The Climate Policy Hold-Up:
How intellectual property rights on abatement technologies undermine international environmental agreements

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Abstract

Many OECD countries have embraced the notion that innovation in abatement technologies can make cuts in emissions of global pollutants economically less painful or even painless due to the rents earned on proprietary eco-innovations that improve on abatement costs. Technological first movers reap these innovation rents e.g. in the form of patent royalties as other countries adopt innovations to reduce emissions. We examine how intellectual property rights (IPRs) on abatement technologies interact with international environmental agreements (IEAs) and identify a fundamental hold-up problem between signatories and the firm holding the patent. Increased commitment by signatories makes them more exploitable as it reduces the elasticity of demand for the new technology, the price of which is determined endogenously. This strategic interaction between IPRs and IEAs reduces the stability of IEAs and can result in signatories to abate less than non-signatories and global abatement to be less than in the absence of an eco-innovation. The country hosting the innovating firm would prefer not to grant IPRs despite most of the deadweight loss occurring and most of the royalties originating abroad.

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1 Introduction

It is by now accepted wisdom that a successful resolution of the challenges raised by anthropogenic climate change will have to involve the rapid international diffusion of new technologies (Jaffe et al. 2005, Fischer and Newell 2008). This diffusion will allow countries around the world to gain access to improvements in the greenhouse gas (GHG) emission intensity of production. Such improvements are seen to be a prerequisite for achieving the types of ambitious mitigation targets implied by the IPCC (2009).

It is fair to say that policy-makers in the leading industrialized countries have embraced the new paradigm of green technological change with considerable enthusiasm. One reason is that the diffusion of green technologies as a climate change strategy would seem to play to the strengths of developed countries in knowledge-intensive industries Frankhäuser et al. (2008). Some commentators in fact believe that first-mover advantages are present, implying rewards for an ambitious technology policy.

The academic assessment of how cooperation on climate change and international technology cooperation might interact has been more equivocal than that of the policy-makers. The difficulty in assessing the merits of the arguments regarding the international diffusion of green technologies arises because the process lies at the intersection of two global public goods problems. On the one hand, there is the problem of agreeing on commitments on costly mitigation. The economic literature on international environmental agreements (IEAs) has understood for some time now that strategic considerations will exert strong centrifugal forces on countries considering cooperation on abatement (Barrett 1994, Carraro and Siniscalco 1993). On the other, there is the problem of international knowledge sharing in green technologies and the inherent trade-offs between knowledge diffusion and safeguarding proper incentives for knowledge creation. The question of the right nature and shape of intellectual property rights (IPRs) for green technologies has received considerable attention (Hall and Helmers 2010, e.g.) and forms part of an increasingly rich literature on climate change and technological change (Popp et al. 2010, Popp 2010). The intersection of both public goods problems in the context of the international diffusion of green technologies is important because the respective externalities not only coexist, but also interact in sometimes complex ways (Jaffe et al. 2005).

The present paper represents a first attempt to study how the specific institutions intended to solve the two global public goods problems of international technology diffusion and global GHG abatement provision interact. Our aim is to provide a proof of principle, and the flavor of the exercise is strictly positive. Taking an international system of perfectly enforceable IPRs as given, we study how its presence impacts on the nature and shape of IEAs on GHG mitigation efforts on the one hand and technology diffusion on the other. Combining benchmark models from the literature on IEAs and IPR, the notion of IEAs employed in this paper is one of self-enforcing equilibria of a participation game between identical nations (Barrett 1994) while our notion of diffusion is the degree to which the technology is adopted relative to its adoption in the absence of an IPR system. The key result of our paper is that rather than help resolve the global technology diffusion challenge, the interaction between IPRs and IEAs gives rise to new difficulties. One of them is the emergence of a hold-up problem in abatement commitment. The source of the problem is that commitments entered into when the IEA is negotiated change the demand elasticity of countries with respect to new technologies: More ambitious commitments lead to less demand elasticity. Under an IPR regime, innovators price their innovations such as to exploit their proprietary control over access to the technology. Anticipating this, fewer countries join the IEA, if at all, and those that do commit to a lower amount of abatement than they would in the absence of IPRs. Signatories might even abate less than non-signatories. The identification of this hold-up effect adds a new result to understand the effect of IPRs on knowledge diffusion and offers a novel characterization of the interaction between IPRs and IEAs. The strength of the hold-up effect also depends in important ways on the characteristics of the new technology: The greater the efficiency advantage of the new technology over the existing one, the harder it is for IEAs to form and to deliver abatement benefits. Among further implications of this result is that the first-mover effect popular among policy-makers may not exist: The country hosting the innovator can typically make itself better off by giving the innovation away for free. This is by no means the first paper to look jointly at green technologies and abatement at an international level. The intersection has been attracting the interest of economists for some time. Buchholz and Konrad (1995) study strategic technology choice by countries prior to negotiations. Stranlund (1996) considers strategic technology transfers and its welfare effects. Tol et al. (2001) examine issue linkage through technology diffusion in a climate game. Most recently Barrett (2006) and Hoel and de Zeeuw (2010) frame the problem as two global public goods provision games in which countries need to cooperate on both R&D provision and abatement. The key difference to the existing papers is that we study the effect of innovator behavior under IPRs on the IEA formation process. The innovator here is not a country, but a firm holding IPRs in an advanced technology. In this, the paper is related to a literature on endogenous pricing of abatement technologies under environmental regulation (Laffont and Tirole 1996, David and Sinclair-Desgagné 2005, Requate 2005, Perino 2010) in which the regulatory choices of a government and the pricing by the innovator interact in a sometimes deleterious fashion. Endogenous pricing of abatement technologies under environmental regulation (Laffont and Tirole 1996, David and Sinclair-Desgagné 2005, Requate 2005, Perino 2010) in which the regulatory choices of a government and the pricing by the innovator interact in a sometimes deleterious fashion.

