International cooperation on the environment: The case for a green innovation club

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Abstract

International cooperation on green house gas mitigation has proven difficult. First, the levels of abatement are insufficient as countries tend to only consider their own benefit of abatement. Second, low global levels of abatement imply too weak incentives for green innovation.

In this paper we analyze closer cooperation on green innovation between countries. Our point of departure is that willing countries should form a *green innovation club*. This involves agreeing on setting up a patent pool between member countries' innovating firms. All member countries invest in a break through green technology, and share the income from an eventual success.

We show that a club based on patent pooling can increase global investments in green innovation. Moreover, since member countries benefit from increasing their abatement, the club also spurs global abatement. The club takes advantage of the monopoly power introduced by intellectual property rights in order to attract members. Free-riding nonmembers license the technology from the club, while members that invested in the development access the technology for free. This is enough to keep members in the club even if members abate more than nonmembers.

1 Introduction

Provision of global environmental goods like a stable climate necessitates cooperation between countries. Cross country cooperation is particularly difficult when it is costly for individual countries to reduce their environmental demands. Environmental innovation promises to de-couple the relationship between production and environmental degradation making it less costly to reduce the latter. Today countries try hard to increase their cooperation on green house gas (GHG) mitigation, however, there is little initiative with respect to cooperating on green innovation promoting zero emission technologies. On the contrary, inspired by the US inflation reduction act, countries

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seem to seek building their own national champions when providing subsidies for new zero emission technology.[1]

In this paper we analyze closer cooperation on green innovation between countries. Our point of departure is that willing countries should form a *green innovation club*. This involves agreeing on setting up a patent pool between member countries' innovating firms. A patent pool implies that all firms within the pool are free to use all patents on zero emission technology developed by the pool. Firms in countries not being members of the club pay to use the patents, and furthermore, pool member firms share the income from outside firms' licensing.[2]

The main purpose of the club is to increase global innovation effort in zero emission technologies. However, a green innovation club does not only have to be about developing zero emission technologies. In case innovation is successful, club countries should use the opportunity to also coordinate their environmental policies as this will increase the welfare of the club countries. Clearly, the common environmental policy must not be overly ambitious as the club then risk loosing members.

In order to analyze the prospects for an innovation club based on patent pooling, we set up a simplified reduced form model. In the model there are no innovating firms or emission abating firms, only countries. However, a county gains from innovation as its emission abating firms reduce their abatement costs. Moreover, a country may additionally benefit if innovation happens in one of its innovating firms as the country will then get extra income from the monopoly power implied by the patent.

Our focus is on a break through technology that requires high intial investments in research and development in order to have a chance of success. Examples are zero emission aircrafts, fusion power and carbon capture and storage.[3]. Governments play a pivotal role as they must provide a large share of the intial investment due to both the inherent risk and the positive knowledge spill-overs from frontier research. Government support can then be used as leverage for patent pooling.

Within this set up, we find that a green innovation club based on patent pooling will both bring the level of green innovation and the level of environmental goods provision closer to the globally optimal levels. Intellectual property rights (IP) ensure monopoly power to a single developer. In the

[1] See for instance, The Economist, February 4-10, 2023.

[2] An example of a famous patent pool was the aircraft pool formed in 1914 at the brink of World War 1. The major firms in the pool were the Wright brothers and Glen Curtis as their patents were suspected to block further development of aircraft technology. By the end of World War 1 far more firms had entered the pool and all these firms were entitled to use patents royality-free. On the other hand, most of the royality income accrued to founding firms as they held the major patents, see Scotchmer (2004). In a green innovation club, governments financing private firms' research, development, and demonstration (RD&D) into green technologies, should condition their support on receiving firms forming a patent pool across borders.

[3] See for instance Hoffert et al. (2002) for an interdisciplinary argument for the necessity of intensive RD&D effort in advanced abatement technology.

competition for achieving IP, the club member countries force their individual innovating firms to unite in a patent pool. The club countries therefore only needs one success in the group of firms in order to receive the patent that benefits all members. Compared to when countries act on their own, this increases the incentive for the individual countries to support green innovation. Hence, the club will increase global innovation effort in zero emissions technologies. According to IEA (2019), this is highly desirable as investments in carbon capture and storage technologies, large scale battery parks, advanced biofuels and hydrogen fuel-cell solutions lag behind for what is necessary for reaching ambitious green house gas emission reduction goals.

Firms within the club countries charge firms in non-members countries a fee for licensing the technology, and these monopoly rents are shared among firms in the member countries. In this way the welfare improving technology, once developed, is still distributed to all countries such that environmental goods provision increases also in non-member countries. Moreover, the sharing of license income incentives countries to stay in the club and to more GHG abament than they would have done outside the club. The green innovation club therefore also ensures a higher level of global GHG mitigation.

The latter effect of the club seems highly needed. The current development in global greenhouse gas (GHG) emissions is not promising, since global emissions increased from 2017 to 2018, with little change from 2018 to 2019. In 2022 global GHG emissions reached their highest level ever. It is uncertain whether the nationally determined contributions (NDCs) made by individual countries in the Paris Agreement (UNFCCC, 2015) will be carried out. Moreover, even if the NDCs are fulfilled they are critically insufficient, and global temperatures are set to increase far more than the 1.5 degree target.

