The Global Climate Game

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Abstract

The present paper studies emissions abatement in a global game of technological investments. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but green. Technological investments are strategic complements. While such games typically have multiple equilibria, uncertainty about the green technology's true potential leads to selection of a unique equilibrium. Applied to international environmental agreements, the model yields sharp predictions on when a treaty targeting abatement technologies gets ratified. Under well-identified conditions, countries adopt the dirty technology even though that is inefficient. In a two-stage version of the game, I study the incentive to cooperate on green R&D prior to signing an international agreement. When used to inform domestic policy, the model suggests a novel policy of network subsidies. A network subsidy virtually guarantees efficient adoption of the green technology but is not, in equilibrium, paid out.

1 Introduction

Climate change is among the most exacting of modern-day challenges. What makes the problem especially complex is its truly global nature. If a country reduces its emissions, it essentially provides a global public good. To prevent the good from getting under-provided, strong international environmental agreements (IEAs) are needed. Yet the economic literature typically predicts that IEAs cannot achieve much either (Barrett, 1994). The reason is that participation in the IEA is voluntary and countries have strong free-rider incentives.

A later literature suggests that IEAs targeting technological investments, rather than abatement directly, can fare better (Barrett, 2006; Hoel and de Zeeuw, 2010; Harstad, 2012; Battaglini and Harstad, 2016). The argument is quite intuitive: technologies may exhibit network externalities, spillovers, or other types of strategic complementarities that turn the prisoner's dilemma à la Barrett (1994) into a coordination game with large-scale green investments as an equilibrium.[1] However, coordination games typically have multiple equilibria. Which equilibrium eventually prevails cannot be predicted on the basis of underlying fundamentals and coordination failures may easily occur (Mielke and Steudle, 2018). The same problem also arises in other contexts where green goods exhibit network effects, like the markets for electric vehicle (Li et al., 2017; Clinton and Steinberg, 2019) or solar panels (Baker et al., 2013).

The standard model's conclusion that coordination games of technological investment are inherently unpredictable is dissatisfying for several reasons. First, one would expect economic, environmental, or technological fundamentals to play a role in equilibrium selection. Second, treaties like the Montreal Protocol or the Paris Agreement are ratified by nearly all countries, suggesting that coordination failures are not an important problem for actual IEAs. Third, experimental evidence confirms that individuals do coordinate their actions in coordination games, though not always on the Pareto dominant equilibrium (Barrett and Dannenberg, 2012, 2017). What we want, therefore, is a novel theory of IEAs, one that reconciles the strategic complementarity in technological investments with economic intuition and the observed ability of players to coordinate.

This paper proposes that global games provide the necessary machinery for such a theory. Global games are incomplete information games in which players receive private noisy signals of the true game played (Carlsson and Van Damme, 1993; Frankel et al., 2003). In this paper, I use global games to study emissions abatement. Rather than

[1]There are various reasons for technological investments to exhibit strategic complementarities. It can describe increasing returns to scale or network effects (Katz and Shapiro, 1985; Li et al., 2017; Baker et al., 2013), a reduced-form way to model learning-by-doing and experience, political penalties like trade restrictions on those not adopting the green technology (Nordhaus, 2015), or even fears of crossing a climate tipping point which only the breakthrough technology is able to avoid (Barrett and Dannenberg, 2012).

target emissions directly, players invest in either of two technologies. While the first is cheap and dirty, the second is expensive but green. One could think of the latter in terms of a breakthrough technology (Barrett, 2006; Hoel and de Zeeuw, 2010), though it is open to many other interpretations as well. I assume that technological investments are strategic complements. The game is a global game because players observe the green technology's true potential with some idiosyncratic noise.

My approach has several advantages compared to the typical model of IEAs targeting technologies. First, the global game has a unique equilibrium, allowing me to formulate sharp and intuitive conditions under which the green technology gets adopted. Investments in the green technology are made if, and only if, the perceived potential of the green technology is above some threshold. However, in well-specified cases players will adopt the dirty technology even though they would be better off had all adopted the green technology instead (and they know it). This prediction is consistent with Barrett and Dannenberg's (2017) finding that players are able to coordinate their actions but not always on the Pareto dominant equilibrium.

Second, the approach is realistic in terms of its informational assumptions. There are many uncertainties surrounding climate change and beliefs vary vastly (Hornsey et al., 2016). Within the model, one is free to interpret this uncertainty in different ways. Uncertainty could pertain to the true severity of climate change, the location of a dangerous tipping point, or the true potential of a breakthrough technology. And although many have studied how incomplete information affects the performance of IEAs (Kolstad, 2007; Barrett and Dannenberg, 2012; Martimort and Sand-Zantman, 2016), none consider uncertainty with idiosyncratic, player-specific (posterior) beliefs. The latter, however, are crucial. Idiosyncrasies in players' signals cause equilibrium selection in the global game.

Third, when applied to domestic markets the unique equilibrium facilitates policy design. A prediction from standard coordination games is that taxes or subsidies to stimulate green investments may need to be extremely high (Sartzetakis and Tsigaris, 2005; Mielke and Steudle, 2018). This can be politically infeasible. In contrast, my analysis suggests a simple yet very cheap policy that guarantees efficient green investments. I call it a network subsidy. Like standard subsidies, a network subsidy provides a (financial) reward to adopters of the green technology. But the amount paid to an individual investor is contingent on total green investments. As I show, it is possible to construct a simple network subsidy scheme that guarantees efficient adoption of the green technology but does not, in equilibrium, require the policymaker to pay anything. Intuitively, the network subsidy serves as a kind of insurance against small green networks. In so doing, it boosts green investments and therefore is never claimed.

The remainder of the paper is structured as follows. In Section 2, I present the main model and briefly discuss the game of complete information. In Section 3, I add uncertainty to the analysis and show that the global game has a unique equilibrium. This section also discusses strategies to improve the performance of IEAs and, in the context of domestic policy, introduces the notion of network subsidies. Section 4 concludes.

