R&D and Climate Clubs

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Abstract

Provision of global public goods necessitates coordination and cooperation between countries. This is particularly difficult in view of the fact that public goods encourage free riding. Moreover, if the costs of contributing is high the incentive to free ride on others' contributions becomes even more severe. A necessary part of the solution to sustain global cooperation is cost-reducing innovation. But the most advanced and premature technologies often require heavy start-up costs. This model considers a scenario where the chance of ending up as the single developer that harvest all the revenue of a breakthrough technology is too small to tempt investments. When countries do not have the incentive to undertake unilateral development of risky innovation projects, they should conduct research jointly. We consider an international environmental agreements (IEA) that includes an R&D club where members share the sales revenues from licensing their cost-reducing technology to non-members. An R&D and climate club can sustain a higher number of members and thus more abatement than a standard IEA. If the costs (abatement costs or research costs) are sufficiently high, the club will achieve full membership and the social optimal level of abatement.

Key words: Climate change, Research & Development, Technology cooperation, International cooperation, Self-enforcing international environmental agreements

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1 Introduction

The main reason for considering a treaty that connects technology and abatement is to unravel the pessimistic results in global public good problems. The theoretic literature on international environmental agreements (IEA) has repeatedly stated that classical climate agreements, focusing mainly on emission reduction, cannot be expected to achieve much. This has been throughly studied in the standard literature on IEAs, referring to the early contributions by Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). The free rider incentive prevents full cooperation. Given that implementing a global price on carbon has proven very difficult both in theory and in practice, concerted global action on cost-reducing R&D may thus be worth aiming for in international negotiations.

In standard IEAs, such as Barrett (1994), the threat of leaving the coalition is inadequate. One less member only implies marginally less abatement. In our paper the potential threat of defection is much larger. When leaving the club as the pivotal member, the club breaks down and the technology will not be invented. Thus, the R&D and climate club can sustain a much higher level of cooperation.

Standard self-enforcing IEA models considers a two-stage game of coalition formation. In the first stage, referred to as the membership stage, countries decide whether to sign the agreement and join a climate coalition. In the second stage, the abatement stage, countries choose their contributions to the public good. Non-members set their abatement levels non-cooperatively. Whereas members of the coalition collude their payoffs and maximize aggregate welfare cooperatively. In this way the positive abatement exernality between members is counted for, and the treaty's aggregate abatement level proceeds towards the social optimal. Non-members, on the other hand, maximize their utility individually and non-cooperatively.

In this paper we consider a different type of treaty which builds on the standard self-enforcing IEA. The setup is placed close to the original framework by Barrett (1994). Our model add an intermediate stage, the investment stage, where countries choose whether to invest in R&D in order to develop an improved technology. In a classical IEA the investments in technology are unilateral if it is an option at all. In a club, on the other hand, the investment decision becomes cooperative in addition to collectively deciding abatement levels.

The R&D is directed towards an advanced cost-reducing abatement technology associated with so called breakthrough technologies (see Barrett (2006); Hoel and de Zeeuw (2010)). Examples in this category are carbon capture and storage (CCS) and fusion energy production. Innovation in premature technologies involves a severe risk of failure and the gain from investing in R&D is therefore highly uncertain. Countries are assumed to be risk neutral and welfare maximizing, and will only invest in R&D if it gives higher expected welfare. If a country succeed in developing a new technology it gains reduced abatement costs, which will give more abatement in equilibrium, and possible market revenue from distributing the technology to other less successful countries. If a country is the only one succeeding it becomes the main provider of the new innovation and will behave like a monopolist. The monopolist license the developed technology to the rest of the world. The license fee is set equal to unsuccessful countries' willingness to pay. If more than one country succeed there will be several providers and hence, the market for the innovation becomes competitive and the license price falls to zero. The chance of becoming the single provider decrease as more countries invest in R&D. Unilateral incentives to invest will therefore depend on other countries actions. In our framework we study the special case where no countries choose to invest in the non-cooperative equilibrium. In cases where environmental externalities have not been fully internalized in market prices, it is likely that the investment level in relevant technologies are significantly below the socially desirable level.

In an R&D and climate club the investment decision and the abatement level becomes cooperative. The countries that sign a membership agree to share the license revenue in case of a success in the group of members, and all members access the technology for free. It is then no longer a single country's success that is important, but rather a success in the group of members, independent of which specific country that completed the innovation process. This illustrates the returns to scale in joining an R&D club: when pooling their resources the probability of inventing a successful technology increases. The cost however, is sharing the revenues with all members.

This model shows that in a world where no one performs R&D unilaterally, a club could find it beneficial to develop the technology. Establishing a club will give more abatement in equilibrium by all countries, both members and non-members. If the cost of abatement or the R&D start-up costs are sufficiently high an R&D and climate club can achieve full membership and reach the social optimal level of abatement.

The paper is organized as followed: Section 2 sums up the literature that focus on connecting IEAs and technology development. Then, section 3 introduces the model framework. The classical IEA is outlined and solved in section 4 and compared to the R&D and climate club in section 5. Section 7 ends the paper with a discussion of the results and possible extensions.

2 Literature

The challenge for international cooperation on global climate issues is to decrease or avoid the mechanisms that cause free-rider incentives. Free riding is especially problematic at the international level, where global regulatory institutions are not available. Free riding on international cooperation leads so insufficient participation (too few countries join IEAs) and insufficient compliance (the treaty is not stable and members opt out over time).[1] We consider mainly the first type of free rider incentive, but will discuss the time consistency of the club memberships in section 6.

To figure out how to improve future IEAs the literature has suggested issue linkage . For a long time this has been proposed in both the economic (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. (See Maggi (2016) for a comprehensive literature review on

[1] This two-parted separation of the free rider incentives was introduced by Finus (2008) in order to categorize the two main approaches in the literature of IEAs: Reduces stage games study insufficient participation and infinitely repeated games investigates compliance.

linking issues in international cooperation).[2]

Common examples of linked issues are trade (access to inner markets) or research cooperation (access to an improved technology). An unstable IEA (public good) combined with a stable R&D agreement (club good) may increase the participation rate up to a certain threshold, (but not necessarily full participation which is the case in Carraro and Siniscalco (1997)). Issue linkage implies that countries signing a membership are required to hold simultaneous membership in both treaties. In the real world we do observe that countries cooperate in several policy dimensions at the same time when entering agreements and coalitions such as NATO, UN, WTO/GATT, EU and ASEAN. Another example is the Montreal Protocol which regulated the members' production of CFC gases in addition to prohibiting trade in CFCs with non-members. It has been suggested that this connection of policy issues was key to the protocol's success and the restoration of the Ozon layer.

