The Global Climate Game

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Abstract

This paper studies emissions abatement in a global game of technological investments. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but green. Technological investments are strategic complements. While such games typically have multiple equilibria, uncertainty about the green technology's true potential leads to the selection of a unique equilibrium. The equilibrium may be payoff dominated. I specify sharp conditions under which the green technology is universally adopted. Implications for the design of domestic and international policies are discussed.

1 Introduction

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

There currently exist more than 3,000 IEAs.[2] Out of those, not one could turn the tides of ever-increasing greenhouse gas emissions. The literature typically describes this

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

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

failure as a prisoner's dilemma where participation in an IEA is voluntary and countries have strong free-rider incentives (Barrett, 1994).

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

The element of unpredictability complicates the design of IEAs. To nevertheless form expectations on the performance of an IEA when the underlying game has multiple equilibria, Barrett and Dannenberg (2012, 2017) take coordination games to the lab. Contrary to what the typical theory predicts, they find that subjects *do* coordinate their actions (though not always on the efficient equilibrium). This suggests IEAs targeting technological investment or R&D might work indeed. Yet from a policy point of view, reliance on experiments alone to predict which outcome eventually prevails is insufficient. To inform policy it is not enough to know *what* happens; we must know *why* it happens.

In this paper, I propose global games as a practical tool to study IEAs. I construct a bare-bones model of technological investment. Players choose to invest in either of two technologies. The first is cheap and dirty, the second expensive but green. An individual player's payoff from investing in the green technology is increasing in the number of other players that invest in it (and vice versa). The game is a global game because players receive private noisy signals of the green technology's true potential. In contrast to the standard theory, my *global* coordination game of technological investment has a unique equilibrium. This allows me to perform comparative statics and talk policy. Subsidies on the green technology, taxes on the dirty technology, a carbon price, or trade restrictions on countries not adopting the green technology all facilitate selection of a more favorable equilibrium.

There are various reasons for technological investments to exhibit strategic complementarities. First, it can describe increasing returns to scale or network effects

(Katz and Shapiro, 1985) such as exist for electric vehicles (Li et al., 2017) or solar electricity (Baker et al., 2013). Second, it can represent a reduced-form way to model learning-by-doing and experience. If there are more users of the technology today, there will be more experience with it tomorrow, lowering maintenance and operational costs. Third, it may be a political phenomenon. Climate clubs can impose trade restrictions on those not adopting the green technology, effectively lowering the net cost of green investment (Barrett, 1997; Nordhaus, 2015). And fourth, it could be driven by fears of crossing a climate tipping point which only the breakthrough technology is able to avoid (Barrett and Dannenberg, 2012).

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

2 Model and Analysis

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

Each player chooses to invest in either of two technologies. The first, called L, is an low-potential, low-cost technology. If a player does not invest in L, s/he invests in H, a high-potential but high-cost green technology. Compared to investment in L, the marginal environmental benefit of investing in H is $b > 0$. Without loss of generality, I represent the investment decision of player i by a binary variable $x_i \in \{0, 1\}$ such that $x_i = 1$ denotes investment in H.[3] I define m to be the total number of *other* players who invest in the green technology, i.e. $m = \sum_{j \neq i} x_j$.

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

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

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

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

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

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

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

[3] Continuous action spaces are considered in Section 2.2.

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

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

2.1 The Global Climate Game

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

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

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

The term ε_i captures idiosyncratic noise in i's private signal. It is common knowledge that ε_i is an i.i.d. draw from the uniform distribution on $[-\varepsilon, \varepsilon]$.[4] I assume that ε is small, $2\varepsilon < \min\{c^H(N) - c^L - \underline{B}, \overline{B} - c^H(0) + c^L\}$.

There is a conceptual distinction between global games uncertainty as in (2) or more standard models of incomplete information (Kolstad, 2007; Barrett and Dannenberg, 2012; Martimort and Sand-Zantman, 2016). Under the standard approach toward uncertainty, players' beliefs are perfectly correlated because all share the same information.

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

In a global game, player's priors are perfectly correlated as well, but their *posteriors* are not due to the element of idiosyncratic noise, however small, in private signals. It is hard to overestimate the importance of this difference.

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

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

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

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

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

Multiplicity. The problem of determining m is key and lies at the heart of equilibrium multiplicity in complete information coordination games (see Proposition 1 and Barrett, 2006; Hoel and de Zeeuw, 2010; Barrett and Dannenberg, 2017). For intermediate signals s_i, player i's best-response critically depends on m as $\pi_i^\varepsilon(1 \mid s_i, N) > \pi_i^\varepsilon(0 \mid s_i, N)$ while at the same time $\pi_i^\varepsilon(1 \mid s_i, 0) < \pi_i^\varepsilon(0 \mid s_i, 0)$. Without knowing what others will do, there is no ground to favor one equilibrium over the other and it makes no sense to focus on a particular equilibrium expecting it will eventually prevail.

Remarkably, it turns out that players *can* form rational beliefs on m in a global game. Somewhat paradoxically, uncertainty about b catalyzes a process in which players can eliminate most strategies as irrational and that in the end allows for very sharp predictions on m. This process is called iterated dominance.

