The Global Climate Game

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February 18, 2021

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Abstract

I study emissions abatement in a game of technological investments. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but clean, and technological investments are strategic complements. The paper makes three contributions. First, it resolves complications due to equilibrium multiplicity in games of technological investment by addressing equilibrium selection through the use of global games. The unique equilibrium may be inefficient, in which case policy interventions are needed. This leads to my second contribution, which is to introduce network subsidies. Network subsidies virtually guarantee efficient adoption of the clean technology but do not, in equilibrium, require any payments to be made. Third, a two-stage extension of the game sheds a new light on the (mostly experimental) literature on institutional choice. In particular, players decide in stage 1 whether or not to make technological investments strategic complements in stage 2; that is, they choose between playing a prisoners' dilemma or a coordination game in the second stage. In contrast to the existing literature, my global games approach allows me to characterize a unique equilibrium irrespective of the type of game chosen by the players. The two-stage game has a unique perfect Bayesian equilibrium and allows for sharp predictions.

1 Introduction

Climate change is among the most exacting of modern-day challenges. In order to reduce cleanhouse gas emissions to the extent required to prevent dangerous climate change, large-scale investments in clean technologies are necessary. These investments, however, are costly and their benefits imperfectly understood. Thus we face a strategic situation in which clean investment are required on behalf of multiple agents, leading to a coordination problem under uncertainty. In this paper, I present what is perhaps the most bare-bones model to study this type of decision problem. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but clean, and technological investments are strategic complements. My contribution is threefold.

First, I show that uncertainty about the clean technology leads to selection of a unique equilibrium. This result is derived using the machinery of global games (Carlsson and Van Damme, 1993) and resolves the complications due to equilibrium multiplicity often encountered in the literature on clean technologies. As many authors have acknowledged, a focus on clean technologies often causes equilibrium multiplicity (Barrett, 2006; De Coninck et al., 2008; Hoel and de Zeeuw, 2010; Hong and Karp, 2012; Harstad, 2012; Battaglini and Harstad, 2016). The intuition is that technological investments can exhibit positive spillovers or other kinds of strategic complementarities (Bulow et al., 1985), turning the game into a coordination game with multiple equilibria. There are several reasons why technological investments may exhibit strategic complementarities. Among those discussed in the literature on clean technologies are network effects (Katz and Shapiro, 1985; Greaker and Midttømme, 2016; Li et al., 2017; Mielke and Steudle, 2018; Clinton and Steinberg, 2019); cost sharing: (De Coninck et al., 2008); R&D in breakthrough technologies (Barrett, 2006; Hoel and de Zeeuw, 2010); tipping points (Barrett and Dannenberg, 2017); climate clubs (Nordhaus, 2015); technological and knowledge spillovers (Kverndokk and Rosendahl, 2007; Fischer and Newell, 2008; Gerlagh et al., 2009; Aghion and Jaravel, 2015; Harstad, 2016); social norms (Allcott, 2011; Nyborg, 2018b; Kverndokk et al., 2020; Andor et al., 2020); and reciprocity (Nyborg, 2018a).

Equilibrium multiplicity makes the outcome of a game hard to predict. This complicates policymaking; moreover, it is intuitively dissatisfying. First, one would expect economic, environmental, or technological fundamentals to play a role in equilibrium selection. Second, experimental evidence confirms that individuals coordinate their actions in coordination games, though not always on the Pareto dominant equilibrium (Barrett and Dannenberg, 2012, 2017). Third, treaties like the Montreal Protocol or the Paris Agreement are ratified nearly universally, suggesting that coordination is possible in the real world as well. The unique equilibrium I derive admits these properties: players coordinate their actions, the equilibrium may be Pareto dominated, and coordination on the clean technology is more likely as the clean investments become inherently more attractive, ceteris paribus.