2 Main Model

Consider a world consisting of N players. When talking about domestic climate policy, players can be industries, firms, or even individual consumers, as the application demands. In the context of an IEA, I think of players as countries.

Each player chooses to invest in either of two technologies. The first, called L, is a cheap and dirty technology. If a player does not invest in L, s/he invests in H, an expensive but environmentally-friendly green technology. One could think of H as a breakthrough technology (Barrett, 2006; Hoel and de Zeeuw, 2010). Compared to investment in L, the marginal environmental benefit of investing in H is $b > 0$. Without loss of generality, I represent the investment decision of player i by a binary variable $x_i \in \{0, 1\}$ such that $x_i = 1$ corresponds to investment in H. Continuous action spaces are treated in Section 3.3. For each player i, define m to be the total number of *other* players who invest in the green technology, i.e. $m = \sum_{j \neq i} x_j$.

Investments are costly. Let the marginal cost of investing in L be constant at c^L. Given m, let the cost of investment in H be $c^H(m)$. I assume that c^H is a decreasing function of m, so $c^H(m+1) < c^H(m)$ for all $m = 0, 1, ..., N-1$. There are various interpretations to this assumption. First, it can describe network effects (Katz and Shapiro, 1985; Greaker and Midttømme, 2016). Some technologies, like electric vehicles (Li et al., 2017) or solar electricity (Baker et al., 2013), simply require a large enough user-base for investment to be profitable at the individual investor level. Second, it can represent a reduced-form way to model dynamic strategic complementarity through learning-by-doing and experience. Most technological investments require repeated maintenance and occasional re-investments. If there are more users of the technology today, there will be more experience with it tomorrow, likely leading to lower costs. Third, it may be a political instrument. Climate clubs (Nordhaus, 2015) can impose trade restrictions on players not adopting the green technology. If the climate club gets larger, these restrictions become more expensive for players outside the club, effectively lowering the net cost of green investment. And fourth, it can be a way to model fears of crossing a dangerous climate tipping point (Barrett, 2013; Barrett and Dannenberg, 2014).

Combining the above elements, the payoff to player i is:

$$\pi_i(x_i \mid b, m) = \begin{cases} b \cdot m - c^L & \text{if} \quad x_i = 0 \\ b \cdot (m+1) - c^H(m+1) & \text{if} \quad x_i = 1 \end{cases}. \tag{1}$$

The assumption that a player investing in the dirty technology ($x_i = 0$) enjoys benefits $b \cdot m$ due to green investments by others captures the idea that the green technology provides a "global public good". This assumption seems realistic in the interpretation of players as countries since emissions anywhere affect the climate everywhere. Importantly though, it is not a crucial assumption. A model where these benefits are enjoyed only upon green investment (a club good) or even not at all (private goods) will deliver equivalent results.[2]

Inspecting (1), note that investment in the green technology is a dominant strategy for all $b > c^H(1) - c^L$. Alternatively, investment in L is a dominant strategy for all $b < c^H(N) - c^L$. In between, the game has multiple equilibria.

Proposition 1. *For all $b \in (c^H(N) - c^L, c^H(1) - c^L)$, the game has two strict Nash equilibria.*

(i) In one equilibrium, all players invest in the high-potential technology and payoffs are $b \cdot N - c^H(N)$.

(ii) In the other equilibrium, all players invest in the low-potential technology and payoffs are $-c^L$.

(iii) Payoffs are strictly higher in the high-potential equilibrium.

[2] Formally, define $\Delta\pi_i(b, m) := \pi_i(1 \mid b, m) - \pi_i(0 \mid b, m)$. My analysis and its results apply, at least qualitatively, as long as $\Delta\pi_i(b, m)$ is increasing in both b and m.

If the game is played by private individuals like households, firm, or industries, a policymaker can levy taxes on the dirty technology and else offer subsidies to stimulate green investments. Consistent with the existing literature (Sartzetakis and Tsigaris, 2005; Greaker and Midttømme, 2016; Mielke and Steudle, 2018), I find that the tax or subsidy t^c required to guarantee (efficient) green investment may need to be high in the game of complete information:

$$t^c \geq c^H(1) - c^H(N). \tag{2}$$

Especially when complementarities in green investments are strong, t^c will be substantial.

Environmental economists have long recognized the possibility of equilibrium multiplicity in games of technological investments (Barrett, 2006; Hoel and de Zeeuw, 2010; Barrett and Dannenberg, 2012, 2017; Mielke and Steudle, 2018). Due to a lack of sharp theoretical predictions in such games, experimental methods are used to form expectations about outcomes. From a policy maker's point of view, reliance on experiments alone to predict which equilibrium gets selected is somewhat dissatisfying. To inform policy it is not enough to know *what* happens; we must know *why* it happens. This motivates the global climate game.

3 The Global Climate Game

Strategic complementarities in green investments drive equilibrium multiplicity under common knowledge of b, the marginal environmental benefit of green investment. Thinking of H as a novel, up-and-coming breakthrough technology, the assumption of perfect information appears too strong. There are many uncertainties surrounding a new technology's present or future potential. Besides those, there is uncertainty about the climate system itself, de facto affecting the benefits of green investments. Damages due to climate change are ambiguous. And the location or severity of tipping points only the breakthrough technology can avoid may be unknown.

Uncertainty and signals. For these reasons, I henceforth assume that the true parameter b is unobserved. Rather, it is common knowledge that b is drawn from the uniform distribution on $[\underline{B}, \overline{B}]$ where $\underline{B} < c^H(N) - c^L$ and $\overline{B} > c^H(0) - c^L$. Each player i in addition receives a private noisy signal s_i of b, given by:

$$s_i = b + \varepsilon_i. \tag{3}$$

The term ε_i captures idiosyncratic noise in i's private signal. It is common knowledge that ε_i is an i.i.d. draw from the uniform distribution on $[-\varepsilon, \varepsilon]$.[3] I assume that ε is small, $2\varepsilon < \min\{c^H(N) - c^L - \underline{B}, \overline{B} - c^H(0) + c^L\}$.

