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Correct (and misleading) arguments for using market-based pollution control policies*

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Abstract

One argument in favor of market based pollution control policies is sometimes exaggerated, and a different argument is usually ignored. Regardless of whether investment is fixed or endogenous, market based policies might lead to a higher or lower equilibrium abatement compared to the level under command and control policies. Therefore, economists should be cautious about trying to convince anti-market environmentalists of the benefit of market based policies on the grounds that these promote environmental goals. However, market based policies reduce regulatory uncertainty. Under command and control emissions policies, there are multiple rational expectations competitive equilibria at the investment stage. From the standpoint of individual firms, this multiplicity looks like regulatory uncertainty. Market based policies eliminate this uncertainty. These results hold in an environment with common knowledge about market fundamentals. In a global games setting the unique investment equilibrium under command and control emissions policies is constrained efficient.

Keywords: tradable permits, coordination games, multiple equilibria, global games, regulatory uncertainty, climate change policies, California AB32

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1 Introduction

Two aspects of the comparison between command and control and market based emissions policies appear to have gone unnoticed: (i) Although market based policies reduce the social cost of abatement, compared to inefficient command and control policies, the former do not globally reduce the *marginal* social abatement cost; they therefore do not necessarily lead to a higher socially optimal level of abatement. (ii) When the current policymaker cannot make binding commitments to future policy levels (and there is common knowledge about market fundamentals), and firms make lumpy investment decisions that affect their future abatement costs, command and control policies give rise to multiple competitive equilibria. From the standpoint of the individual firm, this multiplicity is indistinguishable from regulatory uncertainty. In the same circumstance, there is a unique (socially optimal) competitive equilibrium under market based policies, and therefore no regulatory uncertainty.

Market based policies encourage similar firms to make different investment decisions, increasing the differences in firms' abatement costs and thereby increasing the efficiency gains from trade in permits. A command and control policy, in contrast, encourages firms to all make the same investment decision, thereby preserving or increasing firm homogeneity. Thus, command and control policies may appear to cause little efficiency loss, because in equilibrium there would be little trade even if it were allowed. However, this firm homogeneity may be a consequence of the anticipated lack of opportunity for trade. Taking into account the effect of the policy regime on the aggregate investment decisions provides a more accurate measure of the efficiency gains from trade in permits.

Some contingencies that will affect future policies are endogenous to the economy, but exogenous to individual (small) firms. For example, the optimal future level of abatement depends on the future abatement costs, which depend on earlier investment decisions. A simple example demonstrates that market based policies reduce the regulatory uncertainty arising from current aggregate investment decisions. Consider an industry with many identical small (non-strategic) firms, each of which has the opportunity to make a discrete investment that reduces its average and marginal abatement costs. The firms know that in the next period the policymaker will set the *ex post* socially optimal level of abatement. All agents know the marginal pollution damage curve, and they know that the future social marginal abatement cost curve depends on the fraction of firms that make the investment, and on whether the regulator uses market based policies. In this setting, without exogenous uncertainty, taxes and cap-and-trade policies are equivalent, so hereafter assume that the market based option is cap-and-trade. The non-market alternative gives each firm the same non-tradable emissions allowance.

The anticipation that the regulator will use non-tradable permits induces a coordination

game among non-atomic agents at the investment stage. Firms know that investment by a larger fraction of firms reduces the industry abatement cost curve. They therefore understand that the second-stage emissions allowance is a decreasing function of the fraction of firms that invest. Furthermore, the investment becomes more attractive, the lower is the anticipated emissions allowance. Thus, the use of a non-tradable emissions allowance in the second stage makes the first stage investment decisions strategic complements. In the simplest case with *ex ante* identical firms, there are in general two rational expectations competitive equilibria, neither of which is socially optimal: all firms invest or none of them do. This multiplicity of equilibria creates “strategic uncertainty”: firms cannot rationally predict industry behavior. They therefore cannot rationally predict the regulator’s behavior. From the standpoint of the individual firm this strategic uncertainty looks like regulatory uncertainty.

In contrast, under the cap-and-trade policy there is a unique rational expectations competitive equilibrium. An increase in the fraction of firms that invest reduces the (second period) equilibrium price of tradable permits, thus reducing the value of the investment. The investment decisions are therefore strategic substitutes, leading to a unique, socially optimal equilibrium to the investment game. Rational firms can predict the level of permits, and the permit price in the second stage. In this example (analyzed in detail in the next three sections), the commitment to use market based policies eliminates regulatory uncertainty even though the actual level of the policy is determined in the future.

This example assumes that firms have common knowledge. Suppose instead, in the scenario where the regulator chooses the level of non-tradable emissions after investment, that each firm receives a private signal about a market fundamental. Here there is a unique competitive equilibrium – a well-known result from the global games literature (Carlsson and Van Damme 1993), (Morris and Shin 2003). Surprisingly, the unique equilibrium in the global game is constrained socially efficient. That is, an arbitrarily small amount of uncertainty about market fundamentals not only eliminates the multiplicity of equilibria, but it also insures that the resulting equilibrium level of investment is the same as the social planner would choose, given the constraint of using non-tradable permits. This result occurs even though the social planner’s objective is to minimize the sum of abatement and investment costs and environmental damages, while firms care only about abatement and investment costs.

These results are of general interest to the theory of regulation and they are of particular interest in the climate change debate. There is considerable disagreement about the type of greenhouse gas regulations to use, and widespread recognition that current policymakers cannot lock in future policies. California law AB32, which mandates *future* reductions in greenhouse gas emissions, exemplifies these two points. Chapter 5 of AB32 recommends the use of market-based mechanisms, without mentioning either taxes or tradable permits. The bill gives future

regulators discretion over the manner of implementing the mandate. Governor Schwarzenegger had wanted the bill to guarantee a market based mechanism; shortly after signing the bill, he issued an executive order forming a Market Advisory Committee to design a cap-and-trade market. Some sponsors of the bill considered this attempt to lock in the form of implementation inconsistent with the intent of the law (Robinson 2007). The bill also gives future policymakers discretion over the extent of implementation. Article 38599 gives the Governor the right to adjust the targets “in the event of extraordinary circumstances, catastrophic events, or threat of significant economic harm”.

This paper shows that economists should not promote market based policies on the grounds that these are “environmentally friendly”, i.e. that they lead to larger levels of abatement in equilibrium. That claim can easily be false. In addition to the usual efficiency argument in favor of market based policy, the paper identifies the more subtle fact that these policies tend to reduce regulatory uncertainty. Furthermore, a high likelihood of regulators using market based policies affects investment decisions, leading both to more efficient decisions and greater firm cost heterogeneity – and therefore greater gains from subsequent market based policies. The paper also contributes to the theory of global games.

Jaffe, Newell, and Stavins (2003) survey the literature on pollution control and endogenous investment. Many papers in this literature, including Biglaiser, Horowitz, and Quiggin (1995), Kennedy and Laplante (1999), Montero (2002), Fischer, Parry, and Pizer (2003), Moledina, Polasky, Coggins, and Costello (2003), Tarui and Polasky (2005) and Tarui and Polasky (2006) assume that firms behave strategically with respect to the regulator: firms believe that their investment decisions will affect future regulation. Several paper, including Malueg (1989), Milliman and Prince (1989), Requate (1998), and Karp and Zhang (2002) treat firms as non-strategic. A related literature discusses the relation between technology *development* and regulation (Popp 2006), (Jaffe and Palmer 1997), (Newell, Jaffe, and Stavins 1999), (Taylor, Rubin, and Hounshell 2005). None of these papers discuss multiple equilibria, so they do not consider the relation between the policy instrument and the existence of regulatory uncertainty. I am not aware of previous notice that market based policies can reduce the optimal level of abatement, or previous recognition of the efficiency of the unique equilibrium in a global games setting.

2 The model

The model consists of an investment period followed by an abatement period; firms have rational expectations. I begin with a model in which firms are identical prior to investment and there is no exogenous uncertainty; Section 5 relaxes those assumptions. In the first period, each firm makes a binary decision: it does not invest in a new technology ($K = 0$) or it does

invest ($K = 1$). The individual firm's decision determines that firm's abatement cost function in the second period. The aggregate decisions determine the industry-wide abatement cost function. In the second period, the regulator chooses the required level of abatement, or equivalently, the allowable level of emissions, in order to minimize the sum of abatement costs and environmental damage. There are two possible trade regimes: trade in permits is either allowed or it is prohibited. The trade regime is known at the investment stage; it is determined outside the model, e.g. by political forces.

For an arbitrary baseline level of emissions e^{base} and an actual level of emissions e , abatement in the second period is $a \equiv e^{base} - e$. The individual firm's abatement cost, $\tilde{c}(a, K)$, is increasing and convex in abatement. Investment decreases both abatement costs and marginal abatement costs.