My second contribution is to propose network subsidies. Like standard subsidies, a network subsidy provides adopters of the clean technology with a (financial) reward. Yet the amount paid to an individual investor is contingent on total investments. As I show, it is possible to construct a simple network subsidy scheme that guarantees efficient adoption of the clean technology but does not, in equilibrium, require the policymaker to pay anything. Intuitively, the network subsidy serves as an insurance against small clean networks. In so doing, it boosts clean investments and therefore is never claimed. This result is independent of the application to clean technologies and suggests that network subsidies are worth studying in other environments characterized by strategic complementarities.

Lastly, my third contribution is to addresses an open question in the literature on institutional design. A growing body of literature studies the endogenous formation of institutions to overcome "cooperation problems arising in prisoners' dilemmas, public goods games, and common pool resource games (Dannenberg and Gallier, 2019)". The idea is that players, prior to playing a game, can have a say in the type of game they will be playing. Barrett and Dannenberg (2017), for example, run experiments in which players can choose between plating either a prisoners' dilemma or a coordination game. Since coordination games of complete information have multiple equilibria, it is nor a priori clear what players will choose: while the coordination game offers them a chance to end up in a better equilibrium, if coordination fails they are worse off than in the prisoners' dilemma. There is no clear game theoretic prediction when such a two-stage game is played under complete information, which is why the literature resorts to experiments in an attempt to make predictions. On the other hand, if the second stage is a global game it will have a unique equilibrium, irrespective of the type of game chosen. In this case, I prove that the two-stage game has a unique perfect Bayesian equilibrium. I identify sharp conditions under which players will choose the coordination game (in a nutshell, the cost of picking a coordination game has to be low enough) and can perform comparative statics with respect to primitives of the model. In this sense, my theory formalizes several experimental findings on these types of games (Barrett and Dannenberg, 2017; Dal Bó et al., 2018; Dannenberg and Gallier, 2019).

For example, consider international environmental agreements (IEAs). A classic insight is that IEAs targeting emissions abatement directly are essentially a prisoners' dilemma and can achieve very little (Carraro and Siniscalco, 1993; Barrett, 1994). On the other hand, a more recent literature argues hat treating targeting *technologies* may be more successful (Barrett, 2006; De Coninck et al., 2008; Hoel and de Zeeuw, 2010; Hong and Karp, 2012; Harstad, 2012; Battaglini and Harstad, 2016). As discussed, I show that such a game will have a uniquely determined equilibrium – and this means that players, in stage 1, can assign well-defined prior probabilities to the event that the efficient equilibrium is chosen in a coordination game. The question my result addresses is then a rather fundamental one: what type of treaty do countries choose to sign, one aiming at abatement directly, or one focusing on technologies?

In my model, equilibrium selection is catalyzed by uncertainty about the clean technology.[1] For this technical reason alone, it is convenient to consider games of incomplete information when studying clean technologies. In addition, however, the assumption seems realistic. There are many uncertainties surrounding climate change and individual 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.

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. Section 4 introduces network subsidies, while Section 5 discusses a two-stage game of instutional choice. Finally, Section 6 extends the analysis to continuous action spaces, and Section 7 concludes.

[1]This type of "global uncertainty" turns the game into a global game. However, other approaches toward equilibrium selection also exist. For example, Poisson games (Matsui and Matsuyama, 1995; Myerson, 1998, 2000; Makris, 2008), i.e. games in which players are uncertain about the number of other players playing the game. Poisson coordination games also have a unique equilibrium as the uncertainty becomes arbitrarily small. Evolutionary approach: (Kandori et al., 1993).

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 the dirty technology, is a cheap and dirty technology. If a player does not invest in the dirty technology, s/he invests in H, an expensive but environmentally-friendly clean technology. One could think of H as a breakthrough technology (Barrett, 2006; Hoel and de Zeeuw, 2010). Compared to investment in the dirty technology, 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 6. For each player i, define m to be the total number of *other* players who invest in the clean technology, i.e. $m = \sum_{j \neq i} x_j$.