Considering climate change and mitigation the link between abatement policy and abatement-cost technology has been seen as intrinsic (as in Hoffert et al. (2002)) since innovation is crucial for combating climate change. Both issues are somewhat connected already and many existing policies target both issues. The literature connecting IEAs to innovation is widespread and several approaches has been explored. 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. On the other hand, 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.

Buchholz and Konrad (1994) considered a possible "hold-up problem" that might arise if technology choice precedes agreements on abatement. Then countries have an incentive to commit to low-quality technologies before they enter the negotiation of the agreement. In this way research effort might decrease prior to negotiations. 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. If agreements can be renegotiated it enables countries to design an agreement that achieve social optimal level of R&D investments and emissions.

As we construct a very uncomplicated framework without differentiating between sectors, other scholars have studied a similar approach in a more specific manner. As an example, Strand (2007) considers technology treaties aimed alternative energy sources, replacing fossil fuels. This framework investigate how such treaties affect the incentives of fossil fuel producers, and how it might motivate them to extract more and at a faster rate, which again raise aggregate emissions. We do not specify sectors and are therefor not modeling their response to the club.

de Coninck et al. (2008) discuss international technology-oriented agreements (TOAs) as part of constructing international climate-change policy. They outline four categories for organizing R&D pooling: (i) Knowledge sharing and coordination, which include meetings, planning, infor-

[2] Maggi (2016) distinguishes between three types of linkage, and the categories relate to three different analytical methods: Enforcement linkage typically focus on repeated games; negotiation linkage typically focus on bargaining games; and participation linkage typically focus on simple coalition-formation games (in contrast to the division by Finus and Caparrós (2015) which discusses issue linkage concerning Membership models and Compliance models, but not Negotiation models). Our R&D and climate club belongs to the third category considering coalition-formation games.

mational exchange and coordinating the research agenda. (ii) R&D agreements, which include jointly research, funding commitments and mutual agreements to expand domestic research investments. (iii) Technology transfers (financing research projects across borders) and (iv) Technology deployment mandates such as renewable portfolio standards. In our model the R&D and climate club belongs to the second category of TOAs where research effort is pooled in order to achieve a shared success.

One might ask whether it actually is underinvestments in abatement technologies compared to other types of R&D. Although it is hard to find data on global aggregate R&D spending on dirty and clean technologies, several sources indicate that the former greatly outperforms the latter. Aghion et al. (2016) find that the number of new patents is higher within dirty transportation technologies. Jaffe et al. (2003) argue that there are several economic rationales for why R&D in climate relevant technologies are especially vulnerable for underinvestment. When the abatement exernality is not taken into account, countries do not see the need for an improved technology that reduces costs when abating more. The market for R&D in abatement technologies relies heavily on the stability of domestic and international policy, and in case of an insufficient IEA R&D-investments will be too low.

Another possible reason for under-investment is knowledge spillovers, non-excludability and public benefits. Then the developer is unable to capture the full revenue of its investments, which reduces the incentives to perform R&D. However, this will depend on the type of technology considered, and to what degree one is able to fully exclude free riders. We will assume that international intellectual property rights are fully enforced, and that countries manage to protect their research from leaking to other countries. Our purpose is not to investigate the spillover externality[3], but the returns to scale that emerge when countries manage to share the gains from their joint research. This is the reason for why we name our type of linkage a club and not a technology treaty.

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. In this framework club members coordinated their actions in order to maximize the welfare of the group. In this way one member's cooperative action becomes Pareto optimal for all members.

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. The good must therefore be characterized with some degree of excludability, and clubs will accordingly never provide pure public goods such as R&D with a high degree of spill. A club good is a subtype of public goods which inhibit excludability, but are to some degree non-rival in consumption. It can be discussed whether innovations and technology actually can be excludable at all, as this would depend on the enforcement of intellectual property rights and patents.

[3] This has been studied by El-Sayed and Rubio (2014), which builds on the framework of Kamien et al. (1992), where countries cooperate on R&D investments to fully internalize spillover effects but act non-cooperatively in their abatement decision. This agreement promotes cooperation, but the effects on participation is modest. Kamien et al. (1992) analyze different ways of coordinating research in order to internalize knowledge spillovers, where R&D spillovers are internalized when firms pool their research effort.

3 Model outline:

Consider a world of $N > 2$ countries. We assume countries are symmetric, denoted by $i \in I$, where $I = \{1, ..., N\}$. Each country emits a pollutant that disturb a shared environmental good, such as the atmosphere. A contribution to the public good is interpreted as one unit abatement (pollution reduction), where q_i is the national abatement level. We choose to rule out strategic abatement decisions across countries by assuming linear benefits of abatement:

$$B(Q) = \beta Q + \sigma q_i \tag{1}$$

where $\beta > 0$ is a positive constant equal for all countries, $\sigma \geq 0$ is local co-benefits of national abatement and $Q = \sum_{i=1}^{N} q_i$ is the global aggregate abatement level.