There is a conceptual distinction between global games uncertainty as in (3) or more standard models of incomplete information (Kolstad, 2007; Barrett and Dannenberg, 2012; Martimort and Sand-Zantman, 2016). Under the standard approach toward uncertainty, players' beliefs are perfectly correlated because all share the same (incomplete) information. In a global game, player's priors are perfectly correlated as well, but their *posteriors* are not due to the element of idiosyncratic noise, however small, in private signals. It is hard to overestimate the importance of this difference.

Expectations. Because b and individual noises are drawn independently from a uniform distribution, I note that:

$$\mathbb{E}[b \mid s_i] = \frac{1}{2\varepsilon} \int_{s_i-\varepsilon}^{s_i+\varepsilon} y \, dy = s_i \tag{4}$$

Given the signal s_i and green investments m, player i's expected payoff is therefore:

$$\pi_i^{\varepsilon}(x_i \mid s_i, m) = \begin{cases} m \cdot s_i - c^L & \text{if} \quad x_i = 0 \\ (m+1) \cdot s_i - c^H(m+1) & \text{if} \quad x_i = 1 \end{cases}. \tag{5}$$

For ease of the analysis later on, let me define the expected *gain* from investing in H, rather than L, as:

$$\Delta_i^{\varepsilon}(s_i, m) = \pi_i^{\varepsilon}(1 \mid s_i, m) - \pi_i^{\varepsilon}(0 \mid s_i, m) = s_i + c^L - c^H(m+1). \tag{6}$$

Assuming players are expected payoff maximizes, they invest in the high-potential technology if and only if $\Delta_i^{\varepsilon}(s_i, m) > 0$, i.e. when $\pi_i^{\varepsilon}(1 \mid m, s_i) > \pi_i^{\varepsilon}(0 \mid m, s_i)$. But there is a problem with this condition. What will m be?

Multiplicity. The problem of determining m lies at the heart of equilibrium multiplicity in complete information coordination games (see Proposition 1 and Barrett, 2006; Hoel and de Zeeuw, 2010; Barrett and Dannenberg, 2017). For intermediate signals s_i, player i's best-response critically depends on m as $\Delta_i^{\varepsilon}(s_i, N) > 0$ while at

[3] Nothing critical hinges on the assumed distributions but they make life easy, see Frankel et al. (2003) for a heavily formal treatment.

the same time $\Delta_i^\varepsilon(s_i, 0) < 0$. Without knowing what others will do, there is no ground to favor one equilibrium over the other and it makes no sense to focus on a particular equilibrium expecting it will eventually prevail.

In contrast to the typical model, however, it turns out that players *can* form rational beliefs on m in a global game. Somewhat paradoxically, uncertainty about b catalyzes a process in which players can eliminate most strategies as irrational and that in the end allows for very sharp predictions on m. This process is called iterated dominance. For a general (and abstract) analysis, the reader is referred to Frankel et al. (2003).

Strict dominance. Suppose player i receives a signal $s_i > c^H(1) - c^L + \varepsilon$. In this case, s/he knows that $b > c^H(1) - c^L$ with absolute certainty (see (3)). But if $b > c^H(0) - c^L$, green investment is a dominant strategy. In economic terms, the marginal environmental benefit of investing in the green technology (b) is so high, or climate change so severe, it warrants incurring even a very high increase in the cost of investment ($c^H(1) - c^L$). Writing $\overline{s}^0 = c^H(0) - c^L + \varepsilon$, it follows that $\Delta_i^\varepsilon(\overline{s}^0, m) > 0$ for all $m = 0, 1, ..., N-1$. In contrast, when player i receives a much lower signal $s_i < c^H(N) - c^L - \varepsilon$, s/he learns that $b < c^H(N) - c^L$ in which case dirty investment is a dominant strategy. The marginal environmental gain from adopting the green technology is so low not even a small increase in investment costs is worth it. Writing $\underline{s}^0 = c^H(N) - c^L - \varepsilon$, s/he knows that $\Delta_i^\varepsilon(\underline{s}^0, m) < 0$ for all $m = 0, 1, ..., N-1$.

I conclude that any player i invests in H for all signals $s_i > \overline{s}^0$. Similarly, all players definitely invest in L for signals $s_i < \underline{s}^0$. This is not much of an improvement compared to the game of complete information, where the range of b for which one or the other type of investment is strictly dominant was larger.[4] If anything there appears to be more scope for equilibrium multiplicity in the global game. There is a crucial distinction between the games though. In the complete information game, player i not only knows the true b, s/he also knows that everyone knows b, and that everyone knows that everyone knows b, and so on.[5] In comparison, player i's knowledge about what any j knows is much more vague in the global game. If s/he receives private signal s_i, all s/he can say is that j must have seen some signal in $[s_i - 2\varepsilon, s_i + 2\varepsilon]$. This brings me to a crucial step in the analysis.

Iterated dominance. The points $\overline{s}^0$ and $\underline{s}^0$ are found under the assumption that no player plays a strictly dominated strategy. But if players know of each other they won't

[4] I mean that $\overline{s}^0 > C^H(1) - c^L$ while $\underline{s}^0 < c^H(N) - c^L$, where the right-hand sides of these inequalities are the boundaries of strict dominance in the complete information game, see Proposition 1.

[5] Formally, one says that b is *common knowledge*. See Aumann (1976) and Rubinstein (1989).

play a strictly dominated strategy, each player i can construct bounds on the posterior probability that any other player j invests in either L or H. After all, j definitely does not invests in L when $s_j > \overline{s}^0$, which implies that the *minimum* probability player i can assign to the event that player 1 invests in H is simply $\Pr(s_j > \overline{s}^0 \mid s_i)$. By the same token, player j will certainly invest in L for all $s_j < \underline{s}^0$, so the *maximum* probability with which player i can believe j will invest in H is $\Pr(s_j > \underline{s}^0 \mid s_i)$.