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

Suppose player 1 receives a signal $s_1 > c^H(0) - c^L + \varepsilon$. In this case, s/he knows that $b > c^H(0) - c^L$ with absolute certainty (see (2)). But if $b > c^H(0) - c^L$, green investment is a dominant strategy. Writing $\bar{s}^0 = c^H(0) - c^L + \varepsilon$, it follows that $\pi_1^\varepsilon(1 \mid \bar{s}^0, m) > \pi_1(0 \mid \bar{s}^0, m)$ for all $m \geq 0$. Player 1 invests in H for all signals $s_1 > \bar{s}^0$.

Similarly, I define $\underline{s}^0 = c^H(2) - c^L - \varepsilon$ and conclude that player 1 invests in L for all signals $s_1 < \underline{s}^0$.

Player 2 knows that player 1 will never play a strictly dominated strategy. Due to this simple fact, s/he can construct rational bounds on the posterior probability that player 1 invests in either L or H. After all, player 1 never invests in L for $s_i > \overline{s}^0$, which implies that the *minimum* probability player 2 can assign to the event that player 1 invests in H is simply $\Pr(s_1 > \overline{s}^0 \mid s_2)$. By the same token, player 1 invests in L for all $s_1 < \underline{s}^0$

$\Pr(s_1 > \underline{s}^0 \mid s_2)$

$$\Pr \tag{5}$$

Now consider player 2. Knowing that player 1 invests [in the green technology] for all $s_1 > \overline{s}^0$, player 2 expects a *strictly* higher payoff from green investment even when $s_2 = \overline{s}^0$. After all, player 2 then knows that $b \geq c^H(0) - c^L$. But s/he is precisely indifferent between either type of investment when $b = c^H(0) - c^L$ and player 1 invests in L. Yet if $s_2 = \overline{s}^0$ indeed, player 2 knows that $s_1 > \overline{s}^0$ with probability 1/2, in which case player 1 invests.

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Convergence. The above procedure can be carried on indefinitely, which I leave that to the patient reader. It yields a sequence of points $(\overline{s}^k)_{k=0}^{\infty}$, where each $\overline{s}^{k+1}$ is the solution to

$$\begin{aligned}&\Pr(s_j > \overline{s}^k \mid \overline{s}^{k+1}) \cdot \left[2\overline{s}^{k+1} - c^H(2)\right] + \Pr(s_j < \overline{s}^k \mid \overline{s}^{k+1}) \cdot \left[\overline{s}^{k+1} - c^H(2)\right] \\ &= \Pr(s_j > \underline{s}^k \mid \overline{s}^{k+1}) \cdot \overline{s}^{k+1} - c^L\end{aligned} \tag{6}$$

$$\begin{aligned}&\Pr(s_j > \underline{s}^k \mid \underline{s}^{k+1}) \cdot \left[2\underline{s}^{k+1} - c^H(2)\right] + \Pr(s_j < \underline{s}^k \mid \underline{s}^{k+1}) \cdot \left[\underline{s}^{k+1} - c^H(2)\right] \\ &= \Pr(s_j > \overline{s}^k \mid \underline{s}^{k+1}) \cdot \overline{s}^{k+1} - c^L\end{aligned} \tag{7}$$

Equations (6) and (7) look complicated but have a deep economic intuition.

Starting from $\overline{s}^0$ and $\overline{s}^1$, an inductive argument at once reveals that $\overline{s}^{k+1} < \overline{s}^k$ for all $k \geq 0$. Moreover, I note that $\overline{s}^k > c^H(N) - c^L - \varepsilon$ for all k since at $s_i = c^H(N) - c^L - \varepsilon$, investing in L is strictly dominant. It follows that $(\overline{s}^k)_{k=0}^{\infty}$ is bounded. But a bounded monotone sequence converges; let $\overline{s}^*$ denote its limit.

In game theoretic parlance, it is said that investment in the green technology is *iteratively dominant* for all signals $s_i > \overline{s}^*$, while investment in the dirty technology is iteratively dominant for all signals $s_i < \underline{s}^*$.

Main result.

From the definition of convergence, it is known that $|\overline{s}^k - \overline{s}^{k+1}| \to 0$ and $|\underline{s}^k - \underline{s}^{k+1}| \to 0$ as $k \to \infty$. And since $\overline{s}^* = \lim_{k\to\infty} \overline{s}^k$. Plugging this into (6) yields the following system of equations:

$$\begin{aligned} \frac{1}{2} \cdot \left[2\overline{s}^* - c^H(2)\right] + \frac{1}{2} \cdot \left[\overline{s}^* - c^H(1)\right] &= p \cdot \overline{s}^* - c^L, \\ \frac{1}{2} \cdot \left[2\underline{s}^* - c^H(2)\right] + \frac{1}{2} \cdot \left[\underline{s}^* - c^H(1)\right] &= (1-p) \cdot \underline{s}^* - c^L, \end{aligned} \tag{8}$$

where $p := \Pr(s_j > \underline{s}^* \mid \overline{s}^*)$. One can reduce (8) further, which yields:

$$\frac{3}{2} \cdot (\overline{s}^* - \underline{s}^*) = p \cdot \overline{s}^* - (1-p) \cdot \underline{s}^*. \tag{9}$$

Equation (9) is satisfied if either $p = (1-p) = 3/2$ or else $\overline{s}^* = \underline{s}^*$. Since the former is impossible to achieve using Earthly mathematics, it follows that $\overline{s}^* - \underline{s}^* = 0$. This conclusions has a major implication. Iterated dominance leads to the selection of a unique equilibrium.