Investments are costly. Let the marginal cost of investing in the dirty technology be constant at d. Given m, let the cost of investment in H be $c(m)$. I assume that c is a decreasing function of m, so $c(m+1) < c(m)$ 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 clean technology. If the climate club gets larger, these restrictions become more expensive for players outside the club, effectively lowering the net cost of clean 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:

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

The assumption that a player investing in the dirty technology ($x_i = 0$) enjoys benefits $b \cdot m$ due to clean investments by others captures the idea that the clean 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 clean investment (a club good) or even not at all (private goods) will deliver equivalent results.[2]

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

Proposition 1. *For all $b \in \left(\frac{c(N)-d}{N}, c(1) - d\right)$, the game has two strict Nash equilibria.*

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

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

(iii) Payoffs are strictly higher in the clean equilibrium.

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 clean 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 (i.e. turn into a dominant strategy) clean investment may need to be high in the game of complete information:

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

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

[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.

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 clean investments drive equilibrium multiplicity under common knowledge of b, the marginal environmental benefit of clean 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 clean 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 $\underline{B} < c(N) - d$ and $\overline{B} > c(1) - d$. Each player i in addition receives a private noisy signal b_i of b, given by:

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

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, $2\varepsilon < \min\{c(N) - d - \underline{B}, \overline{B} - c(1) + d\}$. Clearly, when player i receives the signal b_i, s/he does not know the signal b_j of any other player j, though s/he does know that $b_j \in [b_i - 2\varepsilon, b_i + 2\varepsilon]$.

There is a conceptual distinction between global games uncertainty as in (3) or more standard models of incomplete information (Kolstad, 2007; Barrett and Dannenberg,

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

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:

$$\mathbb{E}[b \mid b_i] = \frac{1}{2\varepsilon} \int\limits_{b_i-\varepsilon}^{b_i+\varepsilon} y \, dy = b_i. \tag{4}$$

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

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

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

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

Assuming players are expected payoff maximizes, they invest in the high-potential technology if and only if $\Delta_i^\varepsilon(b_i, m) > 0$. 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 b_i, player i's best-response critically depends on m as $\Delta_i^\varepsilon(b_i, N) > 0$ while at the same time $\Delta_i^\varepsilon(b_i, 0) < 0$. 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 $b_i > c(1) - d + \varepsilon$. In this case, s/he knows that $b > c(1) - d$ with absolute certainty (see (3)). But if $b > c(1) - d$, clean investment is a dominant strategy. In economic terms, the marginal environmental benefit of investing in the clean technology (b) is so high, or climate change so severe, it warrants incurring even a very high increase in the cost of investment ($c(1) - d$). Writing $\overline{b}^0 = c(1) - d + \varepsilon$, it follows that $\Delta_i^\varepsilon(\overline{b}^0, m) > 0$ for all $m = 0, 1, ..., N - 1$. In contrast, when player i receives a much lower signal $b_i < c(N) - d - \varepsilon$, s/he learns that $b < c(N) - d$ in which case dirty investment is a dominant strategy. The marginal environmental gain from adopting the clean technology is so low not even a small increase in investment costs is worth it. Writing $\underline{b}^0 = c(N) - d - \varepsilon$, s/he knows that $\Delta_i^\varepsilon(\underline{b}^0, m) < 0$ for all $m = 0, 1, ..., N - 1$.

I conclude that any player i invests in H for all signals $b_i > \overline{b}^0$. Similarly, all players definitely invest in the dirty technology for signals $b_i < \underline{b}^0$. 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 b_i, all s/he can say is that j must have seen some signal in $[b_i - 2\varepsilon, b_i + 2\varepsilon]$. This brings me to a crucial step in the analysis.