Define the firm's benefit of emissions, $c(e, K)$, as the negative of abatement costs: $c(e, K) \equiv -\tilde{c}(a, K)$. The firm's marginal benefit of emissions is $c_e(e, K) \equiv \tilde{c}_a(a, K)$, equal to the marginal abatement cost. The assumptions above imply that $c(\cdot)$ is increasing and concave in e and decreasing in K , with $c_e(e, 1) - c_e(e, 0) < 0$. This inequality implies that the business-as-usual (BAU) level of emission, i.e. the level that satisfies $c_e(e, K) = 0$, is decreasing in K .

The firm's cost of investment is ϕ . The fraction of firms that invest is $0 \leq \kappa \leq 1$. If $0 < \kappa < 1$, firms are heterogenous in the second stage, when the regulator decides on the level of pollution permits.

Each (non-atomic) firm is given an emissions allowance of e , independently of whether it invested. The mass of firms is normalized to 1, so aggregate emissions are e . The damage function is $D(e)$, an increasing convex function. If firms that did not invest emit at the rate e^0 and firms that did invest emit at the rate e^1 , total emissions are $(1 - \kappa)e^0 + \kappa e^1 = e$ and social costs (abatement costs plus investment costs plus environmental damages) are

$$P(e^0, e^1, \kappa) \equiv -(1 - \kappa)c(e^0, 0) - \kappa c(e^1, 1) + \kappa\phi + D(e). \quad (1)$$

This model contains two notable assumptions. The first is that investment is lumpy at the firm level, but since firms are individually small, investment appears smooth at the societal level. The second assumption, that the regulator gives each firm the same level of permits, is consistent with the assumption of *ex ante* identical firms. In the absence of trade, a regulator's ability to condition the endowment of emissions permits on the investment decision would solve the efficiency problem at the abatement stage. However, that conditioning requires that the regulator is able to distinguish across firms, and it creates perverse incentives at the investment stage because firms that invest will receive lower allowances.

3 The abatement stage

This section establishes that trade in permits might either increase or decrease the socially optimal level of emissions for a given κ . By equalizing heterogeneous firms' marginal abatement costs, trade in permits certainly reduces total abatement costs. However, the socially optimal level of emissions depends on marginal, not on total abatement costs. Trade in permits can shift up the industry (aggregate) marginal abatement cost curve over an interval; if marginal damages intersect the industry marginal benefit curve in this interval, trade increases the optimal level of emissions (i.e., it decreases the optimal level of abatement).

In the absence of trade, and given the assumption that all firms receive the same level of permits, all firms emit at the same rate, so $e^0 = e^1 = e$. Subscripts denote partial derivatives and superscripts indicate the firm's investment decision. Given κ , the first order condition for the minimization of social costs is

$$D'(e) = (1 - \kappa) c_e(e, 0) + \kappa c_e(e, 1) \quad (2)$$

and the second order condition is

$$S \equiv -((1 - \kappa) c_{ee}^0 + \kappa c_{ee}^1) + D'' > 0.$$

Equation (2) implicitly defines the optimal e^* as a function of κ : $e^* = e(\kappa)$. More investment (higher κ) reduces the optimal level of emissions:

$$\frac{de^*}{d\kappa} = -\frac{c_e^0 - c_e^1}{S} < 0. \quad (3)$$

Now consider the optimal level of emissions in the presence of trade. Trade in permits equates investors' and non-investors' marginal costs, and the price of permits equals this marginal cost. Let e be each firm's endowment of permits, and e^t the equilibrium purchases of each non-investor – those with higher marginal abatement costs. Since the mass of purchases equals $(1 - \kappa) e^t$, each of the κ low cost firms (the investors) must be willing to sell $\frac{(1 - \kappa) e^t}{\kappa}$. In an interior equilibrium, the conditions for quantity (e^t) and price (p) are

$$c_e(e + e^t, 0) = c_e\left(e - \frac{(1 - \kappa) e^t}{\kappa}, 1\right) \quad (4)$$

$$c_e(e + e^t, 0) = p(e, \kappa). \quad (5)$$

Equation (4) implicitly defines the function $e^t = e^t(e; \kappa)$. The assumption that the equilibrium is interior means that the price is positive and the low cost firms do not sell all of their permits:

$$c_e(e + e^t(e; \kappa), 0) > 0 \text{ and } e - \frac{(1 - \kappa) e^t(e; \kappa)}{\kappa} > 0. \quad (6)$$

The assumption that the equilibrium is interior merely simplifies the discussion. Given κ , the planner's problem is to choose e to minimize

$$W(e; \kappa) = -(1 - \kappa) c(e + e^t, 0) - \kappa c\left(e - \frac{(1 - \kappa) e^t}{\kappa}, 1\right) + D(e). \quad (7)$$

Using equations (4) and (5), the first order condition is

$$D'(e) = (1 - \kappa) c_e(e + e^t, 0) + \kappa c_e\left(e - \frac{(1 - \kappa) e^t}{\kappa}, 1\right) = p(e, \kappa). \quad (8)$$

Assuming that the planner's problem is convex, the second order condition holds:

$$S^t \equiv \frac{d^2 W}{de^2} = -(1 - \kappa) c_{ee}^0 \left(1 + \frac{de^t}{de}\right) - \kappa c_{ee}^1 \left(1 - \frac{1 - \kappa}{\kappa} \frac{de^t}{de}\right) + D'' > 0. \quad (9)$$

3.1 Comparison of pollution levels with and without trade, given κ

This section compares the equilibrium levels of pollution permits with and without trade in permits for a given κ , with $0 < \kappa < 1$. The two levels are equal at $\kappa = 0$ or $\kappa = 1$, where there is no incentive to trade, so those limiting cases are not interesting for this analysis.

The individual firm's marginal benefit of emissions equals its marginal abatement cost. The social marginal benefit of emissions, $G(e; \kappa, j)$, $j = \text{trade, no trade}$, equals the industry marginal abatement cost:

$$G(e; \kappa, j) \equiv ((1 - \kappa) c_e^0 + \kappa c_e^1), \quad j = \text{trade, no trade}. \quad (10)$$

With trade, the two types of firms have the same marginal benefits, p , so $G(e; \kappa, \text{trade}) = p(e, \kappa)$. Without trade, the industry marginal benefit of emissions $G(e; \kappa, \text{no trade})$ is a convex combination, with weights equal to $1 - \kappa$, κ , of the marginal benefit of emissions for the two types of firms (those who did not invest and those who did). For some levels of e and κ and for some technologies, $G(e; \kappa, \text{trade}) > G(e; \kappa, \text{no trade})$, as Example 1 shows. If this inequality is satisfied at the socially optimal level of emissions without trade, then trade increases the socially optimal level of emissions.

Example 1 Suppose that the marginal benefit of emissions without investment is $c_e(e, 0) = 1 - e$ for $e \leq 1$ and the marginal benefit with investment is $c_e(e, 1) = 1 - be$ for $e \leq \frac{1}{b}$, where $b > 1$. Marginal benefits of emissions are 0 for $e > 1$ without investment, and marginal benefits are 0 for $e > \frac{1}{b}$ with investment. The dotted and the dashed lines in Figure 1 graph these marginal benefits.¹ With $\kappa = 0.5$, in the absence of trade the marginal benefit of emissions is the kinked solid line labelled $G(e, 0.5, \text{no trade})$; for $e < \frac{1}{b}$ the slope of this line is $\frac{1+b}{2}$ and for

¹ For this specification, the firm that invests would, in the absence of trade, not use emissions permits in excess

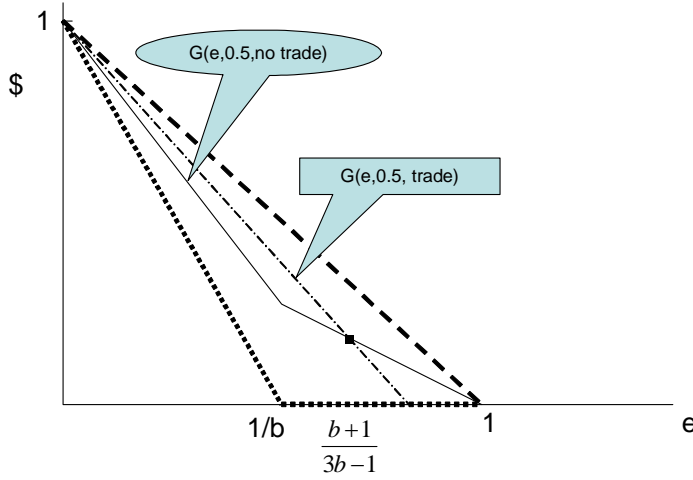


Figure 1: Dotted and dashed lines show marginal benefit of emissions with and without investment, respectively. The two solid lines show the social marginal benefit of emissions with and without trade for $\kappa = 0.5$

$e > \frac{1}{b}$ the slope is $\frac{1}{2}$. With trade, the equilibrium level of trade is $e^t = \frac{b-1}{b+1}e$ and the marginal social benefit of emissions is the straight line labelled $G(e, 0.5, \text{trade})$, with slope $\frac{2b}{b+1} > 1$. Since $\frac{1+b}{2} > \frac{2b}{1+b}$ $G(e, 0.5, \text{trade}) > G(e, 0.5, \text{no trade})$ for small e . For all emissions levels $e < \frac{b+1}{3b-1}$ the social marginal benefit of emissions is higher when permits are tradable. A necessary and sufficient condition for the optimal level of emission with trade to exceed the optimal level without trade is for the latter to be less than $\frac{b+1}{3b-1}$.

