The Global Climate Game

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Abstract

I study emissions abatement in a global game of technological investments. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but clean, and investments exhibit technological spillovers. The paper makes two main contributions. My first contribution is to resolve complications due to equilibrium multiplicity in games of technological investment by addressing equilibrium selection through the use of global games. In well-identified cases the unique equilibrium is inefficient, motivating policy intervention. This leads to my second contribution, the introduction of network subsidies. A network subsidy allows the policymaker to correct for the entire externality deriving from technological spillovers but does not, in equilibrium, cost anything. Albeit derived in the context of climate change, the concept of a network subsidy is general and contributes to public economics generally.

1 Introduction

Climate change is a coordination failure of existential proportions. In order to reduce greenhouse gas emissions and 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 investments exhibit technological spillovers.

My first contribution is to show that uncertainty about the clean technology leads to selection of a unique Bayesian Nash equilibrium. This result is derived using the machinery of global games (Carlsson and Van Damme, 1993; Frankel et al., 2003) and resolves complications caused by 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); climate 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 (Nyborg et al., 2006; 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 and complicates policymaking; moreover, it is intuitively dissatisfying for several reasons. First, one would expect economic, environmental, or technological fundamentals to play a role in equilibrium selection. Second, experimental evidence confirms that individuals manage to coordinate their actions in coordination games (Barrett and Dannenberg, 2012, 2017). Third, international treaties like the Montreal Protocol or the Paris Agreement are ratified by overwhelming majorities of countries, 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.

In much of the environmental literature, equilibrium selection is treated somewhat implicitly. Two approaches are especially prevalent. One approach hand-picks, or at minimum focuses on a particular equilibrium. Thus, players may be a priori assumed to pursue symmetric strategies (Harstad, 2012; Harstad et al., 2019), or to coordinate on the Pareto dominant outcome (Barrett, 2006; Hoel and de Zeeuw, 2010). These papers have generated many tried and tested insights, yet the question remains why we should expect real-world players to behave according to the essentially ad hoc assumptions entertained by the authors. Another approach treats the coordination problem as theoretically indecisive and relies on lab experiments to make predictions (Barrett and Dannenberg, 2012, 2014, 2017; Calzolari et al., 2018; Dengler et al., 2018). While these papers, too, have had a lasting influence on the way we think about possible strategies to fight climate change, it is unclear whether and how to generalize their experimental findings to settings outside the laboratory. My explicit focus on equilibrium selection complements these approaches. It provides sharp conditions under which we would expect rational players to coordinate on the Pareto dominant equilibrium of the game. It also identifies one possible mechanism that, at a theoretical level, explains the behavior observed in the lab.

The unique equilibrium of the game may be inefficient. For intermediately high clean investment benefits, players adopt the dirty technology even though they would be better off were all to adopt the clean technology instead. This result calls for policy intervention.

My second contribution is the introduction of network subsidies. Like standard subsidies, a network subsidy offers adopters of the clean technology a (financial) reward. Yet the amount paid to an individual investor is contingent on total adoption. As I show, it is possible to construct a simple network subsidy scheme that corrects the entire network externality deriving from players' ignorance of the technological spillovers caused by their clean investment but does not, in equilibrium, cost the policymaker anything. Key to this result is the property that the amount of subsidy paid to each individual investor is a function of aggregate clean investments. Since adoption of the clean technology is more attractive when the number of other players adopting it is higher due to the technological spillover, it is quite intuitive that the network subsidy can decrease in aggregate clean technology adoption without negatively affecting players' incentives. My result is to show that this intuition can be exploited smartly: the policymaker can offer a network subsidy scheme such that what is paid when *all* players adopt the clean technology is zero while at the same time creating incentives to adopt the clean technology whenever that is Pareto dominant (in expectations). Intuitively, the network subsidy insures adopters of the clean technology against the event they would enjoy few technological spillovers since many others adopted the dirty technology. 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 contexts where strategic complementarities occur.