Iterated dominance. The points $\overline{b}^0$ and $\underline{b}^0$ 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 probability that any other player j invests in either the dirty technology or H. After all, j definitely does not invests in the dirty technology when $b_j > \overline{b}^0$, which implies that the *minimum* probability player i can assign to the event that player 1 invests in H is simply $\Pr(b_j > \overline{b}^0 \mid b_i)$. By the same token, player j will certainly invest in the dirty technology for all $b_j < \underline{b}^0$, so the *maximum* probability with which player i can believe j will invest in H is $\Pr(b_j > \underline{b}^0 \mid b_i)$.

[4] I mean that $\overline{b}^0 > C^H(1) - d$ while $\underline{b}^0 < c(N) - d$, 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).

With these probabilities, it is straightforward to derive boundaries on the posterior beliefs of player i on m. When i receives signal b_i, the lowest probability s/he can assign to the event that $x_j = 1$ is $\Pr(b_j > \overline{b}^0 \mid b_i)$, and so the highest probability of $x_j = 0$ is given by $\Pr(b_j < \overline{b}^0 \mid b_i) = 1 - \Pr(b_j > \overline{b}^0 \mid b_i)$. 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 $[\Pr(b_j > \overline{b}^0 \mid b_i)]^n \cdot [\Pr(b_j < \overline{b}^0 \mid b_i)]^{N-n-1}$. 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 $\binom{N-1}{n}[\Pr(b_j > \overline{b}^0 \mid b_i)]^n \cdot [\Pr(b_j < \overline{b}^0 \mid b_i)]^{N-n-1}$. Analogously, the highest probability that any n players j play $x_j = 1$ while the others play $x_j = 0$ is therefore $\binom{N-1}{n}[\Pr(b_j > \underline{b}^0 \mid b_i)]^n \cdot [\Pr(b_j < \underline{b}^0 \mid b_i)]^{N-n-1}$.

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

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

and

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

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

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

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

while also

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

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

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

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

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

and

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

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

Given the facts that $\overline{b}^1 < \overline{b}^0$ and $\underline{b}^1 > \underline{b}^0$, an inductive argument at once establishes that $\overline{b}^{k+1} < \overline{b}^k$ and $\underline{b}^{k+1} > \underline{b}^k$ for all $k \geq 0$. Moreover, I note that $\overline{b}^k \geq \underline{b}^k$ for all k

since it is clearly impossible that investment in both the dirty technology and H is dominant at the same signal. It follows that $(\overline{b}^k)_{k=0}^{\infty}$ and $(\underline{b}^k)_{k=0}^{\infty}$ are bounded. But bounded monotone sequences have to converge; let $\overline{b}^*$ and $\underline{b}^*$, respectively, be their limits. In game theoretic parlance, it is said that investment in the clean technology is *iteratively dominant* for all signals $b_i > \overline{b}^*$. Investment in the dirty technology is iteratively dominant for all signals $b_i < \underline{b}^*$.

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

$$\overline{b}^* + d - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n+1)}{2^{N-1}} = \underline{b}^* + d - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n+1)}{2^{N-1}} = 0. \tag{13}$$

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

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

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

While theoretically Proposition 2 is 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).

I should emphasize that Proposition 2 really has two parts. Generally, the global climate game has a unique equilibrium. This is the first part of the proposition. Only in the special case where the noise ε vanishes does the model predict perfect coordination of *actions* (i.e. clean or dirty investment) with probability 1. The reason is that an

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

equilibrium is defined in terms of *strategies*, not actions. A strategy only yields an action once we plug a signal into it. But if the noise ε is not vanishing, signals can lie apart – in fact, some players may receive signals above b^* while others see a signal below it – and this may lead to coordination failure in terms of actions (but, again, not strategies). The implication is that empirically observed coordination failures are not at odds with, and therefore do not by themselves invalidate the model.

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 clean technology instead (and even though they know it). Intuitively, clean investment will be too risky when b is low since the noise in signals forces a player to believe that others may think that clean investment is dominated. Barrett and Dannenberg (2012) appear to share this view when they write that "players could use risk-dominance as a selection rule." For 2×2 games, their statement is backed by the theoretical literature: 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 becomes vacuous when there are more than two players (or actions) as risk-dominance is only defined for 2×2 games. Though generalizations such as p-dominance have been developed (Morris et al., 1995), these are not, in general, predictive for equilibrium selection (Frankel et al., 2003).