It is easy to construct examples where inequality $G(e; \kappa, \text{trade}) > G(e; \kappa, \text{no trade})$ never holds, i.e. cases where trade reduces the socially optimal level of emissions:

Example 2 Let $c_e(e, 0) = 1 - e$ as in the previous example, but set $c_e(e, 0) = b(1 - e)$ with $b < 1$. Some tedious calculation shows that for all $0 < \kappa < 1$ trade reduces the social marginal benefit of emissions and therefore reduces equilibrium emissions.

These two examples show that trade in permits might either encourage or discourage stricter regulation.

of $\frac{1}{b}$, so those permits would create no additional environmental damage. We can make one of two modifications in order to use this functional form to study either the investment or the abatement decision: (i) choose the marginal damages such that in equilibrium $e < \frac{1}{b}$ for all values of κ with or without trade (ii) perturb the marginal benefit for the investing firm so that the investing firm has positive marginal benefits for $\frac{1}{b} \leq e < 1$ (instead of 0 marginal benefits as the example assumes). The appendix discusses this example further. In Figure 3 and Example 3 below, I use the first modification, by making the marginal damage curve sufficiently high.

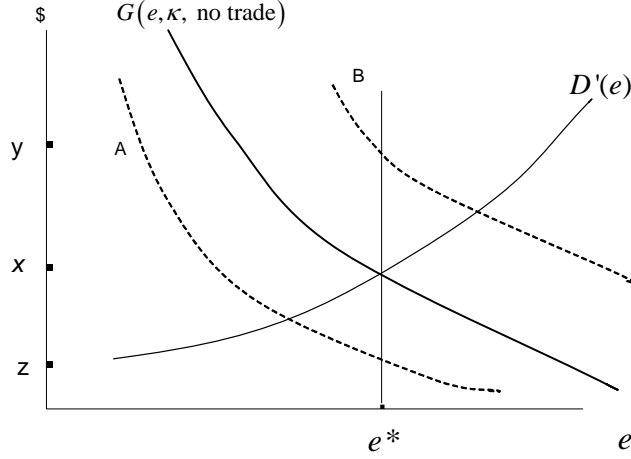


Figure 2: Comparison of emissions level for given $0 < \kappa < 1$, without trade (solid curve) and with trade (curves labelled A and B).

Equation (2) and the first part of equation (8) have the same form, but they have different arguments. They are identical if $e^t = 0$. The following proposition uses this fact to determine the effect of trade on the equilibrium level of emissions, holding investment fixed.

Proposition 1 Assume that $0 < \kappa < 1$, define $e^* = e^*(\kappa)$ as the optimal level of emissions in the absence of trade, and define $e^t(e; \kappa)$ as the equilibrium level of purchases (under trade) per non-investing firm for given e, κ . Assume that at $e^*(\kappa)$ the with-trade equilibrium is interior, i.e. the two inequalities in (6) hold. A sufficient condition for trade in permits to decrease the equilibrium level of emissions (i.e. to lead to stronger environmental regulation) is

$$\Delta(\kappa, e^*(\kappa), s) \equiv c_{ee}(e^* + s, 0) - c_{ee}\left(e^* - \frac{(1 - \kappa)s}{\kappa}, 1\right) < 0 \quad (11)$$

for all $0 \leq s \leq e^t(e^*(\kappa); \kappa)$. A sufficient condition for trade to lead to weaker environmental regulation is for inequality (11) to be reversed for all $0 \leq s \leq e^t(e^*(\kappa); \kappa)$.

Proof. Figure 2 shows the graph of $G(e, \kappa, \text{no trade})$ (the negatively sloped solid curve) and the level of e^* . Trade decreases the equilibrium level of emissions if and only if $G(e^*, \kappa, \text{trade}) < G(e^*, \kappa, \text{no trade})$, as shown by the curve labelled “A”. If $G(e^*, \kappa, \text{trade}) > G(e^*, \kappa, \text{no trade})$, as shown by curve labelled “B”, trade increases the equilibrium level of emissions.

Define

$$\tilde{G}(e, \kappa, s) \equiv (1 - \kappa)c_e(e + s, 0) + \kappa c_e\left(e - \frac{(1 - \kappa)s}{\kappa}, 1\right),$$

the social marginal benefit of emissions given e, κ and permit purchases of level s (per non-investing firm). Using this definition, $\tilde{G}(e, \kappa, s) = G(e, \kappa, \text{trade})$ for $s = e^t(e, \kappa)$, and $\tilde{G}(e, \kappa, s) = G(e, \kappa, \text{no trade})$ for $s = 0$.

Thus,

$$\begin{aligned} G(e; \kappa, \text{no trade}) - G(e; \kappa, \text{trade}) &= \tilde{G}(e, \kappa, 0) - \tilde{G}(e, \kappa, e^t) = \\ &= - \int_0^{e^t} \frac{\partial \tilde{G}(e, \kappa, s)}{\partial s} ds = - (1 - \kappa) \int_0^{e^t} \left(c_{ee}(e + s, 0) - c_{ee}\left(e - \frac{(1-\kappa)s}{\kappa}, 1\right) \right) ds. \end{aligned} \quad (12)$$

Evaluating this expression at $e = e^*(\kappa)$ implies the sufficient conditions in the Proposition. ■

The fact that trade in permits reduces abatement costs implies that the with-trade industry marginal abatement cost curve cannot lie above the no-trade industry marginal abatement curve for all levels of emissions. The insight behind Proposition 1 is that the two curves can cross, so that there can exist intervals over which the with-trade marginal abatement curve does lie above the no-trade curve. When such an interval exists, there is some marginal damage function $D'(e)$ for which trade increases the optimal level of emissions.

Relative to the optimal emissions levels with trade, the optimal levels without trade require over-emissions by the firms that invested, and under-emissions by the firms that did not invest. To a first order approximation, both of these departures from the first best outcome result in welfare losses proportional to the slope of the marginal cost curves, c_{ee} . Suppose for example that we begin at an arbitrary level of emissions, e , without trade and then move toward trade by shifting one unit of emissions from low cost to high cost firms. The marginal cost of the former increases by approximately $|c_{ee}(e, 1)|$ and the marginal cost of the latter decreases by approximately $|c_{ee}(e, 0)|$. The two-firm average of marginal abatement costs therefore decreases if $c_{ee}(e, 0) - c_{ee}(e, 1) < 0$. If this inequality holds, the reallocation of permits – a movement toward trade – reduces the industry marginal cost of abatement. The proposition extends this marginal analysis to non-marginal changes. The appendix provides a graphical perspective of the result. (Proposition 1 is reminiscent of the conclusion that a discriminating monopoly might sell either more or less than a monopoly that cannot discriminate.)

4 The investment stage

This section establishes that when permits are not tradable, firms play a coordination game at the investment stage, leading in general to multiple (non-optimal) competitive investment equilibria and resulting regulatory uncertainty. In contrast, the unique investment equilibrium when permits are tradable is socially optimal.

4.1 No trade in permits

When more firms invest (κ is larger), industry marginal abatement costs are lower, so the equilibrium number of permits is lower (equation (3)). The representative firm takes κ as given. The firm forms (point) expectations about this parameter, and these expectations are correct in equilibrium. The firm's belief about κ (equal to its equilibrium value) affects its optimal investment decision. In the investment stage, a firm's net benefit of investing equals the difference between the costs when it does not invest, $-c(e(\kappa), 0)$, and the costs when it does invest, $-c(e(\kappa), 1) + \phi$. The benefit of investing is therefore

$$\Pi^{nt}(\kappa) = c(e(\kappa), 1) - c(e(\kappa), 0) - \phi. \quad (13)$$

Differentiating this expression and using equation (3) implies

$$\frac{d\Pi^{nt}(\kappa)}{d\kappa} = \frac{(c_e^1 - c_e^0)^2}{S} > 0. \quad (14)$$

(The superscript nt denotes “no trade”.) A larger anticipated value of κ increases the incentive to invest: the investment decisions are strategic complements.

