From a global perspective, costs are obviously minimized when the country with the lowest costs for research infrastructure makes the investment. □

Proof Proposition 4. Production firms' abatement is according to $a_{t,T}=p_T/b_t$ (see Eq. (3)). With p_T^*, $a^*=p_T^*/b_t$, such that $p_T^*=b_t a^*$ implements second-best abatement levels. Note that, as $a_i=\bar{e}_i-\epsilon_i$, an initial allocation of permits according to $\epsilon_i^*=\bar{e}_i-a^*$ can also implement the second-best solution in terms of abatement. □

Appendix C. Further proofs

Proof Lemma 1.

$$\begin{aligned}
f&=\frac{b_o}{2}(a_{o,N})^2-\frac{b_n}{2}(a_{n,N})^2+p_N[a_{n,N}-a_{o,N}],\\
&=p_N^2\left[\frac{1}{2b_o}-\frac{1}{2b_n}+\frac{1}{b_n}-\frac{1}{b_o}\right],\\
&=p_N^2\left[\frac{1}{2b_n}-\frac{1}{2b_o}\right]=p_N^2\left[\frac{b_o-b_n}{2b_ob_n}\right].\ \square
\end{aligned}$$

Proof Lemma 3. Based on (13) and using (12), we can rewrite the feasibility constraint as follows:

$$\lambda p_T^*[[1-\alpha]\bar{E}-m\lambda a^*]\geq 0\quad\Leftrightarrow\quad[1-\alpha]\bar{E}\geq m\lambda a^*\quad\Leftrightarrow\quad 1-\lambda\underbrace{\frac{ma^*}{\bar{E}}}_{<1}\geq\alpha.$$

We next observe that for any λ, there exists a uniquely determined $\overline{\alpha}(\lambda)$

$$\overline{\alpha}(\lambda):=1-\lambda\frac{ma^*}{\bar{E}}$$

and that $0<\overline{\alpha}(\lambda)<1$ for λ-values in $[\underline{\lambda},1]$. This follows from

$$\frac{ma^*}{\bar{E}}<1$$

and thus $\overline{\alpha}(1)>0$, $\overline{\alpha}(\underline{\lambda})<1$ and that $\overline{\alpha}(\lambda)$ is monotonically decreasing in λ. □

Proof Lemma 4. We assume that some other country invested into research infrastructure. Then, the costs faced by local government i given in (14) (with $F_i=0$) can be written as

$$\begin{aligned}
&\Pi(\hat{k}(p_N))\left[\hat{f}(p_N)+g_n(p_N)+p_N[\bar{e}_i-\bar{\epsilon}_i-a_{n,N}]+\delta\sum_{i=1}^{m}[\bar{e}_i-a_{n,N}]-\frac{p_N}{m}[\bar{E}-\bar{\mathcal{E}}]+p_Na_{n,N}\right]\\
&+[1-\Pi(\hat{k}(p_N))]\left[g_o(p_O)+p_O[\bar{e}_i-\bar{\epsilon}_i-a_{o,O}]+\delta\sum_{i=1}^{m}[\bar{e}_i-a_{o,O}]-\frac{p_O}{m}[\bar{E}-\bar{\mathcal{E}}]+p_Oa_{o,O}\right],
\end{aligned}$$

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

Proof Lemma 5. If we subtract K_i^{NIC} from both sides of (15), and subtract F_i, we obtain

$$\begin{aligned} -F_i \geq\ & \Pi(\hat{k}(p_N)) \left[\hat{f}(p_N) + g_n(p_N) - g_o(p_O) + p_N[\overline{e}_i - \overline{\epsilon}_i - a_{n,N}] - p_O[\overline{e}_i - \overline{\epsilon}_i - a_{o,O}] + \delta \mathrm{m}[a_{o,O} - a_{n,N}]\right] \\ & + \frac{\Pi(\hat{k}(p_N))}{m}\left[-p_N[\overline{E} - \overline{\mathcal{E}} - m a_{n,N}]\right] - \frac{\Pi(\hat{k}(p_N))}{m}\left[-p_O[\overline{E} - \overline{\mathcal{E}} - m a_{o,O}]\right] \end{aligned} \tag{24}$$