The model that we use to generate these results is a simple extension of the now classic model by Barrett (1994) and has some parallels with Barrett (2006) which also models the simultaneous presence of an old and a new technology, differentiated by unit abatement costs. These models conceive of IEAs as a participation game. We employ this framework to model the technology user countries. The main departure in our model lies in allowing countries to choose a continuous combination of abatement technologies rather than a discrete choice between technologies. We consider the optimal abatement levels and coalition sizes under three scenarios. We designate a benchmark scenario based on Barrett (1994) in which a single technology is available. This contrasts with a second scenario under which two technologies with (potentially) different marginal costs curves are provided competitively at the international level. As the marginal costs of abatement are increasing for each technology, increasing the number of technologies leads to more abatement by all countries and higher national and global welfare. We then compare this scenario with one in which the new technology is provided monopolistically and the patent holder sets the royalty on the abatement technology after countries inside the IEA have decided on their abatement commitment. A comparison of these scenarios leads to our main propositions. Their content is intriguing: In general, innovation is globally beneficial. However, if innovators pursue the 'green race', countries strategically reduce their abatement commitment in anticipation of rent extraction by the innovator. In the presence of a 'green race', IEAs feature less signatories and signatories might abate less than non-signatories. The reason is novel: An IEA now acts as a technology demand side cartel: Signatories may even abate less than non-signatories. Also, contrary to the spirit of the green race, the more innovative the new technology, the better the country hosting the innovator does from giving the technology away for free. It is also possible that global abatement with IPRs is less than in a world without a green innovation.

In the following section, we quickly introduce the basic benchmark model of a climate change participation game by Barrett (2006). We then extend the model in the direction of a competitive supply of a horizontal innovation and demonstrate the optimal technology mix and coalition formation. These are summarized in Proposition 1. In section 4, we study the same setting, but now under proprietary technology supply. This gives rise to five additional propositions on abatement levels, coalition size, and the choice of the IPR regime. Section 5 concludes.

2 The Analytical Framework and IEA with only one Technology

Following Barrett (2006) we assume that there are N ex-ante identical countries facing a global public good problem. Each country i receives a benefit of

$$B_i = \frac{b}{N} Q, \tag{1}$$

where Q is the aggregate level of contribution to the public good (GHG abatement). Abatement q_i is costly,

$$C_i = \frac{c}{2} q_i^2. \tag{2}$$

This is the standard case analyzed in Barrett (1994, 2006) which serves as a lower benchmark. The timing is as follows. First, countries simultaneously decide whether to join the

IEA, then the signatories cooperatively choose their abatement levels and last non-signatories simultaneously and non-cooperatively set abatement levels.

In the last stage, a non-signatory solves the following optimization problem taking abatement by signatories and the size of the IEA-coalition as given.

$$\max_{q_i^n} \frac{b}{N}Q - \frac{c}{2}\left(q_i^n\right)^2, \tag{3}$$

where q_i^n is abatement by a non-signatory country i using the old technology.

Imposing symmetry among all non-signatories the equilibrium abatement levels are

$$q_{onetech}^n = \frac{b}{cN}, \tag{4}$$

$$\tag{5}$$

which is increasing in the marginal benefits of abatement and decreasing in the cost parameter and the number of countries (i.e. the extent of the free-rider problem).

Anticipating choices by non-signatories, signatories solve the following (cooperative) optimization problem

$$\max_{q_i^s} k_{onetech}\frac{b}{N}\left[\sum_{k_{onetech}} \bar{q}_i^s + (N - k_{onetech})\frac{b}{cN}\right] - \frac{c}{2}(\bar{q}_i^s)^2, \tag{6}$$

where $k_{onetech}$ is the number of signatories (i.e. $N - k_{onetech}$ is the number of non-signatories) in the case where only one technology is available.

Equilibrium abatement by a signatory is

$$\bar{q}_{onetech}^s = k_{onetech}\frac{b}{cN}, \tag{7}$$

which is $k_{onetech}$ times abatement by non-signatories.

The conditions for the number of signatories k^* of a self-enforcing IEA are well known from Barrett (1994). They require that in equilibrium no signatory has an incentive to unilaterally leave the IEA and no non-signatory an incentive to unilaterally join the IEA.

$$\pi^n_{onetech}(k^*_{onetech} - 1) \leq \pi^s_{onetech}(k^*_{onetech}), \tag{8}$$

$$\pi^n_{onetech}(k^*_{onetech}) \geq \pi^s_{onetech}(k^*_{onetech} + 1), \tag{9}$$

where $\pi^s_{onetech}(k)$ and $\pi^n_{onetech}(k)$ is the welfare of a signatory or non-signatory country respectively for the case with only one technology being available. As in Barrett (2006) the number of signatories k^* is three for all $N \geq 3$. A proof is given in the appendix.