The necessary and sufficient condition for multiple equilibria are

$$\Pi^{nt}(0) = c(e(0), 1) - c(e(0), 0) - \phi < 0 \quad (15)$$

$$\Pi^{nt}(1) = c(e(1), 1) - c(e(1), 0) - \phi > 0. \quad (16)$$

The net cost of adopting if no other firm adopts is $\Pi^{nt}(0)$. Inequality (15) implies that a firm does not want to invest if it knows that no other firm will invest ($\kappa = 0$); here the firm knows that the environmental standards will be lax. The net benefit of adopting if all other firms adopt is $\Pi^{nt}(1)$. Inequality (16) implies that it pays a firm to invest if all other firms do so; here the firm knows that abatement standards will be strict.

If equations (15) and (16) hold there is an interior unstable equilibrium that satisfies $\Pi(\kappa_u) = 0$, where $0 < \kappa_u < 1$. At κ_u a firm is indifferent between investing and not investing. This equilibrium is unstable; for example, if slightly fewer than the equilibrium number of firms invest ($\kappa < \kappa_u$), it becomes optimal for all other investors to change their decisions, and decide not to invest. In summary, we have

Proposition 2 *Inequalities (15) and (16) are necessary and sufficient for the existence of two stable boundary equilibria (all firms or no firms invest) and one unstable interior equilibrium. If either inequality fails, there exists a unique boundary equilibrium.*

If ϕ is very small, it is always optimal to invest; it is never optimal to invest if ϕ is very large. Multiplicity requires that ϕ is neither very large nor very small.

4.2 The equilibrium value of κ under tradable permits

As is the case without trade in permits, an increase in the number of adopters (larger κ) causes the regulator to use stricter environmental standards (smaller e). Totally differentiating equation (8), using the second order condition $S^t > 0$, implies

$$\frac{de}{d\kappa} = \frac{c_{ee}^0 c_{ee}^1}{\kappa S^t} \left(\frac{e^t}{\kappa c_{ee}^0 + (1 - \kappa) c_{ee}^1} \right) < 0. \quad (17)$$

(The appendix shows intermediate steps for the derivations of several equations.)

A larger value of κ has an ambiguous effect on the purchases per non-adopter, e^t . Totally differentiating equation (4), the equilibrium condition for quantity traded, implies

$$\frac{de^t}{d\kappa} = \frac{-\frac{\Delta}{S^t} \left(\frac{c_{ee}^0}{\kappa c_{ee}^0 + (1 - \kappa) c_{ee}^1} \right) + \frac{1}{\kappa}}{\kappa c_{ee}^0 + (1 - \kappa) c_{ee}^1} c_{ee}^1 e^t. \quad (18)$$

This equation shows that a sufficient condition for the purchases per non-adopter to increase with the number of adopters is $\Delta(\kappa, e, e^t) < 0$. From Proposition 1, this inequality also implies that trade in permits leads to tighter environmental regulations, given κ .

The effect of investment on the equilibrium permit price is not obvious. For a given level of permits, a higher level of investment obviously decreases the equilibrium price. However, a higher level of investment decreases the equilibrium level of permits. The first effect always dominates, so higher κ reduces the equilibrium price of permits:²

$$\frac{dp}{d\kappa} = \frac{c_{ee}^0 c_{ee}^1 e^t}{S^t (\kappa c_{ee}^0 + (1 - \kappa) c_{ee}^1)} \frac{D''}{\kappa} < 0. \quad (19)$$

The cost incurred by the firm that invests, net of receipts from sales of permits, is

$$-c \left(e - \frac{1 - \kappa}{\kappa} e^t, 1 \right) + \phi - p \frac{1 - \kappa}{\kappa} e^t.$$

The cost incurred by the firm that does not invest, net of payments from purchases of permits, is

$$-c(e + e^t, 0) + p e^t.$$

The benefit of investing (equal to the cost savings) when trade in permits is allowed is the difference between these two costs:

$$\begin{aligned} \Pi^t(\kappa) \equiv & (-c(e + e^t, 0) + p e^t) - \left(-c \left(e - \frac{1 - \kappa}{\kappa} e^t, 1 \right) + \phi - p \frac{1 - \kappa}{\kappa} e^t \right) = \\ & c \left(e - \frac{1 - \kappa}{\kappa} e^t, 1 \right) - c(e + e^t, 0) - \phi + p \frac{1}{\kappa} e^t. \end{aligned} \quad (20)$$

²An informal argument explains this result. The equilibrium level of emissions is the same under the cap-and-trade and the tax policy. The equilibrium permit price in the former equals the equilibrium tax in the latter. Since greater investment reduces the industry marginal cost of abatement, it must reduce the equilibrium tax – and the equilibrium permit price.

(The superscript t denotes “trade”.) Using the equilibrium conditions (4) and (5) the derivative of the benefit of adoption is³

$$\frac{d\Pi^t}{d\kappa} = \frac{e^t}{\kappa} \frac{dp}{dk} < 0. \quad (21)$$

This inequality states that under tradable permits, investments are strategic substitutes: an increase in the number of other investors decreases the incentive for any firm to invest. The monotonicity of $\Pi^t(\kappa)$ implies that for $0 < \kappa < 1$ there is at most one root of $\Pi^t(\kappa) = 0$. In summary:

Proposition 3 *When permits are tradable, investment decisions are strategic substitutes; there always exists a unique rational expectations competitive equilibrium. The equilibrium involves the fraction $0 < \kappa < 1$ of firms investing if and only if there is a solution to the equation $\Pi^t(\kappa) = 0$ for $0 < \kappa < 1$. Therefore, an interior equilibrium exists if and only if*

$$\Pi^t(0) > 0 > \Pi^t(1). \quad (22)$$

If $\Pi^t(1) > 0$ then the unique equilibrium is $\kappa = 1$, and if $\Pi^t(0) < 0$ then the unique equilibrium is $\kappa = 0$.

Of course, only the level of κ , not the identity of the investors is determinate when $0 < \kappa < 1$.

4.3 Trade’s effect on the incentive to invest

Homogenous firms all make the same investment decision under command and control emissions policies. Therefore, firms are homogenous ex post, so there is no apparent efficiency loss from the prohibition against trade. In contrast, with market based policies homogenous firms are induced to make different investment decisions, leading to ex post heterogeneity and resulting gains from trade. In this sense, the possibility of trade creates the rationale for trade. Of course, the assumption of ex ante homogenous firms is not realistic, but the point here is that the anticipation of market based policies is likely to increase firm heterogeneity, via the investment decision. Command and control policies are more likely to reinforce firm homogeneity.

Now consider the relation between the levels of investment in the two trade scenarios. Recall that $e(0)$ and $e(1)$ are the socially optimal levels of emissions when $\kappa = 0$ and $\kappa = 1$, respectively; in these cases, trade plays no role since all firms have the same abatement costs in the second period. Let e^{t1} be the equilibrium level of purchases per non-adopting firm in

³The equality in (21) is easiest to derive using the first rather than the second line of equation (20). Note that $\Pi^t(\kappa)$ depends on κ via the effect of κ on e , e^t , the ratio $\frac{1-\kappa}{\kappa}$, and finally on $p(\kappa)$. In view of the equilibrium conditions (4) and (5), the effect via each of the first three channels is 0, so we are left with the effect of κ on $\Pi^t(\kappa)$ via its effect on p .

the hypothetical situation where $\kappa = 1$ and a “single firm” (more formally: a set of firms of measure zero) deviates by not investing, and instead buys e^{t1} permits at the equilibrium price p^1 . The deviating firm obtains the consumer surplus

$$CS \equiv c(e(1) + e^{t1}, 0) - c(e(1), 0) - p^1 e^{t1} > 0. \quad (23)$$

The non-deviating firms (when $\kappa = 1$) each sell an infinitesimal amount to the deviating firms⁴, receiving infinitesimal producer surplus. This fact and equations (13), (20) and (23) imply

$$\Pi^t(1) = \Pi^{nt}(1) - CS < \Pi^{nt}(1). \quad (24)$$

The possibility of trade decreases the benefit of investment when $\kappa = 1$, because a firm knows that by deviating and not investing, it obtains consumer surplus.

Denote s as the equilibrium level of sales of an adopting firm in the hypothetical situation where $\kappa = 0$ and a “single firm” deviates by adopting, and then selling s permits at price p^0 . The deviating firm obtains the producer surplus

$$PS \equiv c(e(0) - s, 1) - c(e(0), 1) + p^0 s > 0. \quad (25)$$

Non-deviating firms (when $\kappa = 0$) each buy an infinitesimal amount⁵ and receive infinitesimal consumer surplus. Therefore

$$\Pi^t(0) = \Pi^{nt}(0) + PS > \Pi^{nt}(0). \quad (26)$$

Inequalities (24) and (26) and the monotonicity of $\Pi^t(\kappa)$ and $\Pi^{nt}(\kappa)$ imply that the curves must cross a single time. This fact means that there can be large differences between the investment equilibria with and without trade. For example, the configuration $\Pi^{nt}(0) < 0 < \Pi^t(1) < \Pi^{nt}(1)$ is possible. These inequalities imply that the unique equilibrium with trade requires $\kappa = 1$, but there are two stable equilibria ($\kappa = 0$ and $\kappa = 1$) without trade. In addition, it is easy to construct an example for which there is a unique interior equilibrium with trade, but two boundary equilibria without trade. The only possibility that can be ruled out is that there is a *different unique* boundary equilibrium with and without trade. For example, the case where $\kappa = 1$ with trade and the unique equilibrium without trade is $\kappa = 0$ violates inequality (24).

