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Abstract

The success of global climate policies over the coming decades depends on the diffusion of 'green' technologies. This requires that international environmental agreements (IEAs) and trade-related intellectual property rights (TRIPs) interact productively. Using a simple and tractable model, we highlight the strategic reduction in abatement commitments on account of a hold-up effect. In anticipation of rent extraction by the innovator signatories might abate less than non-signatories turning the IEA 'brown'. Self-enforcing IEAs have fewer signatories and diffusion can reduce global abatement under TRIPs. Countries hosting patent holders extract rents from TRIPs, but may be better off without them.

JEL codes: Q54, Q55, O34, O33, L12

Keywords: International climate policy; diffusion of innovations; intellectual property rights; hold-up problem.

1 Introduction

Over the next 20 to 25 years, much of climate-relevant technological change is expected to come from the international diffusion of technologies that are already known (Metz et al. 2007).[1] While some of these 'green' technologies are in the public domain, the vast majority of them is owned by private corporations located in industrialized countries (Hall and Helmers 2013, Reichman et al. 2008). These entities expect to enjoy the benefits of ownership of their intellectual property rights (IPRs) for most of the next two decades. This expectation rests, at the international level, on mechanisms such as the system of Trade-Related Intellectual Property Rights (TRIPS) that obligates countries that aspire to World Trade Organization (WTO) membership to erect a domestic system of effective and enforceable IPRs.

Recent discussions have started to challenge the merits of IPRs on climate-relevant technologies and their enforcement through TRIPS. International bodies and non-governmental organizations have floated ideas for possibly drastic limitations on TRIPs for such technologies on the grounds of encouraging their adoption in developing countries and of international equity considerations (Lee et al. 2009). Examples for such limitations include compulsory licensing and revocation of IPRs in developing countries (UNFCCC 2010). Individual countries, such as India, have also suggested shorter patent durations for climate-relevant technologies (WTO 2013). This contrasts with the position of policy-makers in industrialized countries in which most of the corporations with the relevant IPR are located. They have declared their intention to defend vigorously the international protection of 'green' IPR and push ahead with TRIPs (Rimmer 2009), not least because many have embraced the notion that the patent rents that will be generated in the course of diffusing 'green' technologies under TRIPs will offset some of the domestic costs of climate policies (Foxon 2010, Fankhauser et al. 2008). Whether TRIPS constitute the right institutional mechanism under which the process of diffusion of 'green' technologies should take place is therefore under debate. Advancing this debate, however, will require not only a better understanding of issues of distribution in international climate policies, namely how rents from green technologies are shared internationally. At least equally important are issues of efficiency that arise where decisions on international systems of IPRs intersect with international agreements on greenhouse gas emissions.

In the present paper, we explore a new mechanism through which a global system of IPRs affects the efficiency of global climate policies. This mechanism captures the impact of *strategic* considerations when countries decide on individual contributions to an international environmental agreement (IEA) on greenhouse gas (GHG) emissions in the presence of IPRs on abatement technologies. The impact arises in the form of a hold-up problem that affects both the formation and the content of the IEA on GHG emissions reductions. The mechanism presented here is therefore in addition to the first-order concern that IPRs on 'green technologies' create temporary monopolies that restrict diffusion and decrease abatement, which is the necessary deadweight loss associated with IPR-based innovation rewards (Scotchmer 2004). The hold-up problem affects equilibrium abatement levels and

[1] Influential research has claimed that stabilizing the carbon stock in the atmosphere until 2050 at around 500 ppm can be plausibly met by a portfolio of currently existing technologies ('stabilization wedges') while underlying output growth continues (Pacala and Socolow 2004).

the coalition size of the IEA, creating a significant additional distortion above and beyond the deadweight loss of monopoly. In what follows, we establish the presence and impact of the hold-up problem and point to possible solutions.

In order to deliver results that are intelligible in the context of a well-established literature, we adopt a parsimonious modeling approach for IEA formation and performance that builds directly on the now classic model by Barrett (1994). In the same spirit, we assume a global system of TRIPs, as intended by its proponents, and study how its presence impacts on the formation of an IEA, on aggregate abatement, on global welfare, and on the welfare of countries that host innovators.[2] The participation game in the present paper involves identical countries in a world of linear benefits and quadratic costs of abatement (Barrett 2006). There is an incumbent abatement technology that is freely available. An alternative technology exists, but the IPRs are owned by a private innovator. Against this background, countries simultaneously decide in stage 1 whether or not to join an IEA. In stage 2, those who joined the IEA cooperatively commit to minimum abatement efforts. These commitments can be met using any combination of the incumbent and the new technology, as in Gancia and Zilibotti (2005) and Perino (2008). In stage 3, the innovator sets per-unit license fees for the use of the new technology by signatories and non-signatories. Fourth, signatories make adoption decisions honoring any minimum abatement commitment made in the second stage. In the final stage 5, non-signatories simultaneously and non-cooperatively make abatement and adoption decisions. In comparison to the existing literature, the novel element here is the technology pricing step in stage 3 which occurs between the setting of abatement targets by an IEA and their implementation by individual signatories.[3]

Using this model structure, we proceed in three steps. We first derive the equilibrium abatement levels for a given size of the IEA and compare the equilibrium outcomes with the standard results. This comparison yields the effects of hold-up that play out at the interface of IEA choices and TRIPS: Mitigation efforts committed to during the negotiation of the IEA reduce the demand elasticity of countries with respect to new technologies (Lemma 1). Under TRIPs, innovators price their innovations such as to exploit their proprietary control over access to the technology and increase the technology license fee when signatories of the IEA have more ambitious abatement targets (Lemma 2). Anticipating this, signatories not only internalize the public good dimension of their abatement efforts, but also strategically choose their future demand elasticity for the new technology. This reduces their abatement efforts compared to a world without proprietary pricing of the new technology. *In extremis*, a fully fledged TRIPS can lead to IEAs of any size becoming either redundant for climate policy or involving **less** abatement by signatories than by non-signatories (Proposition 1). While an outcome of a highly stylized model, this stark result highlights the presence of strong interactions between international IPR policies and climate change mitigation policies.

As a second step, we connect these findings with the literature on self-enforcing IEAs. Using the equilibrium concept common to this literature, TRIPS reduces the number of

[2]Limitation of space dictate leaving out some important subtleties and problems raised by the recent literature on IEAs. Crucial problems arising in implementation have been addressed e.g. by Böhringer and Lange (2005), Eichner and Pethig (2009) and Gersbach and Winkler (2011).

[3]In contrast to the standard Barrett model, the present approach is more explicit about the commitment character of self-enforcing IEAs at the national level by separating target setting and implementation into separate stages.

signatories (Proposition 2) and can lead to **lower** aggregate abatement overall compared to the case without innovation (Proposition 3).[4] Globally, innovation of a second technology always improves welfare on account of the cost diversification effect (Proposition 4). However, the country hosting the innovator is **worse off** with TRIPs in force than without (Proposition 5). The reason is that, while TRIPs generates patent rents that contribute to national welfare, it also crowds out abatement by all other countries, and disproportionately so by the IEA. Since all countries, with or without the innovator, are linked together through the climate commons, the resulting climate change damages from enforcing TRIPs are always strictly larger than the patent rents.

In the third and final step, we discuss possible solutions to the hold-up problem, restricting the discussion to solutions that do not require a protracted process of revoking TRIPS on 'green' technologies. Such solutions are, for instance, internationally funded patent buyouts as advocated in the context of pharmaceuticals. The common element is that each one severs, in a different way, the functional link between countries' international abatement commitments and the prices they face for access to more advanced technologies. We highlight one particularly salient possible improvement, namely the announcement of a price ceiling by the innovator host country.