Now, multiplying with −1, inserting for $\overline{\epsilon}_i = \alpha \overline{e}_i$, using $a_{n,N} = a_{o,O} = \hat{a}$ (Eq. (12)) and isolating country-specific terms yields

$$\begin{aligned} & F_i + \Pi(\hat{k}(p_N))[\overbrace{-[p_O - p_N][[1-\alpha]\overline{e}_i - \hat{a}]}^{\text{Impact from permit trade}} + \overbrace{\frac{[p_O - p_N]}{m}[[1-\alpha]\overline{E} - m\hat{a}]}^{\text{Impact from refunding of profit}}] \\ & \leq \Pi(\hat{k}(p_N))[g_o(p_O) - g_n(p_N) - \hat{f}(p_N)] = \Pi(\hat{k}(p_N))\hat{f}(p_N)\frac{b_o - b_n}{b_n}, \end{aligned} \tag{25}$$

writing $g_o(p_O)$ as $g_o(\hat{a})$ and $g_n(p_N)$ as $g_n(\hat{a})$ using Eq. (12) and setting $\hat{a} = a_{n,N} = p_N/b_n$. Note that $\hat{f}(p_N)[b_o - b_n]/b_n > 0$. Minor re-arrangements and inserting for $p_T = \lambda p_T^*$ lead to (16). □

Proof Proposition 5. (i) As $\alpha = \overline{\alpha}(\lambda^\circ)$, the second term on the LHS of Eq. (17)—the price-change effect—is now independent of λ, and increasing the cooperation level up to λ° requires no change in α.

Eq. (17) is based on (16), using that $\hat{f}(\lambda p_N^*) = (\lambda p_N^*)^2(b_o - b_n)/(2b_n b_o)$ and dividing by λ. Then, the RHS increases in λ. The first term on the LHS decreases in λ, as the denominator increases with λ,

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

Accordingly, increasing λ to λ° will lead to a situation in which Condition (16) is fulfilled for at least one country, as λ° is defined as the minimum cooperation level for which at least one country has an incentive to create a research infrastructure.

(ii) If $\alpha = \overline{\alpha}(\lambda)$, the proof is as before, except that now a decrease in α has to be taken into account. When $\alpha = \overline{\alpha}(\lambda)$, an increase in λ needs to be accompanied by a decrease in α to ensure that the carbon price target remains feasible (non-negative profit of the trading agency, see Lemma 3). For net-buyers on the permit market with $\overline{e}_i > \overline{E}/m$, the change in α reinforces the impact of an increase in λ.

In both cases, no research infrastructure investment may take place initially because local planners anticipate that $\hat{k}(\lambda p_N^*) = 0$, i.e. applied research firms would not become active. Only with $\hat{k}(\lambda^\circ p_N^*) > 0$ and the resulting higher carbon prices, applied research firms will become active. □

Proof Proposition 6. The condition $k(\lambda p_N^*) > 0$ implies that applied research firms become active and use the research infrastructure once it is created and an innovation cluster is in place. At the given λ and α, no country has incentives to create a research infrastructure. Based on (16), no country invests if

$$\frac{F_i}{\Pi(\hat{k}(\lambda p_N^*))} - \lambda[p_O^* - p_N^*][1-\alpha]\left[\overline{e}_i - \frac{\overline{E}}{m}\right] > \hat{f}(\lambda p_N^*)\frac{b_o - b_n}{b_n} \quad \text{for} \quad i = 1, \ldots, m.$$

Accordingly, the prevailing α is too high (low) for net-buyers (net-sellers), i.e.

$$\text{for } \overline{e}_i > \frac{\overline{E}}{m} \ \text{(net-buyers)}, \quad \alpha > 1 - \frac{\dfrac{F_i}{\Pi(\hat{k}(\lambda p_N^*))} - \hat{f}(\lambda p_N^*)\dfrac{b_o - b_n}{b_n}}{\lambda[p_O^* - p_N^*]\left[\overline{e}_i - \dfrac{\overline{E}}{m}\right]},$$

$$\text{for } \overline{e}_i < \frac{\overline{E}}{m} \ \text{(net-sellers)}, \quad \alpha < 1 - \frac{\dfrac{F_i}{\Pi(\hat{k}(\lambda p_N^*))} - \hat{f}(\lambda p_N^*)\dfrac{b_o - b_n}{b_n}}{\lambda[p_O^* - p_N^*]\left[\overline{e}_i - \dfrac{\overline{E}}{m}\right]},$$

and for Condition (16) to hold, α needs to be lowered (increased) for net-buyers (net-sellers).