4.4 Social optimality and the timing of actions

Several points follow from the analysis above: (i) When permits are tradable, the outcome produces the social optimum regardless of whether the regulator announces the emissions quota

⁴This fact implies that the equilibrium price is $p^1 = c_e(e(1), 1)$ and e^{t1} satisfies $c_e(e(1) + e^{t1}, 0) = p^1$.

⁵Therefore $p^0 = c_e(e(0), 0)$ and s satisfies $c_e(e(0) - s, 1) = p^0$.

before or after firms decide on investment. (ii) When permits are not tradable, the outcome may depend on whether the regulator announces the quota before or after firms decide on investment. If the regulator credibly announces the emissions level before investment occurs, the equilibrium investment is “constrained optimal”; the constraint arises from the prohibition against trade. (iii) Trade in permits eliminates regulatory uncertainty, regardless of when the regulator announces the level of emissions permits. Without trade in permits, regulatory uncertainty occurs only when the regulator cannot credibly announce the emissions level at the investment stage. (iv) Trade in permits can increase or decrease the equilibrium level of emissions, regardless of whether investment is fixed or endogenous, and regardless of whether the regulator announces the abatement level before or after investment.

The first claim is widely known and easily established. Consider the social planner who is able to choose both κ and e , allowing trade. This planner wants to minimize environmental damages plus abatement and investment costs, $W(e; \kappa) + \kappa\phi$. (See equation (7).) The first order condition for this problem at an interior solution is

$$\frac{dW(e; \kappa)}{d\kappa} + \phi = -\Pi^t(\kappa) = 0. \quad (27)$$

This first order condition is identical to the condition for an interior competitive equilibrium. The second order condition for an interior equilibrium, $\frac{d\Pi^t(\kappa)}{d\kappa} < 0$, is identical to the condition that an interior competitive equilibrium is stable. The conditions for a boundary optimum are the same as the conditions for boundary competitive equilibria.

Define the second best outcome as the outcome where the planner chooses both κ and e , under the constraint that trade in emissions is prohibited. The second claim uses the following proposition; the proof is in the Appendix:

Proposition 4 (a) *In the second best outcome, the planner chooses to have all or no firms invest ($\kappa = 1$ or $\kappa = 0$ is constrained optimal).* (b) *The planner who can credibly commit to the level of emissions before investment occurs, achieves the second best outcome.*

An immediate consequence of this Proposition is:

Corollary 1 *In the absence of trade, when the regulator announces the emissions ceiling after investment, one of the competitive equilibria coincides with the second best outcome (the “constrained optimum”).*

Proof. The corollary is trivial when there are two multiple competitive equilibria, because these are both on the boundary, as is the second best outcome. The proof of Proposition 4b establishes the corollary when there is a unique competitive equilibrium. ■

The third claim relies on the uniqueness of the rational expectations equilibrium with trade, the lack of uniqueness without trade, and Proposition 4. The fourth claim relies on Proposition 1 and on the fact that equilibrium investment without trade can be larger or smaller than equilibrium investment with trade.

Figure 3 shows an example of the equilibrium level of emissions as a function of investment costs, ϕ , for three scenarios, using the abatement cost functions in Example 1 with $b = 1.5$ and marginal damage of pollution e . As the equilibrium value of κ ranges from 1 to 0 with increasing investment costs, the level of emissions ranges from 0.4 to 0.5. The positively sloped dashed curve shows emissions when these are tradable; the solid step function shows emissions when these are not tradable but the regulator announces emissions before investment; the dashed line segment shows the “interval of multiplicity” (0.104, 0.127) for which there are two equilibria (either $e = 0.4$ or $e = 0.5$) when the regulator chooses the non-tradable emissions level after investment.

Under trade, emissions is a continuous non-decreasing function of ϕ ; without trade (but credibly committing to emissions levels before investment) emissions is a step function. In this example, the step occurs at $\phi = 0.117$. The emissions levels are equal in the two scenarios at high or at low levels of ϕ , where the equilibrium level of κ is either 0 or 1. However, for low-intermediate costs ($.10667 \leq \phi \leq .117$) emissions are higher with trade; for high-intermediate costs ($.117 \leq \phi \leq .125$) emissions are lower with trade. This qualitative comparison hold in general; with trade, emissions is a continuous non-decreasing function of ϕ , and without trade (but credible announcements of emissions levels), emissions is a non-decreasing step function of ϕ .

In this example, the interval of multiplicity (when non-tradable permits are chosen after investment) includes the interval over which tradeable emissions take interior values. For this example, whenever there is an interior equilibrium with trade, there are multiple equilibria without trade. The figure also illustrates Corollary 1. Taking into account the endogeneity of investment greatly increases the set of parameter values under which trade can either increase or decrease the level of equilibrium emissions.

5 Investment as a global game

There are number of ways in which uncertainty changes the equilibrium problem and might yield a unique equilibrium in the absence of trade, even when the regulator announces the emissions level after investment. This section examines the setting known as a “global game”, following Morris and Shin (2003). Previous applications of global games include models of currency attacks (Morris and Shin 1998), bank runs (Goldstein and Pauzner 2005) and resale

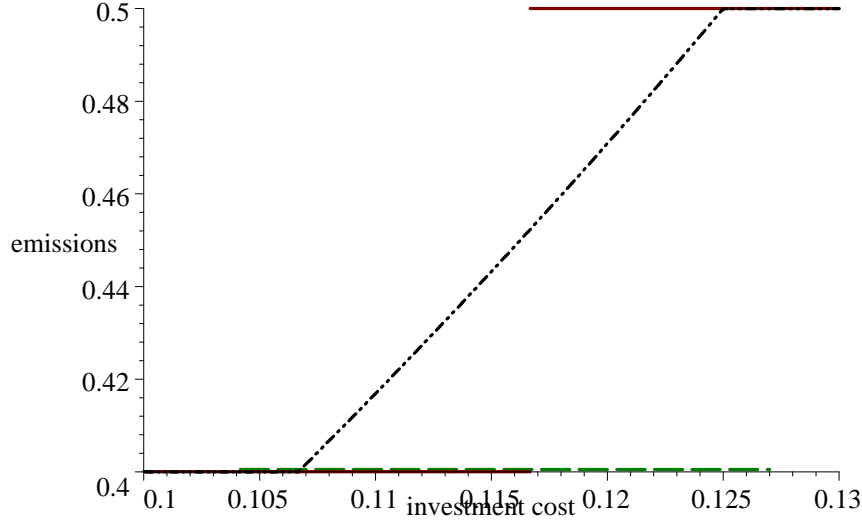


Figure 3: Positively sloped dashed curve: Equilibrium emissions with trade. Solid step function: Equilibrium emissions without trade when regulator announces emissions before investment. Interval of $0.104 < \phi < .127$ shown by dashes: region of multiple equilibrium without trade when regulator announces emissions after investment. Abatement costs given in Example 1 with $b = 1.5$ and marginal damages $= e$,

markets (Karp and Perloff 2005).

Suppose that firm i has investment cost $\phi_i = \bar{\phi} + \epsilon x_i$ where $\epsilon > 0$ and x_i is a random variable with pdf $p(x)$. The parameter $\bar{\phi}$ is unknown and all firms begin with a diffuse prior on $\bar{\phi}$ (a uniform prior over the real line). After observing its private cost, a firm forms a posterior belief on $\bar{\phi}$. As ϵ shrinks toward 0, each firm knows that with high probability all firms have approximately the same costs, and they all know that all firms know this, and so on with higher order beliefs.

The equilibrium to this game is a mapping from the signal ϕ_i to the action space: {invest, do not invest}. There is a unique equilibrium to this game, and that equilibrium does not depend on $p(x)$ or ϵ . The unique equilibrium survives iterated deletion of dominated strategies. This equilibrium can be calculated by determining the optimal action for an agent who receives signal ϕ_i and believes that κ , the measure of agents who invest, is uniformly distributed over the interval $[0, 1]$. Without loss of generality, suppose that a firm that is indifferent between investing and not investing decides to invest.

Using Prop 2.1 in Morris and Shin (2003), a firm wants to invest if and only if its signal ϕ_i satisfies

$$\phi_i \leq \phi^c \equiv \int_0^1 (c(e(\kappa), 1) - c(e(\kappa), 0)) d\kappa. \quad (28)$$

In equilibrium the fraction of firm that invest is

$$\kappa^c \equiv \int_{-\infty}^{\frac{\phi^c - \bar{\phi}}{\epsilon}} p(x) dx.$$

For $\phi^c - \bar{\phi} \neq 0$ (an almost-certain event) this fraction approaches 0 or 1 as $\epsilon \rightarrow 0$, depending on whether $\phi^c - \bar{\phi}$ is negative or positive.