The abatement cost is increasing and convex and its curvature depends on country i's investment decision $F \in \{0, F\}$.[4] If the country invest $F > 0$ it will successfully develop a breakthrough technology with probability p, and with probability $(1-p)$ it fails:

$$C_i(q_i) = c\frac{q_i^2}{2} \qquad \text{if} \quad F = 0 \tag{2}$$

$$\mathbb{E}[C_i(q_i)] = \big[p(1-\alpha)c + (1-p)c\big]\frac{q_i^2}{2} - F \qquad \text{if} \quad F > 0 \tag{3}$$

In case of success abatement costs are reduced by a share $(1-\alpha) \in (0, 1)$. A higher α, representing the breakthrough technology, implies a better technology. The success probability p is stochastically independent across all countries (which implies that we rule out knowledge spillover between countries, i.e, each country's R&D does not influence the research probability in another country). Country i's expected net benefits is given by:

$$U_i = \beta \sum_{i=1}^{N} q_i + \sigma q_i - c\frac{q_i^2}{2} \qquad \text{if} \quad F = 0 \tag{4}$$

$$\mathbb{E}[U_i] = \beta \sum_{i=1}^{N} q_i + \sigma q_i - \big[p(1-\alpha)c + (1-p)c\big]\frac{q_i^2}{2} - F \qquad \text{if} \quad F > 0 \tag{5}$$

A single country will unilaterally set its marginal cost of abatement equal to its marginal benefits of abatement, taking as given everyone else's abatement level, which is the usual Cournot conjecture. The country will abate more if the cost-reducing technology is developed and adopted, hence $\alpha > 0$:

$$q_i^{NC} = \frac{\beta + \sigma}{(1-\alpha)c} \quad \text{for} \quad \alpha \in [0, 1), \quad \forall \quad i \in I \tag{6}$$

From a social optimal perspective the global net benefits from abatement is given by aggregating each country's welfare $U^{FC} = \sum_{i=1}^{N} U_i$, whereas the full cooperative abatement levels for an

[4]It is easy to accommodate that some basic research is conducted with $F = 0$ and that the investment level determines the probability of research success, hence the probability of success without considerable research effort is close to negligible $p^B \approx 0$.

individual country are given by equalizing the marginal benefits of abatement to the global marginal benefits of abatement:

$$q_i^{FC} = \frac{N\beta + \sigma}{(1-\alpha)c} \quad \text{for} \quad \alpha \in [0,1), \quad \forall \quad i \in I \tag{7}$$

Intuitively, the social optimal abatement level is higher than the non-cooperative, $q_i^{NC} < q_i^{FC}$. Every country is better off with the full cooperative abatement level, but no one has an incentive to choose q_i^{FC} unilaterally.

Since all countries are equal there are only two possible outcomes. We can therefore apply the notation $\{q_0^{NC},\, q_0^{FC}\}$ for the individual business as usual abatement level ($F = 0$) or failed research ($\alpha = 0$), and $\{q_\alpha^{NC},\, q_\alpha^{FC}\}$ denotes the individual abatement level when the technology is successfully developed or adopted ($\alpha > 0$).

If only one country succeed in developing the new technology it seize its monopoly power by licensing the technology to un-successful countries at the price ℓ. (If more than two countries succeed the price of the technology falls to zero due to Bertrand competition). The license fee is derived as the welfare improvement when adopting the technology, such that all unsuccessful countries will find it beneficial to license the technology from the developer and pay the fee:

$$U_i{}^{NT} \leq U_i{}^{T} - \ell$$

Where $U_i{}^{NT}$ is the welfare of a country without technology, $\alpha = 0$, and $U_i{}^{T}$ is the welfare of a country that adopt the technology $\alpha > 0$. Suppose that in the total of N countries, $h \in [0, N]$ countries adopt the technology and $N - h$ do not. A single country is willing to buy and adopt the technology at a price ℓ if:

$$\begin{aligned} &\beta h q_\alpha^{NC} + \beta(N-h-1)q_0^{NC} + [\beta+\sigma]q_0^{NC} - c\frac{(q_0^{NC})^2}{2} \\ &\leq \beta h q_\alpha^{NC} + \beta(N-h-1)q_0^{NC} + [\beta+\sigma]q_\alpha^{NC} - c(1-\alpha)\frac{(q_\alpha^{NC})^2}{2} - \ell \end{aligned}$$

where $q_0^{NC} = \frac{\beta+\sigma}{c}$ and $q_\alpha^{NC} = \frac{\beta+\sigma}{(1-\alpha)c}$. The license fee is then the following:

$$\ell \equiv \frac{(\beta+\sigma)^2}{2c}\frac{\alpha}{(1-\alpha)} \tag{8}$$

If there is a monopolistic provider of the technology each un-successful country must pay the license ℓ and the single technology provider receives the revenue $(N-1)\ell$ from licensing the technology to everyone else.

Lemma 1. *The license fee is derived such that all non-members adopt the new technology*

- The license fee is increasing in the quality of the technology: $\frac{d\ell_n}{d\alpha} > 0$, since a better and more effective technology is more valuable for non-investing or un-successful countries.
- The license fee is decreasing in the marginal cost: $\frac{d\ell_n}{dc} < 0$. If the cost paramter is high,

the technology α becomes realtively less effective, and contries are less willing to pay for the cost-reducing innovation.

- The license fee is increasing in the co-benefit $\frac{d\ell_n}{d\sigma} > 0$ and the public benefit $\frac{d\ell_n}{d\beta} > 0$ from abatement since this increases the incentive to abate more.
- The license fee is independent of how many countries that adopt the technology: N and h

3.1 Non-cooperative investment decision

Since the non-cooperative abatement level is lower (6) than the full cooperative (7), individual countries experience less need to reduce abatement costs and hence weak incentives to invest in R&D. A country's non-cooperative investment decision depends on expected welfare and includes the possible monopoly revenue from becoming the only supplier and the expected cost of adopting the technology. A non-cooperative country i does not have the incentive to invest as long as the expected welfare improvement when investing, $\mathbb{E}[U_I^{NC}] - F$, is smaller than the expected welfare when not investing $\mathbb{E}[U_{NI}^{NC}]$:

$$\mathbb{E}[U_{NI}^{NC}] > \mathbb{E}[U_I^{NC}] - F \quad \forall \quad x \in [0, N-1] \tag{9}$$