(i) For a given λ, lowering α is always possible (see Lemma 3).

(ii) An increase in α may violate the feasibility constraint (Lemma 3) such that additional constraints on α are imposed.

We discuss the possibility of $\alpha < 0$ and $\alpha > 1$ at the end of Section (6.3). □

Proof Proposition 7. Based on Equation (25), with $\tilde{\epsilon}$ instead of $\alpha\bar{e}_{i^*}$, and without any share from the trading agency's profit, the Incentive Constraint to create an innovation cluster for Country i^* is

$$\frac{F_{i^*}}{\Pi(\hat{k}(p_N))} - [p_O - p_N][\bar{e}_{i^*} - \tilde{\epsilon} - \hat{a}(\lambda)] \leq \underbrace{g_o(p_O) - \hat{f}(p_N) - g_n(p_N)}_{\hat{f}(\lambda p_N^*)(b_o - b_n)/b_n}. \tag{26}$$

It determines $\tilde{\epsilon}$ independent of $\tilde{\alpha}$ and $\tilde{\pi}$. To ensure a non-negative profit of the trading agency under both carbon prices, we assumed that the agency has zero profit in case of the lower carbon price (p_N),

$$p_N[\bar{E} - m\hat{a} - \tilde{\alpha}\bar{E} + \tilde{\alpha}\bar{e}_{i^*} - \tilde{\epsilon}] - \tilde{\pi} = 0. \tag{27}$$

The equation is based on Eq. (13), taking into account that country i^* receives $\tilde{\epsilon}$ instead of $\tilde{\alpha}\bar{e}_i^*$. When we take into account that the agency's profit is zero when the new technology is detected ($T = N$) and that a positive profit otherwise is equally distributed to all countries except i^*, the Equally Well-off Condition requires

$$\begin{aligned}
&\Pi(\hat{k}(p_N))[\hat{f}(p_N) + g_n(p_N) + p_N[\bar{e}_{i^*}[1-\tilde{\alpha}] - \hat{a}]] + [1 - \Pi(\hat{k}(p_N))][g_o(p_O) + p_O[\bar{e}_{i^*}[1-\tilde{\alpha}] - \hat{a}]] \\
&\quad + \delta[\bar{E} - m\hat{a}] + \frac{1-\Pi(k)}{m-1}[p_O[[1-\tilde{\alpha}]\bar{E} - m\hat{a} + \tilde{\alpha}\bar{e}_{i^*} - \tilde{\epsilon}] - \tilde{\pi}] \\
&\quad = \Pi(\hat{k}(p_N))[\hat{f}(p_N) + g_n(p_N) + p_N[\bar{e}_{i^*} - \tilde{\epsilon} - \hat{a}]] + [1 - \Pi(\hat{k}(p_N))][g_o(p_O) + p_O[\bar{e}_{i^*} - \tilde{\epsilon} - \hat{a}]] \\
&\quad\quad + \delta[\bar{E} - m\hat{a}] + F_{i^*} - \tilde{\pi}.
\end{aligned} \tag{28}$$

Using (27), Equation (28) reduces to

$$\underbrace{[\Pi(\hat{k}(p_N))p_N + [1 - \Pi(\hat{k}(p_N))]p_O]}_{=:\bar{P}}[\tilde{\epsilon} - \tilde{\alpha}\bar{e}_{i^*}] + \underbrace{[\frac{1-\Pi(\hat{k}(p_N))}{m-1}[\frac{p_O}{p_N} - 1] + 1]}_{=:T}\tilde{\pi} = F_{i^*}. \tag{29}$$