Now consider the problem for the regulator who can choose κ in the first period and then choose the emissions allowance in the second – maintaining the assumption that there is no trade in emissions. This regulator obtains a signal $\phi_r = \bar{\phi} + \epsilon_r x_r$ where x_r is a random variable with density $p_r(x_r)$. With slight abuse of notation, denote as ϕ the regulator's expectation of industry-wide average investment costs, conditional on its signal. Since the regulator's payoff is linear in investment costs, it minimizes expected total costs by choosing κ and $e^0 = e^1 = e$ to minimize $P(e, e, \kappa)$ defined in equation (1). As shown in the proof of Proposition 4, this function is concave in κ so the optimal investment decision, denoted κ^s , is always on the boundary. With the tie-breaking assumption that a planner who is indifferent chooses to invest, the decision is to set $\kappa = 1$ if and only if

$$\phi \leq \phi^s \equiv c(e(1), 1) - c(e(0), 0) + D(e(0)) - D(e(1)). \quad (29)$$

In both the competitive equilibrium and under the social planner who chooses κ directly, there is a threshold signal, below which investment occurs. The expected amount of investment is higher, the lower is the threshold signal. Even if the thresholds ϕ^c and ϕ^s coincide, the equilibrium amount of investment under this social planner and in the competitive equilibrium might nevertheless differ. The planner and firms might have different distributions of signals; in addition, κ^s is always a boundary value, whereas it is possible that $0 < \kappa^c < 1$. However, as noted above, κ^c approaches a boundary 0 or 1 as ϵ approaches 0 (for $\phi^c - \bar{\phi} \neq 0$). In addition, if both ϵ and ϵ_r are small, both the firm and the regulator have approximately the same posterior expectation of $\bar{\phi}$. Thus, if $\phi^c = \phi^s$, for any $\epsilon^* > 0$, the probability that $|\kappa^c - \kappa^s| < \epsilon^*$ (i.e., that the outcomes are “essentially the same”) can be made arbitrarily close to 1 by choosing sufficiently small ϵ, ϵ_r .⁶ In contrast, if $\phi^c \neq \phi^s$, for sufficiently small ϵ, ϵ_r there exist values of $\bar{\phi}$ at which $|\kappa^c - \kappa^s| \approx 1$. These observations motivate the comparison of the thresholds ϕ^c and ϕ^s . If $\phi^c = \phi^s$ the equilibrium outcomes are “essentially the same” when the firms

⁶In this sentence, “the probability” is a conditional probability, conditioned on the event that nature chooses $\bar{\phi}$ from a finite connected subset of the real line that includes parts of the dominance regions. Without such conditioning, “the probability” is not well-defined because agents have diffuse priors over $\bar{\phi}$.

and the regulator have essentially the same information (ϵ and ϵ_r are small). If $\phi^c \neq \phi^s$ the outcomes are likely to be different even if the firms and the regulator have essentially the same information.

In this model the externality is associated with emissions, and only indirectly with investment. The competitive level of investment is socially optimal when the regulator uses market based methods, such as tradable permits, to correct the emissions externality; the regulator does not need a second policy instrument to target investment. The use of non-tradable permits results in a constrained optimum level of emissions, conditional on the level of investment. Why then does the competitive level of investment not always result in the constrained optimal investment level, in the case of command and control policies chosen after investment? In the common-knowledge scenario analyzed in the previous section, we saw that the answer was simply that there can be multiple competitive equilibria. Corollary 1 shows that one of these equilibria is constrained optimal, so the other (when it exists) is not constrained optimal. However, we know that the strategic uncertainty in the global games setting leads to a unique equilibrium. Since there is a unique equilibrium in the global games setting, the intuition from the tradable permits case seems applicable: If the planner corrects the emissions externality, the market yields the correct level of investment. The fact that the policy intervention, under command and control, is only a *constrained* optimum, does not appear relevant. This reasoning leads to the conjecture that $\phi^c = \phi^s$, an equality that states that the competitive equilibrium and the social planner's outcome would differ significantly only if the firms and the planner have different information (i.e., if ϵ or ϵ_r are non-negligible).

The following proposition confirms this conjecture; the proof is in the Appendix:

Proposition 5 *The two thresholds (in the global game and in the social planner's problem) are equal: $\phi^c = \phi^s$. Therefore, when firms and the social planner have essentially the same information, the competitive equilibrium and the constrained social optimum are “essentially the same” (as defined above).*

Example 3 *Let the abatement costs be as in Example 1 and let emissions damages be $D(e) = \frac{\delta}{2}e^2$, with $\delta > b - 1$. This inequality insures that for all κ , at the equilibrium level of emissions a firm that invests has a positive marginal benefit of emissions. The threshold investment cost in the global game and for the social planner is*

$$\phi^c = \phi^s = \frac{1}{2}\delta(b-1) \frac{b+\delta+1}{b(b+\delta)(\delta+1)}.$$

This function is increasing in both b and δ . (The discontinuity in the step function in Figure 3 equals ϕ^s .) A larger value of b increases the reduction in abatement cost due to investment. A larger value of δ decreases the equilibrium level of emissions for all κ . Either of these changes makes investment more attractive, increasing the threshold level of investment costs.

It is worth emphasizing that, when firms and the planner have essentially the same information, the global games equilibrium is (constrained) *socially* optimal. It is not true that the global games equilibrium maximizes the expected payoff to the industry. The industry as a whole would like to have all firms rather than no firms invest, given expected costs ϕ , if and only if

$$\phi \leq \phi^{cartel} \equiv c(e(1), 1) - c(e(0), 0). \quad (30)$$

Equations (29) and (30) show that $\phi^{cartel} < \phi^s$. Thus, the global games equilibrium does not maximize the industry payoff; it maximizes society's constrained payoff.

The model in this section treats the investment cost ϕ as the random variable, but there are many other possibilities. The game described above involves private values of investment costs, ϕ_i . We can also consider the situation where the payoff depends on the common value of a parameter. For example, with the functions in Example 3, the value to the firm of investing, for all κ , is an increasing function of δ , because a larger value of δ reduces the equilibrium emissions allowance. Suppose that firms begin with diffuse priors over δ and then each receives a private signal δ_i of this common value. With minor changes in assumptions about the distribution of the signal, we can apply Proposition 2.2 of Morris and Shin (2003) to show that there is a threshold equilibrium in this setting, a value δ^c such that firms invest if and only if $\delta_i \geq \delta^c$. There is also a threshold signal in the social planner's problem, δ^s . The parameter δ , unlike ϕ , affects the equilibrium level of emissions conditional on κ ; δ consequently enters nonlinearly the firm's and the social planner's payoff obtained by substituting in the equilibrium level of e . However, as ϵ and ϵ_r approach 0, the uncertainty with respect to δ is of no consequence in either problem. There remains only the strategic uncertainty about other agents' actions, arising from the lack of common knowledge; of course this uncertainty is the reason for the unique equilibrium in the global game setting. Thus, provided that the firms and the regulator have essentially the same information, the competitive equilibrium leads to approximately the same outcome as the social planner's problem; that is, $\delta^c = \delta^s$.

If there is a public signal about ϕ (or about δ in the linear example), the competitive equilibrium might not be unique, and therefore might not duplicate the constrained socially optimal equilibrium. In the presence of a public signal, uniqueness requires that the private signal is "sufficiently more precise" than the public signal.

An alternative to the global games model studied above is worth considering briefly. Suppose that firm i 's investment cost is a draw from the *known* distribution $p(\phi)$. Unlike in the global game, the firm's private information tells it nothing about the other firms' costs, since the distribution (and all its parameters) are known at the outset. Brock and Durlauf (2001) provide an example of such a game. As the support of $p(\phi)$ shrinks, firms become more similar, and the game approaches the deterministic game in the previous section. However, if there is suffi-

cient variability in the private cost, there is a unique equilibrium. A simple example illustrates this claim. Let ϕ take two values, ϕ_l and ϕ_h with equal probability, with (known) mean $\bar{\phi}$; moreover, suppose that in the deterministic game there are multiple equilibria if $\phi = \bar{\phi}$. At one extreme, let ϕ_l and ϕ_h be very close to $\bar{\phi}$. In this case, it is obvious that there remain multiple equilibria in the game with uncertainty. At the other extreme, let ϕ_l and ϕ_h be sufficiently far from $\bar{\phi}$ so that they both lie in “dominance regions”. In this case it is obvious that there is a unique equilibrium to the investment game. This example illustrates a situation in which uniqueness requires a sufficient amount of uncertainty. In contrast, in the global games setting, an arbitrarily small amount of uncertainty yields uniqueness. Herrendorf, Valentinyi, and Waldman (2000) examine another setting in which agent heterogeneity leads to uniqueness.