While this is the first paper to look at the interaction of a fully fledged TRIPS and IEA formation and performance, this is by no means the first paper to look jointly at green technologies and abatement at an international level. 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. Harstad (2012, 2015) studies a different hold-up problem arising from investment in superior abatement technology prior to international negotiations taking place. Benchekroun and Ray Chauduri (2014) find that eco-innovations can reduce the stability of IEAs when using a farsighted stability concept. While our contribution shares features with these other papers, there are several key differences. One is our interest in the effect of TRIPs on the international adoption of existing technologies and on the IEA formation process. Given this focus on diffusion, we do not consider upstream innovation and investments into national or international R&D programs such as Harstad (2015), Benchekroun and Ray Chauduri (2014), Hoel and de Zeeuw (2010) and Barrett (2006). Connected to this, our paper features a firm holding IPRs in an advanced technology rather than a country. In this, the paper relates to a different literature that studies 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. This parallel is in clear evidence in our headline results.

In the following section, we introduce the model of a climate change participation game when an alternative technology can be provided under proprietary technology supply. Section 3 analyses the model for a fixed number of signatories to the IEA and identifies the key

[4] Adoption of a green technology has also been found to increase emissions in some cases by Perino and Requate (2012). However, there innovation is vertical, policy domestic and pricing of the technology competitive.

strategic effect of the paper: the climate policy hold-up. Section 4 studies coalition formation and presents results on coalition size, aggregate abatement and welfare effects of the IPR regime in comparison to a world with competitive supply or absence of the new technology. Section 5 discusses alternative systems of knowledge sharing and section 6 concludes. Proofs are in the appendix.

2 Analytical framework

Following Barrett (2006), we model a world in which there are N ex-ante identical countries facing a global public good problem. Each country i receives a benefit of

$$B^i = bQ, \tag{1}$$

where $Q = \sum_i q^i$ is the aggregate level of contribution to the public good (GHG abatement) and $b > 0$ is the country i's marginal benefit from abatement.

There are two abatement technologies available that can be used in any combination:[5] One is an incumbent technology embodying knowledge that is not protected by an IPR and is competitively provided on the market. We denote by $x^i \geq 0$ the amount of abatement that is carried out in country i using that incumbent technology. The marginal cost of the incumbent abatement technology is x^i. The other abatement technology is a new alternative that relies on privately owned IPRs. We denote by $y^i \geq 0$ the amount of abatement that is carried out in country i using the alternative technology, for which the IPR owner charges a technology license fee of $p \geq 0$. Employing an additional unit of the alternative technology therefore requires country i to give up p plus the marginal cost of abatement for this technology denoted by dy^i (with $d > 0$). To summarize, total abatement is the sum of the abatement carried out using either of the technologies, $q^i = x^i + y^i$, and country i's total abatement costs are given by

$$C^i\left(x^i, y^i\right) = \frac{1}{2}(x^i)^2 + \frac{d}{2}(y^i)^2 + py^i. \tag{2}$$

The timing is as follows. In stage 1, countries simultaneously decide whether to sign an IEA. In stage 2, signatories cooperatively commit to minimum abatement efforts anticipating monopolistic pricing of the new technology. In stage 3, the innovator sets per-unit prices (license fees) for the use of the new technology for signatories and non-signatories exploiting third-degree price discrimination. Fourth, signatories make adoption decisions honoring any abatement commitment made in the second stage. In stage 5, non-signatories simultaneously and non-cooperatively make abatement and adoption decisions. As usual, the game is solved by backwards induction.

3 TRIPs and IEAs with exogenous membership

We now turn to solve the last four stages of the game described above, excluding for the moment the coalition formation stage. Treating the number of signatories as exogenous in

[5]The ability to use both technologies at the same time deviates from Barrett (2006) where technologies are mutually exclusive, but shares similarities with Harstad (2012). Negative abatement in any one of the two technologies is excluded.

this way helps to identify the important change in the strategic setting of an IEA induced by TRIPs. The coalition formation stage that gives rise to a self-enforcing IEA is then covered in section 4.

3.1 Stage 5: Abatement and adoption by non-signatories

In the last stage of the game, non-signatories individually solve the following optimization problem

$$\max_{x^i,y^i} bQ - \frac{1}{2}\left(x^i\right)^2 - \frac{d}{2}\left(y^i\right)^2 - p^n y^i, \tag{3}$$

where x^i and y^i, again, are the amounts of abatement provided through the old and new technology, respectively. p^n is the license fee paid by non-signatories for using the new technology.

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

$$x^n = b, \tag{4}$$

$$y^n = \frac{b - p^n}{d}. \tag{5}$$

The amount of abatement provided by the non-signatory country using the incumbent technology increases in the marginal benefits of abatement b. The use of the alternative abatement technology also increases in b, but only net of the license fee charged by the innovator, and decreases in the marginal cost of using the alternative technology d.

3.2 Stage 4: Abatement and adoption by signatories

In the abatement and adoption stage, signatories solve an optimization problem of the form

$$\max_{x^i,y^i} b\left[\sum_k (x^i + y^i) + (N-k)\left(b + \frac{b-p^n}{d}\right)\right] - \frac{1}{2}\left(x^i\right)^2 - \frac{d}{2}\left(y^i\right)^2 - p^s y^i, \tag{6}$$

$$s.t. \quad x^i + y^i \geq \bar{q}, x^i \geq 0, y^i \geq 0$$

where $\bar{q}$ is the minimum level of abatement each signatory committed to in the IEA and $k \in \{0, N\}$ is the number of signatories to the IEA. Signatories maximize their domestic welfare. Cooperation is therefore limited to the commitment stage of the IEA. This highlights the commitment character of abatement choices as part of an IEA that is not explicitly modeled in the standard Barrett model where commitment and abatement occur in the same stage of the game.[6]

[6]This might seem contrary to the spirit of self-enforcing IEAs covered in section 4. But there is a subtlety here: The requirement of self-enforcement in IEAs highlights the difficulties of international policy commitment between sovereign nations. The domestic policy commitment assumed here is less demanding. While domestic policy commitment is not perfect, its successful provision is one of the very function of government institutions. If governments could not restrict their own future actions to some degree, a credible patent system would be infeasible. Models in which governments implement internationally declared abatement targets rely on this ability to commit at home. To this extent, the commitment we make explicit here is already implicitly present in the basic Barrett model.

Two cases can arise at the abatement stage. Either the abatement target constraint imposed by the IEA is binding or it is not. If it is binding, abatement is split over the two technologies such that

$$x^s_{bind} = \frac{d\bar{q} + p^s}{1+d}, \tag{7}$$

$$y^s_{bind} = \frac{\bar{q} - p^s}{1+d}. \tag{8}$$

Signatories (s) therefore minimize costs by applying the equi-marginal principle. As a result, abatement levels of both technologies depend on the abatement target $\bar{q}$ and the price paid for the new technology by signatories p^s.

If the minimum abatement target constraint is not binding, signatories' abatement levels for the two technologies are

$$x^s_{nonbind} = b, \tag{9}$$

$$y^s_{nonbind} = \frac{b - p^s}{d}, \tag{10}$$

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 the minimum abatement level committed to by signatories in the IEA is binding, depends of course on the license fee chosen by the innovator. If the license fee charged for the use of the new technology p^s is sufficiently low, i.e. below a critical level $\hat{p}^s(\bar{q})$, signatories might choose to abate more than the minimum level of $\bar{q}$. The critical fee level is determined by the condition that the sum of (9) and (10) is equal to the minimum abatement target $\bar{q}$. This yields

$$\hat{p}^s(\bar{q}) = b(1+d) - d\bar{q}. \tag{11}$$

Demand for the new technology by signatories is therefore given by

$$y^s(p^s) = \begin{cases} \frac{b-p^s}{d} & if \quad p^s \le \hat{p}^s(\bar{q}) \\ \frac{\bar{q}-p^s}{1+d} & if \quad p^s > \hat{p}^s(\bar{q}) \end{cases}. \tag{12}$$

From (12) follows the first important building block of the climate policy hold-up problem under TRIPs.