From these equations, we obtain Equation (22) in the proposition. We re-arrange (27) to obtain

$$\tilde{\alpha} = \frac{\tilde{\pi}}{p_N[\bar{e}_{i^*} - \bar{E}]} + \underbrace{\frac{m\hat{a} + \tilde{\epsilon} - \bar{E}}{\bar{e}_{i^*} - \bar{E}}}_{=:V}. \tag{30}$$

We insert (30) into (29) to obtain

$$\begin{aligned}
&\bar{P}\left[\tilde{\epsilon} - \left[\frac{\tilde{\pi}}{p_N[\bar{e}_{i^*} - \bar{E}]} + V\right]\bar{e}_{i^*}\right] + T\tilde{\pi} = F_{i^*} \\
&\Leftrightarrow \bar{P}\tilde{\epsilon} - \bar{P}\frac{\tilde{\pi}}{p_N[\bar{e}_{i^*} - \bar{E}]}\bar{e}_{i^*} - \bar{P}V\bar{e}_{i^*} + T\tilde{\pi} = F_{i^*} \\
&\Leftrightarrow \tilde{\pi} = \frac{F_{i^*} - \bar{P}\tilde{\epsilon} + \bar{P}V\bar{e}_{i^*}}{T - \frac{\bar{P}\bar{e}_{i^*}}{p_N[\bar{e}_{i^*} - \bar{E}]}}.
\end{aligned}$$

Plugging this back into (30) yields $\tilde{\alpha}$. □

Proof Lemma 6. Production firms' abatement is according to $a_{t,T} = p_T/b_t$ (see Equation (3)) such that $p_T^{fb} = b_t a_T^{fb} = \delta m$ implements the first-best abatement level. Let $\bar{\epsilon}_i^n$ denote permit endowments of country i in case the new technology is discovered. Given the new technology is detected and $p_T = p_N$ prevails, and taking into account that $p_O = p_N$, production firm i's maximal willingness to pay for the new technology, denoted by WTP_i^{fb}, is

$$\begin{aligned}
WTP_i^{fb} &= g_o(a_{o,N}) + p_N[\bar{e}_i - \bar{\epsilon}_i^n - a_{o,N}] - g_n(a_{n,N}) - p_N[\bar{e}_i - \bar{\epsilon}_i^n - a_{n,N}] \\
&= \frac{b_o}{2}\left(\frac{p_N}{b_o}\right)^2 - p_N\frac{p_N}{b_o} - \frac{b_n}{2}\left(\frac{p_N}{b_n}\right)^2 + p_N\frac{p_N}{b_n} \\
&= \frac{p_N^2}{2b_n} - \frac{p_N^2}{2b_o} = p_N^2\frac{b_o - b_n}{2b_n b_o} =: WTP^{fb}.
\end{aligned} \tag{31}$$

Thus, the license holder sets $f^{fb} = WTP^{fb} = p_N^2\frac{b_o - b_n}{2b_n b_o}$. □

Proof Proposition 8. A country invests in an innovation cluster if $K_i^{IC,fb} - K_i^{NIC,fb} + F_i \leq 0$ with

$$\begin{aligned}
K_i^{IC,fb} &= \Pi(\hat{k}(p_N)) \left[\hat{f}(p_N) + g_n(p_N) + p_N[\overline{e}_i - \overline{\epsilon}_i^n] + \delta \sum_{j=1}^{m} [\overline{e}_j - a_{n,N}] - \frac{p_N[\overline{E} - \overline{\mathcal{E}}^n]}{m} \right] \\
&\quad + \left(1 - \Pi(\hat{k}(p_N))\right) \left[g_o(p_O) + p_O[\overline{e}_i - \overline{\epsilon}_i^o] + \delta \sum_{j=1}^{m} [\overline{e}_j - a_{o,O}] - \frac{p_O[\overline{E} - \overline{\mathcal{E}}^o]}{m} \right] \\
K_i^{NIC,fb} &= \left[g_o(p_O) + p_O[\overline{e}_i - \overline{\epsilon}_i^o] + \delta \sum_{j=1}^{m} [\overline{e}_j - a_{o,O}] - \frac{p_O[\overline{E} - \overline{\mathcal{E}}^o]}{m} \right],
\end{aligned}$$

and with $\overline{\epsilon}_i^o$ ($\overline{\mathcal{E}}^o$) and $\overline{\epsilon}_i^n$ ($\overline{\mathcal{E}}^n$) denoting permit endowments in case the new technology is not or is discovered at the individual (aggregate) level.