With this in mind, we suggest the green innovation club as a compliment to the Paris agreement in order to increase emission reduction for both club participants and non-member countries, that is, countries that continue to be only a party to the Paris agreement. The two-dimensional club arrangement does not have to attract all countries in order to further reduce emissions. If successful, the club will increase global abatement levels for all countries in and outside the club by making the new cost-reducing technology available to the world.

Our setup is inspired by the classical framework by Barrett (1994a), which models a climate agreement as a two-staged sequential game with a membership and an abatement stage. First countries decide whether to join, thereafter choosing their abatement contribution to the public good. Non-members set their abatement levels non-cooperatively, whereas members collude and maximize aggregate welfare. In this way the positive externality is counted for between members, but the free-rider incentive is large such that most countries choose to stay out. In our paper the potential threat of defection is larger, because everyone benefits from the new abatement technology being developed. When choosing not to join the club, a country not only looses the possibillity to profit from an innovation, but the chance of having acces to a new and better technology is also reduced. This increases the incentive to join the green innovation club.

In a seminal paper on the theory of clubs, Buchanan (1965) considered clubs as a private alternative to the optimal provision of a special class of public goods, later known as club goods. Clubs can be defined as organizations whose members collectively produce/consume a good that no single member find it beneficial to provide or finance alone. In order to sustain the club, it must be possible to exclude outsiders from taking part of the revenue the club provides. In our model this is solved in a novel way by explicitly including intellectual property rights. All club members get free access to the new technology, while nonmembers must license the technology from the club.

The paper is organized as follows: Section 2 gives a review of relevant literature on connecting IEAs and technology development. Then, in section 3 we introduce our simplified model and derive the first-best. Section 4 solve the model for unilateral RD&D and abatement decisions, while Section 5 solve the model with a green innovation club. An extended version of the model with endogenous investments is outlined in section 6. Lastly, the paper's findings are summarized and discussed in section 7.

2 Literature

The results from 30 years of negotiations on climate agreements are in line with predictions from the theoretic literature on IEAs: International cooperation targeting emission reductions has had minor effects. The literature has repeatedly stated that classical climate agreements, focusing mainly on emission reduction, cannot be expected to achieve much because the free-rider incentive prevents full cooperation, see Hoel (1992); Carraro and Siniscalco (1993); Barrett (1994b).

Several scholars have studied technology development in relation to international abatement cooperation (Carraro and Siniscalco, 1997; Barrett, 2006; Hoel and de Zeeuw, 2010; El-Sayed and Rubio, 2014; Rubio, 2017). Our point of departure differs from the above-mentioned contributions in that we recognize that there exist intellectual property rights (IP) that ensure revenue to the single developer that succeeds with innovation.[4]

Moreover, our definition of a breakthrough technology differs from Barrett (2006), Hoel and de Zeeuw (2010) and Rubio (2017). We do not consider a silver bullet technology that completely removes all GHG emissions. In our opinion this is unlikely because GHG emissions comes from a wide range of economic activities and sectors. Our technology, if successfully developed, gives a non-marginal shift in the abatement cost curve, without removing the cost of abatement altogether. We name the innovation a breakthrough technology since a certain amount of investment is needed to initiate and carry out the innovation process.

On the one hand, our paper is more in line with Gersbach and Riekhof

[4] Some would maybe argue that IP does not work on the international level. However, alternatives to IP exist, such as secrecy.

(2022), which also looks at technologies that do not reduce abatement costs to zero and includes IP. On the other hand, we include cooperation on both abatement and RD&D, while Gersbach and Riekhof (2022) allow countries to set abatement non-cooperatively through a shared emission permit market.

Barrett (2006) concludes that in general the focus on technology development cannot improve the performance of IEAs unless technology adoption involves increasing returns due to knowledge spillovers or network externalities. Hoel and de Zeeuw (2010) show that if the adoption costs of a breakthrough technology vary with the level of R&D, it can result in a large stable coalition, however, only on R&D cooperation. This is in line with Rubio (2017), who also finds that R&D cooperation may lead to large global emission reductions due to the silver bullet aspect of the new technology.

As far as we know, our contribution is the first contribution to combine emission reduction targets with binding RD&D investments in a two-dimensional technology club. Thus, members of a stable coalition in our model have both lower emissions and higher R&D investment than nonmember countries. This aspect contrasts Rubio (2017) and Hoel and de Zeeuw (2010), where the technology agreement is a one-dimensional treaty, and cooperation on technology is an alternative to cooperation on abatement.

Our green innovation club involves a type of issue linkage. Scholars have discussed issue linkage as an answer to the free-rider problem in both the economic literature (Cesar and de Zeeuw, 1996; Carraro and Marchiori, 2004; Barrett, 2006) and the political science literature (Davis, 2004; Urpelainen, 2013; Hovi et al., 2017). Linkage connects environmental negotiations to other interrelated economic issues, typically a club-good whose benefits are exclusive to its members and thus cannot be reaped by free-riders[5]. In the real world we do observe that countries cooperate in several policy dimensions when entering agreements; one example is the Montreal Protocol which regulated the production of CFC gases in addition to prohibiting members to trade CFC chemicals with nonmembers. Linking climate and trade examples is studied by Barrett (1994a, 1999) and Nordhaus (2015).