The probability mass function of a binomial random variable S is $P(S = s) = \binom{n}{s} p^s (1-p)^{n-s}$, where s is the number of successes from n trials. Then the probability that "at least two" succeed is given by $\big[1 - P(S=1) - P(S=0)\big]$ where $P(S=0) = (1-p)^n$ and $P(S=1) = np(1-p)^n$. We use this in order to derive the expected utilities where x or $x+1$ countries invest:

$$\mathbb{E}[U_{NI}^{NC}] = \underbrace{(1-p)^x U_0}_{\text{Everyone else fails}} + \underbrace{xp(1-p)^{x-1}\Big(U_\alpha - \ell\Big)}_{\text{only one other succeed}} + \underbrace{\Big[1 - (1-p)^x - xp(1-p)^{x-1}\Big]U_\alpha}_{\text{at least two others succeed}}$$

$$\begin{aligned}\mathbb{E}[U_I^{NC}] = &\underbrace{(1-p)^{x+1}U_0}_{\text{Everyone fails}} + \underbrace{p(1-p)^x\Big(U_\alpha + (N-1)\ell\Big)}_{\text{only I succeed}} \\ &+ \underbrace{xp(1-p)^x\Big(U_\alpha - \ell\Big)}_{\text{only one other succeed}} + \underbrace{\Big[1 - (1-p)^{x+1} - (x+1)p(1-p)^x\Big]U_\alpha}_{\text{at least two succeed}}\end{aligned}$$

where $x \in [0, N-1]$. Using these expressions we can rewrite condition (9) into:

$$0 > p(1-p)^x \Big[U_\alpha - U_0 + \big[(N-1) + \frac{p}{1-p}x\big]\ell\Big] - F \tag{10}$$

where U_0 and U_α are country i's utility level when everyone choose the same non-cooperative abatement level, q_0^{NC} or q_α^{NC}. We will restrict our analysis to only consider those type of technologies that are not unilateral optimal to invest in with the following assumption:

$$\text{A1}_{x=0}^{NC}: \quad 0 > p\Big[U_\alpha - U_0 + (N-1)\ell\Big] - F \tag{11}$$

which is a necessary and sufficient condition for the non-cooperative Nash equilibrium to be the scenario where no country prefer to invest, given the choices made by the other countries.

Lemma 2. *There is no unilateral investment in equilibrium as long as assumption (11) holds.*

4 Baseline: The classic IEA

In the setup of a standard IEA the members collaborate on abatement only, such that R&D decisions are non-cooperative. Members maximize the joint welfare of abatement, and abate more as countries join the coalition and their benefits of abatement is included. The game sequence of an classical IEA without an R&D club is given by:

1. Membership stage: Each country decide whether to join an IEA
2. Investment stage (unilateral):
   - (2a) Each and every country i invest in R&D individually if its profitable
   - (2b) Each country set the license fee (only relevant if a technology is developed)
3. Abatement stage: All countries take the technology $\alpha \in [0, 1)$ as given
   - (3a) Members set their abatement level cooperatively
   - (3b) Non-members decide their abatement level independently

3. Abatement stage

We solve the game by backward induction, starting with the third stage. Non-members and members will decide their abatement levels simultaneously and independently. In stage (3b) non-members decide their unilateral abatement level by maximizing the twofold net welfare, depending on whether the breakthrough technology $\alpha \in (0, 1)$ is available and distributed:

$$\max_{q_i} \quad U_n = \begin{cases} \beta Q + \sigma q_i - (1-\alpha)c\frac{q_i^2}{2} & \text{if} \quad \alpha > 0 \\ \beta Q + \sigma q_i - c\frac{q_i^2}{2} & \text{if} \quad \alpha = 0 \end{cases}$$

Each non-member's abatement level is given by (6). It is clear that a non-member that adopts the breakthrough technology will abate more non-cooperatively than countries without the technology.

In stage (3a) IEA-Members set their abatement level cooperatively with respect to the coalitions' members. The coalitions' net welfare is also twofold, depending on whether someone has developed the technology. Suppose $s \in [0, N]$ countries sign the IEA and become members:

$$\max_{q_i} \quad U_{IEA} = \begin{cases} \beta(sq_i + (N-s)q_\alpha^{NC}) + \sigma q_i - (1-\alpha)c\frac{q_i^2}{2} & \text{if} \quad \alpha > 0 \\ \beta(sq_i + (N-s)q_0^{NC}) + \sigma q_i - c\frac{q_i^2}{2} & \text{if} \quad \alpha = 0 \end{cases}$$

Each club-member's abatement level is given by:

$$q_\alpha^{IEA} = \frac{(s\beta + \sigma)}{(1-\alpha)c} \quad \text{for} \quad \alpha \in [0,1) \quad \text{and} \quad \forall \quad s \in [0,N] \tag{12}$$

Lemma 3. *Members increase their abatement level with respect to the number of members. If all countries join, i.e. $s = N$ then the abatement level in the club coincides with the full cooperative abatement level in (7) and if no countries join, i.e., $s = 0$ it coincides with the non-cooperative level in (6).*

2. Investment stage

When the R&D decision is individual and assumption (11) holds, the sequence of stage 1 and 2 does not matter since stage 2 is not linked to the IEA. Given a technology α the members set the license fee according to (8). However, stage (2b) will only be relevant if a technology has been successfully developed in stage (2a), but since the expected welfare improvement is negative no one will perform research in equilibrium, and the license fee will never be applied.

1. Membership stage:

At this stage each country decides whether to join the IEA. Suppose there exist an IEA with $s \in [0,N]$ members. A single country will decide to join the IEA, and increase the number of members to $s+1$, if this raises its utility $U_0^{FR} < U_0^{IEA}$ with respect to some s. Inserting for (6) and (12) with $\alpha = 0$, we see that this condition never holds for any $s \in [0,N]$.