Lemma 1 *(Price elasticity of technology demand) If the IEA's abatement targets are binding, i.e. $p^s > \hat{p}^s(\bar{q})$, then the price elasticity of demand for the new technology by signatories*

$$\epsilon_{y^s} = \frac{p^s}{\bar{q} - p^s}, \tag{13}$$

is a decreasing function of their abatement target $\bar{q}$.

Lemma 1 constitutes the demand side component of the hold-up problem: The more ambitious the abatement target of signatories, the higher the market power of the firm owning the patent for the new technology. This has important strategic ramifications for both innovator and signatories: While the innovator will aim to exploit this market power optimally when pricing the technology, signatories have an incentive to decrease the abatement target in order to limit the innovator's market power.

3.3 Stage 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 (5) and (12), respectively. This leads to the second building block of the hold-up effect, namely strategic technology pricing that exploits abatement commitments under appropriate circumstances.

Lemma 2 *(Strategic technology pricing) The innovator sets equilibrium prices for signatories and non-signatories to the IEA according to*

$$p^n = \frac{b}{2}, \tag{14}$$

$$p^s = \begin{cases} \frac{b}{2} & if \quad \bar{q} \leq \hat{q} \\ \frac{\bar{q}}{2} & if \quad \bar{q} > \hat{q} \end{cases}. \tag{15}$$

The license fee to be paid by signatories increases in their abatement target for all $\bar{q} > \hat{q} = b\sqrt{\frac{1+d}{d}}$.

As has been established in the previous subsection, abatement targets are not binding if the price of the new abatement technology is sufficiently low. In this case signatories choose to exceed their targets. When setting the license fee for signatories, the innovator hence faces the choice between making the abatement target binding by setting a price above $\hat{p}^s(\bar{q})$ and charging a lower price which results in abatement above target. Which is more profitable depends on the target signatories committed to in the IEA. The threshold level $\hat{q}$ is the level where the innovator is exactly indifferent between the two pricing options. Note that this critical level of signatories' abatement target is below equilibrium abatement by non-signatories ($\hat{q} < x^n + y^n$) yet imposes a binding constraint under conditions discussed further below. By assumption, the innovator chooses the strategy that induces commitments to be nonbinding and sets $p^s = \frac{b}{2}$ whenever $\bar{q} = \hat{q}$.

To summarize, abatement by country type and technology is

$$x^n = b, \tag{16}$$

$$y^n = \frac{b}{2d}, \tag{17}$$

$$x^s(\bar{q}) = \begin{cases} b & if \quad \bar{q} \leq \hat{q} \\ \bar{q}\frac{1+2d}{2+2d} & if \quad \bar{q} > \hat{q} \end{cases}, \tag{18}$$

$$y^s(\bar{q}) = \begin{cases} \frac{b}{2d} & if \quad \bar{q} \leq \hat{q} \\ \bar{q}\frac{1}{2+2d} & if \quad \bar{q} > \hat{q} \end{cases}. \tag{19}$$

3.4 Stage 2: Abatement commitments by signatories

The defining feature of an IEA is that its signatories cooperatively agree to commit to minimum abatement levels $\bar{q}$. In doing so, they internalize the public good character of abatement within the group of signatories. This allows IEAs to improve on the pure non-cooperative state and at the same time creates incentives to form a self-enforcing IEA (discussed in the next section) as abatement by signatories is increasing in the number of countries joining the IEA. The decision on abatement commitments is complicated, though, by the proprietary supply of the new abatement technology. Since the patent holder will supply signatories and non-signatories at differential prices, signatories, acting cooperatively, will not behave as price takers, but correctly anticipate the effect of their abatement commitments on future license fees. Since the elasticity of demand for the new technology by signatories (Lemma 1) and, hence, their license fee are functions of the IEA's abatement target (if it is binding), the more signatories are committing to abate, the more they become exploitable by the patent holder (lemma 2). The hold-up problem therefore changes the decision problem at the commitment stage. The partial internalization of the public good problem and the hold-up effect work in opposite directions. The former increases abatement by signatories compared to non-signatories but the latter reduces it.

Signatories face the following optimization problem

$$\begin{aligned}\max_{\bar{q}} \quad & b\left[k\left[x^s\left(\bar{q}\right)+y^s\left(\bar{q}\right)\right]+\left(N-k\right)\left(b+\frac{b}{2d}\right)\right] \\ & -\frac{1}{2}\left(x^s\left(\bar{q}\right)\right)^2-\frac{d}{2}\left(y^s\left(\bar{q}\right)\right)^2-p^s\left(\bar{q}\right)y^s\left(\bar{q}\right).\end{aligned} \tag{20}$$

Note that for all $\bar{q} \leq \hat{q}$ welfare of signatories is independent of $\bar{q}$ because commitments are not binding below this threshold. Signatories are indifferent between all $\bar{q} \in [0, \hat{q}]$ and each of these outcomes would be equivalent to a case without an IEA. This is apparent when observing that the critical level of abatement $\hat{q}$ is smaller than abatement by non-signatories.

Assuming for a moment that agreed targets turn out to be binding and imposing symmetry, the welfare maximizing abatement target that signatories commit to is

$$\bar{q}_{bind} = bk\frac{4(1+d)}{4(1+d)-1}, \tag{21}$$

with $1 < \frac{4(1+d)}{4(1+d)-1} < 4/3$, i.e. abatement is higher than if the new technology were not available (see appendix A.1). Next we need to identify the condition under which the abatement target will indeed impose a binding constraint. Imposing $\bar{q}_{bind} > \hat{q}$ yields the minimum level of the cost parameter of the new technology $\hat{d}(k)$ above which the IEA's targets are meaningful,

$$d > \hat{d}(k) = \frac{3-2k^2+k\sqrt{4k^2-3}}{4(k^2-1)}. \tag{22}$$

This minimum cost parameter defines a cost threshold: If the new technology renders abatement sufficiently cheap, then its international adoption by signatories is not subject to strategic consideration. Note that the parameter, $\hat{d}$ is decreasing in k, but strictly positive for all $k > 1$. The more signatories there are to the IEA, therefore, the lower the cost of the new technologies needs to be in order to escape the hold-up effect. As the following proposition shows, the cost parameter therefore also determines the fundamental character of the IEA.

Proposition 1 *(The Hold-Up Effect and 'Green', 'brown' and redundant IEAs) For a given number of IEA signatories $k > 1$, the abatement target committed to by each signatory in the presence of a new technology protected by TRIPs depends on the cost parameter of the new technology in the following way:*

- *For all $d > \hat{d}(k)$, the abatement target is binding, smaller than without TRIPs, but higher than if the new technology is not available. Specifically,*
  - *For all $d \geq \bar{d}(k) = \frac{5-4k+\sqrt{16k^2-16k+1}}{8(k-1)}$ abatement by a signatory is (weakly) larger than abatement by a non-signatory. The presence of the IEA increases total abatement, i.e. the IEA is 'green'.*
  - *For all $\hat{d}(k) < d < \bar{d}(k)$ abatement by a signatory is strictly smaller than by a non-signatory. Total abatement is less than without an IEA and decreasing in the number of signatories, i.e. the IEA is 'brown'.*
- *For all $d \leq \hat{d}(k)$, the abatement target is not binding. Signatories abate the same as non-signatories, which is (weakly) more than the collectively agreed target, i.e. the IEA is redundant.*

The double effect of TRIPS on abatement choices are best understood by comparing the content of Proposition 1 with the case in which the new technology is competitively provided (i.e. no TRIPs). This is a special case of the current model where $p^s = p^n = 0$.[7] Under TRIPS, two separate effects decrease abatement targets relative to the competitive benchmark: Firstly, countries face higher (and differentiated) prices for the new technology. This is the standard effect that pricing above marginal costs reduces abatement compared to the situation where the technology is provided competitively. The second effect are the strategic distortions between signatories and patent holder that reduce abatement even further. Figure 1 separates the two effects graphically by plotting abatement levels as a function of the abatement cost parameter of the new technology d. The difference between abatement by a signatory under competitive provision (e) to abatement when license fees are ex-ante fixed at their equilibrium levels (c) represents the first effect due to the change in prices. The strategic reduction of abatement caused by the hold-up problem is illustrated by the difference between (c) and (a). The figure also illustrates that monopolistic pricing and price discrimination substantially reduce abatement, but do not create 'brown' IEAs (see appendix). The latter phenomen requires the hold-up problem, which induces signatories to abate less than non-signatories for the range of parameters identified above.