Proposition 3. *For all $b \in \left(\frac{c(N)-d}{N}, b^*\right)$, 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 clean technology instead.*

While Proposition 2 backs the focus on a unique equilibrium in coordination games of technological investment, Corollary 3 adds the qualification that coordination will not always be on the Pareto dominant equilibrium. This stands in contrast to the standard and often implicit assumption in the environmental literature that players will coordinate on the efficient equilibrium (Barrett, 2006; Hoel and de Zeeuw, 2010).

The paradox of Corollary 3 is that players may coordinate on the dirty technology despite knowing they are better off if instead they could coordinate on the clean technology. It is a tragedy of the commons of sorts. Because both individual investors and society as a whole are worse off in this case, it motivates policy intervention. The next section elaborates.

4 Network Subsidies

In this section, I study the problem of a domestic policymaker who wants to stimulate clean investments by individuals, firms, or industries. Different from the application to IEAs, the policymaker has taxes and subsidies at its disposal.[7]

Looking at (14), the global climate game predicts that taxes and subsidies will work whenever they cause an effective decrease of $c(m) - d$ 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.[8]

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

$$t \geq \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n)}{2^{N-1}} - c(N). \tag{15}$$

Importantly, recall that $c(n)$ is decreasing in n due to the strategic complementarities in clean investments. This implies that $\sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n+1)}{2^{N-1}} < c(1)$. Comparing (2) and (15) therefore reveals that $t < t^c$. If network effects are strong, this difference 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; Kverndokk and Rosendahl, 2007; Gerlagh et al., 2009; 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 clean investments.

Proposition 4. *The tax or subsidy t^c required to guarantee adoption of the clean technology in a game of complete information may be substantially lower than the tax or subsidy t required in the global game.*

[7] Angeletos et al. (2006)

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

Unfortunately, subsidy spending may need to be very high if many players adopt the green technology, leading to budgetary issues. To overcome this problem, I suggest a policy of *network subsidies*. Like standard subsidies, a network subsidy is offered contingent on adoption of the clean technology. But the sum paid to individual investors is decreasing in the total amount of clean investments. In particular, let a policymaker offer the following simple network subsidy:

$$s^*(m) = c(m+1) - c(N), \tag{16}$$

for all $m = 0, 1, ..., N-1$. In words, when player i adopts the clean technology and m others have done so too, i receives a subsidy equal to $c(m+1) - c(N)$. With this subsidy, the expected gain to investing is:

$$\Delta_i^{\varepsilon}(b_i, m) + s^*(m) = b_i + d - c(N), \tag{17}$$

which is positive for all $b_i \geq c(N) - d$. Assuming that ε is sufficiently small, each player i therefore adopts the clean technology for all $b > c(N) - d$. But this is also the condition for clean investments to be Pareto dominant. It follows that all players invest in the clean technology whenever that is socially efficient, in which case each receives a subsidy of $s^*(N-1) = c(N) - c(N) = 0$. The network subsidy therefore guarantees overall adoption of the clean technology whenever that is efficient but does not cost the policymaker anything.

Proposition 5. *Let ε be sufficiently small. A network subsidy equal to* (16) *guarantees investment in the clean technology for all $b > c(N) - d$ but does not, in equilibrium, cost the policymaker anything.*

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

The requirement that signals are sufficiently precise drives the extreme result in Proposition 5. But it is also restrictive. What if signals are less precise?