Finally, there is also a small literature connecting abatement cooperation to innovation without tying the issues together within one common agreement: de Coninck et al. (2008) discuss international knowledge sharing and find that coordination can increase the effectiveness of IEAs. In contrast, Strand (2007) argues that technology cooperation aimed at alternative energy sources can affect the incentives of fossil-fuel producers, motivating them to extract more. Buchholz and Konrad (1994) consider a possible hold-up problem if choice of technology precedes agreements on abatement. Then countries have an incentive to commit to low-quality technologies before they enter the negotiation in order to obtain non-ambitious emission reduction targets. However, Harstad (2012) shows that in a dynamic context where both size and length of the agreement is negotiated, the hold-up problem may actually be beneficial. Not

[5]See Maggi (2016) for a comprehensive literature review on issue linkage in international cooperation

being able to contract on innovation of green technologies enable countries to design an agreement that achieve the social optimal level emissions. Harstad (2012), however, neither consider technologies that can benefit from collective R&D effort nor the possibility to earn on technology licensing.

3 The model

In order to illustrate the potential gains from a green innovation club, we set up the simplest possible model inspired by Barrett (1994a). Consider a world with $n \geq 3$ symmetric countries denoted by $i \in \{1, ..., n\}$. Each country is involved in activities degrading the global environment which again harms all countries. The environmental degradation can be abated at a cost $c(q_i)$, in which q_i is abatement by country i. Let total abatement be denoted by $Q = \sum_i q_i$, and let the benefit of abatement to each of the countries be denoted by βQ where β is a positive constant.

In each country there are firms being able to develop break through zero emission technologies. In order to get them started, governments must pay a share of their R&D investments. Governments may use this a leverage for setting up an international patent pool, e.g., a green innovation club. Since members of the patent pool will share all income from IP, IP costs are not real costs to member countries of the innovation club, but only to outsider countries.

When modelling the R&D process, we closely follow Gersbach and Riekhof (2022). Denote the investment need to kick-start the innovation process by F. We think of F as encompassing research, development and demonstration, and it should be interpreted as an annualized cost over the lifetime of the new technology. By investing F the country has a probability p of developing a break through low emission technology[6]. Note that for any investment smaller than F, the probability of a break through is zero, while for any investment greater than F, the probability is still p.[7]

If one or more countries succeed and country i adopts the new technology, the innovation will induce a downward shift in the marginal abatement cost curve. Thus, we propose the following abatement cost function:

$$C(q_i) = \frac{c}{2}(q_i)^2 - \alpha q_i \text{ where } \alpha \in \{0, a\}$$

where c and a are parameters. If no country succeeds in innovating, or if country i does not adopt the new technology despite one or more countries having succeeded, we have $\alpha = 0$ (for all countries or only for country i).

We assume that the research processes are independent, which implies a fixed probability for every innovation process in each symmetric country

[6] When we write a country has a probability p of success with the innovation, we acctually imply the innovating firms in the country.

[7] F can be interpreted as the *efficient* level of research within a specific area. In order to have a chance of success you likely need to put significant effort into the endavour. Moreover, at any point there is a limited number of researchers having the necessary expertice. Increasing innovation expenditures beyond F could thus imply little extra gain.

(equal to p). The number of countries that choose to invest thus gives us a fixed number of trials in total. These characteristics corresponds to the binomial probability distribution, where the number of successes is binomially distributed.[8]

The probability that at least one country succeeds in developing the new technology $P(k)$, out of $k \leq n$ countries that try, is given by the probability that not everyone fails:

$$P(k) = 1 - (1-p)^k$$

where one trial is each country that invests F. We have $P_k' > 0$ and $P_k'' < 0$. One possible interpretation of $P_k' > 0$ is that countries conduct the innovation project in slightly different ways, and hence, the aggregated success probability increases.

Finally, if only one country has success, this country will obtain intellectual property rights (IP) allowing the country to charge a license ℓ to other countries wanting to utilize the innovation. One the other hand, if more than one country have success, we assume that competition drives the price for access to the technology down to zero.

4 First best

An omnipotent planner would first choose the number of countries that should invest F in innovation k^*. Then, knowing whether the innovation activity was successful, the planner would choose the abatement level q^* for each country.