'Brown' IEAs follow from the condition that for $d = \hat{d}(k)$ it holds that $\bar{q}_{bind} = \hat{q}$ with the latter being smaller than total abatement by non-signatories (see above). The upper bound of the 'brown' IEA interval $\bar{d}$ is derived from the condition $\bar{q}_{bind} = x^n + y^n$. For 'brown' IEAs the hold-up effect dominates the public good effect in an IEA facing a new abatement technology protected by TRIPs.

The lower bound of the cost parameter of the new technology for 'brown' IEAs is driven by the lack of credibility for even laxer abatement targets. Reducing the target even more would

[7] See benchmark 2 in appendix A.1.

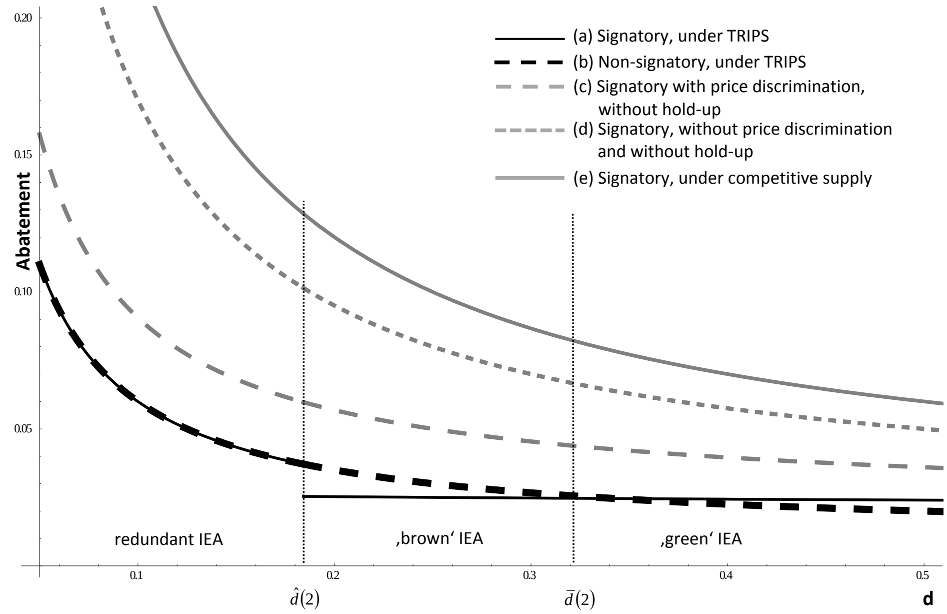

Figure 1: Abatement levels by (a) signatories under TRIPS and (b) non-signatories under TRIPs and by signatories (c) under discriminatory but ex-ante fixed pricing at $p^s = \frac{2k(1+d)}{3+4d}$ and $p^n = \frac{b}{2}$, i.e. at equilibrium prices but without the hold-up, (d) under uniform pricing at $p^s = p^n = \frac{b}{2}$ and (e) under competitive provision of the new technology ($N = 100; b = 0.01; k = 2$).

induce the patent holding firm to abandon price-discrimination. This, in turn, renders the abatement incentives for signatories and non-signatories identical. Signatories hence would want to abate more than required by the rules of the IEA. As we assumed that an IEA only imposes minimum abatement requirements, the IEA becomes void.

Before we solve the final stage of the game, the coalition formation, let's take stock of the effects of TRIPs on outcomes given the number of signatories to an IEA is exogenous. First, TRIPs create market power that induces the patent holding firm to set a license fee that raises the costs of using the new technology above its social marginal costs. We therefore observe the standard static inefficiency associated with intellectual property rights: abatement by the new technology is less than in the absence of TRIPs. The second main effect is new: the demand elasticity - and hence the level of the license fee - is a function of abatement targets agreed to in the IEA. More ambitious targets make signatories more reliant on the new technology and hence more vulnerable to exploitation by the innovator. Consequently, signatories commit to laxer targets in the IEA stage internalizing their joint effect on the license fee. This strategic interaction between signatories and the innovator is a product of the hold-up effect, and for a higher number of signatories, the new technology needs to be increasingly cost-saving relative to the incumbent one in order to escape the effect.

4 TRIPs and self-enforcing IEAs

This section analyzes how monopolistic provision of the new technology affects the equilibrium size of the coalition forming an IEA, aggregate welfare and abatement and welfare of the innovator's home country. We start by applying the standard stability conditions for a self-enforcing IEA,

$$\pi^n(k^* - 1) \leq \pi^s(k^*), \tag{23}$$
$$\pi^n(k^*) \geq \pi^s(k^* + 1), \tag{24}$$

to the two possible outcomes of the commitment stage (binding/non-binding targets). Assuming that abatement targets are binding, the only stable coalition contains two countries ($k^* = 2$) and requires that abatement using the new technology is sufficiently costly, i.e. $d \geq \frac{\sqrt{7}-2}{4} \approx 0.1614$. This threshold is always less restrictive than the feasibility threshold $\hat{d}(k)$ evaluated at $k^* = 2$.[8] Hence, given that $N \geq 3$, the optimal coalition size is independent of both b and N since the stability conditions depend on neither. In this case, the number of signatories is always smaller than in the cases where either only one technology is available or both are priced competitively since in both cases $k^*_{bench} = 3$ (see appendix A.1). However, it can be shown (see appendix) that it is not uniquely the hold-up problem that causes the coalition size to shrink. The same also happens in the two exogenous pricing scenarios (c) and (d) presented in Figure 1.

If abatement using the new technology is sufficiently cheap ($d \leq \frac{2\sqrt{13}-5}{12}$), then all countries are indifferent between no IEA and any IEA with one or more signatories. The multiplicity of equilibria arises because commitments made as part of the IEA are nonbinding and hence have no effect on outcomes and payoffs. 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.

The core questions of this paper are the impact of TRIPs on the formation of IEAs, the commitments that countries enter into when they form, and the welfare effects associated with this outcome. To characterize these impacts, we again compare the above equilibrium of the participation game under TRIPs with the equilibrium under competitive supply of the new technology.

Proposition 2 *(Number of Signatories)*

- *For all $d > \hat{d}(2)$ the equilibrium number of signatories in a self-enforcing IEA is two ($k^* = 2$) and hence strictly smaller than in the absence of TRIPs.*

- *For all $d \leq \hat{d}(2)$ the equilibrium number of signatories to a self-enforcing IEA is between zero and N, but all countries behave exactly like non-signatories, and abatement levels and payoffs are independent of the number of signatories. Compared to an absence of TRIPS, any IEA concluded is therefore substantively empty.*

[8]Simply observe that $\hat{d}(2) = \frac{2\sqrt{13}-5}{12} \approx 0.184 > \frac{\sqrt{7}-2}{4} \approx 0.1614$.