3 The Upper Benchmark: Two technologies are provided at competitive prices

In contrast to the previous section, we now introduce a new abatement technology that is simultaneously available with the first. This new technology is non-proprietary and therefore freely available. Total abatement $q_i = x_i + y_i$ by country i can hence be achieved by using any mix involving non-negative abatement levels of the incumbent (x_i) and the new (y_i) technology.[1] A country's abatement costs are given by

$$C_i = \frac{c}{2}x_i^2 + \frac{d}{2}y_i^2. \tag{10}$$

The timing is the same as in the previous section. In the last stage, a non-signatory

[1] The ability to use both technologies at the same time deviates from Barrett (2006) where technologies are mutually exclusive.

solves the following optimization problem

$$\max_{x_i^n, y_i^n} \frac{b}{N} Q - \frac{c}{2} \left(x_i^n\right)^2 - \frac{d}{2} \left(y_i^n\right)^2 . \tag{11}$$

Imposing symmetry among all non-signatories, equilibrium abatement levels are

$$x^n_{comp} = \frac{b}{cN}, \tag{12}$$

$$y^n_{comp} = \frac{b}{dN}. \tag{13}$$

Note that non-signatory countries' abatement levels neither depend on existence or size of the coalition nor on signatories' abatement. A signatory solves the following optimization problem

$$\max_{x_i^s, y_i^s} k_{comp} \frac{b}{N} \left[\sum_{k_{comp}} \bar{q}_i^s + \left(N - k_{comp}\right) \frac{b}{N} \frac{c+d}{cd} \right] - \frac{c}{2} \left(x_i^s\right)^2 - \frac{d}{2} \left(y_i^s\right)^2 . \tag{14}$$

Equilibrium abatement by a signatory is

$$x^s_{comp} = k_{comp} \frac{b}{cN}, \tag{15}$$

$$y^s_{comp} = k_{comp} \frac{b}{dN}. \tag{16}$$

The conditions for the number of signatories k^*_{comp} of a self-enforcing IEA are analogous to those presented above. Profit functions of both signatories and non-signatories are multiples of their counterparts in the previous section. The size of a self-enforcing IEA is therefore again three. A proof is given in the appendix.

Proposition 1 *The presence of a second abatement technology that is freely available unambiguously increases abatement by both signatories and non-signatories but does not affect the size and stability of an IEA.*

While the stability and size of the IEA are not affected by the presence of a second, competitively provided technology, aggregate abatement levels increase. Country-level and aggregate abatement by the incumbent technology are the same as in the case when only the incumbent technology is available. However, for any finite d there will be some additional abatement provided by the new technology. For all $d < c$ abatement is more than twice that provided if only the incumbent technology is available.

4 Monopolistic Pricing

With the benchmark of a free technology established, we now turn to the core of the paper. Assume that in contrast to the previous section, the new technology is managed in a proprietary way: The owner of the technology is an innovator that holds a global patent to the new abatement technology. Implicitly, of course, this assumes that global patents exist and are perfectly enforceable at zero cost.

Assume for the sake of argument that the potential innovator is a private firm. The technology itself can be produced at zero cost. The firm's profits therefore consist exclusively of revenues from intellectual property rents or royalties. The firm maximizes profits, which implies monopoly pricing of the technology. This is a stylized representation of the commonly held belief that technological leadership in abatement or green technologies could not only solve the climate (or other environmental) problem but also generate national wealth in the form of royalties.

The timing is as follows. First, countries simultaneously decide whether to sign an IEA. Second, signatories cooperatively commit to minimum abatement efforts anticipating monopolistic pricing of the new technology, their own future abatement decisions and finally the response by non-signatories. Third, the innovator sets per-unit prices for signatories and non-signatories exploiting third-degree price discrimination. Fourth, signatories make adoption decisions honoring any abatement commitment made in the third stage. Fifth, non-signatories simultaneously and non-cooperatively make abatement and adoption decisions.

4.1 Abatement and adoption by non-signatories

In the last stage, a non-signatory solves the following optimization problem

$$\max_{x_i^n, y_i^n} \frac{b}{N}Q - \frac{c}{2}\left(x_i^n\right)^2 - \frac{d}{2}\left(y_i^n\right)^2 - p^n y_i^n, \tag{17}$$

where x_i^n and y_i^n, again, are the amounts of abatement provided by the old and new technology, respectively. p^n is the per-unit price (license fee) paid for using the new technology.

Assuming an interior solution and imposing symmetry among all non-signatories the equilibrium abatement levels are

$$x^n = \frac{b}{cN}, \tag{18}$$

$$y^n = \frac{b - p^n N}{dN}. \tag{19}$$

Note that abatement by non-signatories using the old technology is the same as in the previous two cases while the amount of abatement provided by the new technology depends on the level of the license fee payable by non-signatories p^n.

4.2 Abatement and adoption by signatories

In the abatement and adoption stage signatories solve the following optimization problem

$$\max_{x_i^s, y_i^s} \frac{b}{N}\left[\sum_{k_{mon}} (x_i^s + y_i^s) + (N - k_{mon})\left(\frac{b}{cN} + \frac{b - p^n N}{dN}\right)\right] - \frac{c}{2}(x_i^s)^2 - \frac{d}{2}(y_i^s)^2 - p^s y_i^s, \quad (20)$$

$$s.t. \quad x_i^s + y_i^s \geq \bar{q}^s,$$

where $\bar{q}^s$ is the minimum level of abatement signatories committed to in the IEA. Signatories maximize their domestic welfare. Cooperation is therefore limited to the commitment stage of the IEA, the signing of which again is driven purely by national interests. This highlights the commitment character of abatement choices as part of an IEA that was not present in the standard Barrett model where commitment and abatement occur in the same stage of the game.