Denote global aggregate utility exclusive innovation costs by $\Gamma^*(\alpha)$:

$$\Gamma^*(\alpha) = \max_q \left\{ n \left[n\beta q - \frac{c}{2} q^2 + \alpha q \right] \right\} \text{ where } \alpha \in \{0, a\}$$

Note that since countries are symmetric, the planner will set the same level of abatement in all countries, e.g., $q_i = q \forall i$. Total abatement is then equal to nq. Solving yields:

$$q^*(\alpha) = \frac{\beta n + \alpha}{c}$$

Inserting we obtain for $\Gamma^*(\alpha)$:

$$\Gamma^*(\alpha) = \frac{n(\beta n + \alpha)^2}{2c} \text{where } \alpha \in \{0, a\}$$

Hence, when deciding the level of innovation investment, the planner solves:

[8] The probability mass function of binomial random variable is $\Pi(s) = \binom{k}{s} p^s (1-p)^{k-s}$ where s is the number of successes from k trials.

$$\max_k \left\{ \left(1-(1-p)^k\right)\Gamma^*(a) + (1-p)^k\Gamma^*(0) - kF \right\}$$

which leads to the first order condition:

$$-\ln(1-p)(1-p)^k \left(\frac{2\beta n^2 + na^2}{2c}\right) = F \tag{1}$$

where $-\ln(1-p)$ is a positive constant. If F is not preventively high, since $(1-p)^k$ is declining in k, (1) have an interior solution with $1 \leq k^* < n$.

5 Unilateral policies

Our point of departure is a Paris type of treaty in which each country chooses whether to innovate and sets its level of abatement independently. The game then proceeds in three stages: First, the country decides whether to invest F, second, in case another country is the sole innovator, the country decides whether to use the new technology and pay the license ℓ (alternatively set the license and earn income), and third, the country decides its level of abatement knowing whether it has access to the innovation or not. We solve the game by backward induction:

5.1 Setting abatement levels

Denote each country's utility exclusive innovation costs and license fee in case of success by $U^{NC}(a)$ and in case of no success $U^{NC}(0)$. Since the license fee is a fixed cost, it will not influence the abatement decision. Hence, in stage three country i solves:

$$\max_{q_i} \left\{ \beta \sum_{i=1}^{n} q_i - \frac{c}{2}(q_i)^2 + \alpha q_i \right\} \text{ where } \alpha \in \{0, a\} \tag{2}$$

The unilateral levels of abatement is hence given:

$$q^{NC}(\alpha) = \frac{\beta + \alpha}{c}, \alpha \in \{0, a\} \tag{3}$$

where we have dropped the subscript i since all countries are assumed identical. We see that abatement is increasing in α. The cost reduction, measured at an abatement level of $\frac{\beta}{c}$, when the new technology arrives is equal to $2a/\beta * 100$ percent.

5.2 Adopting the new technology

We may have that only one country succeeds, or that more countries succeed. In case of the latter, all countries will adopt since the new technology will be available for free. With a monopolistic supplier of the new technology, every country must decide whether to adopt the technology at a price ℓ. Suppose that $x \in [1, n-1]$ other countries have already adopted the innovation (the sole innovating country off course utilizes the innovation). Then a country will choose to be the $x+1$ country to adopt if:

$$(\beta(x+1)+a)\frac{\beta+a}{c}+\beta(n-1-x)\frac{\beta}{c}-\frac{c}{2}(\frac{\beta+a}{c})^2-\ell$$

$$\geq \beta x\frac{\beta+a}{c}+\beta(n-x)\frac{\beta}{c}-\frac{c}{2}(\frac{\beta}{c})^2.$$

where the top line show the net utility of the $x+1$ country to adopt the new technology, and the bottom line is the net utility to the same country of not being the $x+1$ country to adopt.

By rearranging, we obtain the following adoption condition: $\ell \leq (2\beta + a)a/2c$. Note that the condition is independent of x, e.g., the number of other countries that have adopted. Thus, the sole innovator can do no better than to set:

$$\ell^* = \frac{(2\beta+a)a}{2c}, \tag{4}$$

and have all countries adopting the innovation. The sole innovator then earns $\ell^*(n-1)$. To sum up, we have the following proposition:

Proposition 1 *If an innovation happens, all countries will adopt the new technology even if there is only one innovating country and this country has IP.*

We can thus define:

$$U^{NC}(a) = \frac{((2n-1)\beta+a)(\beta+a)}{2c},$$

$$U^{NC}(0) = \frac{(2n-1)\beta^2}{2c}$$

where $U^{NC}(0)$ is the welfare of each country given that no innovation has happened, and $U^{NC}(a)$ is the welfare of each country in case innovation has happened (absent eventual licensing costs or licensing income and innovation costs).

5.3 Investment in innovation

When a country decides to invest, there are four possible outcomes: (i) the country becomes the sole owner of the patent on the technology and earn license income, (ii) some other country becomes the sole owner of the patent, and the country will pay the license fee, (iii) more than one country succeeds and the rents are competed away such that all countries can adopt the new technology for free, and lastly, (iv) no country succeeds.

Consider then a situation in which $y \in [0, n-1]$ other countries has invested. In such a situation, an additional country that invests may earn the following expected welfare:

$$
\begin{aligned}
E[W_I^{NC}] = & P(y+1)U^{NC}(a) + (1 - P(y+1))U^{NC}(0) \\
& + p(1-p)^y \ell^*(n-1) - yp(1-p)^{y-1}\ell^* - F
\end{aligned} \tag{5}
$$

where $P(y+1) = 1 - (1-p)^{y+1}$ is the probability of at least one success when $y+1$ countries invest F. The first term is the expected net benefit of abatement in case of success. The second term is the expected net benefit in case of failure. The third term is the expected license income if the country is the only one succeeding, and the fourth term is the expected license cost if just one other country succeeds and obtains the patent. The fifth term is the investment cost.