The first part of the proposition highlights how IPRs on the new abatement technology have a detrimental effect on the stability of effective IEAs. The intuition for this is straightforward. Recall that incentives to join (or not to leave) an IEA are created by the abatement response by other signatories induced by entry into the coalition. The higher price for the new technology, price discrimination between signatories and non-signatories and the hold-up problem between the patent holder and signatories to the IEA dampens this response. As a result, the equilibrium number of signatories drops from three to two for all but the most productive of abatement technologies if a global patent is granted. Part two of Proposition 2 follows from Proposition 1. For the remainder of this section, we focus on the more interesting case in which IEAs yield binding minimum abatement targets, starting first with a consideration of global abatement levels.

The effect of TRIPs on global abatement, relative 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.

We can also compare the outcome under TRIPs with the case where there is only the incumbent technology and an alternative new technology is not available. While both signatories and non-signatories always abate more if the new technology is available than if this is not the case (diversification effect), the number of signatories is reduced by one which increases total abatement for 'brown' IEAs and decreases it for 'green' IEAs (size effect). Hence, for 'brown' IEAs both effects work in the same direction and total abatement under TRIPs is higher than without a new technology. However, for 'green' IEAs the two effects are antagonistic. The diversification effect, however, becomes smaller the higher the cost parameter d of the new proprietary technology: Expensive technologies deliver fewer gains from diversification. As can be seen from Figure 1 the difference in abatement efforts between signatories and non-signatories increases in d. For sufficiently large values of d, the IEA size effect dominates the diversification effect and as a result, in a world with TRIPs, eco-innovation can reduce global abatement. This defines a threshold value $\tilde{d}(N) = \frac{1}{16}\left(N - 6 + \sqrt{N^2 + 12N - 12}\right)$ whose implications are the matter of Proposition 3.

Proposition 3 *(Aggregate abatement) For all $N \geq 3$, b and $d > \tilde{d}(N)$, a second technology becoming available on a proprietary basis is associated with less aggregate abatement than when only the incumbent technology is available.*

To illustrate Proposition 3, Figure 2 presents global abatement under the monopolistic provision of the new technology and two benchmark cases (1: only incumbent technology available; 2: both technologies priced competitively) using a specific numerical example. Does Proposition 3 imply that innovation might reduce welfare if patents are granted? Not so. On the one hand, a reduction in global abatement results in a loss of social benefits induced by a deterioration of environmental quality. On the other hand, the horizontal nature of innovation and the fact that both technologies are used in equilibrium imply that any given level of abatement is achieved at lower social costs than if only one technology is available. Hence, if the cost saving effect dominates the loss incurred due to lower overall abatement, global welfare increases as a result of innovation even in situations when global

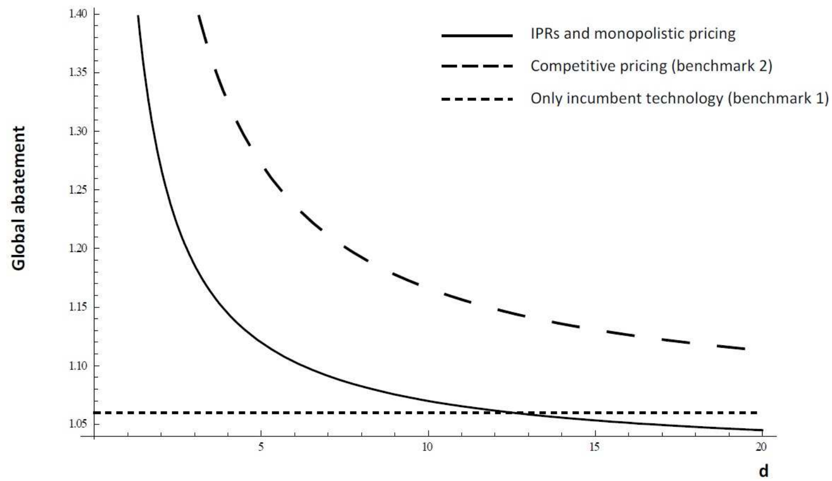

Figure 2: Global abatement with and without a global patent and with only the incumbent technology ($N = 100; b = 0.01$).

abatement is reduced. The dominance of the cost saving effect in the present set-up is the message of the following proposition.

Proposition 4 *(Global welfare) Global welfare is, ceteris paribus, always higher when the additional technology is protected by IPRs compared to only the incumbent technology being available.*

Propositions 3 and 4 contain the key results on the effect of TRIPs on green technologies for the global outcome in terms of environmental quality and welfare. Taken together, their message confirms that from a welfare perspective, diffusion is desirable irrespective of the presence of TRIPs regime. However, the gains from diffusion do not necessarily give rise to enhanced environmental quality. In this stylized setting, it is a distinct possibility that total abatement will decrease. The positive welfare effects arise mainly in the form of lower abatement costs. The hold-up problem created by the interplay of IEA and TRIPs introduces an additional dampening effect when considering what benefits technology diffusion will deliver to global society.

A final consideration in our analysis are the welfare effects not at the aggregate level, but at the level of the country that hosts the innovating firm. These effects are of interest in light of the arguments that green technologies will yield significant patent rents to host countries that we reviewed in the introduction. Is it true that proprietary management of green innovations is a boon to the countries hosting the innovator? Do countries benefit from being a winner of the so-called 'green race' (Friedman and Hot 2008). The answer depends on the benchmark used for comparison. Given the symmetry assumed in our model, it certainly holds that, given a global patent is granted to the innovating firm, it is always strictly better hosting the successful firm than not. Clearly, it is better winning the prize than paying for it. However, an interesting insight from the simple model of IEA and TRIPs is that such proprietary management of the innovation may not be in the interest of the host country. Given a domestic firm wins the R&D race, a globally enforceable perfect patent turns out to be harmful to the host country's welfare.

Proposition 5 *(Host country welfare) The home country of the innovating firm is worse off under a global patent than when the new technology is competitively available to all countries at marginal costs given that the new technology has already been developed.*

Proposition 5 holds regardless of whether the home country is a signatory or not. Generally, the result that patents induce static inefficiencies and hence a loss in post-innovation welfare compared to a competitive provision of the new technology would not be surprising. What makes it noteworthy is that this holds in the present case despite the fact that most of the deadweight loss of the firm's monopolistic pricing occurs in other countries and most of the royalties are paid by foreigners. The capturing of rents via the royalty payments is outweighed by the negative impact on the global public good induced by monopoly pricing. The proponents of green patent rents are therefore half right: Narrow measures of economic performance like GDP are likely to be higher with proprietary management of green innovations than without. Broader domestic welfare measures, however, that include damages from the global environmental good are here unambiguously lower without patents. Enforcing IPRs in green innovations backfires. The presence and nature of the effect is most easily verified for non-signatories due to the linear-quadratic specification of the model. Abatement provided by the incumbent technology is not affected by IPRs and hence can be ignored in this context while abatement by the new technology in the case with IPRs ($\frac{b}{2d}$) is half of what it would be in the absence of monopolistic pricing ($\frac{b}{d}$). Hence, the base on which the license fee is charged and the reduction in abatement are exactly the same. For each non-signatory, the country hosting the innovating firm receives royalties of size $\frac{b}{2} \cdot \frac{b}{2d} = \frac{b^2}{4d}$ but sees its environmental benefits reduced by $b \cdot \frac{b}{2d} = \frac{b^2}{2d}$, where $\frac{b}{2}$ is the license fee and b the marginal domestic benefit of abatement. The latter is exactly twice the former. A similar argument can be made for signatories and hence IPRs generate a net loss in terms of domestic social welfare given the new technology exists, even for the country receiving all the royalty payments.

