The Global Climate Game

Roweno J.R.K. Heijmans
r.j.r.k.heijmans@uvt.nl

Tilburg University

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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. Without policy interventions, players may adopt the dirty technology even if payoffs are higher when all invest in the green technology instead. To remedy this inefficiency, I propose the concept of a network subsidy. A network subsidy virtually guarantees adoption of the green technology but is not, in equilibrium, paid out. I also use the model to shed a new light on international environmental agreements.

1 Introduction

This paper develops a simple analytic model of emissions abatement in a global game.[1] Rather than target emissions directly, players focus on technological investments. I use my model to study climate policy and international environmental agreements (IEAs).

[1]Global games are incomplete information games in which players receive private noisy signals of the true game drawn (Carlsson and Van Damme, 1993; Frankel et al., 2003).

There currently exist more than 3,000 IEAs.[2] Out of those, not one has turned the tides of ever-increasing greenhouse gas emissions. The literature typically describes this failure as a prisoner's dilemma where participation in an IEA is voluntary and countries have strong free-rider incentives (Barrett, 1994).

It has been proposed that a focus on abatement technologies or R&D, rather than emissions directly, can improve the performance of IEAs (Barrett, 2006; Hoel and de Zeeuw, 2010). The intuition is that technologies may exhibit network externalities, technological spillovers, learning-by-doing, scale economies, or other strategic complementarities turning the prisoner's dilemma à la Barrett (1994) into a *coordination game* with large-scale green investment as an equilibrium. Unfortunately, coordination games usually have multiple equilibria. The mere fact that some outcome is an equilibrium of the game is therefore not predictive of actual behavior. Though a focus on technologies or R&D could improve the performance of an IEA, that is no guarantee it actually will. Indeed, the possibility of coordination failure lurks ominously around the corner.

The element of unpredictability complicates the study and design of IEAs that target technological investments. To nevertheless form expectations on the performance of an IEA when the underlying game has multiple equilibria, Barrett and Dannenberg (2012, 2017) take coordination games to the lab. Contrary to what the typical theory predicts, they find that subjects *do* coordinate their actions (though not always on the efficient equilibrium). This suggests that a focus on technological investment or R&D could improve the performance of IEAs indeed. Yet to inform policy it is not enough to know *what* happens; we must know *why* it happens. What we need is a novel theory of IEAs, one that reconciles the strategic complementarity in technological investments with the observed ability of players to coordinate their actions.

In this paper, I propose global games as a practical tool to study IEAs. I construct a bare-bones model of technological investment. Players choose to invest in either of two technologies. The first is cheap and dirty, the second expensive but green. An individual player's payoff from investing in the green technology is increasing in the number of other players that invest in it (Barrett, 2006; Hoel and de Zeeuw, 2010; Greaker and Midttømme, 2016; Mielke and Steudle, 2018). The game is a global game because players receive private noisy signals of the green technology's true potential. In contrast to the typical model, my *global* coordination game of technological investment has a unique equilibrium. This allows me to perform comparative statics and talk policy.

[2] See https://iea.uoregon.edu/ for an extensive database.

Subsidies on the green technology, taxes on the dirty technology, a carbon price, or trade restrictions on countries not adopting the green technology all facilitate selection of a more favorable equilibrium.

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 (Barrett, 1997; Nordhaus, 2015), or even fears of crossing a climate tipping point which only the breakthrough technology is able to avoid (Barrett and Dannenberg, 2012).

The assumption of uncertainty seems uncontroversial. Despite decades of scientific progress, much remains unclear when it comes to climate change. Due to the elementary structure of my model, one is free to interpret this uncertainty in different ways. Uncertainty could pertain to the true severity of climate change, to the location of a dangerous tipping point, or to the true potential of a novel breakthrough technology. Either way my analysis complements a growing literature on the performance of IEAs under incomplete information (Kolstad, 2007; Barrett and Dannenberg, 2012; Martimort and Sand-Zantman, 2016). The crucial difference between a global games and typical models of incomplete information is the way beliefs are formed. Standers models assume common knowledge of prior and posterior beliefs. In a global game, players receive private noisy information so their posteriors only correlate. The distinction matters: coordination games with shared posteriors have multiple equilibria. My assumption on the structure of beliefs appears to capture elements of reality. Beliefs about climate change are know to vary vastly (Hornsey et al., 2016).