Suppose that exactly n players have chosen to adopt the clean technology, whereas the remaining $N-n$ players invested dirty. If the policymaker offers the network subsidy scheme s^* specified in (16), total spending on the subsidy is then simply $n \cdot s^*(n)$

We know from (17) that an expected payoff maximizing player i adopts the clean technology for all $b_i > c(N) - d$ when offered a network subsidy scheme s^*. What we want to know, therefore, is the probability that any player i's signal satisfies this inequality. Conditional on b and ε, it is given by:

$$\Pr[b_i < c(N) - d \mid b, \varepsilon] = \Pr[\varepsilon_i < c(N) - d - b \mid b, \varepsilon] = \frac{1}{2} - \frac{b + d - c(N)}{2\varepsilon}, \tag{18}$$

where the final equality holds for all $c(N) - d - \varepsilon \leq b \leq c(N) - d + \varepsilon$, while it is either 0 or 1 otherwise. Clearly, the probability that $b_i > c(N) - d$ is simply the complement of (18):

$$\Pr[b_i > c(N) - d \mid b, \varepsilon] = 1 - \Pr[b_i < c(N) - d \mid b, \varepsilon]. \tag{19}$$

There are precisely $\binom{N}{n}$ different ways in which n players out of N can adopt the clean technology. Thus, the total probability that n players adopt the green technology (while N_n invest dirty), given b and ε, is:

$$p(n \mid b, \varepsilon) = \binom{N}{n} \cdot \left[\frac{1}{2} - \frac{b + d - c(N)}{2\varepsilon}\right]^n \cdot \left[\frac{1}{2} + \frac{b + d - c(N)}{2\varepsilon}\right]^{N-n}, \tag{20}$$

when $c(N) - d - \varepsilon \leq b \leq c(N) - d + \varepsilon$, and $p(n \mid b, \varepsilon) = 0$ otherwise. The following proposition summarized our discussion.

Proposition 6. *Let the policymaker offer a network subsidy equal to* s^*. *For all* $b \notin (c(N) - d - \varepsilon, c(N) - d + \varepsilon)$, *spending on the network subsidy is zero. For* $b \in (c(N) - d - \varepsilon, c(N) - d + \varepsilon)$, *expected spending on the network subsidy is*

$$S^\varepsilon = \sum_{n=0}^{N} p(n \mid b, \varepsilon) \cdot n \cdot s^*(n) > 0. \tag{21}$$

Since the prior probability that $b \in (c(N) - d - \varepsilon, c(N) - d + \varepsilon)$ *is* $2\varepsilon/(\overline{B} - \underline{B})$, *the expected spending on a network subsidy before* b *is drawn is equal to* $2\varepsilon \cdot S^\varepsilon/(\overline{B} - \underline{B})$, *which vanishes to 0 as* $\varepsilon \to 0$.

Importantly, network subsidies work in environments with complete information too. Nowhere crucial in deriving the network subsidy given by (16) did I use the fact that players are uncertain about the clean technology's true potential b.

Proposition 7. *If a network subsidy equal to* (16) *is offered in the game with common* *knowledge of b, it also implements the efficient equilibrium of the game without costing the policymaker anything.*

The logic of a network subsidies does not rely on the application to climate change either. Any market where (i) individual actions exhibit strategic complementarities and (ii) private agents do not take the beneficial effect of their own actions on others into account may potentially coordinate on an inefficient equilibrium. A network subsidy then offers an inexpensive way out of this trap. The observation suggests that network subsidies are worth studying in economics more generally.

The notion of a network subsidy developed in this paper is somewhat related to the idea of sequentially offered exclusionary contracts offered by an incumbent firm to exclude market entry of a new firm (Segal and Whinston, 2000).

5 Institutional Choice

A growing body of literature studies the endogenous choice of institutions to overcome "cooperation problems arising in prisoners' dilemmas, public goods games, and common pool resource games (Dannenberg and Gallier, 2019)". This literature motivates the question of what will happens when the strategic complementarities in (clean) investments are endogenous to players' decisions. That is, would happen if players could endogenously set up institutions that generate strategic complementarities in investments, prior to actually investing?