Lemma 4. *With no unilateral investments in R&D no country has the incentive to join a standard IEA in equilibrium.*

Proof. Insert for (6) and (12) into the following condition to see that it is a contradiction

$$U_0^{FR} < U_0^{IEA} \quad \forall \quad s \in [0,N]$$

$$\beta(N-s)q_0^{NC} + \beta s q_0^{IEA} + \sigma q_0^{NC} - c\frac{(q_0^{NC})^2}{2} < \beta(N-s-1)q_0^{NC} + \beta(s+1)q_0^{IEA} + \sigma q_0^{IEA} - c\frac{(q_0^{IEA})^2}{2}$$

$$0 < (\beta+\sigma)[q_0^{IEA} - q_0^{NC}] - c\frac{(q_0^{IEA})^2 - (q_0^{NC})^2}{2}$$

$$0 < (\beta+\sigma)[\frac{(s\beta+\sigma)}{c} - \frac{\beta+\sigma}{c}] - \frac{(s\beta+\sigma)^2 - (\beta+\sigma)^2}{2c}$$

$$0 < -(s-1)^2$$

which does not hold for any $s \in [0,N]$. Therefore, it must be the case that $U_0^{FR} > U_0^{IEA}$ for all $s \in [0,N]$ and no country has the incentive to join a standard IEA in equilibrium. □

This implies that not-participating the IEA, i.e., free riding, is a dominant strategy and the Nash equilibrium of this game is unique. (This is indicated by the U_0^{FR} lying everywhere above the U_0^{IEA} curve in Figure 1). In equilibrium no one joins the IEA. This is a Prisoner's Dilemma since each country can do no better than not participating, but its social optimal that everyone participate. The Nash equilibrium is denoted by the dotted circle. On the horizontal axis of this figure is the number of *other countries* that join the IEA, such that this illustrates the incentive to a single country.

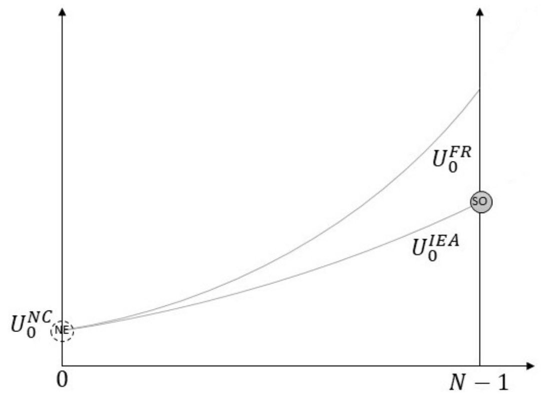

Figure 1: The IEA game, with no technology

This standard IEA does not achieve any members, $s = 0$ in equilibrium, and thus no increase in the aggregate abatement level in equilibrium compared to the business as usual:

$$Q_0^{NC} = Nq_0^{NC} = N\frac{\beta + \sigma}{c} \tag{13}$$

5 R&D & Climate Club

In an R&D and climate club the members act as one unity in the market for technology. Their interest is to achieve a single success in the group of member countries, and in the case of success they share the revenue from the lisence fee, given by $\frac{N-m}{m}\ell$, where $m \geq 2$ is the number of possible members in the club. Since the license fee is independent of coalition members, the licensing revenue is decreasing in the number of members.

Members access the technology at a zero price, $\ell_m = 0$, while the club charge a positive license fee on non-member, $\ell_n = \ell$. The agreement enters into force if at least $\tilde{m}$ countries join the R&D and climate club. Each member must invest the fixed cost F when the number of members meet the ratification threshold.

Even though the cost of investing is the same as in the non-cooperative case, the probability of success increases in the number of members. For the club to become the technology provider it only needs a single success in the group of member countries. The probability that at least one member is successful is given by $P(S \geq 1) = 1 - P(S = 0)$ which can be written as:[5]

$$P(m) = 1 - (1 - p)^m \tag{14}$$

The probability is increasing and diminishing in the number of members $m \in [2, N]$, such that $P'(m) > 0$ and $P''(m) < 0$.

[5]In the working paper by Gersbach and Riekhof (2017) they claim that the approximation $P(m) \approx \frac{pm}{1+p(m-1)}$ is satisfactory, if one need a simplifying expression for solving other features of the model.

The game sequence of the R&D and climate club is as follows:

1. Membership stage: Each country decides whether to join the R&D and climate club
2. Investment stage:
   - ($2a_1$) Non-members do not invest according to A1
   - ($2a_2$) Club members invest F
   - (2b) Members set the license fee ℓ_n such that all non-members buy the technology
3. Abatement stage:
   - (3a) Members decide their abatement level, q_m cooperatively
   - (3b) Non-members $n = N - m$ behave non-cooperatively and set q^{NC}:

3. Abatement stage.

We solve by backward induction and stage (3b) is identical to the standard IEA where non-members set the abatement levels (6) for $\alpha \in [0, 1)$. At stage (3b) members set their abatement levels maximizing their joint welfare given that a technology has been developed:

$$\max_{q_i} \quad U_m = \beta(mq_m + (N-m)q_\alpha^{NC}) + \sigma q_m - (1-\alpha)c\frac{(q_m)^2}{2}$$

Each club-member's abatement level is given by:

$$q_m = \frac{(m\beta + \sigma)}{(1-\alpha)c}$$

2. Investment stage

First, in stage (2b) given a technology α the members set the license fee $\ell_n = \ell$, given by (8), on non-members and $\ell_m = 0$ on members. (This stage is not relevant for non-members as they do not invest). Similar to the standard IEA game, in stage ($2a_1$) non-members invest non-cooperatively and according to assumption (11) no one finds it optimal to invest in R&D unilaterally.

In the last sub-stage, ($2a_2$), members invest according to the R&D and climate club agreement. Drawing on the assumption in (11), we can write a condition for when the club finds it beneficial to invest in the technology when the alternative, or the treat, is no club and no technology. Given a number of members, $\tilde{m}$, a single member-country is willing to invest in R&D if:

$$U_0 \leq \mathbb{E}[U_{\tilde{m}}] - F \tag{C_m}$$

where $\mathbb{E}[U_{\tilde{m}}] = P(\tilde{m})U_{\tilde{m}} + (1 - P(\tilde{m}))U_0$. The left hand side is the Nash equilibrium from the business as usual scenario (or the standard IEA). In other words, this condition follows from the assumption of no unilateral investments in the non-cooperative Nash equilibrium.[6] Condition (C_m) states the number of members that are necessary to sustain an R&D and climate club.

$$0 \leq P(\tilde{m})\Big[(N-\tilde{m})\beta q_\alpha^{NC} + (\tilde{m}\beta + \sigma)q_{\tilde{m}} - c(1-\alpha)\frac{1}{2}(q_{\tilde{m}})^2 + \frac{N-\tilde{m}}{\tilde{m}}\ell_n - U_0\Big] - F$$

Then $\tilde{m}$ is the minimum level of participation. This level will be the club's ratification threshold at which the agreement enters into force.