In case the single country does not invest, it earns the following expected welfare:

$$
E[W_{NI}^{NC}] = P(y)U^{NC}(a) + (1 - P(y))U^{NC}(0) - yp(1-p)^{y-1}\ell^* \tag{6}
$$

Here, the first term is the expected net benefit of abatement in case some other country has success. The second term is the expected net benefit in case no country has success. The third term is the expected license cost if only one country succeeds and obtains the patent.

Country $y+1$ will only invest if $E[W_I^{NC}] \geq E[W_{NI}^{NC}]$. From (5) and (6) we then have the following investment criterion:

$$
p(1-p)^y \left[U^{NC}(a) - U^{NC}(0) + \ell^*(n-1)\right] \geq F,
$$

that is, the probability that the country entering the patent competition will be the sole inventor times the gain for the country of bringing about the innovation has to be larger than the investment cost. Note that as long as one or more other countries invest, the only reason for the $y+1$ country to invest is the possibillity of being a unique innovator. .

Inserting for $U^{NC}(a)$, $U^{NC}(0)$, and $\ell^*(n-1)$, we have:

$$
p(1-p)^y \left(\frac{4na\beta - 2a\beta + na^2}{2c} \right) = F \tag{7}
$$

Since $(1-p)^y$ is declining in y, (7) may have an interior solution y^* fixing the number of countries that will invest in the unilateral game. Comparing (7) to (1), we have the following proposition:

Proposition 2 *The number of countries that invest will be too low in the unilateral solution, e.g., $y^* < k^*$.*

Proof. We can show that $-\ln(1-p) > p$ for $p \in \langle 0, 1 \rangle$ noting that the inequality can be written $(1-p)e^p < 1$. Further, noting that $(1-p)e^p$ is declining in p and equal to 1 for $p = 0$. Finally, we have $\frac{2\beta n^2 + na^2}{2c} > \frac{4na\beta - 2a\beta + na^2}{2c}$ as long as $n \geq 2$. ■

In the next section the question is to what extent a green innovation club can induce more countries to invest, and therefore, bring a about a situation closer to the first best level of investing k^*.

6 Green innovation club case

The stage game with a club is different. In the first stage, the club sets a minimum particpation clause, that is, the club will only come into being if a minimum of m^* members enter the club. In order to increase the level of global investment in zero emission technologies, we must have $m^* \geq y^* + 1$. This implies that no single country will invest in innovation given that the club is formed.[9]

Also, in the first stage, the club agrees on an abatement schedule, $q^m(m)$. In case of success, the schedule instructs each member how much abatement each member should carry out. The level of abatement will generally depend on the number of members. Our point of departure is that members set $q^m(m)$ maximizing the welfare of each club member, which is the same as maximizing the joint welfare of the club. This may, however, imply an overly high level of abatement encouraging countries to leave the club even if the innovation is a success. The schedule $q^m(m)$ therefore needs to fulfill a partcipation constraint which we return to below.

In the second stage individual countries decides to become members of the club which amounts to investing F. Note that the number of members may exceed m^*.

In the third stage, having invested F, members accept $q^m(m)$ if the investment effort is a success. If the innovation does not materialize, the club dissolves, the game ends, and all countries set $q^{NC}(0)$.

In the fourth stage, in case of success, the club sets the highest possible license fee ℓ^* according to (4) such that all non-members adopt. This maximizes the clubs patent earnings and leads to more global abatement. Furthermore, non-members set their level of abatement to $q^{NC}(a)$ and pay the license.

6.1 The abatement schedule of the club

We start by defining the following expressions for welfare:

$$U^m(m) = m\beta q^m + (n-m)\beta q^{NC}_{|\alpha=a} - \frac{c}{2}(q^m)^2 + aq^m + \frac{(n-m)\ell^*}{m}, \quad (8)$$

$$U^{nm}(m) = m\beta q^m + (n-m)\beta q^{NC}_{|\alpha=a} - \frac{c}{2}(q^{NC}_{|\alpha=a})^2 + aq^{NC}_{|\alpha=a} - \ell^* \quad (9)$$

where $U^m(m)$ is the *ex post* welfare of club members, and where $U^{nm}(m)$ is the *ex post* welfare of non-members, both expressions given that the club has

[9] Formally, this amounts to $p(1-p)^{m^*}\left[U^{NC}(a) - U^{NC}(0) + \ell^*(n-1)\right] < F$.

success. Note that if a club is formed and is successful, a non-member will always choose to pay the license fee and abate according to $\alpha = a$.

The club then chooses $q^m(m)$ by solving:

$$\max_{q^m(m)} \{mU^m(m\} \tag{10}$$

given:

$$U^m(m) \geq U^{nm}(m-1) \tag{11}$$

The unconstrained solution to (10) is $(m\beta + a)/c$. Hence, $q^m(m)$ is increasing in m, which may imply that (11) is not fulfilled for all $q^m(m)$. The optimal $q^m(m)$ is then the solution to $U^m(m) = U^{nm}(m-1)$. In the Appendix A1 we show that this gives a uniquely defined abatement schedule $q^m(m) \forall m \in [2, n]$. Note that $q^m(m)$ must be defined for all $m \in [2, n]$ in order to make it possible for potential member countries to decide whether to become members in the second stage of the game. As already argued $q^m(m)$ is *ex post* optimal, and thus, credible.