2 Model and Analysis

Consider a world consisting of $N+1$ players. In the context of an IEA, players are interpreted as countries. When talking about domestic climate policy, players will be more disaggregated bodies like sectors, firms, or even individual consumers, as the application demands.

Each player chooses to invest in either of two technologies. The first, called L, is an low-potential, low-cost technology. If a player does not invest in L, s/he invests in H, a high-potential but high-cost 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 $x_i = 1$ denotes investment in H. I treat continuous action spaces in Section 2.4. 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 $m = 0, 1, ..., N$. There are various interpretations to this assumption. First, it can describe network effects (Katz and Shapiro, 1985). 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.

Combining the elements above, 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.[3]

[3]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, mutatis mutandis, as long as $\Delta\pi_i(b, m)$ is increasing in both b and m.

Inspecting (1), note that investment in the green technology is a dominant strategy for all $b > c^H(0) - c^L$. Alternatively, investment in L is a dominant strategy for all $b < c^H(N) - c^L$. Otherwise, the game has multiple equilibria.

Proposition 1. *For all $b \in (c^H(N) - c^L, c^H(0) - c^L)$, the game has two strict Nash equilibria.*

(i) In one equilibrium, all players invest in the high-potential technology and payoffs are $b \cdot (N+1) - c^H(N+1)$.

(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.

Environmental economists have long recognized the possibility of incentives to coordinate technological investments (Barrett, 2006; Hoel and de Zeeuw, 2010; Barrett and Dannenberg, 2012, 2017). 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.

2.1 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 though. 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:

$$s_i = b + \varepsilon_i. \tag{2}$$

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 $[-\varepsilon, \varepsilon]$.[4] 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 (2) 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 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:

$$\mathbb{E}[b \mid s_i] = \frac{1}{2\varepsilon} \int_{s_i-\varepsilon}^{s_i+\varepsilon} y \, dy = s_i \tag{3}$$

Given the signal s_i, player i's expected payoff is therefore:

$$\pi_i^\varepsilon(x_i \mid s_i, m) = \begin{cases} m \cdot s_i - c^L & \text{if} \quad x_i = 0 \\ (m+1) \cdot s_i - c^H(m+1) & \text{if} \quad x_i = 1 \end{cases}. \tag{4}$$

Assuming players are expected payoff maximizes, they invest in the high-potential technology if and only if $\pi_i^\varepsilon(1 \mid m, s_i) > \pi_i^\varepsilon(0 \mid m, s_i)$. 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 $\pi_i^\varepsilon(1 \mid s_i, N) > \pi_i^\varepsilon(0 \mid s_i, N)$ while at the same time $\pi_i^\varepsilon(1 \mid s_i, 0) < \pi_i^\varepsilon(0 \mid s_i, 0)$. Without knowing what others will do, there

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

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.

Remarkably, 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. I discuss a two-player version of my game to convey the main intuition. For a general (and abstract) analysis, the reader is referred to Carlsson and Van Damme (1993) or Frankel et al. (2003).

Strict dominance. Suppose player i receives a signal $s_i > c^H(0) - c^L + \varepsilon$. In this case, s/he knows that $b > c^H(0) - c^L$ with absolute certainty (see (2)). 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 ($c^H(0) - c^L$). Writing $\overline{s}^0 = c^H(0) - c^L + \varepsilon$, it follows that $\pi_i^\varepsilon(1 \mid \overline{s}^0, m) > \pi_i(0 \mid \overline{s}^0, m)$ for all $m \geq 0$. In contrast, when player i instead receives a much lower signal $s_i < c^H(2) - c^L - \varepsilon$, s/he learns that $b < c^H(2) - c^L$ 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 $\underline{s}^0 = c^H(2) - c^L - \varepsilon$, s/he knows that $\pi_i^\varepsilon(1 \mid \underline{s}^0, m) < \pi_i^\varepsilon(0 \mid \underline{s}^0, m)$ for all $m \geq 0$.