Proposition 2. *There exists a unique threshold s^* such that each player i invests in the high-potential technology for all $s_i > s^*$, while s/he invest in the low-potential technology for all $s_i < s^*$. It is given by:*

$$s^* = 2^{-N} \sum_{k=0}^{N} \binom{N}{k} \cdot c(k+1) - c^L. \tag{10}$$

For a two-player game, the threshold s^* simplifies to:

$$s^* = \frac{c^H(2) + c^H(1)}{2} - c^L. \tag{11}$$

Note that the unique equilibrium can be inefficient (and players know it). Intuitively, green investment will be too risky when b is low since the noise in signals forces a player to believe that others may think that green investment is dominated. Barrett and Dannenberg (2012) appear to share this view when they write: "players could use risk-dominance as a selection rule." For 2×2 games, this is theoretically founded by the global games approach: Carlsson and Van Damme (1993) establish that any 2×2 global game selects the risk dominant equilibrium of the underlying true game. But the result does not generalize to more general games, and for a very simple reason: risk-dominance is only defined for two-player, two-action games. Though generalizations of the risk-dominance concept have been developed – most notably p-dominance due to (Morris et al., 1995) – these are not, in general, predictive for equilibrium selection in larger global games (Frankel et al., 2003).

2.2 Investment Shares And Continuous Actions

A strong assumption was that players' actions are discrete: they are constrained to invest only in one technology. Though strong indeed, this assumption is not important for my mains results. The following section elaborates.

Let there again be $N+1$ players. Each player chooses an $x_i \in [0,1]$, interpreted as the *share* of i's investments in the high-potential green technology H. Define $m = \sum_{j \neq i} x_i$ to be the total share of investments in H by all players who are not i. A player investing in L faces marginal investment costs of c^L. Given m, the marginal cost of investment in H is $c^H(m + x_i)$, which is decreasing in m.[5] Upon learning the signal s_i, player i's expected payoff to playing x_i is:

$$\pi_i^\varepsilon(x_i \mid m) = (m + x_i) \int b \cdot f_i^\varepsilon(b \mid s_i)\, db - x_i \cdot c^H(m + x_i) - (1 - x_i) \cdot c^L. \tag{12}$$

Like before, the problem with (12) is that player i does not know m, the actions of all other players.

To see that this model yields equivalent predictions to one where investment is a priori constrained to be discrete (Section 2.1), one need only realize the game is solved by iterated dominance. I constructed the point $\overline{s}^0$ such that the payoff to investing in H is *strictly* larger than the payoff to investing in L for any signal $s_i > \overline{s}^0$ (even if no other player invests in H, i.e. $m = 0$). Any strategy that prescribes $x_i < 1$ therefore yields a strictly lower payoff than simply playing $x_i = 1$ for $s_i > \overline{s}^0$. Yet this implies that $x_i \neq 1$ is strictly dominated whenever $s_i > \overline{s}^0$.

Proposition 3. *Consider the global game with continuous action spaces $x_i \in [0,1]$ for all players i. Then there exists a unique threshold s^* such that each player i invests*

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

in the high-potential technology for all $s_i > s^*$, while s/he invest in the low-potential technology for all $s_i < s^*$.

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

2.3 Policy Design

Because the global climate game has a unique equilibrium, it is possible to perform comparative statics. Looking at (**??**), there are multiple ways to lower the green investment threshold. Each will require a (relative) decrease of $c^H(m) - c^L$ for some or all $m = 0, 1, ..., N$. I discuss several possibilities.

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

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

Sequential participation.

3 Discussion and Conclusions

This paper studies climate change mitigation in a global game. The focus is on abatement through technological investment. Players invest in either of two technologies. One technology is cheap and dirty, the other expensive but with a high green potential. I consider environments in which investments are strategic complements and where the true (relative) abatement potential of the green technology is unobserved.

My approach advances the literature on international environmental agreements in several ways. First, it addresses the issue of multiple equilibria directly. Though many papers on IEAs and technological investments find multiple equilibria, these either ignore equilibrium selection altogether (Barrett, 2006; Hoel and de Zeeuw, 2010) or else rely on experimental methods to determine which equilibrium eventually obtains (Barrett and Dannenberg, 2012, 2017). In contrast, the global climate games makes sharp analytical prediction on which equilibrium gets selected.

Second, it shows that

matters how uncertainty is modeled. The devil is in the details.

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A Proofs

Proof of Proposition 2

Proof of Proposition 3