6.2 Membership decision

When choosing to become a member, there are two possibilities: Either the number of potential members is $m^* - 1$ such that one additional member will be pivotal for the club coming into being, or the number of potential members is already equal or greater than m^*.

If the number of potential members is $m^* - 1$, the club will come into being if one additional member joins. The expected welfare of becoming a club member is then given by:

$$E[W^m] = P(m^*)U^m(m^*) + (1 - P(m^*))U^{NC}(0) - F$$

where $P(m^*) = 1 - (1-p)^{m^*}$. The first term is the probability of success multiplied with the welfare of club members in case of success and the second term is the probability of failure multiplied with the welfare of club members in case of failure.

If the number of members stays at $m^* - 1$, the club will not be formed, and the expected welfare of the pivotal member is:

$$E\left[W^{NC}\right] = P(y^*)U^{NC}(a) + (1 - P(y^*))U^{NC}(0) - y^* p(1-p)^{y^*-1}\ell^*,$$

that is, the welfare when y^* countries engage in innovation (but not the country in question).

Thus, we have that a country will decide to become a member in a club with $m^* - 1$ members if $E[W^m(m^*)] \geq E[W^{NC}]$. By inserting for expected welfare and rearranging, we obtain:

$$P(m^*)\left[U^m(m^*) - U^{NC}(0)\right] - P(y^*)\left[U^{NC}(a) - U^{NC}(0)\right] \geq F - y^* p(1-p)^{y^*-1}\ell^* \tag{12}$$

where the expression on the left hand side is the expected increase in welfare by becoming a member of the club. We have $P(m^*) > P(y^*)$ since $m^* > y^*$ and $U^m(m^*) \geq U^{NC}(a)$ since $q^m(m^*)$ maximizes the welfare of the club members.

On the right hand side is the net cost of memebership F substracted expected license payments if not becoming a member $y^* p(1-p)^{y^*-1}\ell^*$ (if only one other country has success).

Moreover, since y^* is given as a function of the parameters and $P(m^*)\left[U^m(m^*) - U^{NC}(0)\right]$ is increasing in m^*, the condition (12) may hold for some minimum level of $m \geq y^* + 1$. This will among others depend on the necessary investment F.

If the number of members already is equal to $m \geq m^*$, the expected welfare of becoming a club member is given by

$$E\left[W^m\right] = P(m+1)\left[U^m(m+1)\right] + (1 - P(m+1))U^{NC}(0) - F$$

while the expected welfare of staying out is given by:

$$E[W^{nm}(m)] = P(m)U^{nm}(m) + (1 - P(m))U^{NC}(0).$$

A country will decide to become a member in a club with $m \geq m^*$ members if $E[W^m(m+1)] \geq E[W^{nm}(m)]$. By inserting for expected welfare and rearranging, we obtain:

$$P(m)\left[U^m(m+1) - U^{nm}(m)\right] \tag{13}$$

$$+p(1-P(m))\left[U^m(m+1) - U^{NC}(0)\right] \geq F$$

The first term is the expected net benefit of entering the club given that the club will anyhow come into being and invest in innovation, while the second term above is the probability that the entering country will innovate times the benefit of entering the club given that the club will not have success without its last member. Assuming that $q^m(m)$ is bounded by the condition $U^m(m) \geq U^{nm}(m-1)$, see (11), we have that condition (13)

$$p(1-P(m))\left[U^m(m+1) - U^{NC}(0)\right] \geq F$$

Here, the probability that the last member will be the member to innovate $p(1-P(m))$ is decreasing in m. The utility of becoming a club member $U^m(m+1)$ is however increasing in m such that (13) hold for some minimum level of m.

7 Equilibriums in the club game

7.1 High investment cost

We now assume that investments costs are so high that no single country will invest, e.g., the following holds: $p\left[U^{NC}(a) - U^{NC}(0) + \ell^*(n-1\right] < F$.

Hence $y^* = 0$, while club members may still commit to invest F if $m \geq m^*$. In case the club does not form, no innovation will happen and countries will have $U^{NC}(0)$ for sure.

When $y^* = 0$, we have an obvious candidate for minimum participation clause. Rewriting (12) for $y^* = 0$, the minimum participation clause is implicitly defined by:

$$(1 - (1-p)^{m^*}) \left[U^m(m^*) - U^{NC}(0)\right] = F \tag{14}$$

If m is below m^* and as long as the right hand side of (14) is increasing in m, the club will not be formed if $m < m^*$.[10] Hence, the minimum participation clause is credible since it does not pay countries to form a club when the number of potential members is below the minimum participation clause.