I conclude that either player $i = 1, 2$ invests in H for all signals $s_i > \overline{s}^0$. Similarly, both players invest in L for all 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.[5] 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 j knows b, and that j knows that i knows b, and so on. In comparison, player i's knowledge about what 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 play a strictly dominated strategy, each player i can construct bounds on the posterior

[5] I mean that $\overline{s}^0 > C^H(1) - c^L$ while $\underline{s}^0 < c^H(2) - c^L$, where the right-hand sides of these inequalities are the boundaries of strict dominance in the complete information game, see Proposition 1.

probability that 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 $\Pr(s_j > \underline{s}^0 \mid s_i)$.

Plugging these probabilities into the expected payoffs (4), player i solves for points $\overline{s}^1$ and $\underline{s}^1$ implicitly defined by:

$$\begin{aligned} &\underbrace{\Pr(s_j > \overline{s}^0 \mid \overline{s}^1) \cdot \left[2\overline{s}^1 - c^H(2)\right] + \Pr(s_j < \overline{s}^0 \mid \overline{s}^1) \cdot \left[\overline{s}^1 - c^H(1)\right]}_{\text{Lowest expected payoff to invest in } H, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0} \\ = &\underbrace{\Pr(s_j > \underline{s}^0 \mid \overline{s}^1) \cdot \overline{s}^1 - c^L}_{\text{Highest expected payoff to invest in } L, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0}, \end{aligned} \tag{5}$$

and

$$\begin{aligned} &\underbrace{\Pr(s_j > \underline{s}^0 \mid \underline{s}^1) \cdot \left[2s_2 - c^H(2)\right] + \Pr(s_j < \underline{s}^0 \mid \underline{s}^1) \cdot \left[\underline{s}^1 - c^H(1)\right]}_{\text{Highest expected payoff to invest in } H, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0} \\ = &\underbrace{\Pr(s_j > \overline{s}^0 \mid \underline{s}^1) \cdot \underline{s}^1 - c^L}_{\text{Lowest expected payoff to invest in } L, \text{ given } \overline{s}^0 \text{ and } \underline{s}^0}. \end{aligned} \tag{6}$$

In economic terms, equation (5) 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 payoff to investing in H is higher than the highest expected payoff from investing in L 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 payoff to investing in H is lower than the lowest expected payoff from investing in L, so investment in L is a dominant strategy for all $s_i < \underline{s}^1$. Moreover, note that $\Pr(s_i > \overline{s}^0 \mid \overline{s}^0) = 1/2$ and

$$\frac{1}{2} \cdot \pi_i^{\varepsilon}(1 \mid \overline{s}^0, 1) + \frac{1}{2} \cdot \pi_i^{\varepsilon}(1 \mid \overline{s}^0,) > \pi_i^{\varepsilon}(1 \mid \overline{s}^0, 0) > \pi_i^{\varepsilon}(0 \mid \overline{s}^0, 0), \tag{7}$$

which together imply that $\overline{s}^1 < \overline{s}^0$ and $\underline{s}^1 > \underline{s}^0$.