Consider the example of an international environmental agreement (IEA). While IEAs targeting abatement directly are often modeled as prisoners' dilemmas (c.f. Carraro and Siniscalco (1993) or Barrett (1994)), a more recent literature suggests that treating targeting *technologies* may be more successful (Barrett, 2006; De Coninck et al., 2008; Hoel and de Zeeuw, 2010; Hong and Karp, 2012; Harstad, 2012; Battaglini and Harstad, 2016). The intuition is simple: 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 clean investments as an equilibrium.[9] Clearly, countries can decide what kind of treaty to sign prior to actually signing it. So when will countries choose to target technologies rather than abatement?

[9]Another interpretation would be a model where only the dirty technologies exist and players can first decide whether or not to engage in R&D and *invent* a clean technology, after which it is decided which technology they adopt.

To study institutional choice, I turn the game in Section 3 into a two-stage game. In stage 1 of the game, players vote on whether or not to create strategic complementarities in technological investments into the second stage. There is a decision-rule mapping votes into a choice of game. Here, I assume that strategic complementarities are "created" only if player unanimously vote in favor but, importantly, my predictions would be equivalent were I instead to assume that a simple majority suffices.[10] In any case, *if* strategic complementarities are created each player incurs a commonly known cost $k > 0$.

Next, stage 2 is the game studied in Section 3, with one important exception: there are strategic complementarities in clean investments if and only if players voted to create those in stage 1. The game has the following stages:

1. Players vote on the type of game to be played. They must choose between *(i)* a game with fixed investment costs, or *(ii)* a game where clean investments are exhibit cost spillovers. If *(ii)* is chosen, all incur a cost k.

2. Players receive their signals of b and play the game decided upon in stage 1.

Players in stage 1 make a tradeoff between the cost of turning turn stage 2 into a coordination game and the benefit of an increased likelihood that the clean technology gets adopted. To see this, observe that a player adopts the clean technology in the prisoners' dilemma without strategic complementarities whenever $b_i > c(1) - d$, but this same player will adopt the clean technology in the coordination game with strategic complementarities already for $b_i > b^*$.

Essentially, then, the choice to create strategic comlementarities in stage 2 is a gamble with a known cost and an stochastic gain. Straightforward backward induction establishes that players will rationally choose to take this gamble as long as the cost k is no higher than k^*, given by:

$$\begin{aligned} k^* = & \frac{\overline{B} - c(1) + d}{\overline{B} - \underline{B}} \left[N \cdot \frac{b^* + c(1) - d}{2} - c(N) + c(1) \right] \\ & + \frac{c(1) - d - b^*}{\overline{B} - \underline{B}} \left[N \cdot \frac{b^* + \overline{B}}{2} - c(N) + d \right]. \end{aligned} \tag{22}$$

[10] In international negotiations, decisions of this kind are routinely made by a vote. For example, the rules of procedure for meetings of the parties to the ozone agreements say that "decisions... on all matters of substance shall be taken by a two-thirds majority vote..." (see http://ozone.unep.org/Publications/VC Handbook/Section 3 Rules of Procedure/Rules of procedure.shtml).

Proposition 8. *The two-stage game has a unique perfect Bayesian equilibrium. In the first stage of the game, players choose to generate strategic complementarities in clean investments if and only if $k \leq k^*$. In the second stage of the game, player i adopts the clean technology if and only if (i) $b_i > c(1) - d$ when the game does not exhibit strategic complementarities; or (ii) $b_i > b^*$ when the game does exhibit strategic complementarities.*

If $k < k^*$, each player strictly prefers that strategic complementarities are generated in order to subsequently play a coordination game. Hence, simple majority and unanimous voting rules lead to the same outcome in this model – they 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 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 (22), a strategy of trade sanctions (Nordhaus, 2015) or restrictions on foreign direct investments can stimulate ratification of IEAs targeting clean technologies in the two-stage game. Interpreting such policies as an increase in the effective cost of dirty investments k, they are two mutually reinforcing effects.