On the one hand, more countries will enter as long as (13) holds. On the other hand, (13) does not hold, we have a clear candidate for an equilibrium. No country regrets becoming a member, since when $m = m^*$ each single country is pivotal and thus if one country exits, the club will not form and expected welfare will decline for this country (as well as for all other countries). Finally, no non-member country regrets free-riding, since when $m = m^*$, the club will be formed anyway and as long as (13) does not hold for $m = m^* + 1$, no country regrets not joining.

We have the following proposition:

Proposition 3 *When F is high such that $y^* = 0$, forming a club with a minimum participation clause $m = m^*$, as defined in (14), will bring the level of green innovation and the level of pollution abatement closer to the globally optimal levels.*

Proof. See numerical example below. ■

It is the threat of not having a club that makes the member countries finding it worthwhile to remain in the club. This is in the spirit of Buchanan (1965) who writes that clubs can be defined as organizations whose members collectively produce/consume a good that no single member find it beneficial to provide or finance alone. Lastly, no country will leave the club *ex post* since $q^m(m)$ is set such that it is never profitable for a country to leave the club.

7.2 Low investment cost

We now assume F is low, such that $y^* > 0$ (but still lower than k^*, e.g., the first best level of investments). In this case the minimum participation clause plays no role as (13) may hold for all $m \in [2, n]$. Thus, in the case of "low investment cost" we may get full participation in the club.

We have the following proposition:

[10] It is hard to show analytically that the term $(1 - (1-p)^m) \left[U^m(m) - U^{NC}(0)\right]$ is monotonically increasing in m for all values of the parameters. The term $(1 - (1-p)^m)$ is definitly increasing in m. The terms inside the brackets is also increasing in m for a wide range of parameter sizes.

Proposition 4 *When F is low such that $y^* > 0$, forming a club and setting an abatement scheduel $q^m(m)$ may lead to full particpation in the club $m = n$, and hence, since $y^* < k^*$ and $q^m(n) > q^{NC}_{|\alpha=a}$, the club will bring the level of green innovation and the level of pollution abatement closer to the globally optimal levels.*

Proof. See numerical example below ■

Note that the globally optimal welfare level cannot be reached even if $m = n$. The reason is that the club will only form and abate optimally if the club has success. If the club does not have success, we are back to the non-cooperative solution.

8 Numerical illustrations

In order to illustrate the case with high F we present a simple numerical example. We set the number of countries to $n = 10$ and the probability p for a single success equal to 0.1. If all countries invest, the probability of at least one success is then 72 percent. Let further $\beta = 6$, $a = 3$ and $c = 3$. Given the parameters the optimal club abatement schedule can be calculated. Note that the schedule is independent of the neccessary R&D investment F.

Figure 1 The optimal club abatement schedule

Figure 1 should be placed here

In the figure, we have the number of club members on the x-axis. On the y-axis, we measure the level of abatement, e.g., reduction in GHG emissions per country. The flat grey line is abament by the single country given that the innovation has happened (and the country has adapted the new technology). The black continuous line is the abatement level that maximizes the welfare of the individual club members, while the stipled black line in the optimal club abatement schedule $q^m(m)$. Remember that the optimal club abatement schedule ensures that it is never profitable to leave the club ex post.

The optimal club abatement schedule is uniquely given for any set of reasonable parameters n, β, a, and c. We note that for $n = 10$, it coincides with the unconstrained solution to (10), e.g., $(m\beta + a)/c$. Then it drops significantly for $m = 9$, which ensures that the tenth member of the club will not leave the club. If $q^m(9)$ were to be set higher, the tenth member would leave the club, and all club members would loose from the loss in global abatement effort.

Then in the next figure we show the equilibrium number of members for different F:

Figure 2 Equilibrium number of members in the club

Figure 2 should be placed here

In the figure, we have the the neccessary R&D investment F on the x-axis. On the y-axis, we measure the number of countries investing F. The downward sloping grey line is the number of single countries that will invest without a club. We see that if $F = 5$, only one country will invest, while if $F = 7,5$, no country will invest.

However, for $F \in [7.5, 17.5]$ it is still possible to get full membership in the club. This is illustrated by the grey stipled line, which coincides with the first best level of investing k^* over the same range. In order to get the club going, the club must set a minimum participation clause, which is illustrated by the black stipled line. Below this level it is not optimal for the single country to become a member in the club. In the range $F \in [7.5, 17.5]$, the minimum participation clause works as coordination device. The club needs to reach a certain number of members before it becomes optimal for members to invest.

If F exceeds 17.5, full participation is neither possible nor optimal. It is then hard to get more than 3 (4) members, and hence the level of investment falls short of the optimal investment. The equilibrium number of members will then be equal to the minimum participation. Still the club improves global welfare as without the club, we get no investment. Note that a higher F now implies more members. The rationale is that a higher F makes the cut off value of m for which the club becomes profitable higher. The minimum participation clause is set to the cut off value, and this is also exactly the number of memebers the club will get.

Finally, it is possible to produce essentially the same picture as in Figure 2 for any set of reasonable parameters n, β, a, and c.