In my model, equilibrium selection is catalyzed by uncertainty about the clean technology.[1] 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. 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 the type of uncertainty with idiosyncratic, player-specific (posterior) beliefs studied here.

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, and Section 5 concludes.

2 Main Model

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

Each player chooses to invest in either of two technologies. The first, called the dirty technology, is a cheap and dirty technology. If a player does not invest in the dirty technology, s/he invests in the clean technology, an expensive but environmentally-friendly clean technology. One could think of the clean technology as a breakthrough

[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. Another well-known approach derives equilibrium selection as a dynamic outcome of a process of evolutionary selection (Kandori et al., 1993).

technology (Barrett, 2006; Hoel and de Zeeuw, 2010). Compared to investment in the dirty technology, the marginal environmental benefit of investing in the clean technology 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 the clean technology. 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 the clean technology 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 (Bollinger and Gillingham, 2012; Gillingham and Bollinger, 2021), 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:

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

There are two externalities associated with investment in the clean technology. The first is an *environmental externality* and relates to the parameter b, the positive impact an individual player's investment in the clean technology has on the environment for all other players – think of reduced CO2 emissions. The second is a *network externality* and relates to the investment cost function c, i.e. it captures the fact that a player's investment in the clean technology lowers the cost of clean technological investment for all other players – think of technological or knowledge spillovers.

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 $b < c(N) - d$. In between, the game has multiple equilibria.

Proposition 1. *For all $b \in (c(N) - d, c(1) - d)$, the game has two strict pure strategy Nash equilibria. In one equilibrium, all players adopt the dirty technology and individual payoffs are $-d$; in the other, all adopt the clean technology and individual payoffs are $b \cdot N - c(N)$. The equilibrium in which the clean technology gets adopted is Pareto dominant.*

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. But the assumption of perfect information is strong. There are large numbers of uncertainties surrounding many clean technologies'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 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:

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

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 $[-\varepsilon, \varepsilon]$.[2] I assume that ε is sufficiently 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 (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 (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:

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

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

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

Define the expected *gain* from investing in the clean technology, rather than the dirty technology, as:

$$\Delta_i^{\varepsilon}(b_i, m) = \pi_i^{\varepsilon}(1 \mid b_i, m) - \pi_i^{\varepsilon}(0 \mid b_i, m) = b_i + d - c(m+1). \tag{5}$$

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,

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

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 environments of complete information, 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 (2)). 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 the clean technology 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.[3] 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.[4] 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

[3] 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.

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

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 the clean technology. 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 the clean technology 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 the clean technology is $\Pr(b_j > \underline{b}^0 \mid b_i)$.

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 (4), player i solves for points $\overline{b}^1$ and $\underline{b}^1$ implicitly defined by:

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(b_j > \overline{b}^0 \mid \overline{b}^1)\right]^n \cdot \left[\Pr(b_j < \overline{b}^0 \mid \overline{b}^1)\right]^{N-n-1} \cdot \Delta_i^\varepsilon(\overline{b}^1, n)}_{\text{Lowest expected gain from investing in the clean technology, given } \overline{b}^0 \text{ and } \underline{b}^0} = 0, \tag{6}$$

and

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

In economic terms, equation (6) 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 the clean technology positive when $b_i > \overline{b}^1$. It follows that investment in the clean technology 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 the clean technology 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

$$2^{1-N} \sum_{n=0}^{N-1} \binom{N-1}{n} \Delta_i^{\varepsilon}(\overline{b}^0, n) > \Delta_i^{\varepsilon}(\overline{b}^0, 0) \geq 0, \tag{8}$$

while also

$$2^{1-N} \sum_{n=0}^{N-1} \binom{N-1}{n} \Delta_i^{\varepsilon}(\underline{b}^0, n) < \Delta_i^{\varepsilon}(\underline{b}^0, N-1) \leq 0, \tag{9}$$