With these probabilities, it is straightforward to derive boundaries on the posterior beliefs of player i on m. When i receives signal s_i, the lowest probability s/he can assign to the event that $x_j = 1$ is $\Pr(s_j > \overline{s}^0 \mid s_i)$, and so the highest probability of $x_j = 0$ is given by $\Pr(s_j < \overline{s}^0 \mid s_i) = 1 - \Pr(s_j > \overline{s}^0 \mid s_i)$. Combining those, the lowest probability that a given number of n players j play $x_j = 1$, while the remaining $N-n-1$ play $x_j = 0$, is therefore simply $[\Pr(s_j > \overline{s}^0 \mid s_i)]^n \cdot [\Pr(s_j < \overline{s}^0 \mid s_i)]^{N-n-1}$. Moreover, since there are $N-1$ players other than i, there are a total of $\binom{N-1}{n}$ distinct ways in which exactly n of them can play $x_j = 1$. The lowest probability that any n players j play $x_j = 1$ while the others play $x_j = 0$ is therefore $\binom{N-1}{n}[\Pr(s_j > \overline{s}^0 \mid s_i)]^n \cdot [\Pr(s_j < \overline{s}^0 \mid s_i)]^{N-n-1}$. Analogously, the highest probability that any n players j play $x_j = 1$ while the others play $x_j = 0$ is therefore $\binom{N-1}{n}[\Pr(s_j > \underline{s}^0 \mid s_i)]^n \cdot [\Pr(s_j < \underline{s}^0 \mid s_i)]^{N-n-1}$.

Plugging these beliefs into expected payoffs (5), player i solves for points $\overline{s}^1$ and $\underline{s}^1$ implicitly defined by:

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(s_j > \overline{s}^0 \mid \overline{s}^1)\right]^n \cdot \left[\Pr(s_j < \overline{s}^0 \mid \overline{s}^1)\right]^{N-n-1} \cdot \Delta_i^{\varepsilon}(\overline{s}^1, n)}_{\text{Lowest expected gain from investing in } H, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0} = 0, \tag{7}$$

and

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(s_j > \underline{s}^0 \mid \underline{s}^1)\right]^n \cdot \left[\Pr(s_j < \underline{s}^0 \mid \underline{s}^1)\right]^{N-n-1} \cdot \Delta_i^{\varepsilon}(\underline{s}^1, n)}_{\text{Highest expected gain from investing in } H, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0} = 0. \tag{8}$$

In economic terms, equation (7) says the following. Given that player j does not play a strictly dominated strategy, $\overline{s}^1$ is the threshold such that even the lowest expected gain from investing in H positive when $s_i > \overline{s}^1$. It follows that investment in H is a dominant strategy for all $s_i > \overline{s}^1$. Similarly, $\underline{s}^1$ is the point such that even the highest gain from investing in H is lower than the lowest expected payoff from investing in L, so investment in L is a dominant strategy for all $s_i < \underline{s}^1$.

Since $\Pr(s_i > \overline{s}^0 \mid \overline{s}^0) = \Pr(s_i > \underline{s}^0 \mid \underline{s}^0) = 1/2$, note that

$$2^{1-N} \sum_{n=0}^{N-1} \binom{N-1}{n} \Delta_i^{\varepsilon}(\overline{s}^0, n) > \Delta_i^{\varepsilon}(\overline{s}^0, 0) \geq 0, \tag{9}$$

while also

$$2^{1-N} \sum_{n=0}^{N-1} \binom{N-1}{n} \Delta_i^{\varepsilon}(\underline{s}^0, n) < \Delta_i^{\varepsilon}(\underline{s}^0, N-1) \leq 0, \tag{10}$$

which together imply that $\overline{s}^1 < \overline{s}^0$ and $\underline{s}^1 > \underline{s}^0$. Intuitively, player i is just indifferent between both green and dirty investments when s/he observes $s_i = \overline{s}^0$ and no other player invests in the green technology. But if s/he observes $s_i = \overline{s}^0$, there is a strictly positive probability any other player j observes $s_j > \overline{s}^0$ and thus invests in the green technology, in which case i's expected payoff is strictly higher when going green. For this reason, player i is willing to adopt the technology even for some lower signals, by virtue of the expected spillovers from others' green investments.

Starting with the simple observation that some strategies are strictly dominated for all players (the points $\overline{s}^0, \underline{s}^0$), I showed that players can form rational posterior upper and lower bounds on the probability that others will invest in a the green technology. But in a coordination, these bounds are critical and lead to additional strategies being strictly dominated (the points $\overline{s}^1, \underline{s}^1$). Yet if player i knows that all other players will invest in H (or L) for all signals higher than $\overline{s}^1$ (or lower than $\underline{s}^1$), yet more strategies can be eliminated, yielding points $\overline{s}^2$ and $\underline{s}^2$, et cetera.

Convergence. The above procedure can be carried on indefinitely, which I leave to the patient reader. It yields two sequences of points $(\overline{s}^k)_{k=0}^{\infty}$ and $(\underline{s}^k)_{k=0}^{\infty}$, where $\overline{s}^{k+1}$ and $\underline{s}^{k+1}$ are the solutions to

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(s_j > \overline{s}^k \mid \overline{s}^{k+1})\right]^n \cdot \left[\Pr(s_j < \overline{s}^k \mid \overline{s}^{k+1})\right]^{N-n-1} \cdot \Delta_i^{\varepsilon}(\overline{s}^{k+1}, n)}_{\text{Lowest expected gain from investing in } H \text{, given } \overline{s}^k \text{ and } \underline{s}^k} = 0, \tag{11}$$

and

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(s_j > \underline{s}^k \mid \underline{s}^{k+1})\right]^n \cdot \left[\Pr(s_j < \underline{s}^k \mid \underline{s}^{k+1})\right]^{N-n-1} \cdot \Delta_i^{\varepsilon}(\underline{s}^{k+1}, n)}_{\text{Highest expected gain from investing in } H \text{, given } \overline{s}^k \text{ and } \underline{s}^k} = 0, \tag{12}$$

respectively. Equations (11) and (12) give mathematical expression to essentially the same economic intuition that underlay (7) and (8).