If the constraint imposed by the IEA is binding, abatement is split as follows over the two technologies (proof see appendix)

$$x^s = \frac{d\bar{q}^s + p^s}{c + d}, \quad (21)$$

$$y^s = \frac{c\bar{q}^s - p^s}{c + d}. \quad (22)$$

Signatories choose the cost minimizing way to achieve their abatement commitments made in the IEA which is achieved by applying the equi-marginal principle. As a result, abatement levels of both technologies depend on the level of commitment $\bar{q}$ and price paid for the new technology by signatories p^s.

However, if the minimum level of abatement committed to in the IEA is not binding, signatories' abatement levels for the two technologies are

$$x^s = \frac{b}{cN}, \quad (23)$$

$$y^s = \frac{b - Np^s}{dN}, \tag{24}$$

and therefore identical to non-signatories' abatement choices (if the license fee is the same). In this case actual abatement levels are independent of the initial commitment and only the usage of the new technology depends on the level of the license fee. Whether commitments by signatories are binding depends of course on the license fee chosen by the innovator. The critical level $\hat{p}^s(\bar{q})$ is

$$\hat{p}^s(\bar{q}) = (c+d)\frac{b}{cN} - d\bar{q}. \tag{25}$$

A proof is given in the appendix. Demand for the new technology by signatories is therefore given by

$$y^s(p^s) = \begin{cases} \frac{b-Np^s}{dN} & if \quad p^s < \hat{p}^s(\bar{q}) \\ \frac{c\bar{q}^s - p^s}{c+d} & if \quad p^s \geq \hat{p}^s(\bar{q}) \end{cases} \tag{26}$$

4.3 Technology pricing

The two prices p^s and p^n charged for using the clean technology are set by the innovator to maximize its profits $\pi = k \cdot p^s \cdot y^s(p^s) + (N-k) \cdot p^n \cdot y^n(p^n)$. As the two markets (signatories and non-signatories) are perfectly separated and identities easily observable, the innovator can treat each market independently with demand functions for the new technology given by (19) and (26), respectively. The equilibrium prices are

$$p^n = \frac{b}{2N}, \tag{27}$$

$$p^s = \begin{cases} \frac{b}{2N} & if \quad \bar{q}^s < \hat{q} \\ \frac{c\bar{q}^s}{2} & if \quad \bar{q}^s \geq \hat{q} \end{cases} \tag{28}$$

For a sufficiently high level of commitment by signatories in the IEA stage this commitment will indeed be binding. At the critical level $\hat{q} = \frac{b}{cN}\sqrt{\frac{c+d}{d}}$ the innovating firm is exactly indifferent between the two pricing strategies. Note that this critical level is below equilibrium abatement by non-signatories ($\hat{q} < x^n + y^n$) but, as we will see below, nevertheless sometimes imposes a binding restriction. The proof is given in the appendix.

Abatement by country type and technology is therefore

$$x^n = \frac{b}{cN}, \tag{29}$$

$$y^n = \frac{b}{2dN}, \tag{30}$$

$$x^s\left(\bar{q}^s\right) = \begin{cases} \frac{b}{cN} & if \quad \bar{q}^s < \hat{q} \\ \bar{q}^s \frac{c+2d}{2(c+d)} & if \quad \bar{q}^s \geq \hat{q} \end{cases} \tag{31}$$

$$y^s\left(\bar{q}^s\right) = \begin{cases} \frac{b}{2dN} & if \quad \bar{q}^s < \hat{q} \\ \frac{c\bar{q}^s}{2(c+d)} & if \quad \bar{q}^s \geq \hat{q} \end{cases} \tag{32}$$

4.4 The IEA

Signatories cooperatively agree to commit to minimum abatement levels $\bar{q}^s$ anticipating its effect on equilibrium prices and abatement levels. The corresponding optimization problem is

$$\begin{aligned} \max_{\bar{q}_i^s} \quad & k_{mon}\frac{b}{N}\left[\sum_{k_{mon}}\left[x^s\left(\bar{q}_i^s\right) + y^s\left(\bar{q}_i^s\right)\right] + \left(N - k_{mon}\right)\left(\frac{b}{cN} + \frac{b}{2dN}\right)\right] \\ & -\frac{c}{2}\left(x^s\left(\bar{q}^s\right)\right)^2 - \frac{d}{2}\left(y^s\left(\bar{q}_i^s\right)\right)^2 - p^s\left(\bar{q}_i^s\right)y^s\left(\bar{q}_i^s\right). \end{aligned} \tag{33}$$

Note that for all $\bar{q}^s < \hat{q}$ welfare of signatories is independent of $\bar{q}^s$. Signatories are indifferent between all $\bar{q}^s \in [0, \hat{q}[$ and each of these outcomes would be equivalent to a case without an IEA. This is apparent when considering that the critical level of abatement $\hat{q}$

is smaller than abatement by non-signatories. Hence, agreeing on a minimum abatement level below $\hat{q}$ has no effect on outcomes and leaves signatories in the same position as non-signatories. As we will show later, this gives rise to multiple equilibria (one without and a continuum with an IEA) under some parameter constellations that are, however, payoff-equivalent for all parties.