5 Addressing the strategic distortions of TRIPS on IEAs

The analysis above highlights the important efficiency implications of agreeing on international treaties limiting emissions when such agreements take place against an institutional background in which the international diffusion of climate-relevant technologies is governed by a perfect form of TRIPS. The efficiency implications are the result of strategic distortions that arise between the market power of IP owners and countries' ability to manipulate their demand elasticity for more advanced technologies when negotiating IEAs.

The extent to which the existing form of TRIPS gives rise to the effect described above is an empirical matter that hinges both on the imitability of 'green' technologies and the enforceability of the applicable IPRs in adopter countries (Hall and Helmers 2013, Reichman et al. 2008). In contrast to the pharmaceutical sector, however, there is little empirical data to provide guidance for estimating the scale of the effect. However, the pharmaceutical sector also provides clear lessons on the inertia of international negotiations regarding the ability of an global IPR regime to accommodate exemptions for special sectors (Reichman et al. 2008).

Suggestions for alterations to TRIPS need to be mindful of the difficulty of enshrining such exemptions within existing frameworks, in particular when there is considerable difficulty in delimiting the concept of 'climate-relevant technologies.'

Overcoming the distortions that the presence of TRIPS imposes on the success of IEAs requires severing the link between demand elasticity and technology pricing. One way of severing this link is the implementation of proposals for compulsory licensing as advocated by some members of the UNFCCC Ad-hoc Working Group. This would involve compelling technology owners to license their technology at either fixed or non-discriminatory prices. Since compulsory licensing leads to a form of regulated monopoly (Scotchmer 2004), the regulatory component would break the link between the pricing decision of the innovator and the abatement commitment of potential signatories. This would in turn remove any incentive for countries to evaluate their abatement and signing decision under strategic considerations vis-a-vis the technology provider. Implementing proposals for compulsory licensing, however, would require countries to collectively support a fundamental change to TRIPS itself. The legal basis for IPR in technologies related to climate change would have to shift, with far-reaching implications for investment in research and development for future 'green' technologies .

In light of such implications, a resolution of the hold-up problem that respects existing property rights in the underlying technology are more likely to qualify as feasible. One such resolution is the idea of governments individually or jointly buying out innovators. The appeal of such patent buy-outs is that, properly devised, they have the potential to resolve not just the hold-up problem, but also the deadweight loss of monopoly power that inhibits the diffusion of existing technologies (Kremer 1998). The end effect would be a situation of perfectly competitive supply, as depicted in the highest curve in Figure 2: The formation of the IEA on emissions abatement would be unaffected by the possibility of a hold-up, and global abatement levels would lie strictly above those implied by the monopolistic supply of the additional technology. Despite these desirable properties, there are at least two problems with patent buyouts: One is that they represent a major, and essentially untested, departure from existing IPR systems. The other is that the likely scale of fiscal resources required would give rise to a higher-order problem of an international agreement on contributions from different countries towards the buyout fund (Barrett 2006).

A review of our results above suggests an institutionally much less demanding and also credible mechanism for overcoming the hold-up problem. This mechanism relies on the self-interest of the country in which the innovator is located, rather than that of adopter countries, and therefore only requires domestic policy action. The hold-up problem is resolved by an announcement by the host country early in the process that it will impose, through company taxation or otherwise, a ceiling on the price that can be charged for technology licenses. This price ceiling is determined by the optimal amount of technology diffusion from the host country's point of view, which is strictly greater than that of the innovator. Irrespective of whether the host country is a signatory to the IEA or not, the optimal price ceiling for the new technology lies strictly below the price that the innovator would charge signatories after signing the IEA.[9] Most importantly, the host country's announcement is credible since it

[9]The optimal price ceiling does differ in the signatory status of the host country, with a signatory host country charging a higher price than a non-signatory.

will find it optimal to impose the ceiling in later stages of the game irrespective of signatory status and abatement commitments of itself or other countries. This allows IEA members to negotiate abatement commitments non-strategically (i.e. without the hold-up problem), leading to more abatement and more technology adoption but with somewhat lower rents for the innovator.[10] The country hosting the innovator can therefore make a simple, but important contribution to addressing the strategic distortions of TRIPS on IEA without requiring a fundamental overhaul of existing global institutions. While there are ex-ante fixed price levels that would make everyone strictly better off than in the hold-up case (e.g. case (c) in Figure 1), it is not in the interest of the country hosting the innovator to enforce them.

6 Conclusion

By general agreement, the success of global GHG mitigation policies will over the coming 20 to 25 years depend on the effective diffusion of green technologies from corporate laboratories in industrialized countries to the rest of the world. If correct, such a dependence implies that the success will be shaped by how the institutions for international environmental agreements on emissions reductions and for access to advanced technologies interact. These institutions, the IEAs on GHG emissions and trade-related intellectual property rights, and their interaction is the subject of intense political debate at the international level, but is only beginning to be properly understood due to the inherent complexities of simultaneously resolving problems of international environmental policy and technology policy. This paper examines the interaction between IEA formation and TRIPs in a simple and tractable model. In addition to the predictable result that rent extraction possibilities afforded by a global IPR regime lead not only to higher prices for the new technology and hence less technology adoption than would be globally optimal, the model more importantly highlights a strategic reduction in abatement commitments by countries. As we discuss, the reason is a hold-up effect that induces countries negotiating an international environmental agreement to change their behavior in anticipation of the rent extraction by the innovator. As a result of this hold-up problem, international environmental agreements can be harmful to the environment as they turn from an institutional response to a cooperation problem into one that also addresses a market structure problem. Global welfare from diffusion remains positive, but may be associated with less abatement. Also, pursuing green patent rents 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. Perhaps surprisingly, countries should find it more profitable to give away breakthrough technologies rather than technologies of incremental improvements. The spirit of this paper is strictly positive, and our modeling framework of perfect global patents is deliberately stark in order to draw the effects out as clearly as possible. The weaker patent regimes of the real

[10]While the greater volume of technology adoption raises patent rents for the innovator relative to a situation with hold-up, the quantity effect is insufficient for offsetting the price effect. In other words, the innovator prefers the hold-up situation to the imposition of a price ceiling, even though the latter reduces distortions.

world may already go some way towards attenuating some of the effects brought out in this paper. However, these weaknesses are typically more accidental than deliberate. We explore some policy options that respect existing property rights but avoid the strategic interaction between signatories to an IEA and innovators. While Pareto-improvements over the hold-up case exist they tend not to be stable. However, a price ceiling for license fees imposed by the country hosting the innovator is both time consistent, provides higher levels of abatement and at the same time allows the innovator to earn rents. A comprehensive reconsideration of the regimes that should govern international cooperation on abatement and the diffusion of technologies required to accomplish these abatement goals will need to show awareness of the issues raised here.

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A Appendix

A.1 Benchmarks with freely available technologies

Here we briefly derive the equilibrium quantities and stable coalition size for two cases where technologies are freely available ($p^s = p^n = 0$), i.e. priced competitively. Case 1 (also called benchmark 1) features only one, the incumbent technology while in case (benchmark) 2 both technologies are available. Formally 1 is a special case of 2 with output of the new technology restricted to be zero ($y = 0$).

The equilibrium quantities of non-signatories follow directly from equations (4) and (5). For benchmark 1 they are given by (4) and for benchmark 2 they are $x^n_{b2} = b$ and $y^n_{b2} = \frac{b}{d}$. Since the price setting stage of the technology innovator (stage 3) does not exist, stages 4 and 2 are collapsed into a single stage which substantially simplifies the analysis.