Then, using that $p_N = p_O$ and keeping in mind that $p_N = \lambda p_N^{fb}$ with $p_N^{fb} = \delta m$, i.e. p_N does not necessarily equal δm, only for $\lambda = 1$,

$$\begin{aligned}
K_i^{IC,fb} - K_i^{NIC,fb} &= \Pi(\hat{k}(p_N)) \left[\hat{f}(p_N) + g_n(p_N) + p_N[\overline{e}_i - \overline{\epsilon}_i^n] + \delta \sum_{j=1}^{m} [\overline{e}_j - a_{n,N}] - \frac{p_N[\overline{E} - \overline{\mathcal{E}}^n]}{m} \right] \\
&\quad - \Pi(\hat{k}(p_N)) \left[g_o(p_O) + p_O[\overline{e}_i - \overline{\epsilon}_i^o] + \delta \sum_{j=1}^{m} [\overline{e}_j - a_{o,O}] - \frac{p_O[\overline{E} - \overline{\mathcal{E}}^o]}{m} \right] \\
&= \Pi(\hat{k}(p_N)) \left[\hat{f}(p_N) + g_n(p_N) - g_o(p_O) + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n] + \delta m[a_{o,O} - a_{n,N}] + \delta[\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n] \right] \\
&= \Pi(\hat{k}(p_N)) p_N^2 \left[\frac{b_o - b_n}{2b_n b_o} + \frac{b_n}{2} \left(\frac{p_N}{b_n}\right)^2 - \frac{b_o}{2} \left(\frac{p_N}{b_o}\right)^2 + \delta m \left[\frac{p_N}{b_o} - \frac{p_N}{b_n} \right] \right. \\
&\quad \left. + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n] + \delta[\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n] \right] \\
&= \Pi(\hat{k}(p_N)) \left[p_N^2 \frac{b_o - b_n}{2b_n b_o} + \frac{p_N^2 b_o}{2b_n b_o} - \frac{p_N^2 b_n}{2b_o b_n} + \delta m \frac{p_N(b_n - b_o)}{b_o b_n} + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] \right] \\
&= \Pi(\hat{k}(p_N)) \left[p_N^2 \frac{b_o - b_n}{b_n b_o} + \delta m p_N \frac{(b_n - b_o)}{b_o b_n} + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] \right] \\
&= \Pi(\hat{k}(p_N)) \left[p_N(p_N - \delta m) \frac{b_o - b_n}{b_n b_o} + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] \right],
\end{aligned}$$

and

$$\begin{aligned}
& K_i^{IC,fb} - K_i^{NIC,fb} + F_i \leq 0 \\
& \Leftrightarrow \Pi(\hat{k}(p_N))[p_N(p_N - \delta m) \frac{b_o - b_n}{b_n b_o} + \delta m[\overline{\epsilon}_i^o - \overline{\epsilon}_i^n + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}]] + F_i \leq 0 \\
& \Leftrightarrow \frac{p_N(p_N - \delta m)}{\delta m} \frac{b_o - b_n}{b_n b_o} + [\overline{\epsilon}_i^o + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] + \frac{F_i}{\Pi(\hat{k}(p_N))\delta m} \leq \overline{\epsilon}_i^n .
\end{aligned}$$

To ensure that Country i^{fb} invests and that the other countries receive as many permits as possible, we set

$$\hat{\epsilon}_i = \frac{p_N(p_N - \delta m)}{\delta m} \frac{b_o - b_n}{b_n b_o} + [\overline{\epsilon}_i^o + \frac{\overline{\mathcal{E}}^o - \overline{\mathcal{E}}^n}{m}] + \frac{F_i}{\Pi(\hat{k}(p_N))\delta m}. \quad \square$$

Appendix D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.reseneeco.2021.101229.

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