which together imply that $\overline{b}^1 < \overline{b}^0$ and $\underline{b}^1 > \underline{b}^0$ on account of the fact that $\Delta_i^{\varepsilon}(b_i, m)$ is increasing in b_i for all m. 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 green. For this reason, player i is willing to adopt the clean 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. Given the technological spillovers inherent in investments, these bounds are critical and lead to additional strategies being strictly dominated (the points $\overline{b}^1, \underline{b}^1$). But if player i knows that all other players will invest in the clean technology (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. Inductively proceeding with the above procedure yields two sequences of points $(\overline{b}^k)_{k=0}^{\infty}$ and $(\underline{b}^k)_{k=0}^{\infty}$, where, for all $k \geq 0$ $\overline{b}^{k+1}$ and $\underline{b}^{k+1}$ are the solutions to

$$\underbrace{\sum_{n=0}^{N-1} \binom{N-1}{n} \left[\Pr(b_j > \overline{b}^k \mid \overline{b}^{k+1})\right]^n \cdot \left[\Pr(b_j < \overline{b}^k \mid \overline{b}^{k+1})\right]^{N-n-1} \cdot \Delta_i^{\varepsilon}(\overline{b}^{k+1}, n)}_{\text{Lowest expected gain from clean investment, given } \overline{b}^k \text{ and } \underline{b}^k} = 0, \quad (10)$$

and

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

respectively. Equations (10) and (11) formalize essentially the same economic intuition that underlay (6) and (7).

The same argument used to establish that $\overline{b}^1 < \overline{b}^0$ and $\underline{b}^1 > \underline{b}^0$ can be applied to see that $\overline{b}^{k+1} < \overline{b}^k$ and $\underline{b}^{k+1} > \underline{b}^k$ for all $k \geq 0$. That is, we know that $\Pr[b_j > \bar{b}^k \mid \bar{b}^k] = 1/2$ for all $k \geq 0$. If we suppose that $\bar{b}^{k+1} \geq \bar{b}^k$, plugging this probability into (10) gives a lower bound on the lowest expected gain from clean investment equal to $2^{1-N} \sum_{n=0}^{N-1} \binom{N-1}{n} \cdot \Delta_i^{\varepsilon}(\bar{b}^{k+1}, n) > 0$ (in words, this is the expected gain to player i when s/he receives signal $b_i = \bar{b}^{k+1}$ assuming that every other player j invests in the clean technology iff $b_j > \bar{b}^k$). Since this expected gain is strictly positive, the assumption that $\bar{b}^{k+1} \geq \bar{b}^k$ leads to a contradiction because $\bar{b}^{k+1}$ should solve (10) by definition.

Next 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 the clean technology 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, we know that $|\overline{b}^k - \overline{b}^{k+1}| \to 0$ and $|\underline{b}^k - \underline{b}^{k+1}| \to 0$ as $k \to \infty$. This implies that $\lim_{k\to\infty} \Pr(b_j > \overline{b}^k \mid \overline{b}^{k+1}) = \Pr(b_j > \overline{b}^* \mid \overline{b}^*) = 1/2$ (and the same for $\underline{b}^*$).[5] Plugging this into (10) and (11) yields the following

[5]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, $\underline{b} > \underline{B} + 2\varepsilon$.

equalities:

$$\overline{b}^* + d - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n+1)}{2^{N-1}} = \underline{b}^* + d - \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{c(n+1)}{2^{N-1}} = 0. \tag{12}$$

Clearly, equation (12) is satisfied only if $\overline{b}^* = \underline{b}^*$.

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

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

While theoretically Proposition 2 is a special case of the result in Frankel et al. (2003), it generates several novel insights for environmental economics. 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 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.

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) prove that any 2×2 global game selects the risk dominant equilibrium of the underlying true game. In games with more players or actions, the statement is not generally correct.

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.*

Proposition 3 adds the important qualification that even though players will generally be able to coordinate their investment decision, coordination need not be on the Pareto dominant equilibrium. This stands in contrast to the standard and often implicit assumption in the environmental literature that players can coordinate on the efficient equilibrium (Barrett, 2006; Hoel and de Zeeuw, 2010).