Signatories solve the following optimization problem

$$\max_{x^i, y^i} b\left[k_{b2}\bar{q}^i + (N - k_{b2})b\frac{1+d}{d}\right] - \frac{1}{2}\left(x^i\right)^2 - \frac{d}{2}\left(y^i\right)^2. \tag{A.1}$$

Imposing symmetry among all signatories (s), equilibrium abatement by a signatory is

$$x^s_{b1} = x^s_{b2} = k_{b2}b, \tag{A.2}$$

$$y^s_{b2} = k_{b2}\frac{b}{d}. \tag{A.3}$$

For benchmark 1 the profit of signatories is $\pi^s_{b1} = \frac{b^2}{2}\left(2N - 2k_{b1} + k^2_{b1}\right)$ and the profit of non-signatories is $\pi^n_{b1} = \frac{b^2}{2}\left(2N - 2k_{b1} + 2k^2_{b1} - 1\right)$. Substituting both into condition $\pi^n_{b1}(k^*_{b1} - 1) \leq \pi^s_{b1}(k^*_{b1})$ yields $k^2_{b1} - 4k_{b1} + 3 \leq 0$. This implies $1 \leq k^*_{b1} \leq 3$. Condition $\pi^n_{b1}(k^*_{b1}) \geq \pi^s_{b1}(k^*_{b1} + 1)$ requires that $k_{b1} - 2 \geq 0$. The equilibrium number of signatories is hence $k^*_{b1} = 3$.

Profit functions of both signatories and non-signatories in benchmark 2 are multiples of their counterparts in benchmark 1. The size of a self-enforcing IEA is therefore three ($k^*_{b2} = k^*_{b1} = 3$) in both benchmarks.

For horizontal innovation, 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.

A.2 Optimal abatement and adoption by signatories

The Kuhn-Tucker conditions of optimization problem (6) are

$$b - cx^s - \lambda = 0 \tag{A.4}$$
$$b - dy^s - p^s - \lambda = 0 \tag{A.5}$$
$$\bar{q} - x^s - y^s \leq 0 \tag{A.6}$$
$$\lambda \geq 0 \tag{A.7}$$

If constraint (A.6) is not binding and hence $\lambda = 0$, (A.4) and (A.5) yield . If (A.6) is binding, combining (A.4), (A.5) and (A.6) yields (7) and (8).

A.3 Proof of equation (11)

The price threshold is determined by (9) being equal to (7) and (10) being equal to (8). Using either condition and solving for p^s yields (11).

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 (5), the first order condition yields

$$\frac{b - 2p^n}{d} = 0. \tag{A.8}$$

Solving for p^n yields (14).

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 (8). For $p^s \leq \hat{p}$, the first order condition requires $\frac{b-2p^s}{d} = 0$ and hence $p^s = \frac{b}{2}$. For the latter to be in the specified range ($p^s \leq \hat{p}$) it has to hold that, $\bar{q} \leq q^{nonbind} = \frac{b(1+2d)}{2cd}$.

For $p^s > \hat{p}$, the first order condition requires $\frac{\bar{q}-2p^s}{1+d} = 0$ and hence $p^s = \frac{\bar{q}}{2}$. For the latter to be in the specified range ($p^s > \hat{p}$) it has to hold that, $\bar{q} > q^{bind} = \frac{b(1+d)}{1/2+d}$.

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

$$\frac{b}{2} \cdot \frac{b}{2d} = \frac{\hat{q}}{2} \cdot \frac{\hat{q}}{2(1+d)}, \tag{A.9}$$
$$\hat{q} = b\sqrt{\frac{1+d}{d}}. \tag{A.10}$$

Hence, signatories' commitment binds for all $\bar{q} > \hat{q}$ but does not for all $\bar{q} \leq \hat{q}$.

A.5 Proof of equation (21)

Using $\bar{q} = x^s(\bar{q}) + y^s(\bar{q})$, the first-order condition of (20) is

$$bk - cx^s(\bar{q})\frac{\partial x^s}{\partial \bar{q}} - dy^s(\bar{q})\frac{\partial y^s}{\partial \bar{q}} - \left[p^s(\bar{q})\frac{\partial y^s}{\partial \bar{q}} + y^s(\bar{q})\frac{\partial p^s}{\partial \bar{q}}\right] = 0. \tag{A.11}$$

Substituting in $\frac{\partial x^s}{\partial \bar{q}} = \frac{1+2d}{2(1+d)}$, $\frac{\partial y^s}{\partial \bar{q}} = \frac{1}{2(1+d)}$ and $\frac{\partial p^s}{\partial \bar{q}} = \frac{1}{2}$ derived from (15), (18) and (19) and simplifying, yields,

$$\frac{4bk(1+d) - (3+4d)\bar{q}}{4(1+d)} = 0. \tag{A.12}$$

Solving for $\bar{q}$ yields (21).

A.6 Ex-ante fixed pricing scenarios in Figure 1

A.6.1 Differentiated license fees at equilibrium level

License fees for both signatories and non-signatories are ex-ante fixed at their equilibrium levels, i.e. $p^s = \frac{2kb(1+d)}{3+4d}$ and $p^n = \frac{b}{2}$. Non-signatories hence behave exactly as with endogenous license fees. However, the commitment problem of signatories changes as they no longer have an impact on the license fee charged by the patent holding firm. Equilibrium quantities are:

$$q = \frac{b(1+d)((3+4d)k-4)}{d(3+4d)}, \tag{A.13}$$

$$x^s = bk, \tag{A.14}$$

$$y^s = \frac{b(3k-4+4d(k-1))}{d(3+4d)}. \tag{A.15}$$

For all $k \geq 2$ it holds that $q = \frac{b(1+d)((3+4d)k-4)}{d(3+4d)} > \frac{4kb(1+d)}{3+4d} = \bar{q}$ and that $q = \frac{b(1+d)((3+4d)k-4)}{d(3+4d)} > b\frac{2d+1}{2d} = x^n + y^n$, hence the commitment level of signatories when the license fees are ex-ante fixed at the equilibrium level of the hold-up game is strictly greater than commitment by signatories and abatement by non-signatories in the hold-up game for all relevant coalition sizes.

A.6.2 Uniform license fee at equilibrium level for non-signatories

If license fees for both signatories and non-signatories are ex-ante fixed at the level of non-signatories in the hold-up game ($p^s = p^n = \frac{b}{2}$), then the resulting commitment level is $q = \frac{b(\frac{1}{2}+k(1+d)}{d}$ which is strictly larger than the abatement commitment with differentiated license fee presented above for all coalition sizes.

A.7 Proof of Proposition 2

Condition $\pi^n(k^*-1) \leq \pi^s(k^*)$ imposes an upper bound on the number of signatories.

$$k^* \leq \frac{8d(1+d) + \sqrt{d\left(16d^3 + 32d^2 + 13d - 3\right)}}{4d(1+d)}. \tag{A.16}$$

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

Condition $\pi^n(k^*) \geq \pi^s(k^*+1)$ imposes an lower bound on the number of signatories.

$$k^* \geq \frac{4d(1+d) + \sqrt{d\left(16d^3 + 32d^2 + 13d - 3\right)}}{4d(1+d)}, \tag{A.17}$$

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

Conditions (A.16) and (A.17) have no real solutions if $d < \frac{\sqrt{7}-2}{4} \approx 0.1614$.