1. Membership stage:

At this stage countries decide whether to join the agreement. The member-threshold (C_m) for when the club finds it beneficial to invest gives us this games' Nash equilibrium, which we can compare to the standard IEA game in section 4.

Figure 2 illustrates the new incentive structure of the R&D and climate club game. On the horizontal axis we measure the number of *other countries* that has joined the R&D club. We see that if $\tilde{m}-1$ countries has joined the club country i would choose to join as well since this always gives higher welfare. It is important to notice that as $\tilde{m}$ is the minimum level of participation, it also becomes the max - since no countries has the incentive to join a club with $\tilde{m}+1$ members. We see from the figure that the free rider incentive always dominates the club's welfare above $\tilde{m}$.

The solid grey circle in Figure 2 denotes the Social Optimal equilibrium, which maximize aggregate welfare, and the dotted circle denotes the new Nash equilibrium: When the two payoff

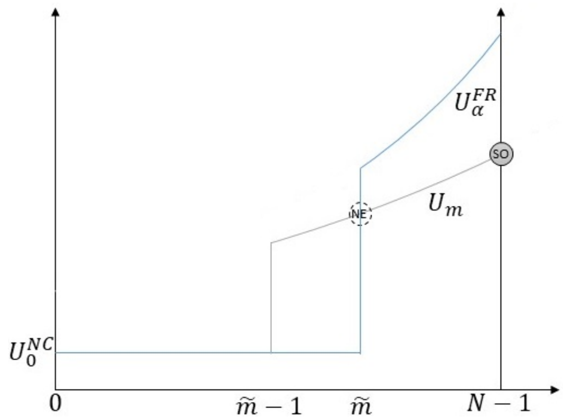

Figure 2: The R&D club

functions cross, as in Figure 2, there is multiple of pure strategy equilibria for each combination of countries that choose to join/free ride. We cannot say which *other* $\tilde{m}-1$ countries that joined the club. All these equilibriums are inefficient if not $\tilde{m} = N$, but they are improved relative to

[6]While the assumption in (11) sets a minimum bound on F, given all exogenous variables, there also exists a maximum bound for F determined by the condition (C_m). The range for which values of F that are relevant for this framework is:

$$p[U_\alpha - U_0 + (N-1)\ell] < F \leq [1-(1-p)^N]\Big[U_\alpha^{FC} - U_0\Big]$$

the standard IEA game since $\tilde{m} > 1$.

Proposition 1. *An R&D and climate club increases the number of members to $\tilde{m} > 1$ compared to the standard IEA where $s = 0$.*

Proof. When $\tilde{m} = 1$ the condition C_m collapses to:

$$0 \leq p\Big[U_\alpha - U_0 + (N-1)\ell\Big] - F$$

which contradicts the assumption in (11). Hence, condition (C_m) only holds for $\tilde{m} > 1$. □

When $\tilde{m}$ countries join the R&D and climate club the aggregate abatement level in equilibrium is given by:

$$Q^{\text{R\&D}} = (N - \tilde{m})q_\alpha^{NC} + \tilde{m}q_{\tilde{m}} = \Big[\tilde{m}(\tilde{m}-1)\beta + N(\beta+\sigma)\Big]\frac{1}{(1-\alpha)c} \tag{15}$$

which is higher than the baseline non-cooperative abatement level (13) in the case of no innovation, $Q_0^{NC} = N\frac{\beta+\sigma}{c}$:

$$Q_0^{NC} < Q^{R\&D} \quad \text{since} \quad 0 < N(\beta+\sigma)\alpha + \tilde{m}(\tilde{m}-1)\beta$$

However, $Q^{R\&D}$ is lower than the full cooperative abatement level with technology if $\tilde{m} < N$, where $Q_\alpha^{FC} = N\frac{N\beta+\sigma}{(1-\alpha)c}$, but they coincides when $\tilde{m} = N$:

$$\lim_{\tilde{m}\to N} Q^{\text{R\&D}} = Q_\alpha^{FC}$$

Stability

The concept of internal and external stability is based on D'Aspremont et al. (1983) and first applied to IEAs by Barrett (1994). This has become the regular stability criteria for all frameworks with reduced stage games. Let I^m denote the set of members and I^{FR} denote the set of non-members, such that $I^m \cup I^{FR} = I$, then the definition of stability is given by:

Definition 1. A coalition is Internally Itale (IS) if there is no incentive for a member to leave the coalition, and a coalition is Externally Stable ES if there is no incentive for a non-member to join the coalition:

$$\begin{aligned} IS: &\quad \pi_i^m(m, q_m) - \pi_i^{FR}(m-1, q_{m-1}) \geq 0 &\quad \forall \quad i \in I^m \\ ES: &\quad \pi_j^m(m+1, q_{m+1}) - \pi_j^{FR}(m, q_m) \leq 0 &\quad \forall \quad j \in I^{FR} \end{aligned}$$

Applied to our framework, joining the club implies a fixed investment cost F, and free riding means not investing according to assumption (11). A single country will never leave the club in the case its the pivotal member, hence one less member would then break the whole club before the technology is developed:

$$IS: \quad U_{\tilde{m}}(\tilde{m}, q_{\tilde{m}}) - F - U_0(\tilde{m}-1, q_{\tilde{m}-1}) \geq 0 \tag{16}$$

But a country will never join if the threshold is met without its participation, since free riding implies avoiding the fixed investment cost and abating the low non-cooperative level:

$$ES: \quad U_{\tilde{m}}(\tilde{m}+1, q_{\tilde{m}+1}) - F - U_{\alpha}^{FR}(\tilde{m}, q_{\tilde{m}}) \leq 0 \tag{17}$$

Conditions () and () defines the Nash equilibrium of the R&D and climate club game, though it can also be interpreted as a stability criteria, which is outlined in appendix D.