There are two sources of equilibrium inefficiency. First, individual players do not incorporate the positive effect of their clean investments on the environment, the environmental externality. Given b, the magnitude of this externality of any player's switch to the clean technology is $(N-1) \cdot b$. Second, individual players do not consider the technological spillovers from their clean investments on other players' net benefit from clean investment, the network externality. Given that m other players invest in the clean technology, the magnitude of this externality is $m \cdot [c(m) - c(m+1)]$. It is a well-established insight in public economics that a policymaker will generally need as many policy instruments as there are externalities to achieve an efficient outcome. While this fact remains true in the present context, I shall now proceed to show how a smart policy scheme can fully correct the network externality without costing the policymaker anything.

4 Network Subsidies

Taxes and subsidies will stimulate adoption of the clean technology whenever they cause an effective decrease of $c(m) - d$ for at least one 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.[6]

The expenditure on subsidies to stimulate clean technology adoption can be substantially mitigated without the need to compromise on efficiency. The key of such a policy is to exploit the structure of a network externality. To see this, suppose the policymaker were to offer player a subsidy $S(m)$ on adopting the clean technology. The amount of subsidy an individual player receives is conditional on m, the number of other players adopting the clean technology. Let $S(m)$ be as follows:

$$S(m) = \underbrace{\frac{N-1}{N}\,[c(N) - d]}_{\text{environmental subsidy}} + \underbrace{c(m+1) - c(N)}_{\text{network subsidy}}. \tag{14}$$

I will go into the details of (14) shortly. First, however, I state the key implication of offering subsidy $S(m)$.

Proposition 4. *If the policymaker offers a subsidy equal to* (14)*, it implements the Pareto dominant Bayesian Nash equilibrium of global climate game.*

The veracity of Proposition 4 can be established through straightforward verification. Conditional on m and $S(m)$, the expected gain (given the subsidy) to player i from investing in the clean, rather than the dirty technology, is given by:

$$\Delta_i^{\varepsilon}(b_i, m) + S(m) = b_i - \frac{c_N - d}{N}. \tag{15}$$

For any m, the expected gain (including subsidies) given by (15) is positive if and only if $b_i > \frac{c(N)-d}{N}$. Thus, a subsidy equal to $S(m)$ incentives players to adopt the clean technology whenever their private signal tells them that coordination on clean technology adoption is Pareto efficient (see Proposition 3).

The subsidy scheme $S(m)$ consists of two parts. One part, the *environmental subsidy*, is standard and works like all subsidies we know of. It is a fixed amount $\frac{N-1}{N}[c(N) - d]$ paid to any player adopting the clean technology, meant to let players internalize the

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

environmental externality from investment in the clean technology. The second part of $S(m)$ is a new type of policy. I call it a *network subsidy.*

Like the environmental subsidy, 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 our present case, the policymaker offers the following 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 network subsidy equal to $c(m+1) - c(N)$. I will now explore the properties and performance of a network subsidy in detail. To this end, I temporarily assume that the policymaker offers *only* the network subsidy given by (16).

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

Like Proposition 4, Proposition 5 can be established through simple verification. Rewrite the expected gain from investing in the clean technology conditional on the network subsidy given by (16), which yields:

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

Clearly, the expected gain (17) is positive, for any m, if and only if $b_i \geq c(N) - d$. Assuming that ε is sufficiently small, each player i therefore adopts the clean technology for all $b > c(N) - d$.[7] Moreover, if all players adopt the clean technology, then from the perspective of any individual player the number of other players adopting the clean technology is just $m = N - 1$. The amount of subsidy payment due to any one adopter is therefore:

$$s^*(N-1) = c(N) - c(N) = 0, \tag{18}$$

which shows that the network subsidy does not cost the policymaker anything in equilibrium when $b > c(N) - d$ and ε is sufficiently small.