Ignoring $\hat{q}$ for a moment and imposing symmetry, the welfare maximizing level of abatement signatories commit to is (a proof is given in the appendix)

$$\bar{q}^{s}_{uncon} = \frac{bk_{mon}}{cN} \frac{4(c+d)}{4(c+d)-c}, \tag{34}$$

which is a function of the number of signatories k_{mon}. Note that $\frac{bk}{cN}$ is commitment by a country in the case where only the incumbent technology is available and that $\frac{4(c+d)}{4(c+d)-c}$ is strictly between 1 and 4/3. The unconstrained optimum is achievable if $\bar{q}^{s}_{uncon} \geq \hat{q}$ which is the case if the number of signatories exceeds the threshold $\hat{k}$.

$$k \geq \hat{k} = \frac{3c+4d}{4\sqrt{d(c+d)}}. \tag{35}$$

For any given c, $\hat{k}$ goes to plus infinity if d approaches zero and converges to 1 if d becomes very big. Equivalently, for any number of signatories k and cost parameter of the incumbent technology c, there is a threshold level of $\hat{d}$ for which the unconstrained welfare maximum can be achieved,

$$d \geq \hat{d}(c,k) = \frac{3-2k^2+k\sqrt{4k^2-3}}{4(k^2-1)} \cdot c \tag{36}$$

$\hat{d}$ is decreasing in k. The set of technologies for which the unconstrained welfare maximum in the IEA's commitment stage can be obtained increases in k.

This leaves three possible outcomes for commitment by signatories. First, for all $d \geq \hat{d}$ a signatory's commitment is given by (34). For $d < \hat{d}$ there are two possible scenarios: Signatories engage in a binding commitment of $\hat{q}$ or they choose any $q^s < \hat{q}$ which results in the commitment not being binding and all countries behaving like non-signatories.

Next we will assess the stability of the self-enforcing IEA for all three cases ($q^s < \hat{q}$, $q^s = \hat{q}$ and $q^s = \bar{q}^s_{uncon}$).

4.5 Signing stage

This section analyzes how monopolistic provision of the new technology affects the equilibrium size of the coalition forming an IEA, aggregate abatement and welfare of the innovator's home country. We start by applying the the equilibrium conditions for a self-enforcing IEA (the same as above) to all three cases of signatories' abatement.

If signatories choose the abatement commitment achieving the unconstrained welfare maximum $\bar{q}^s_{uncon}$, then for all $d \geq \frac{\sqrt{7}-2}{4}c \approx 0.1614c$ the equilibrium number of signatories is two and for all $d < \frac{\sqrt{7}-2}{4}c \approx 0.1614c$ there is no stable coalition and all N countries behave like non-signatories. This threshold is always less restrictive than $\hat{d}(c,k)$ evaluated at $k = 2$ ($\hat{d}(c,2) = \frac{2\sqrt{13}-5}{12} \cdot c \approx 0.184c > \frac{\sqrt{7}-2}{4} \cdot c \approx 0.1614c$). Hence, the following holds,

Lemma 2 *For all $d \geq \frac{2\sqrt{13}-5}{12} \cdot c$ the equilibrium number of signatories is two ($k^* = 2$).*

A proof is given in the appendix. Note that the optimal coalition size is independent of both b and N given that the latter is at least three as stability conditions do not depend on them. In this case the number of signatories is always smaller than in both benchmarks.

For $d < \frac{2\sqrt{13}-5}{12} \cdot c$ and $q^s = \hat{q}$, there is no stable IEA and for $d < \frac{2\sqrt{13}-5}{12} \cdot c$ and $q^s < \hat{q}$ all countries are indifferent between no IEA and any IEA with one or more signatories. That a self-enforcing IEA is not feasible in the former case is intuitive. Incentives to join a self-enforcing IEA are created by an increase in existing signatories' abatement if an additional country joins. However, abatement is independent of the number of signatories k if $q^s = \hat{q} = \frac{b}{cN}\sqrt{\frac{c+d}{d}}$. The multiplicity of equilibria in the latter case where $q^s < \hat{q}$ arises because an IEA which commits to such a low minimum level of abatement has no effect on outcomes and payoffs whatsoever. All countries continue to behave like non-signatories. Hence, there might be IEAs (with up to N signatories) that set minimum abatement levels that will be exceeded by all signatories. Proofs are given in the appendix.

Taken together the results above give rise to the following proposition

Proposition 3 *(Number of Signatories)*

- *For all* $d \geq \frac{2\sqrt{13}-5}{12} \cdot c$ *the equilibrium number of signatories is two* ($k^* = 2$)*.*
- *For all* $d < \frac{2\sqrt{13}-5}{12} \cdot c$ *the equilibrium number of signatories to an IEA is between zero and* N*, but in all cases all countries behave like non-signatories and both abatement levels and payoffs are independent of* k*.*

Intellectual property rights on new abatement technologies have a detrimental effect on the stability of effective IEAs. The equilibrium number of signatories drops from three to two if a global patent is granted for all but the most productive of abatement technologies. For sufficiently productive new technologies IEAs become totally ineffective and the outcome in all equilibria is equivalent to one without an IEA.

When the innovator is granted a global patent this does not only reduce the number of signatories to an IEA but also affects how much signatories abate compared to non-signatories. The amount by which signatories abate more than non-signatories is unambiguously smaller with a global patent than without - and signatories might even abate less than non-signatories.