A.8 Proof of coalition size under ex-ante fixed license fee scenarios

A.8.1 Differentiated license fees at equilibrium level

Abatement levels for signatories when the license fee p^s, now evaluated at $k = 2$ to reflect the coalition size in a self-enforcing IEA, is ex-ante fixed at the equilibrium level of the hold-up game were derived in section A.6. Non-signatories' abatement choices are not affected by the hold-up problem are given by (16) and (17). Substituting them into the stability conditions of a self-enforcing IEA and solving for the critical (strictly positive) ks yields

$$k^* \leq \frac{28 + 108d + 144d^2 + 64d^3 + \sqrt{-89 - 213d + 740d^2 + 3552d^3 + 5504d^4 + 3840d^5 + 1024d^6}}{2(9 + 33d + 40d^2 + 16d^3)}, \quad \text{(A.18)}$$

$$k^* \geq \frac{-6 + 10d + 48d^2 + 32d^3 + \sqrt{36 - 165d - 812d^2 - 224d^3 + 2176d^4 + 2816d^5 + 1024d^6}}{2(9d + 24d^2 + 16d^3)} \quad \text{(A.19)}$$

(A.18) has real solutions for all $d \geq 0.26137$, is bound from above by 3 and drops below 2 for $d < 0.418206$. (A.19) is bound from above by 2 and has no real solution in the interval $[0.132914, 0.530504]$. The latter does not affect stability since in this range countries never want to leave an IEA. Hence, for all $d \geq 0.418206$ the IEA has exactly two members while below this threshold there is no IEA.

A.8.2 Uniform license fee at equilibrium level for non-signatories

Abatement levels for signatories when the license fees p^s and p^n are ex-ante fixed at $\frac{b}{2}$ were derived in section A.6. Non-signatories' abatement choices are again given by (16) and (17). Substituting them into the stability conditions of a self-enforcing IEA and solving for the critical (strictly positive) ks yields

$$k^* \leq \frac{6 + 5d + \sqrt{12 + 28d + 17d^2}}{4(1 + d)}, \quad \text{(A.20)}$$

$$k^* \geq 2, \quad \text{(A.21)}$$

(A.20) has a real solution for all $d \geq 0$, is strictly larger than $\frac{5+\sqrt{17}}{4} > 2$ and has a maximum of $\frac{6+2\sqrt{3}}{4} < 3$ at $d = 0$. The size of a self-enforcing IEA when the uniform license fee is $p = p^s = p^n = \frac{b}{2}$ is therefore $k^* = 2$.

A.9 Proof of Proposition 3

Using the results from A.1 yields global abatement $Q_{b1} = (N+6)b$ if only the incumbent technology is available. Using $k = 2$, (16), (17), (18) and (19) in combination with (21) yields global abatement $Q = b\left[(N-2)\frac{1+2d}{2d} + \frac{16(1+d)}{3+4d}\right]$ with two technologies and IPRs. Setting $Q_{b1} = Q$ and solving for d yields the critical point $\tilde{d}(N) = \frac{1}{16}\left(N - 6 + \sqrt{N^2 + 12N - 12}\right)$. For all $d > \tilde{d}(N)$ global abatement under a patent is less than when only the incumbent technology is available and vice versa.

A.10 Proof of Proposition 4

Global welfare in the benchmark with only the incumbent technology is $W_{one} = b^2\frac{(N-12)}{2}$. Global welfare with two technologies and IPRs is $W = b^2\frac{27(N-2)+64d^3(N-2)+16d^2(9N-2)+4d(27N+10)}{8d(3+4d)^2}$. It holds that $\frac{\partial W}{\partial d} = -\frac{b^2}{8d^2(3+4d)^3}\left[64d^3(3N+10)+16d^2(27N+26)+324d(N-2)+81(N-2)\right]$ which is negative for all $N \geq 2$. Since $\lim_{d\to\infty} W = b^2\frac{(N-2)}{2} > W_{one}$ welfare with two technologies and IPRs is always higher than in the benchmark with only the incumbent technology.

A.11 Proof of Proposition 5

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

$$\pi^n = b^2\left[16\frac{1+d}{3+4d}+(N-2)\frac{1+2d}{2d}-\frac{1}{2}-\frac{1}{8d}+32\frac{1+d}{(3+4d)^2}+\frac{(N-3)}{4d}\right], \tag{A.22}$$

if the country grants a global patent to the innovator and

$$\pi^n_{two} = b^2\left[(N+6)\frac{1+d}{d}-\frac{1}{2}-\frac{1}{2d}\right], \tag{A.23}$$

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

$$-(18N+531)-d(48N+1912)-d^2(32N+2336)-960d^3 \quad < \quad 0. \tag{A.24}$$

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.

A.12 Proof of preferred ex-ante price level of host country

Given ex-ante fixed license fees p^s and p^n, signatories commit to an abatement level of $q(p^s) =$ and split this over technologies according to (7) and (8). Non-signatories will abate $y^n(p^n) = \frac{b-p^n}{d}$ using the new technology (see (5)). Substituting this into the host country's welfare function yields

$$\begin{aligned}\pi^{s,host}(p^s,p^n) \quad &= \quad b\left[k\frac{b(1+d)k-p^s}{d}+(N-k)\frac{b+(b-p^n)}{d}\right]-\frac{1}{2}b^2-\frac{d}{2}\left(\frac{b-p^s}{d}\right) \\ &\quad +(k-1)p^s\frac{bk-p^s}{d}+(N-k)p^n\frac{b-p^n}{d}\end{aligned} \tag{A.25}$$

when the host is a signatory and

$$\begin{aligned}\pi^{n,host}(p^s,p^n) \quad &= \quad b\left[k\frac{b(1+d)k-p^s}{d}+(N-k)\frac{b+(b-p^n)}{d}\right]-\frac{1}{2}(bk)^2-\frac{d}{2}\left(\frac{bk-p^s}{d}\right) \\ &\quad +kp^s\frac{bk-p^s}{d}+(N-k-1)p^n\frac{b-p^n}{d}\end{aligned} \tag{A.26}$$

when the host is a non-signatory. Maximizing each of the two objective function w.r.t p^n and p^s yields $p^n = 0$ in both cases and $p^s = \frac{bk(k-1)}{2k-1}$ when the host is a signatory and $p^s = \frac{b(k-1)}{2}$ when the host is a non-signatory. In case price-discrimination is not feasible, the host country would prefer a uniform license fee of $p = \frac{bk(k-1)}{2N-1}$ regardless of whether it is a signatory or not.

It holds that $p^s(hold{-}up) = \frac{4bk(1+d)}{3+4d} > p^s(hostsignatory) = \frac{bk(k-1)}{2k-1} > p^s(hostnon{-}signatory) = \frac{b(k-1)}{2} > p = \frac{bk(k-1)}{2N-1}$.

A.13 Proof of preferred ex-ante price ceiling of patent holder

If the patent holding firm could ex-ante commit to a fixed level of the license fee and thereby avoid the hold-up problem, it maximizes profits (here equal to revenues) taking the best responses by signatories ($q(p^s) = \frac{bk(1+d)-p^s}{d}$) and non-signatories ($y^n(p^n) = \frac{b-p^n}{d}$) as given. In the case where price-discrimination is feasible this yields $p^n = \frac{b}{2}$ and $p^s = \frac{bk}{2}$. If price-discrimination is not feasible, the patent holder prefers a license fee of $p = b\frac{N+k^2-k}{2N}$. It holds that $p^s(hold-up) = \frac{4bk(1+d)}{3+4d} > \frac{bk}{2} = p^s(innovator) > \frac{bk(k-1)}{2k-1} = p^s(hostsignatory)$.

We now check whether the innovator prefers an ex-ante price ceiling at the level preferred by the host country to the case with hold-up. The difference in profits from selling the new technology to signatories is

$$\frac{b(k-1)k}{2k-1}\frac{bk-\frac{b(k-1)k}{2k-1}}{d} - 2bk\frac{1+d}{3+4d}\frac{bk-2bk\frac{1+d}{3+4d}}{d} = -\frac{b^2k^2(2+6d+4d^2+k-k^2)}{d(3+4d)^2(1-2k)^2}. \qquad \text{(A.27)}$$

For $k = 2$ this reduces to $-\frac{b^2 4(6d+4d^2)}{9d(3+4d)^2} < 0$. Hence, in the hold-up case the innovator earns higher profits from signatories than under the ex-ante price ceiling preferred by the host country.