[7] Formally, for each $b > c(N) - d$ we can find an ε small enough so that $b - \varepsilon > c(N) - d$ will be satisfied. Since for each player i the signal b_i is drawn from $[b - \varepsilon, b + \varepsilon]$ by construction, this implies that each i must receive a signal $b_i > c(N) - d$. Plugged into (17) this yields the statement.

Recall from Proposition 2 that, without policy intervention, a player adopts the clean technology if and only if it receives a signal that exceeds b^*. As $b^* > c(N) - d$, it follows that a network subsidy eliminates part of the equilibrium inefficiency in the global game at zero cost. While this is quite a remarkable result – who doesn't like a free lunch? – it is somewhat overshadowed by the fact that, still, a network subsidy does not eliminate *all* equilibrium inefficiency (see Proposition 3). Or does it?

I argue that, in some sense, it does. Better said, one can show that the network subsidy eliminates all equilibrium inefficiencies associated with the network externality – that is, it incentives players to choose their actions as though they had internalized the entire technological spillover from their clean investment on all other players (though, as we saw, it does so without actually paying them this). Any remaining inefficiency is caused not by the network externality, but by players' failure to incorporate the environmental externality into their decision-making. Perhaps the easiest way to see this is to cleanse the payoff function (1) from the environmental externality so that only the network externality remains, i.e. from which an amount $m \cdot b$ is subtracted for players' payoffs independent of the action they choose. We can do this without objection since such an alternative specification does not affect the expected gain from investment in the clean technology $\Delta_i^{\varepsilon}(b_i, m)$ for any b_i or m, see (5), and the entire analysis was based on this gain function. As a result, the unique equilibrium in this alternative model specification will still be as in Proposition 2; however, coordination on clean technology adoption is now efficient for all $b > c(N) - d$.[8] Yet we know from equation (17) that a network subsidy equal to s^* incentives players to adopt the clean technology for all $b > c(N) - d$ if ε is sufficiently small. Hence, the network subsidy corrects the entire network externality in clean technological investment.

Why does a network subsidy work so well? The key property of a network subsidy set at s^* is that it eliminates all *strategic uncertainty* players face, i.e. the uncertainty a player has about the actions chosen by all other players. The network subsidy thus removes the payoff uncertainty that is a consequence of strategic uncertainty interacted with technological spillovers. In so doing, the network subsidy manages to eliminate all inefficiencies caused by players' failure to internalize the *technological* spillovers inherent in clean investments. Intuitively, then, the network subsidy works like an insurance. It protects individual investors against the risk of small network externalities from clean

[8] For given b, aggregate payoffs in this alternative specification are $-N \cdot d$ when players coordinate on the dirty technology, whereas they are $N \cdot (b - c(N))$ if they coordinate on the clean technology. The latter are greater for all $b > c(n) - d$.

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 played a central role in the preceding result. It is a strong assumption. What happens when 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, that probability is given by:

$$\Pr[b_i < c(N) - d \mid b, \varepsilon] = \Pr[\varepsilon_i < c(N) - d - b \mid b, \varepsilon] = \frac{1}{2} - \frac{b + d - c(N)}{2\varepsilon}, \qquad (19)$$

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 (19):

$$\Pr[b_i > c(N) - d \mid b, \varepsilon] = 1 - \Pr[b_i < c(N) - d \mid b, \varepsilon]. \qquad (20)$$

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:

$$p(n \mid b, \varepsilon) = \binom{N}{n} \cdot \left[\frac{1}{2} - \frac{b + d - c(N)}{2\varepsilon}\right]^n \cdot \left[\frac{1}{2} + \frac{b + d - c(N)}{2\varepsilon}\right]^{N-n}, \qquad (21)$$

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

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*

$$C^\varepsilon = \sum_{n=0}^{N} p(n \mid b, \varepsilon) \cdot n \cdot s^*(n) > 0. \qquad (22)$$

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 as $\varepsilon \to 0$.