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 given 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

$$\begin{aligned}&\Pr(s_j > \overline{s}^k \mid \overline{s}^{k+1}) \cdot \left[2\overline{s}^{k+1} - c^H(2)\right] + \Pr(s_j < \overline{s}^k \mid \overline{s}^{k+1}) \cdot \left[\overline{s}^{k+1} - c^H(1)\right] \\ &= \Pr(s_j > \underline{s}^k \mid \overline{s}^{k+1}) \cdot \overline{s}^{k+1} - c^L,\end{aligned} \tag{8}$$

and

$$\begin{aligned}&\Pr(s_j > \underline{s}^k \mid \underline{s}^{k+1}) \cdot \left[2\underline{s}^{k+1} - c^H(2)\right] + \Pr(s_j < \underline{s}^k \mid \underline{s}^{k+1}) \cdot \left[\underline{s}^{k+1} - c^H(2)\right] \\ &= \Pr(s_j > \overline{s}^k \mid \underline{s}^{k+1}) \cdot \overline{s}^{k+1} - c^L,\end{aligned} \tag{9}$$

respectively. Equations (8) and (9) give mathematical expression to essentially the same economic intuition that underlay (5) and (6).

Starting from 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 a dominant strategy 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 $\lim_{k\to\infty} \Pr(s_j > \overline{s}^k \mid \overline{s}^{k+1}) = \Pr(s_j > \underline{s}^* \mid \underline{s}^*) = 1/2$ (and the same for $\underline{s}^*$).[6]

Plugging this into (8) and (9) yields the following system of equations:

$$\begin{aligned}&\frac{1}{2} \cdot \left[2\overline{s}^* - c^H(2)\right] + \frac{1}{2} \cdot \left[\overline{s}^* - c^H(1)\right] = p \cdot \overline{s}^* - c^L, \\ &\frac{1}{2} \cdot \left[2\underline{s}^* - c^H(2)\right] + \frac{1}{2} \cdot \left[\underline{s}^* - c^H(1)\right] = (1-p) \cdot \underline{s}^* - c^L,\end{aligned} \tag{10}$$

where $p = \Pr(s_j > \underline{s}^* \mid \overline{s}^*)$. One can further reduce (10) by subtracting left-hand-sides

[6]This argument only applies if $\overline{s}^* < \overline{B} - 2\varepsilon$. But we know that $\overline{s}^* < c^H(0) - c^L$ while $2\varepsilon < \overline{B} - c^H(0) + c^L$ by assumption, so we are good to go. By a symmetric argument, $\underline{s} > \underline{B} + 2\varepsilon$.

from right-hand sides and then equating the two, which gives:

$$\frac{3}{2} \cdot (\overline{s}^* - \underline{s}^*) = p \cdot \overline{s}^* - (1-p) \cdot \underline{s}^*. \tag{11}$$

Equation (11) is satisfied if either $p = (1-p) = 3/2$ or else $\overline{s}^* = \underline{s}^*$. Since the former is evidently impossible, it follows that $\overline{s}^* = \underline{s}^*$. This has a major implication.

Proposition 2. *The global climate game has a unique equilibrium that survives iterated dominance. 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 $s_i < b^*$. In the 2-player game, it is given by:*

$$b^* = \frac{c^H(2) + c^H(1)}{2} - c^L. \tag{12}$$

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).

Note that the unique equilibrium can be inefficient (and players 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, this statement is theoretically correct: Carlsson and Van Damme (1993) establish that any 2×2 global game selects the risk dominant equilibrium of the underlying true game. But it is vacuous in games with 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.*

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 subsection elaborates.

2.2 Domestic Policy: Network Subsidies

Because the global climate game has a unique equilibrium, it is possible to perform comparative statics. For simplicity of notation, I consider the two-player game, though it should be clear that my qualitative conclusions generalize. In the two-player global climate game, the threshold signal for adoption of the green technology is.

Looking at (12), there are multiple ways to lower the green investment threshold b^*. Each requires a (relative) decrease of $c^H(m) - c^L$ for $m = 0, 1$ or both.