Lemma 5. *The member threshold $\tilde{m} \in [2, N]$ is a stable Nash Equilibrium.*

6 Time consistency

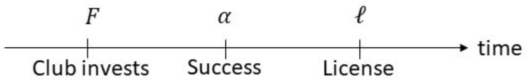

Figure 3: The timeline of a dynamic version of the game

We could consider a dynamic version of the model, to see whether the club is stable over time. Suppose that after the technology has been successfully developed members do not need to invest $F > 0$. Countries will re-optimize to find out wether its beneficial to opt out of the club and instead free ride. As a non-member they can abate less, but the technology would no longer be free. Members must abate more, but share the revenue from licensing the technology. A country would prefer to stay member as long as:

$$U_{FR} \leq U_{\tilde{m}} \tag{C_{Time}}$$

This condition would depend on how many countries that are free riders, hence, how many countries that are members:

$$\beta(N-(m-1))q_{\alpha}^{NC} + \beta(m-1)q_{m-1} + \sigma q_{\alpha}^{NC} - c(1-\alpha)\frac{(q_{\alpha}^{NC})^2}{2} - \ell$$
$$\leq \beta(mq_m + (N-m)q_{\alpha}^{NC}) + \sigma q_m - (1-\alpha)c\frac{(q_m)^2}{2} + \frac{N-m}{m}\ell$$

some terms cancels out and we can rewrite the condition into:

$$m^T(m^T-1)(m^T-3) \leq N\frac{(\beta+\sigma)^2}{\beta^2}\alpha \tag{C_{Time}}$$

This condition always holds for $m^T < 4$ and never holds for $m^T > 4$ which implies that once the club has been established it will always exist, although at a low level of members.

Result 1. *The club will over time collapse to fewer members, $m^T < 4$*

7 Discussion

This model has investigated a new approach to issue linkage in global cooperation in order to increase abatement levels. In particular, we have considered the case where no country invests unilaterally as the Nash Equilibrium of the business as usual scenario and with a standard IEA. This club, which demands countries to join their R&D effort and share the revenue from a successful innovation, will achieve more abatement and ensure that the breakthrough technology is developed. If the fixed investment is sufficiently high all countries will join the club, achieving the goal of a large stable coalition that abate cooperatively. Further extensions of the model will introduce an endogenous link between the investment effort and the quality of the investment.

Appendix A

The non-cooperative investment level

The condition below states whether a single country should invest, depending on how many other countries $x \in [0, N-1]$ that are investing:

$$\mathbb{E}[U_{NI}] > \mathbb{E}[U_I] - F$$

Taking the derivatives: Both expected utilities are increasing in number of countries investing, since the probability of a successful invention increases.

$$\frac{d\,\mathbb{E}[U_I]}{dx} = -(1-p)^{x+1}\big[U_\alpha - U_0 + \big[x-(N-1)\big]\frac{p}{1-p}\ell\big]\ln(1-p) - p(1-p)^x\ell > 0$$
$$\frac{d\,\mathbb{E}[U_{NI}]}{dx} = -(1-p)^x\big[U_\alpha - U_0 - x\frac{p}{1-p}\ell\big]\ln(1-p) - p(1-p)^{x-1}\ell > 0$$

The expected utility when investing increases more gradual, since the chance of ending up with the monopolist's revenue decreases in the number of other countries investing:

$$\frac{d\,\mathbb{E}[U_I]}{dx} < \frac{d\,\mathbb{E}[U_{NI}]}{dx} \quad \text{since} \quad \frac{p}{1-p}\ell < -\Big[U_\alpha - U_0 + \big[[N-1] + x\frac{p}{1-p}\big]\ell\Big]\ln(1-p)$$

Figure 4 displays the sufficient condition (9):

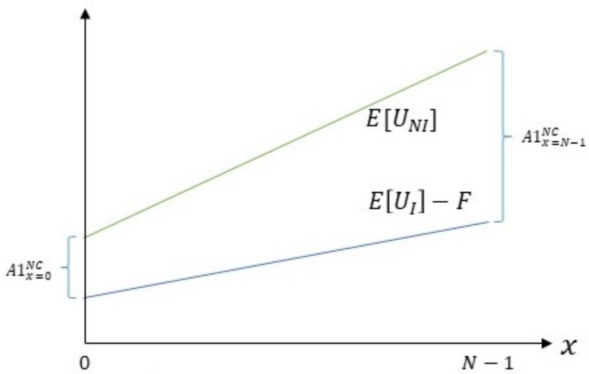

Figure 4: Non-cooperative investment levels

Appendix B

Corner solutions of condition $\mathbf{C}_m$

$$\begin{aligned}
\text{If} \quad \tilde{m} = 1 \quad &\rightleftarrows \quad 0 \le p\Big[2(N-1)\beta + N(\beta+\sigma)\Big]\frac{(\beta+\sigma)}{2c}\frac{\alpha}{1-\alpha} - F \\
&\rightleftarrows \quad 0 \le \underbrace{p\Big[U_\alpha - U_0 + (N-1)\ell\Big] - F}_{A1_{x=0}}
\end{aligned}$$

If $\tilde{m} = N \quad \rightleftarrows \quad 0 \leq P(N)\Big[\frac{(N\beta+\sigma)^2}{(\beta+\sigma)} - (1-\alpha)[\beta(2N-1)+\sigma]\Big]\frac{(\beta+\sigma)}{2c}\frac{1}{1-\alpha} - F$