9 Extensions

9.1 Benefits also when no success

It may seem unrealistic that if a total of mF is spent in a an innovation club, nothing may come out of it. One possibillity is that the knowledge created will benefit future researchers. This will happen in both the case with a club and the case with unilatteral investment, but in the case with a club, total investments will be larger. This again will make the dynamic spill-overs greater, and hence, it will affect the decision to become a member of the club. hence, including some benefit also when there is failure should not affect our main results.

Another possibillity is that the invest in case of no success still creates a cost reduction, e.g., something is learned, but that the cost reduction is non-patentable. Moreover, we would assume that the size of the cost reduction depends on the number of trials, but that it can never exceed a fraction of a. By the same reasoning as in the former paragraph, this should also not affect our results.

9.2 Cost reduction depends on the spending

Here there are two options: I) the cost reduction depends on the number of countries that invest in an identical way independent of having a club or not and II) the cost reduction depends on the level of investment per country. We have solved the model in the latter case, and we still get much of the same results, however, it is now much harder to do the calculations. Then all countries find it welfare improving to invest a little unilaterally and take part in the patent competition. The unilateral investment effort is not affected by establishing a club, such that nonmembers invest the same independent of the club. However, when all nonmembers invest the threat of leaving the club is less serious, and without the threat of no R&D investment it is more challenging to reach high participation when F is high.

10 Concluding discussion

In this paper we have studied a new approach to link issues of R&D and emission reduction in order to increase overall abatement levels. The R&D club requires members to cooperate in two dimensions: They abate cooperatively and coordinate their R&D to increase the probability of success. If the club successfully develops the breakthrough technology, it will achieve more abatement both within and outside the club, because the technology is distributed to nonmembers.

In our framework no country finds it beneficial to abate the full cooperative outcome, and only two countries would join a one-dimensional environmental agreement on abatement. In order to incentivize countries to cooperate we take advantage of the monopoly rights introduced by patents. When the club cooperates, they have a higher chance of receiving the patent and can charge monopoly rents from non members. Establishing a green innovation club is thus Pareto improving. The club increases the probability that a technology is actually developed or has better quality and hence, achieve more abatement globally.

On the one hand, one could argue that the EU is close to a green R&D club. The EU sets tougher GHG abatement targets than other comparable jurisdictions. Moreover, the EU is ambitious concerning technological development. On the other hand, one could ask whether the EU disregards radical technologies, and puts too much focus on improving existing clean technologies marginally, e.g., windmills, solar, housing insulation, etc. At the same time, investments in CCS technologies are falling behind, as well as investments in clean nuclear energy, hydrogen for transport and large-scale stationary battery packs for electricity storage.

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11 Appendix A1

First, we solve:

$$\max_{q^m} \left\{ m \left(m\beta q^m + (n-m)\beta q^{NC}_{|\alpha=a} - \frac{c}{2}(q^m)^2 + aq^m + \frac{(n-m)\ell^*}{m} \right) \right\} \quad (15)$$

This yields:

$$q^*(m) = \frac{m\beta + a}{c} \tag{16}$$

It may be that (16) does not satify the participation restriction. The participation restriction $U^m(m) \geq U^{nm}(m-1)$ can be written:

$$\beta\left[mq^m(m) - (m-1)q^m(m-1) - q^{NC}_{|\alpha=a}\right] + \frac{n\ell^*}{m} \tag{17}$$
$$\geq \frac{c}{2}\left[(q^m(m))^2 - (q^{NC}_{|\alpha=a})^2\right] - a(q^m(m) - q^{NC}_{|\alpha=a})$$

where the first term is the loss in global abatement benefits to the member (and all other countries) when the member leaves the club, the second term is the net increase licensing costs, and the third and the fourth term together is the saving in abatement cost when reducing abatement from $q^m(m)$ to $q^{NC}_{|\alpha=a}$. Denote the last term $\Delta c(q^m(m))$.

The condition (17) can be rewritten to a system of equations. Since $q(m)$ only will come into effect if the club has success, and the investment F is already spent, the participation clause should only ensure that members stay in the club *ex post*. We therefore get the following system of equations:

$$\beta\left[2q^m(2) - q^m(1) - q^{NC}_{|\alpha=a}\right] + \frac{n\ell^*}{2} = \Delta c(q^m(2))$$

$$\beta\left[3q^m(3) - (2)q^m(2) - q^{NC}_{|\alpha=a}\right] + \frac{n\ell^*}{3} = \Delta c(q^m(3))$$

...

$$\beta\left[(n)q^m(n) - (n-1)q^m(n-1) - q^{NC}_{|\alpha=a}\right] + \frac{n\ell^*}{n} = \Delta c(q^m(n))$$

The number of equations is $n-1$ while the number of $q^m(m)$ is n, that is, we also need to set $q^m(1)$. Clearly, we must have $q^m(m) = q^{NC}_{|\alpha=a}$. The system can then be solved to find $\bar{q}(m)$, which works as a constraint for $q^m(m)$. We then have the following simple rule for $q^m(m)$:

$$q^m(m) = \left\{ \begin{array}{l} \frac{m\beta+a}{c} \text{ if } \frac{m\beta+a}{c} \leq \bar{q}(m) \\ \bar{q}(m) \text{ if } \frac{m\beta+a}{c} > \bar{q}(m) \end{array} \right|$$