A direct prediction of the model is that carbon taxes and green subsidies can foster adoption of the green technology by changing the *effective* investment cost difference $c^H(m) - c^L$. Tax credits to buyers of the green technology such as the U.S. Federal Tax Credit for Solar Photovoltaics (Borenstein, 2017) or California's Clean Vehicle Rebate Project (Li et al., 2017) will have similar effects . Exempting adopters of the green technology from other pecuniary or non-pecuniary burdens also lowers the threshold to adoption. Decreased registration fees and road taxes on electric vehicles, or allowing them to drive on bus lanes (like in Oslo, Norway) are some examples.

Talking taxes vs. subsidies, a high enough tax on the dirty technology is budget neutral. Such a tax turns investment in the green technology into an iteratively dominant strategy and no individual will adopt the dirty technology as a result, automatically making net tax revenues on dirty investments zero. On the other hand, green subsidies come with a substantial budgetary burden. Receipt of the subsidy is contingent on adoption of the green technology. But a subsidy will compel individuals to invest in the green technology, in which case *all* individuals adopt the green technology. The government's total expenditure on subsidies will therefore be substantial.

A subsidy is expensive because *if* it is successful at boosting green investments, then it is paid to *all* investors. This is somewhat of a paradox. Investors do not need a subsidy when total green investments are high, as in that case there will be strong network effects which increase individual payoffs anyway. I therefore propose a novel type of policy 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 the 2-player game, suppose a policy maker offers investors the following simple network subsidy:

$$t^*(m) = \begin{cases} \frac{c^H(1) - c^H(2)}{2} & \text{if} \quad m = 0 \\ 0 & \text{if} \quad m = 1 \end{cases} \tag{13}$$

In this case, investors receive no subsidy if both invest in the green technology. If only one of them adopts the green technology, s/he receives a subsidy worth half of the cost saving that would have been realized had both invested. It is easy to verify that this subsidy scheme impels each investor to adopt the green technology for all signals $b_i > c^H(1) - c^L$. If ε is sufficiently small, that means the green technology is adopted whenever $b > c^H(1) - c^L$, in which case green investment is also the efficient equilibrium of the true game. The network subsidy therefore guarantees efficient (green) investments. In addition, when both investors adopt the green technology they receive an individual subsidy of zero. By offering this network subsidy the policy maker therefore forces individual investors to coordinate on the efficient equilibrium without, in equilibrium, paying them anything.

Proposition 3. *A well-chosen network subsidy guarantees investment in the green technology whenever that is efficient but does not have to be paid out.*

The network subsidy serves as a kind 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.

2.3 International Environmental Agreements

Whereas domestic policymakers have a mandate to levy taxes or reward subsidies, no such authority exists in the intergovernmental realm. For the design of IEAs, other measures are needed. One possibility is to make adoption a mandatory condition for participation in free trade agreements (Barrett, 1997; Nordhaus, 2015) or otherwise impose stiff penalties on non-adopters, which is how the Montreal Protocol to protect the ozone layer functions. Another is intensified international cooperation on green R&D. Cross-boundary joint ventures naturally amplify the flow of knowledge or know-how between cooperating parties and increases the pace of technological progress (with lower future costs as a result).

2.4 Investment Shares And Continuous Actions

The preceding analysis 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 $N+1$ 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 $[0, N]$. 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.[7] Upon learning the signal s_i, player i's expected payoff to playing x_i is:

$$\pi_i^{\varepsilon}(x_i \mid m) = (m + x_i) \cdot s_i - x_i \cdot c^H(m + x_i) - (1 - x_i) \cdot c^L. \tag{14}$$

Like before, the problem with (14) 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 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 (5) and (6). 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 (8) and (9)). 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 4. *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

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

has a “bang-bang” equilibrium.

3 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 approach advances the literature on international environmental agreements in several ways. 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 formulate and formalize intuitive ways to improve the design and performance of IEAs targeting technological investment or R&D.

Moreover, I highlight 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.

My paper also fits into a broader recent literature that reassesses the potential of international environmental agreements (Harstad, 2012; Battaglini and Harstad, 2016; Harstad et al., 2019), highlighting once again the potential of IEAs that target technological investments and R&D.