Given the facts that $\overline{s}^1 < \overline{s}^0$ and $\underline{s}^1 > \underline{s}^0$, an inductive argument at once establishes that $\overline{s}^{k+1} < \overline{s}^k$ and $\underline{s}^{k+1} > \underline{s}^k$ for all $k \geq 0$. Moreover, I note that $\overline{s}^k \geq \underline{s}^k$ for all k since it is clearly impossible that investment in both L and H is dominant at the same signal. It follows that $(\overline{s}^k)_{k=0}^{\infty}$ and $(\underline{s}^k)_{k=0}^{\infty}$ are bounded. But bounded monotone sequences have to converge; let $\overline{s}^*$ and $\underline{s}^*$, respectively, be their limits. In game theoretic parlance, it is said that investment in the green technology is *iteratively dominant* for all signals $s_i > \overline{s}^*$. Investment in the dirty technology is iteratively dominant for all signals $s_i < \underline{s}^*$.

Main result. From the definition of convergence, one knows that $|\overline{s}^k - \overline{s}^{k+1}| \to 0$ and $|\underline{s}^k - \underline{s}^{k+1}| \to 0$ as $k \to \infty$. This implies that $\lim_{k\to\infty} \Pr(s_j > \overline{s}^k \mid \overline{s}^{k+1}) = \Pr(s_j > \overline{s}^* \mid \overline{s}^*) = 1/2$ (and the same for $\underline{s}^*$).[6] Plugging this into (11) and (12) yields the following equalities:

$$\overline{s}^* + c^L - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c^H(n+1)}{2^{N-1}} = \underline{s}^* + c^L - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c^H(n+1)}{2^{N-1}} = 0. \qquad (13)$$

Clearly, equation (13) is satisfied only if $\overline{s}^* = \underline{s}^*$. This has a major implication.

Proposition 2. *The global climate game has a unique equilibrium. There exists a unique threshold $b^*(= \overline{s}^* = \underline{s}^*)$ such that each player i invests in the high-potential technology for all $s_i > b^*$, while s/he invest in the low-potential technology for all $s_i < b^*$. When $\varepsilon \to 0$, the threshold b^* is given by:*

$$b^* = \sum_{n=0}^{N-1} \binom{N-1}{n} \cdot \frac{c^H(n+1)}{2^{N-1}} - c^L. \qquad (14)$$

While Proposition 2 is theoretically a special case of the result in Frankel et al. (2003), it generates several novel insights for the literature on IEAs. The global climate game selects a unique equilibrium of the underlying coordination game with multiple equilibria. In this sense, Proposition 2 does away with a concern for coordination failure (Mielke and Steudle, 2018) and theoretically motivates the focus on a single equilibrium in the literature on IEAs (Barrett, 2006; Hoel and de Zeeuw, 2010).

[6] Formally this argument only applies if $\overline{s}^* < \overline{B} - 2\varepsilon$. But we know that $\overline{s}^* < c^H(1) - c^L$ while $2\varepsilon < \overline{B} - c^H(1) + c^L$ by assumption, so we are good to go. By a symmetric argument, $\underline{s} > \underline{B} + 2\varepsilon$.

Note that the unique equilibrium can be inefficient. Players may adopt the dirty technology even if everybody's payoff were higher had they adopted the green technology instead (and even though they know it). Intuitively, green investment will be too risky when b is low since the noise in signals forces a player to believe that others may think that green investment is dominated. Barrett and Dannenberg (2012) appear to share this view when they write: "players could use risk-dominance as a selection rule." For 2×2 games, their statement is correct indeed: Carlsson and Van Damme (1993) establish that any 2×2 global game selects the risk dominant equilibrium of the underlying true game. But the selection criterion cannot apply when there are more than two players as risk-dominance is only defined for 2×2 games. Though generalizations of the concept have been developed (Morris et al., 1995), these are not, in general, predictive for equilibrium selection (Frankel et al., 2003).

Corollary 1. *For all $b \in (c^H(N) - c^L, b^* - \varepsilon)$, the unique equilibrium of the global climate game is inefficient. Players invest in the dirty technology even though payoffs are higher were all to adopt the green technology instead.*

[Here elaborate on the importance of this result with respect to IEA literature.]

The paradox of Corollary 1 is that players may coordinate on the dirty technology despite knowing they are better off if instead they could coordinate on the green technology. Because both individual investors and society as a whole are worse off in this case, it motivates policy intervention. The next subsections elaborate.

3.1 International R&D Platforms

The model so far took strategic complementarities like technological spillovers and learning-by-doing as a primitive. But in the context of an IEA, they may also be endogenous to countries' decisions. A new technology, before being installed, must first be developed. Countries to that end must engage in R&D and related activities. Spillovers and other network effects are then the product of collaborations in international R&D platforms (Hoel and de Zeeuw, 2010). In this sense, a focus on *cooperation* (R&D) could lead to *coordination* (investments in clean technologies). But will it?

To answer this question, the base model of Section 3 needs to be transformed into a two-stage game. In stage 1, countries decide on their participation in an international R&D platform. I assume that the platform is erected only if all countries decide to participate, in which case each incurs a cost of $d > 0$. Unanimity is a reasonable requirement in the international policy realm where participation in the R&D platform is voluntary. One could alternatively assume that the platform is created whenever a *majority* of countries votes in favor but participation is then mandatory for all (c.f. Barrett and Dannenberg, 2017). The latter approach is consistent with majority decisions in the EU Council or Parliament being binding for all member states. As I will discuss, either model yields equivalent predictions. Finally, countries know the prior distribution of b before deciding on their participation in the international R&D platform. This amounts to saying that countries have a vague but imperfect idea about what to expect from the R&D platform, which appears realistic.