Proposition 4 *If the new abatement technology is protected by a global patent, then*

- *For all* $d \geq \frac{c}{8}\left(\sqrt{33}-3\right)$ *signatories abate (weakly) more than non-signatories,*
- *For all* $d \in \left[\frac{2\sqrt{13}-5}{12} \cdot c, \frac{c}{8}\left(\sqrt{33}-3\right)\right[\approx [0.184c, 0.3431c[$ *signatories abate strictly less than non-signatories,*
- *For all* $d < \frac{2\sqrt{13}-5}{12} \cdot c$ *signatories abate the same as non-signatories.*

A proof is given in the appendix. The somewhat surprising effect that signatories sometimes abate less than non-signatories is caused by the strategic interaction between commitments to abate and the price charged for the new technology. Monopoly pricing of a new abatement technology has a detrimental effect on commitments by signatories because they anticipate that commitments make them exploitable. This hold-up problem exists because an increase in commitment reduces the elasticity of demand for the new technology by signatories and hence allows the patent holder to exert more market power. Note that the license fee is strictly increasing in the level of commitment if the latter is binding (see (28)). When signatories co-ordinate their environmental policy they now internalize not only their impact on the global public good but also on the price for the new technology. They hence act as a demand-side cartell and exert downward pressure on the price by reducing demand. If the new technology is sufficiently cheap, the demand-side cartell effect dominates the public good provision effect (see Figure 1).

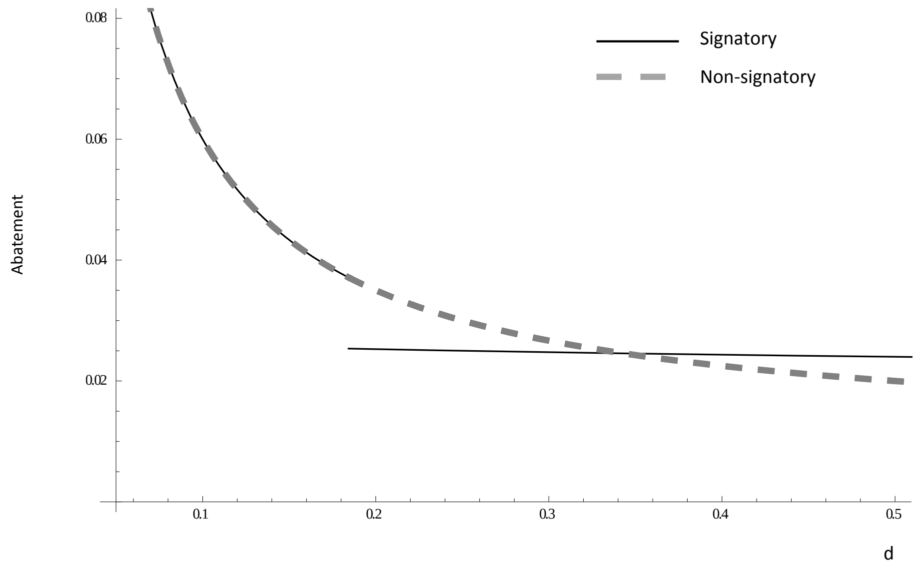

Figure 1: Abatement by signatories and non-signatories under a global patent.

The effect on global abatement compared to the case when the new technology is priced competitively, is clear. Both signatories to the IEA and non-signatories abate less under a global patent than their counterparts that have access to the new technology at marginal costs. Moreover, there are fewer signatories under a global patent (two instead of three) and hence aggregate abatement under a global patent is always less than with a competitively priced new technology, everything else equal.

The comparison with the other benchmark - the case where the new technology is not available at all - is less straightforward. While both signatories and non-signatories always abate more if the new technology is available than if this is not the case, the number of signatories is reduced by one (or if there are more than two signatories with IPRs, the

IEA is totally ineffective). The following proposition compares global abatement under monopolistic provision of the new technology and the case without a new technology.

Proposition 5 *For all* $N \geq 3$, b *and* $d > \frac{c}{16}\left(N - 6 + \sqrt{N^2 + 12N - 12}\right)\left(N + \sqrt{648 + 36N + N^2}\right)$ *aggregate abatement is smaller when the technology is protected by a global patent compared to it not being available at all.*

A proof is given in the appendix. Figure 2 presents global abatement under the monopolistic provision of the new technology and the two benchmark cases using a specific example.

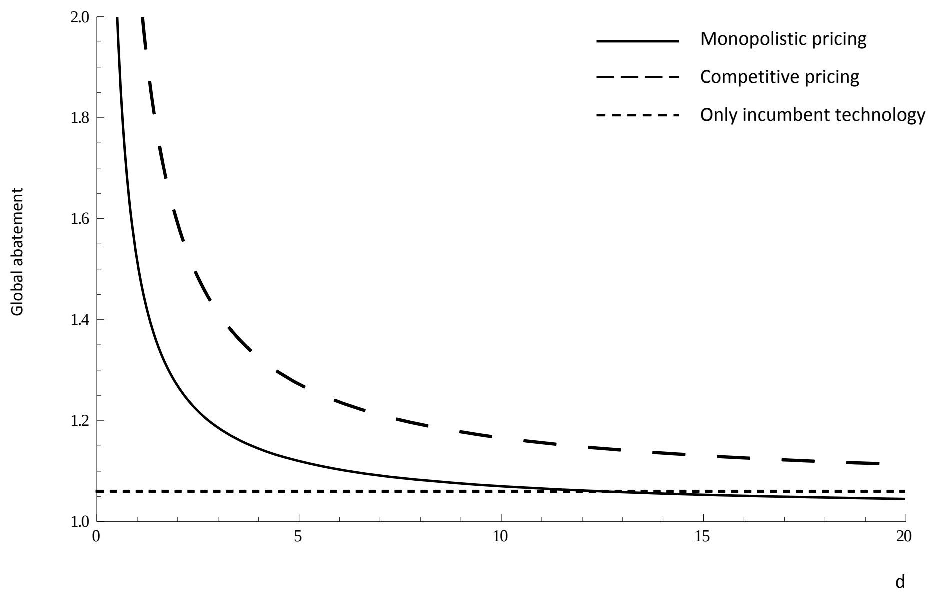

Figure 2: Global abatement with and without a global patent and with only the incumbent technology.