6 Conclusion

The fact that market based pollution policies are generally more efficient than command and control policies is widely understood. However, the argument in favor of market based policies is sometimes exaggerated, and a different argument in favor of these policies usually ignored. Market based – compared to command and control – policies might result in either more or less abatement, regardless of whether investment is fixed or endogenous and regardless of whether the regulator announces the level of permits before or after firms invest. Therefore, economists should be cautious about trying to convince anti-market environmentalists of the benefit of market based policies on the grounds that these promote environmental goals.

However, market based policies do reduce regulatory uncertainty. Under command and control policies, the lumpiness of investment at the firm level, and the fact that future environmental policies (optimally) depend on previous levels of investment, imply that there can be multiple rational expectations equilibria. From the standpoint of individual firms, this multiplicity looks like regulatory uncertainty. Market based policies eliminate this multiplicity of equilibria.

Because command and control policies create incentives for firms to make the same investment decision, these policies tend to reinforce firm homogeneity. This ex post similarity may make it appear that the prohibition against trade in permits is unimportant. In contrast, market based policies encourage firms to make different investment decisions, thus creating or increasing firm heterogeneity, and increasing the efficiency gains from trade. The possibility of trade creates or increases the rationale for trade.

The potential regulatory uncertainty arises only when the regulator conditions emissions level on the previous aggregate investment, i.e. on the current industry abatement cost curve. If the regulator is able to credibly commit to an emissions policy at the investment stage, there is

obviously no regulatory uncertainty, and there is consequently a unique investment equilibrium. This competitive equilibrium is constrained optimal.

The potential regulatory uncertainty, when command and control policies are conditioned on past investment, depends on firms having common knowledge about market fundamentals. Even a small amount of private information about a market fundamental, such as average investment costs or the slope of marginal damages, leads to a unique equilibrium in the investment game. Importantly, this equilibrium is constrained socially optimal: it reproduces the investment and abatement outcome selected by the regulator who (in the absence of trade in permits) can choose investment and emissions directly, or equivalently, the regulator who can choose the level of emissions permits before firms invest. Thus, in the absence of common knowledge about market fundamentals, command and control policies create no regulatory uncertainty and no inefficiency at the investment stage; those policies lead only to the usual inefficiencies arising from misallocation of abatement effort.

These observations are interesting to the field of environmental economics, and regulatory economics more generally. They are of particular interest given the discussion of climate change policies occurring at all governmental levels. California's AB32 is a striking example. This law explicitly recognizes that future emissions levels will be conditioned on future contingencies. It leaves open the possibility of using market based policies, without embracing those policies. There is still opposition to market based policies, so economists should be clear about what they do – and do not – achieve.

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Appendix: Further discussion, technical details and proofs

Discussion of Example 1 These functional forms imply that without investment BAU emissions are $e = 1$ and abatement costs equal $-c(e, 0) = \frac{1}{2} - (1 - \frac{1}{2}e)e$ for $e \leq 1$. With investment, BAU emissions are $e = \frac{1}{b}$ and abatement costs for $e \leq \frac{1}{b}$ equal $-c(e, 1) = \frac{1}{2b} - (1 - \frac{b}{2}e)e$. The constants $\frac{1}{2}$ and $\frac{1}{2b}$ do not affect the abatement decisions, but it is necessary to include the constants when using the example to illustrate the investment decisions. To understand the constants, consider the case with investment. In the absence of an emissions limit the firm that invested maximizes the benefit of emissions by setting $e = \frac{1}{b}$ and obtains benefits $\frac{1}{2b}$. If the firm is required to reduce emissions to $e \leq \frac{1}{b}$ its benefits are $(1 - \frac{b}{2}e)e$. The abatement cost is simply the reduction in benefits, $\frac{1}{2b} - (1 - \frac{b}{2}e)e$.

Discussion of Proposition 1 In Figure 2, in the absence of trade the equilibrium level of emissions is e^* and the industry marginal cost equals x . In order to determine the effect of introducing trade, consider the following question: If the per firm endowment of permits were set to e^* , and firms were allowed to trade, would the price of permits be higher or lower than x ? If the market price is higher under trade, e.g. if the price equals $y > x$ in Figure 2, then the industry marginal cost curve with trade must lie above the industry marginal cost without trade in the neighborhood of point e^* . In that case, the industry marginal cost with trade “resembles” the curve labelled B in Figure 2, and the optimal level of permits under trade is greater than e^* . If the market price is lower under trade, e.g. if the price equals $z < x$ when $e = e^*$, then the industry marginal cost curve under trade must lie below the industry marginal cost without trade (at least in the neighborhood of point e^*). In that case, the industry marginal cost with trade “resembles” the curve labelled A in Figure 2, and the optimal level of permits under trade is less than e^* . In short, trade in permits shifts down the industry marginal cost curve (to a location such as A in Figure 2) if and only if the equilibrium price, under trade, is lower than the industry marginal cost without trade. That marginal cost equals a convex combination of the two types’ marginal abatement costs.

Figure 4 helps in describing the circumstances under which the equilibrium (with-trade) permit price is greater or less than the industry marginal cost without trade, holding the aggregate level of permits fixed at e^* . The figure graphs the demand function for permits and two possible supply functions, labelled “high” and “low”, representing different assumptions about the abatement technology. The firms that did not make the investment buy permits, so their marginal cost falls with e^t . Firms that made the investment sell permits. Under the “low” scenario, investment causes a large fall in marginal abatement costs. Under the “high” scenario, investment causes a smaller fall in marginal abatement costs. Firms that do not invest have the

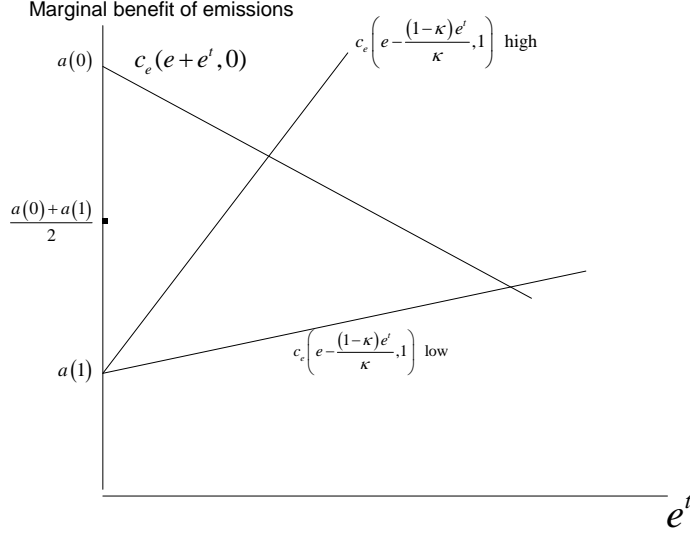


Figure 4: Market for permits under “high” and “low” scenarios, with fixed e and $\kappa = 0.5$.

same marginal cost in both scenarios, so Figure 4 shows a single demand curve. In the absence of trade ($e^t = 0$), the two types of firms have marginal abatement costs $a(0)$ and $a(1)$.

For simplicity, Figure 4 embodies two assumptions. First, $\kappa = 0.5$; second, the intercept of the adopter’s marginal cost, $a(1)$, is the same in the high and the low scenario; the linearity of the curves is not significant. The social marginal benefit of emissions without trade is $\frac{a(0)+a(1)}{2}$ for this particular value of e and for $\kappa = 0.5$. If the investor’s marginal benefit curve is “low”, the equilibrium price is lower than $\frac{a(0)+a(1)}{2}$. This possibility corresponds to curve A in Figure 2. Here the volume of trade is high, and the price is low when permits are tradable. In this case, trade reduces the equilibrium level of e , for given κ . Trade has the opposite effect in the “high” scenario. There the volume of trade is low and the price is high; trade increases the equilibrium level of e for given κ .

For this linear example, trade increases the social marginal benefit of emissions, thereby reducing the equilibrium level of emissions, if and only if the investors’ marginal cost curve is steeper than the non-investors’ curve. Figure 1 and Example 1 insure that this relation holds for sufficiently small e . In that example, the slope of the noninvestors’ marginal cost curve is 1, and the slope of the investors’ curve is $b > 1$ for $e < \frac{1}{b}$.

This graphical analysis helps to understand why trade might either increase or decrease the equilibrium aggregate level of emissions, for a given κ . The optimal level of emissions depends on a comparison of marginal damages and the aggregate marginal abatement cost. In the absence of trade, the aggregate marginal abatement cost is simply a convex combination of

the marginal abatement costs of investor's and non-investors, and therefore (given κ) it depends only on the *level* of the marginal abatement costs of the two types of firms. With trade, firms' emissions do not equal their endowment. Trade equalizes marginal costs for the two types of firms, and the equilibrium level of marginal costs depends on the slopes (not just the levels) of the two marginal costs, as Figure 4 illustrates.