If countries forge an R&D platform, the game moves on to stage 2 in which a green technology is developed and Nature draws its true potential b. Countries then receive their private signals s_i and decide whether or not to adopt the green technology. If countries did not create the R&D platform, no green technology is invented and each country adopts the dirty technology (which could be thought of as the status quo in this case). [7]

Schematically, the timing of the game becomes as follows:

1. Countries decide whether or not to forge a platform for international collaborations on R&D. If the platform is created, each country incurs a cost d.
2. The green technology is developed and b is drawn.
3. Countries receive their signals s_i of b and simultaneously decide whether or not to ratify an IEA that targets adoption of the green technology.

In stage 1 of the game, countries make a tradeoff between the cost of forging an international R&D platform and the gain of playing a coordination game where investments in the green technology might occur. Recall, however, that ratification of the IEA is by no means guaranteed in the second stage of the game. The international collaboration on R&D has turned the second-stage game of technological investments into a coordination game where ratification may be an equilibrium. But if the true b drawn by Nature is low, i.e. if $b < b^*$, countries will adopt the dirty technology despite their prior R&D efforts, see Proposition 2. In this sense, participation in an international R&D platform is a

[7] In this game, signals can be interpreted as national assessments of the technology's potential. Each country is on average correct, but idiosyncratic noise can drive a wedge between the true potential and each country's own assessment of it.

costly investment with a risky return. For countries to participate in an international R&D platform, the cost d should therefore be no higher than d^*, given by:

$$d^* = \frac{\overline{B} - b^*}{\overline{B} - \underline{B}} \left[N \cdot \frac{b^* + \overline{B}}{2} + c^L - c^H(N) \right]. \tag{15}$$

Condition (15) has a clear economic intuition. If countries decide not to collaborate in an R&D platform, the green technology is not developed and each country realizes a payoff of $-c^L$ (their only choice is to use the dirty technology). On the other hand, if countries decide to forge an international R&D platform, they incur the sure cost d. This investment opens up a possibility that the green technology gets adopted by all countries, which is their unique equilibrium choice when $b > b^*$.[8] The prior probability that $b > b^*$ is given by $(\overline{B} - b^*)/(\overline{B} - \underline{b})$. Moreover, conditional on being greater than b^* the expected value of b is $(b^* + \overline{B})/2$, so each country's payoff in this case is simply $N \cdot (b^* + \overline{B})/2 - c^H(N)$. However, even if countries participate in the R&D platform, there remains a possibility that $b < b^*$ and the IEA does not get ratified in stage 2 of the game, so payoffs are $-c^L$. This occurs with probability $1 - (\overline{B} - b^*)/(\overline{B} - \underline{b})$. Combining these elements gives the R&D costs d^* for which countries are just indifferent between forging the platform in the first place or not, which is (15).

Proposition 3. *The two-stage game has a unique perfect Bayesian equilibrium. In the first stage of the game, countries forge an international R&D platform if and only if $d \leq d^*$. In the second stage of the game, countries ratify the IEA and adopt the green technology if and only if $b > b^*$.*

If $d < d^*$, each country strictly prefers that an R&D platform is forged in order to subsequently play a coordination game of technological investments. If the voting rule is unanimous, all countries will therefore vote in favor of creating the platform when $d < d^*$. But the same is true with simple majority voting the outcome of which becomes mandatory for all countries. To see this, note that any country votes in favor of the platform whenever $d < d^*$, while any country votes against for all $d > d^*$. Hence, simple majority voting model leads to unanimous voting, and both assumptions are equivalent in terms of their equilibrium implications.

While in the end it is an empirical question whether the cost of R&D is low enough

[8] To be fully out in the open, the statement should read that each country i adopts the green technology if and only if $b_i > b^*$. But this condition is satisfied with probability 1 if $b > b^*$ and $\varepsilon \to 0$, which for convenience I shall assume.

to warrant international collaborations, the present model conveys some insights on how to improve the odds of R&D platforms being forged. Inspecting (14) and (15), a strategy of trade sanctions (Nordhaus, 2015) or restrictions on foreign direct investments can stimulate ratification of IEAs targeting green technologies in the two-stage game. Interpreting such policies as an increase in the effective cost of dirty investments c^L, they are two mutually reinforcing effects.

First, it directly expands the range of costs d for which countries are willing to participate in international R&D networks, increasing the odds that a green technology gets developed in stage 1. Second, an increase in c^L lowers b^*, see (14). This itself influences the eventual performance of an IEA in two separate ways. On the one hand, it expands the range of bs for which countries adopt the green technology in stage 2 of the game, conditional on there being an R&D platform. On the other hand, a decrease in b^* further extends the range of R&D costs for which countries are willing to collaborate in an international platform. This can be seen by differentiating (15) with respect to b^*:

$$\begin{aligned}\frac{\partial d^*}{\partial b^*} &= \frac{1}{\overline{B}-\underline{B}}\frac{N}{2}(\overline{B}-b^*) - \frac{1}{\overline{B}-\underline{B}}\left[\frac{N}{2}(b^*+\overline{B}) + c^L - c^H(N)\right] \\ &= \frac{c^H(N) - c^L - N\cdot b^*}{\overline{B}-\underline{B}} < 0, \end{aligned} \tag{16}$$

where the inequality follows from the fact that $c^H(N) - c^L < b^*$, see (14).