The reduction in abatement costs and the corresponding increase in aggregate abatement brought about by a new abatement technology is counteracted by the proprietary pricing strategy of the innovator for sufficiently expensive new technologies. Given that a new technology is protected by a global patent, its impact on provision of the global public good might be negative. Note that this does not necessarily imply that welfare is reduced compared to the case of only one technology being available. The reason is that any given amount of abatement can be provided at lower social costs if two technologies are available.

We now turn to the last, and crucial, question: Are eco-innovations green gold or fool's gold? Meaning, does the country hosting the firm that wins the R&D race benefit from doing so? Given the symmetry assumed, it certainly holds that, given a global patent is granted to the innovating firm, it is always strictly better hosting that firm than not. However, given a domestic firm wins the race, it is not at all a good idea to grant a global patent. Although most of the deadweight loss of monopolistic pricing occurs in other countries and most of the royalties are paid by foreigners, the negative impact of monopolistic pricing on the global public good spoils the feast.

Proposition 6 *The home country of the innovating firm is worse off under a global patent than when the new technology is available to all countries at marginal costs.*

A proof is given in the appendix. This holds regardless of whether the home country is a signatory or not. The capturing of rents via the royalty payments is outweighed by the negative impact on the global public good induced by monopoly pricing.

5 Conclusion

Policy-makers have correctly identified innovation in green technologies as an important source of welfare gains in the face of global pollution problems. However, it does not follow necessarily that countries should engage in a race to develop these technologies in order to extract innovation rents from proprietary innovations. As we demonstrate, an innovator trying to reap the innovation rents leads as a first order effect to higher prices for the new technology and hence less technology adoption than would be globally optimal. Secondly, we find that the pursuit of rents from proprietary innovations gives rise to a strategic reduction in abatement commitments by countries. The reason is that adopter countries negotiating an international environmental agreement change their behavior in anticipation of the rent extraction by the innovator. As a result of this hold-up problem, international environmental agreements undergo a dramatic change in character. They decrease in size (except if they are totally ineffective), and at the same time turn from an institutional response to a coordination problem into an institutional response to a market structure problem. Most importantly, pursuing the logic of the 'green race' may not be in the interest of the country hosting the innovator. While it is correct that the innovation rents extracted can offset own abatement expenditures, the gains to the country from a socially optimal global adoption of the technology may exceed the losses from foregoing patent rents. We show that, perhaps surprisingly, countries should find it more profitable to give away breakthrough technologies rather than technologies of incremental improvements.

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A Appendix

A.1 Number of signatories with incumbent technology only

Using equation (7), the profit of signatories is $\pi^s_{onetech} = \frac{b^2}{2cN^2}\left(2N - 2k_{onetech} + k^2_{onetech}\right)$ and the profit of non-signatories is $\pi^n_{onetech} = \frac{b^2}{2cN^2}\left(2N - 2k_{onetech} + 2k^2_{onetech} - 1\right)$. Substituting both into condition $\pi^n_{onetech}(k^*_{onetech}-1) \leq \pi^s_{onetech}(k^*_{onetech})$ yields $k^2_{onetech} - 4k_{onetech} + 3 \leq 0$. This implies $1 \leq k^*_{onetech} \leq 3$.

Condition $\pi^n_{onetech}(k^*_{onetech}) \geq \pi^s_{onetech}(k^*_{onetech}+1)$ requires that $k_{onetech} - 2 \geq 0$. The equilibrium number of signatories is hence $k^*_{onetech} = 3$.

A.2 Optimal abatement and adoption by signatories

The Kuhn-Tucker conditions of optimization problem (20) are

$$\frac{b}{N} - cx^s - \lambda = 0 \tag{A.1}$$

$$\frac{b}{N} - dy^s - p^s - \lambda = 0 \tag{A.2}$$

$$\bar{q}^s - x^s - y^s \leq 0 \tag{A.3}$$

$$\lambda \geq 0 \tag{A.4}$$

If constraint (A.3) is not binding and hence $\lambda = 0$, (A.1) and (A.2) yield . If (A.3) is binding, combining (A.1), (A.2) and (A.3) yields (21) and (22).

A.3 Proof of equation (25)

The price threshold is determined by (23) being equal to (21) and (24) being equal to (22). Using either condition and solving for p^s yields (25).

A.4 Technology pricing

The innovator's profit from license fees paid by a non-signatory is $\pi^n = p^n \cdot y^n(p^n)$. Using (19), the first order condition yields

$$\frac{b - 2p^n N}{dN} = 0. \tag{A.5}$$

Solving for p^n yields (27).

The profit obtained from a signatory is $\pi^s = p^s \cdot y^s(p^s)$ where demand for the new technology is given by the piecewise function (22). For $p^s < \hat{p}$, the first order condition requires $\frac{b-2p^s N}{dN} = 0$ and hence $p^s = \frac{b}{2N}$. For the latter to be in the specified range ($p^s < \hat{p}$) it has to hold that, $\bar{q}^s < q^{non-bind} = \frac{b(c+2d)}{2Ncd}$.

For $p^s \geq \hat{p}$, the first order condition requires $\frac{c\bar{q}^s - 2p^s}{c+d} = 0$ and hence $p^s = \frac{c\bar{q}^s}{2}$. For the latter to be in the specified range ($p^s \geq \hat{p}$) it has to hold that, $\bar{q}^s \geq q^{bind} = \frac{b(c+d)}{Nc(c/2+d)}$.