First, it directly expands the range of costs k for which countries are willing to participate in international R&D networks, increasing the odds that a clean technology gets developed in stage 1. Second, an increase in k 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 clean 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 straightforwardly by differentiating (22) with respect to b^*.

Proposition 9. *In the two-stage game, a strategy of trade sanctions or restricted foreign direct investment imposed on countries not adopting the clean technology in stage 2 (conditional on the clean technology being invented) is an effective way to induce adoption of the clean technology. By implicitly increasing k, these policies have a twofold effect. First, they make the creation of an international R&D platform, and thus a clean technology, more likely in stage 1. Second, and conditional on the R&D platform being created, they make ratification of the IEA targeting clean technologies more likely in stage 2.*

Environmental agreements like the Montreal and Kyoto Protocols or the Paris Agreement are usually signed under the auspices of the United Nations. Proposition 9 suggests that a more comprehensive approach – involving, for example, the World Trade Organization or the Organisation for Economic Co-operation and Development[11] – would offer promising prospects for the development of clean technologies and the ratification of more demanding IEAs.

6 Investment Shares Or 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, as I show here.

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 clean 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 the dirty technology faces marginal investment costs of d. Given m, the marginal cost of investment in H is $c(m)$, which is decreasing in m.[12] Conditional on m, I assume that $c(m + x_i)$ is linearly decreasing in x_i. Upon learning the signal b_i, player i's expected payoff to playing x_i is:

$$\pi_i^{\varepsilon}(x_i \mid m) = (m + x_i) \cdot b_i - x_i \cdot c(m + x_i) - (1 - x_i) \cdot d. \tag{23}$$

Like before, the problem with (23) 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 $\pi_i^{\varepsilon}(1 \mid b_i, m) > \pi_i^{\varepsilon}(x_i \mid b_i, m)$ for all $m \in [0, N]$ and all $b_i > \overline{b}^0$. This is easy to verify. At signals $b_i > \overline{b}^0$, 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 the dirty technology will yield a strictly lower payoff than investment in H alone. It follows that rational players will only invest in the clean technology, i.e. choose $x_i = 1$, for all $b_i > \overline{b}^0$. By the same token, players choose $x_i = 0$ for all $b_i < \underline{b}^0$.

As in the game with discrete investment decisions, any player i can again construct

[11] The OECD's Code of Liberalisation of Capital Movements is "the only multilateral agreement and tool providing for the management of the full range of cross-border capital flows between its 36 members (OECD, 2019)."

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

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 $\overline{b}^1$ and $\underline{b}^1$, 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 10. *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 $b_i > b^*$, while s/he invest in the low-potential technology for all $b_i < b^*$.*

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

7 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 clean 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 clean 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 clean 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 clean 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 makes three contributions. First, in showing that the game has a unique equilibrium it directly addresses the issue of equilibrium multiplicity often encountered in this literature. Equilibrium selection is driven by the assumption of incomplete information, which seems very realistic in the context of clean technologies and climate change. The analysis highlights that the precise way in which one models uncertainty is important. 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.

Second, it exploits the structural properties of strategic complementarities to formulate a new type of policy, called network subsidies. Like standard subsidies, a network subsidy provides adopters of the clean technology with a (financial) reward. But the amount paid to an individual investor is contingent on total investments. As I show, it is possible to construct a simple network subsidy scheme that guarantees efficient adoption of the clean technology but does not, in equilibrium, require the policymaker to pay anything. Intuitively, the network subsidy serves as an insurance against small clean networks. In so doing, it boosts clean investments and therefore is never claimed.

Third, a two-stage extension of my base model provides an overarching theoretical framework for the largely experimental literature on institutional choice (Barrett and Dannenberg, 2017; Dal Bó et al., 2018; Dannenberg and Gallier, 2019). My results formalize several experimental findings that, thus far, were not explained theoretically.

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