Proposition 4. *In the two-stage game, a strategy of trade sanctions or restricted foreign direct investment imposed on countries not adopting the green technology in stage 2 (conditional on the green technology being invented) is an effective way to induce adoption of the green technology. By implicitly increasing c^L, these policies have a twofold effect. First, they make the creation of an international R&D platform more likely in the first stage. Second, and conditional on the R&D platform being created, they make ratification of the IEA targeting green technologies more likely in the second stage.*

Environmental agreements like the Montreal and Kyoto Protocols or the Paris Agreement are usually signed under the auspices of the United Nations. Proposition 4 suggests that a more comprehensive approach – involving, for example, the World Trade Organization or the Organisation for Economic Co-operation and Development[9] – offers

[9]The OECD's Code of Liberalisation of Capital Movements is "the only multilateral agreement

promising prospects for the development of green technologies and the ratification of more demanding IEAs.

3.2 Domestic Policy: Network Subsidies

When applied to IEAs, the model of Section 3 describes strategic behavior between countries. In that environment, there is no natural party with the power to impose rules or otherwise dictate behavior. Solutions to preempt selection of an inefficient equilibrium (Corollary 1) therefore require voluntary measures taken by the countries themselves, like the trade sanctions discussed above. However, the model need not be restricted to IEAs. In this section, I study the problem of a domestic policymaker who wants to stimulate green investments by individuals, firms, or industries. Different from the application to IEAs, the policymaker has taxes and subsidies at its disposal.

Looking at (14), the global climate game predicts that taxes and subsidies will work whenever they cause an effective decrease of $c^H(m) - c^L$ for some or all m. The U.S. Federal Tax Credit for Solar Photovoltaics (Borenstein, 2017), California's Clean Vehicle Rebate Project (Li et al., 2017), or the U.S. National Plug-In Electric Drive Vehicle Credit (Clinton and Steinberg, 2019) are good illustrations. However, tax policies may not always be feasible, political or otherwise. For example, legislation on taxation requires unanimous agreement in the European Union, which is one reason the EU does not have a carbon tax. Subsidies and tax credits, on the other hand, come with a substantial budgetary burden. The Congressional Budget Office expects total cost from tax credits on electric vehicles to be about 7.5 billion U.S. dollars through 2019.[10]

When the policymaker taxes dirty investments or subsidizes the green technology, the tax or subsidy t guarantees efficient green investments if it satisfies:

$$t \geq \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c^H(n)}{2^{N-1}} - c^H(N). \tag{17}$$

Importantly, recall that $c^H(n)$ is decreasing in n due to the strategic complementarities in green investments. This implies that $\sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c^H(n+1)}{2^{N-1}} < c^H(1)$. Comparing (2) and (17) therefore reveals that $t < t^c$. If network effects are strong, this difference

and tool providing for the management of the full range of cross-border capital flows between its 36 members (OECD, 2019)."

[10]See https://www.cbo.gov/sites/default/files/112th-congress-2011-2012/reports/electricvehiclesone-col.pdf

will be substantial. The present analysis therefore suggests that the necessity of very high taxes or subsidies in the typical model (Sartzetakis and Tsigaris, 2005; Greaker and Midttømme, 2016; Mielke and Steudle, 2018) is driven, at least in part, by the assumption of complete information. Paradoxically, uncertainty *lowers* the tax or subsidy required to stimulate efficient green investments.

When the policymaker chooses to subsidize rather than tax, however, even the relatively low subsidy (17) will be expensive. The reason is that a successful subsidy entices all individuals to adopt the green technology, in which case the policymaker ends up spending a total of $N \cdot t$. But *if* all others adopt the green technology, an individual is willing to adopt it even without a subsidy when.[11] Standard subsidies therefore create a catch-22 situation: a subsidy is needed to guarantee efficient green investments while it is not needed if it actually works.

To overcome this problem, I suggest a novel policy instrument called *network subsidies*. Like standard subsidies, a network subsidy is offered contingent on adoption of the green technology. But the sum paid to individual investors is decreasing in the total amount of green investments. In particular, let a policymaker offer the following simple network subsidy:

$$t^*(m) = c^H(m+1) - c^H(N), \tag{18}$$

for all $m = 0, 1, ..., N-1$. In words, when player i adopts the green technology and m others have done so too, i receives a subsidy equal to $c^H(m+1) - c^H(N)$. With this subsidy, the expected gain to investing is $\Delta_i^\varepsilon(s_i, m) + t^*(m) = s_i + c^L - c^H(N)$ for any m. It follows that player i invests in the green technology whenever $s_i \geq c^H(N) - c^L$. Assuming that ε is sufficiently small, each player i therefore adopts the green technology for all $b > c^H(N) - c^L$. But this is also the condition for green investments to be Pareto dominant. It follows that all players invest in the green technology whenever that is socially efficient, in which case each receives a subsidy of $t^*(N-1) = c^H(N) - c^H(N) = 0$. The network subsidy therefore guarantees overall adoption of the green technology whenever that is efficient but does not cost the policymaker anything.

Proposition 5. *Let $\varepsilon \to 0$. A network subsidy equal to* (18) *guarantees investment*

[11] If the subsidy is equal to $t = \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c^H(n)}{2^{N-1}} - c^H(N)$, then players will adopt the green technology for all $b_i > c^H(N) - c^L$. However, assuming all others adopt the green technology an individual player i is willing to invest in it when $b_i > c^H(N) - c^L$ anyway, and the subsidy would not be needed.

in the green technology whenever that is efficient ($b > c^H(N) - c^L$) but does not, in equilibrium, cost the policymaker anything.

For the intuition, think of the network subsidy as a type of insurance. It protects individual investors against the risk of small network externalities from green investments in case many others have adopted the dirty technology. In so doing, it impels individuals toward green investments. The network subsidy does not have to be paid as a result, being conditional on low investments by construction.

Importantly, network subsidies also work in environments with complete information. Nowhere crucial in deriving the network subsidy given by (18) did I use the fact that players are uncertain about the green technology's true potential b.

Corollary 2. *If a network subsidy equal to* (18) *is offered in the game with common knowledge of b, it implements the efficient equilibrium of the game without costing the policymaker anything.*

3.3 Investment Shares And Continuous Actions

The main model assumed discrete actions: players were constrained to invest only in one technology. Though strong indeed, this assumption is not important for my mains results.