Appendix C

Comparative statics of $\mathbf{C}_m$

When performing comparative statics of the condition C_m it is convenient to define two parameters: $\chi = \Big[(\tilde{m}-1)^2\beta^2 + \alpha(\beta+\sigma)[2\beta(N-1) + \frac{N}{\tilde{m}}(\beta+\sigma)]\Big]$ and $\chi'_m \equiv \Big[2(\tilde{m}-1)\beta^2 - \frac{N}{\tilde{m}^2}(\beta+\sigma)^2\alpha\Big]$ and the common denominator is positive for all $m \in [1, N]$:

$$D \equiv P'_m(\tilde{m})\chi + P(\tilde{m})\chi'_m > 0$$

$$D|_{m=1} = \Big[2\beta(N-1)P'_m(\tilde{m}) + \Big(P'_m(\tilde{m}) - P(\tilde{m})\Big)N(\beta+\sigma)\Big](\beta+\sigma)\alpha$$

$$D|_{m=N} = P'_m(\tilde{m})\Big[(N-1)^2\beta^2 + \alpha(\beta+\sigma)[2\beta(N-1) + (\beta+\sigma)]\Big] + P(\tilde{m})\Big[2(N-1)\beta^2 - \frac{1}{N}(\beta+\sigma)^2\alpha\Big]$$

The comparative statics of the condition C_m:

$$\frac{d\tilde{m}}{dp} = -\frac{P'_p(\tilde{m})\chi}{D} < 0$$

$$\frac{d\tilde{m}}{d\sigma} = -2\alpha\frac{P(\tilde{m})\Big[(N-1)\beta + \frac{N}{\tilde{m}}(\beta+\sigma)\Big]}{D} < 0$$

$$\frac{d\tilde{m}}{d\beta} = -2\frac{P(\tilde{m})\Big[[\tilde{m}(\tilde{m}-2)+1]\beta + \alpha\big[(N-1)(2\beta+\sigma) + \frac{N}{\tilde{m}}(\beta+\sigma)\big]\Big]}{D} < 0$$

$$\frac{d\tilde{m}}{d\alpha} = -\frac{P(\tilde{m})\Big[\frac{\chi}{(1-\alpha)} + (\beta+\sigma)\big[2\beta(N-1) + \frac{N}{\tilde{m}}(\beta+\sigma)\big]\Big]}{D} < 0$$

$$\frac{d\tilde{m}}{dc} = \frac{1}{c}\frac{P(\tilde{m})\chi}{D} > 0$$

$$\frac{d\tilde{m}}{dF} = 2(1-\alpha)c\frac{1}{D} > 0$$

Appendix D

$$IS: \quad U_{\tilde{m}}(\tilde{m}, q_{\tilde{m}}) - F - U_0 \geq 0 \qquad (C_m\text{-stability})$$

$$(\tilde{m}\beta+\sigma)q_{\tilde{m}} + (N-\tilde{m})\beta q_{\alpha}^{NC} - c(1-\alpha)\frac{q_{\tilde{m}}^2}{2} + \frac{N-\tilde{m}}{\tilde{m}}\ell - F - (N\beta+\sigma)q_0^{NC} + c\frac{(q_0^{NC})^2}{2} \geq 0$$

$$\left(\frac{(\tilde{m}-1)^2}{\alpha}\frac{\beta^2}{(\beta+\sigma)^2} + 2(N-1)\frac{\beta}{(\beta+\sigma)} + \frac{N}{\tilde{m}}\right)\frac{(\beta+\sigma)^2\alpha}{2c(1-\alpha)} - F \geq 0$$

$$ES: \quad U_{\tilde{m}}(\tilde{m}+1, q_{\tilde{m}+1}) - F - U_{\alpha}(\tilde{m}, q_{\tilde{m}}) \leq 0 \qquad (18)$$

$$(\tilde{m}+1)\beta q_{\tilde{m}+1} + (N-\tilde{m}-1)\beta q_\alpha^{NC} + \sigma q_{\tilde{m}+1} - c(1-\alpha)\frac{(q_{\tilde{m}+1})^2}{2} + \frac{N-\tilde{m}-1}{\tilde{m}+1}\ell - F$$
$$-\Big(\tilde{m}\beta q_{\tilde{m}} + (N-\tilde{m})\beta q_\alpha^{NC} + \sigma q_\alpha^{NC} - c(1-\alpha)\frac{(q_\alpha^{NC})^2}{2} - \ell\Big) \leq 0$$

$$\frac{1}{\tilde{m}+1}\frac{N(\beta+\sigma)^2\alpha - \tilde{m}(\tilde{m}+1)(\tilde{m}-3)\beta^2}{2c(1-\alpha)} \leq F \leq \left(\frac{(\tilde{m}-1)^2}{\alpha}\frac{\beta^2}{(\beta+\sigma)^2} + 2(N-1)\frac{\beta}{(\beta+\sigma)} + \frac{N}{\tilde{m}}\right)\frac{(\beta+\sigma)^2\alpha}{2c(1-\alpha)}$$

$$-\big[2\tilde{m}^2 - 5\tilde{m} + 1\big]\beta^2 \leq \Big[2(N-1)\beta + \frac{1}{\tilde{m}(\tilde{m}+1)}N(\beta+\sigma)\Big](\beta+\sigma)\alpha$$

Appendix E

Consider a pure R&D club

Some scholars have considered pure R&D clubs/treaties where the countries no dot set cooperative abatement levels. This would be easier to achieve, since the cost of joining the club is less when abatement levels do not rise. But this kind of club would never reach the full cooperative abatement levels. We still assume the assumption in (11) holds, then given a number of members $\hat{m}$ a single member-country is willing to invest if the following condition holds:

$$0 \leq P(\hat{m})\Big[U_\alpha - U_0 + \frac{N-\hat{m}}{\hat{m}}\ell_n\Big] - F_{\hat{m}} \tag{19}$$

which sets a lower maximum bound on F compared to C_m, such that less expensive technologies would give full membership. The range for $F_{\hat{m}}$ in the case of non-cooperative abatement levels would then be:

$$p\Big[U_\alpha - U_0 + (N-1)\ell\Big] < F_{\hat{m}} \leq [1-(1-p)^N]\Big[U_\alpha - U_0\Big]$$

Even though full membership is more in reach with this type of pure R&D club, the maximum aggregate abatement level $Q_a^{NC}\frac{N(\beta+\sigma)}{c(1-\alpha)}$ is much lower than the social optimal $Q_\alpha^{FC} = \frac{N(N\beta+\sigma)}{c(1-\alpha)}$, but whether its higher than the social optimal abatement level without a technology depends on the following parameter values:

$$\alpha < \frac{(N-1)\beta}{N\beta+\sigma}$$

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