While the main focus is on environmental agreements, my model is sufficiently elementary to study other applications as well. It can be used to study domestic policies toward 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.

References

Baker, E., Fowlie, M., Lemoine, D., and Reynolds, S. S. (2013). The economics of solar electricity. *Annual Review of Resource Economics*.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46:878–94.

Barrett, S. (1997). The strategy of trade sanctions in international environmental agreements. *Resource and Energy Economics*, 19(4):345–361.

Barrett, S. (2006). Climate treaties and "breakthrough" technologies. *American Economic Review*, 96(2):22–25.

Barrett, S. (2013). Climate treaties and approaching catastrophes. *Journal of Environmental Economics and Management*, 66(2):235–250.

Barrett, S. and Dannenberg, A. (2012). Climate negotiations under scientific uncertainty. *Proceedings of the National Academy of Sciences*, 109(43):17372–17376.

Barrett, S. and Dannenberg, A. (2017). Tipping versus cooperating to supply a public good. *Journal of the European Economic Association*, 15(4):910–941.

Battaglini, M. and Harstad, B. (2016). Participation and duration of environmental agreements. *Journal of Political Economy*, 124(1):160–204.

Borenstein, S. (2017). Private net benefits of residential solar pv: The role of electricity tariffs, tax incentives, and rebates. *Journal of the Association of Environmental and Resource Economists*, 4(S1):S85–S122.

Carlsson, H. and Van Damme, E. (1993). Global games and equilibrium selection. *Econometrica*, pages 989–1018.

Clinton, B. C. and Steinberg, D. C. (2019). Providing the spark: Impact of financial incentives on battery electric vehicle adoption. *Journal of Environmental Economics and Management*, 98:102255.

Frankel, D. M., Morris, S., and Pauzner, A. (2003). Equilibrium selection in global games with strategic complementarities. *Journal of Economic Theory*, 108(1):1–44.

Greaker, M. and Midttømme, K. (2016). Network effects and environmental externalities: Do clean technologies suffer from excess inertia? *Journal of Public Economics*, 143:27–38.

Harstad, B. (2012). Climate contracts: A game of emissions, investments, negotiations, and renegotiations. *Review of Economic Studies*, 79(4):1527–1557.

Harstad, B., Lancia, F., and Russo, A. (2019). Compliance technology and self-enforcing agreements. *Journal of the European Economic Association*, 17(1):1–29.

Hoel, M. and de Zeeuw, A. (2010). Can a focus on breakthrough technologies improve the performance of international environmental agreements? *Environmental and Resource Economics*, 47(3):395–406.

Hornsey, M. J., Harris, E. A., Bain, P. G., and Fielding, K. S. (2016). Meta-analyses of the determinants and outcomes of belief in climate change. *Nature climate change*, 6(6):622–626.

Katz, M. L. and Shapiro, C. (1985). Network externalities, competition, and compatibility. *American Economic Review*, 75(3):424–440.

Kolstad, C. D. (2007). Systematic uncertainty in self-enforcing international environmental agreements. *Journal of Environmental Economics and Management*, 53(1):68–79.

Li, S., Tong, L., Xing, J., and Zhou, Y. (2017). The market for electric vehicles: indirect network effects and policy design. *Journal of the Association of Environmental and Resource Economists*, 4(1):89–133.

Martimort, D. and Sand-Zantman, W. (2016). A mechanism design approach to climate-change agreements. *Journal of the European Economic Association*, 14(3):669–718.

Mielke, J. and Steudle, G. A. (2018). Green investment and coordination failure: An investors' perspective. *Ecological Economics*, 150:88–95.

Morris, S., Rob, R., and Shin, H. S. (1995). p-dominance and belief potential. *Econometrica*, pages 145–157.

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, 105(4):1339–70.

A Characterizations with $N + 1$ players

$$b^* = 2^{-N} \sum_{k=0}^{N} \binom{N}{k} \cdot c(k+1) - c^L. \tag{15}$$