Note that $q^{bind} < q^{non-bind}$ and hence there is a range where the innovator can choose whether signatories' commitment $\bar{q}^s$ is binding or not. The innovator is indifferent between the two outcomes if

$$\frac{b}{2N} \cdot \frac{b}{2dN} = \frac{c\hat{q}}{2} \cdot \frac{c\hat{q}}{2(c+d)}, \tag{A.6}$$

$$\hat{q} = \frac{b}{cN}\sqrt{\frac{c+d}{d}}. \tag{A.7}$$

Hence, signatories' commitment binds for all $\bar{q}^s \geq \hat{q}$ but does not for all $\bar{q}^s < \hat{q}$.

A.5 Proof of equation (34)

(33) is a straightforward maximization problem. Taking the first order condition and solving for $\bar{q}$ yields (34).

A.6 Proof of Proposition 2

Condition $\pi^n_{mon}(k^*_{mon} - 1) \leq \pi^s_{mon}(k^*_{mon})$ imposes an upper bound on the number of signatories.

$$k^*_{mon} \leq \frac{8d(c+d) + \sqrt{d\left(16d^3 + 32cd^2 + 13c^2d - 3c^3\right)}}{4d(c+d)}. \tag{A.8}$$

Which is bound from below by 2 and from above by 3 (if $c = 1$ and d approaches plus infinity).

Condition $\pi^n_{mon}(k^*_{mon}) \geq \pi^s_{mon}(k^*_{mon}+1)$ imposes an lower bound on the number of signatories.

$$k^*_{mon} \geq \frac{4d(c+d) + \sqrt{d\left(16d^3 + 32cd^2 + 13c^2d - 3c^3\right)}}{4d(c+d)}, \tag{A.9}$$

which is bound from below by 1 and from above by 2 (if $c = 1$ and d approaches plus infinity).

Conditions (A.8) and (A.9) have no real solutions if $d < \frac{\sqrt{7}-2}{4}c \approx 0.1614c$.

A.7 Proof of stability of IEA if $q^s \leq \hat{q}$

If $d < \frac{2\sqrt{13}-5}{12} \cdot c$ and $q^s = \hat{q}$ condition $\pi^n_{mon}(k^*_{mon} - 1) \leq \pi^s_{mon}(k^*_{mon})$ requires that

$$\frac{2\sqrt{d(c+d)} - c - 2d}{2cd} + \frac{3c+4d}{8cd} - \frac{(c+2d)^2 + 2c + 3d}{8d(c+d)} \geq 0, \tag{A.10}$$

while $\pi^n_{mon}(k^*_{mon}) \geq \pi^s_{mon}(k^*_{mon} + 1)$ results in exactly the same left hand term as in (A.10) but with the inequality going the other way. Both conditions are independent of k and hence only two outcomes are possible: either no country joins the IEA or all do. Assessing (A.10) for the relevant range of parameters ($d \in \left[0, \frac{2\sqrt{13}-5}{12} \cdot c\right]$) reveals that it never holds (i.e. $\pi^n_{mon}(k^*_{mon}) \geq \pi^s_{mon}(k^*_{mon}+1)$ always holds). For commitment at the threshold, no stable self-enforcing IEA exists.

A.8 Proof of Proposition 4

Output by signatories is given by (34) and and output by non-signatories is

$$q^n_{mon} = \frac{b(c+2d)}{2cdN}. \tag{A.11}$$

Substituting $k^*_{mon} = 2$ into the former it is smaller than the latter if

$$d < \frac{c}{8}\left(\sqrt{33} - 3\right) \approx 0.3431c. \tag{A.12}$$

A.9 Proof of Proposition 5

Equalizing aggregate abatement under a global patent (the sum of (29), (30) and (31) and (32) in combination with (34)) with that of two competitively provided technologies (sum of (12), (13), (15) and (16)), yields a critical point $\tilde{d}(c, N) = \frac{c}{24}\left(N + \sqrt{648 + 36N + N^2}\right) > c$. For all $d < \tilde{d}(c, N)$ abatement under a patent is less than without and vice versa.

A.10 Proof of Proposition 6

If the home country is a non-signatory, welfare is given by

$$\pi^n_{mon} = \frac{b^2}{N^2}\left[16\frac{c+d}{c(3c+4d)} + (N-2)\frac{c+2d}{2cd} - \frac{1}{2c} - \frac{1}{8d} + 32\frac{c+d}{(3c+4d)^2} + \frac{(N-3)}{4d}\right], \quad \text{(A.13)}$$

if the country grants a global patent to the innovator and

$$\pi^n_{comp} = \frac{b^2}{N^2}\left[(N+6)\frac{c+d}{cd} - \frac{1}{2c} - \frac{1}{2d}\right], \quad \text{(A.14)}$$

if it does not. Taking the difference between π^n_{mon} and π^n_{comp} and simplifying yields,

$$\begin{aligned} \pi^n_{mon} - \pi^n_{comp} &= 16\frac{(c+d)\cdot(5c+4d)}{(3c+4d)^2} - \frac{2Nc + 59c + 64d}{8d}, && \text{(A.15)} \\ &= -c^3(18N+531) - c^2d(48N+1912) - cd^2(32N+2336) - 960d^3 < 0. && \text{(A.16)} \end{aligned}$$

The proof for signatory host country is analogous. The host country's welfare is therefore unambiguously higher if it does not grant a patent to the innovator.