The remarkable performance of a network subsidy discussed in Proposition 5 breaks down in the case of non-vanishing noise in signals. This begs the question whether, and how, an effective policy scheme based on the idea of network subsidies can be conceived at zero cost even when the noise in signals is not vanishing.

An intuitive way to implement an effective yet costless network subsidy on clean technological investments is to finance subsidy payments by a "network tax" levied on the dirty technology. Let this subsidy be denoted $s^{**}(m)$; the corresponding tax is denoted $t^{**}(m)$. Thus, if m players adopt the clean technology, aggregate spending on network subsidies is $m \cdot s^{**}(m)$, whereas aggregate revenues from the network tax are $(N - m) \cdot t^{**}(m)$. Given the requirement that the tax-subsidy scheme should be costless, the budget constraint for this policy is:

$$(N - m) \cdot t^{**}(m) - m \cdot s^{**}(m) = 0. \tag{23}$$

The budget constraint (23) imposes that total spending on the network subsidy is matched by total tax income from taxing the dirty technology for any number of clean technology adopters.

Next, the tax-subsidy scheme must correct the network externality deriving from technological spillovers in clean investments. As we have seen before (see Proposition 5 and the subsequent discussion), this condition will be satisfied whenever the expected gain from clean investment, accounting for taxes and subsidies, satisfies:

$$\Delta_i^{\varepsilon}(b_i, m) + s^{**}(m) + t^{**}(m) = b_i + d - c(N), \tag{24}$$

for all $m = 0, 1, ..., N - 1$. Equation (24) represents the incentive constraint of a network tax-subsidy scheme. Combined with the budget constraint, this yields the following scheme:

$$\begin{cases} t^{**}(m) & = \frac{m}{N}\left[c(m+1) - c(N)\right] \\ s^{**}(m) & = \frac{N-m}{N}\left[c(m+1) - c(N)\right] \end{cases}. \tag{25}$$

As the tax-subsidy scheme (25) solves (23) and (24) by construction, the following result is immediate.

Proposition 7. *A network tax-subsidy scheme equal to* (25) *is budget neutral yet corrects equilibrium inefficiencies deriving from players' failure to incorporate technological spillovers in clean investments.*

Endowed with a deeper understanding of how network subsidies work, suppose the policymaker would offer an environmental subsidy to let players incorporate the marginal environmental benefit of their clean investment on all other players on top of the network subsidy. While it is not immediately obvious how high the environmental subsidy offered should be, let us assume it is set at lowest level consistent with efficiency – that is, assume the subsidy to be such that it lets players incorporate the entire environmental externality due to clean investment in the hypothetical case that the externality is just high enough for the policymaker to prefer coordination on clean technology investments. The lowest b for which coordination on clean investments is Pareto dominant is $(c(N) - d)/N$; in this case, if any player invests in the clean technology this produces a positive environmental externality equal to $(c(N) - d)/N$ on $N - 1$ players. Hence, we assume that the policymaker offers an environmental subsidy equal to $\frac{N-1}{N}(c(N) - d)$ to any player adopting the clean technology. Then player i's expected gain (including subsidies) from adopting the clean technology, rather than the dirty technology, is given by

$$\Delta_i^{\varepsilon}(b, m) + s^*(m) + \frac{N-1}{N}(c(N) - d). \tag{26}$$

The expected gain (15) is positive, for any m, if and only if $b_i > \frac{c(N)-d}{N}$. If ε is small enough, this again is equivalent to saying that players adopt the clean technology for all $b > \frac{c(N)-d}{N}$, which is also the condition for clean investments to be Pareto dominant. Thus, for ε small enough, the network subsidy scheme $S()$ allows the policymaker to correct inefficiencies originating from both the environmental and the network externality while paying only for the former. Total spending is $(N - 1)[c(N) - d]$.

The logic of a network subsidies does not rely on the application to climate change. Any market where (i) individual actions exhibit strategic complementarities and (ii) players do not take these into account may 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.

5 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.

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