Let there again be N players. Each player chooses an $x_i \in [0, 1]$, the *share* of i's investments in the high-potential green technology H. Define $m = \sum_{j \neq i} x_i$ to be the total share of investments in H by all players who are not i, where m is now a continuous variable with domain $[0, N - 1]$. A player investing in L faces marginal investment costs of c^L. Given m, the marginal cost of investment in H is $c^H(m)$, which is decreasing in m.[12] Upon learning the signal s_i, player i's expected payoff to playing x_i is:

$$\pi_i^{\varepsilon}(x_i \mid m) = (m + x_i) \cdot s_i - x_i \cdot c^H(m + x_i) - (1 - x_i) \cdot c^L. \tag{19}$$

Like before, the problem with (19) is that player i does not know m, the actions of all other players. Still though, s/he knows that if $x_i < 1$ then $\pi_i^{\varepsilon}(1 \mid s_i, m) > \pi_i^{\varepsilon}(x_i \mid s_i, m)$ for all $m \in [0, N]$ and all $s_i > \overline{s}^0$. This is easy to verify. At signals $s_i > \overline{s}^0$, it is a strictly dominant strategy for player i to invest in H. But if investment in H is strictly dominant, then any strategy prescribing a mixture between H and L will yield a strictly

[12] Clearly I might define c^H to be a decreasing function of m, rather than $m + x_i$, without affecting my main results.

lower payoff than investment in H alone. It follows that rational players will only invest in the green technology, i.e. choose $x_i = 1$, for all $s_i > \overline{s}^0$. By the same token, players choose $x_i = 0$ for all $s_i < \underline{s}^0$.

As in the game with discrete investment decisions, any player i can again construct lower and upper bounds on the probability that some other player j invests exclusively in either of the two technologies. This in turn allows player i to calculate the lowest and highest expected payoff to both types of investment. Yet it is easy to see that such calculations again give rise to the same conditions used to find points $\overline{s}^1$ and $\underline{s}^1$, namely (7) and (8). Going on in this way, one performs the exact same process of iterated dominance as was done for the game with discrete investment choices (equations (11) and (12)). Since that process was shown to end in a single switching-point b^*, the same must be true in a game with continuous actions.

Proposition 6. *Consider the global climate game with continuous action spaces* $x_i \in [0, 1]$ *for all players* i*. Then there exists a unique threshold* b^* *such that each player* i *invests in the high-potential technology for all* $s_i > b^*$*, while s/he invest in the low-potential technology for all* $s_i < b^*$*.*

Even without constraining players' choices to be discrete, the Global Climate Game has a "bang-bang" equilibrium.

4 Discussion and Conclusions

This paper studies climate change mitigation in a global game. The focus is on abatement through technological investment. Players invest in either of two technologies. One technology is cheap and dirty, the other expensive but with a high green potential. I consider environments in which investments are strategic complements. These could for example arise due to network effects, technological spillovers, or learning-by-doing. Consistent with the existing literature on international environmental agreements or private technological investments in green technologies, I demonstrate that the complete information version of my game has multiple equilibria (Barrett, 2006; Hoel and de Zeeuw, 2010; Barrett and Dannenberg, 2012, 2017; Mielke and Steudle, 2018). Equilibrium multiplicity can lead to coordination failure and complicates the design of domestic policies or climate treaties.

To this well-studied framework, I add a little bit of uncertainty. I assume that the true (relative) abatement potential of the green technology is unobserved, which may equally be interpreted as scientific uncertainty about climate change or tipping points to unknown political consequences of ratifying an IEA. Rather than observe the technology's true potential, players receive private noisy signals of it. In this environment, I show that the *global climate game* has a unique in which players adopt the green technology if and only if their private signals exceed an endogenous threshold. For signals below the threshold, players adopt the dirty technology instead.

My paper contributes to the literature on international environmental agreements. To my knowledge, I am the first to theoretically explicitly addresses the issue of multiple equilibria and equilibrium selection in IEA games. Though many papers on IEAs and technological investments find multiple equilibria, these either ignore equilibrium selection altogether (Barrett, 2006; Hoel and de Zeeuw, 2010) or else resort on experimental methods to determine which equilibrium eventually obtains (Barrett and Dannenberg, 2012, 2017). In contrast, the global climate games makes sharp analytical prediction on which equilibrium gets selected. This also allows me to support intuitive ways to improve the design and performance of IEAs in a formal model.

The model can also be used to study domestic policies aimed at large-scale private adoption of green technologies characterized by network effects (Greaker and Midttømme, 2016) like electric vehicles (Li et al., 2017; Clinton and Steinberg, 2019) or solar panels (Baker et al., 2013). Sufficiently high taxes and/or subsidies can turn the unique equilibrium from one where no individual adopts the green technology into one where all do. While taxes are budget-neutral, subsidies are not. This expensiveness of a green subsidy can be remedied by introducing smart network subsidies: a subsidy paid to green investors in case insufficiently many green investments were made. Interestingly, even if the network subsidy is of a relatively low magnitude compared to potential network spillovers, it entices all individuals to adopt the green technology. In a way, the network subsidy serves as a kind of insurance against "low network externalities". By insuring investors against the main risk of adopting the green technology, the network subsidy virtually assures large-scale green investments. As a budgetary side-effect, the policymaker does not have to pay out any subsidies. After all, the subsidy is paid only when few investments are made.

The analysis highlights that the precise way in which one models uncertainty is of critical importance. Although some papers conclude that "shared" uncertainty does not eliminate equilibrium multiplicity in coordination games (Barrett and Dannenberg, 2012; Barrett, 2013), this paper shows the starkly contrasting result that privately held beliefs about the shared game does force selection of a unique equilibrium. The assumed structure of uncertainty matters. My result motivates a rethink of the way environmental economists model uncertainty.

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