Derivation of equation (17) (the effect of k on the equilibrium level of emissions with trade): I begin by showing how κ affects the volume of trade for given e . Differentiating equation (4) with respect to e^t and κ , holding e fixed, implies⁷

$$\frac{\partial e^t}{\partial \kappa} = \frac{c_{ee}^1}{\kappa c_{ee}^0 + (1 - \kappa) c_{ee}^1} \left(\frac{e^t}{\kappa} \right) > 0. \quad (31)$$

If there are more adopters (larger κ) then each non-adopter buys more permits, holding fixed the aggregate supply of permits, e . Hereafter I use the definition of $\Delta = \Delta(k, e, e^t)$ from equation (11), i.e. we set $s = e^t$. Differentiating the planner's first order condition, equation (8) implies

$$\begin{aligned} \frac{de}{d\kappa} &= \frac{(1 - \kappa) \Delta \frac{\partial e^t}{\partial \kappa} - (c_e^0 - c_e^1) + \frac{e^t}{\kappa} c_{ee}^1}{S^t} \\ &= \frac{(1 - \kappa) \Delta \frac{\partial e^t}{\partial \kappa} + \frac{e^t}{\kappa} c_{ee}^1}{S^t} \end{aligned}$$

The second equality uses equation (4). Using equation (31) to eliminate $\frac{\partial e^t}{\partial \kappa}$ and simplifying produces equation (17).

Derivation of equation (18) (the effect of k on equilibrium purchases per non-adopter) I begin by totally differentiating equation (4), again setting $s = e^t$ and using the definition of $\Delta(k, e, e^t)$ from equation (11).

$$\begin{aligned} \frac{de^t}{d\kappa} &= \frac{-\left(\Delta \frac{de}{d\kappa} - c_{ee}^1 \frac{e^t}{\kappa^2} \right)}{c_{ee}^0 + c_{ee}^1 \frac{1-\kappa}{\kappa}} \\ &= \frac{\left(-\Delta \frac{c_{ee}^0 c_{ee}^1}{\kappa S^t} \left(\frac{e^t}{\kappa c_{ee}^0 + (1-\kappa) c_{ee}^1} \right) + c_{ee}^1 \frac{e^t}{\kappa^2} \right)}{c_{ee}^0 + c_{ee}^1 \frac{1-\kappa}{\kappa}} \end{aligned}$$

The second equality uses equation (17). I obtain equation (18) from simplification.

⁷Recall the meaning of superscripts. These indicate that the function is evaluated at arguments corresponding to the type of firm (non-investor or investor). For example $c_{ee}^1 = c_{ee} \left(e - \frac{(1-\kappa)e^t}{\kappa}, 1 \right)$.

The effect of investment on the equilibrium price of permits I begin with an intermediate result. Differentiating equation (4) (holding κ fixed) implies

$$\frac{de^t}{de} = -\frac{\kappa\Delta}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1}.$$

Substituting this result into the expression for $c_{ee}^0 + S^t$ yields

$$\begin{aligned} c_{ee}^0 + S^t &= \\ c_{ee}^0 + \left(-(1-\kappa)c_{ee}^0 \left(1 + \frac{de^t}{de} \right) - \kappa c_{ee}^1 \left(1 - \frac{1-\kappa}{\kappa} \frac{de^t}{de} \right) + D'' \right) &= \\ \kappa c_{ee}^0 \left(1 - \frac{1-\kappa}{\kappa} \frac{de^t}{de} \right) - \kappa c_{ee}^1 \left(1 - \frac{1-\kappa}{\kappa} \frac{de^t}{de} \right) + D'' &= \\ \Delta\kappa \left(1 - \frac{1-\kappa}{\kappa} \frac{de^t}{de} \right) + D'' &= \\ \Delta\kappa \left(1 + \frac{(1-\kappa)\Delta}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) + D'' &= \\ \frac{\Delta\kappa c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} + D'' \end{aligned} \tag{32}$$

With slight abuse of notation, write $p = p(\kappa) = p(e(\kappa), \kappa)$. Totally differentiating equation (5) and using equations (17), (18), and (32) implies

$$\begin{aligned} \frac{dp}{d\kappa} &= c_{ee}^0 \left(\frac{de}{d\kappa} + \frac{de^t}{d\kappa} \right) = \\ c_{ee}^0 \left(\frac{c_{ee}^0 c_{ee}^1}{\kappa S^t} \left(\frac{e^t}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) + \frac{\left(\left(\frac{\Delta}{S^t} \left(\frac{c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) + \frac{1}{\kappa} \right) \right)}{(\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1)} c_{ee}^1 e^t \right) &= \\ \frac{c_{ee}^0 c_{ee}^1 e^t}{S^t (\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1)} \left(\frac{c_{ee}^0}{\kappa} + \left(-\Delta \left(\frac{c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) + \frac{S^t}{\kappa} \right) \right) &= \\ \frac{c_{ee}^0 c_{ee}^1 e^t}{S^t (\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1)} \left(\frac{c_{ee}^0 + S^t}{\kappa} - \frac{\Delta c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) &= \\ \frac{c_{ee}^0 c_{ee}^1 e^t}{S^t (\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1)} \left(\frac{\Delta c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} + \frac{D''}{\kappa} - \frac{\Delta c_{ee}^0}{\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1} \right) &= \\ \frac{c_{ee}^0 c_{ee}^1 e^t}{S^t (\kappa c_{ee}^0 + (1-\kappa)c_{ee}^1) \kappa} D'' < 0 \end{aligned} \tag{33}$$

Proofs

Recall that $e(\kappa)$ is the optimal level of emissions in the absence of trade, conditional on κ . The notation $\frac{de^*}{d\kappa}$ is an abbreviation for $\frac{de(\kappa)}{d\kappa}$.

Proof. (Proposition 4) Part (a) follows from the concavity of the planner's objective function: social costs $P(e^0, e^1, \kappa)$, given in equation (1), subject to the constraint that $e^0 = e^1$. Using the fact that e is chosen optimally, equation (3), and the fact that investment decreases

marginal abatement costs ($c_e(e, 0) - c_e(e, 1) > 0$) the second derivative of $P(e^0, e^1, \kappa)$ with respect to κ is

$$(c_e(e, 0) - c_e(e, 1)) \frac{de}{d\kappa} < 0.$$

Therefore, the planner's objective is concave in κ ; the optimal κ is either 0 or 1.

The constraint mentioned in part (b) is that trade in permits is not allowed. To establish part (b), suppose that the constrained optimal level of investment is $\kappa = 1$. (The proof is similar when it is optimal to have $\kappa = 0$.) This hypothesis implies

$$-c(e(0), 0) + D(e(0)) - D(e(1)) > -c(e(1), 1) + \phi \quad (34)$$

. This inequality states that the difference, under no investment and under full investment, in the sum of the abatement cost and environmental damages, exceeds the cost of having all firms invest, ϕ . If the planner credibly announces $e^*(1)$ at the investment stage, the individual firm does not care what other firms do, and *does not* invest if and only if

$$-c(e(1), 1) + \phi > -c(e(1), 0). \quad (35)$$

Both inequalities (34) and (35) hold if and only if

$$D(e(0)) - c(e(0), 0) > D(e(1)) - c(e(1), 0). \quad (36)$$

Inequality (36) is false because by definition $e(0)$ minimizes social costs conditional on $\kappa = 0$.

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Proof. (Proposition 5) The statement requires that the right sides of inequalities (28) and (29) are equal. Use integration by parts to write

$$\phi^c = \int_0^1 (c(e(\kappa), 1) - c(e(\kappa), 0)) d\kappa = \quad (37)$$

$$((c(e(\kappa), 1) - c(e(\kappa), 0)) \kappa) \Big|_0^1 - \int_0^1 \kappa (c_e(e(\kappa), 1) - c_e(e(\kappa), 0)) \frac{de^*}{d\kappa} d\kappa.$$

Define

$$g(\kappa) \equiv (1 - \kappa) c_e(e(\kappa), 0) + \kappa c_e(e(\kappa), 1).$$

Equation (2) states that $g(\kappa) = D'(e(\kappa))$. Use this relation and make a change of variables in the equation defining ϕ^s to write

$$\begin{aligned}
\phi^s &= c(e(1), 1) - c(e(0), 0) + D(e(0)) - D(e(1)) = \\
&= c(e(1), 1) - c(e(0), 0) - \int_{e(0)}^{e(1)} D'(e) de = \\
&= c(e(1), 1) - c(e(0), 0) - \int_0^1 D'(e) \frac{de^*}{d\kappa} d\kappa = \\
&= c(e(1), 1) - c(e(0), 0) - \int_0^1 g(\kappa) \frac{de^*}{d\kappa} d\kappa.
\end{aligned} \tag{38}$$

Subtracting these two equations give

$$\begin{aligned}
\phi^c - \phi^s &= \\
&= ((c(e(\kappa), 1) - c(e(\kappa), 0)) \kappa) \Big|_0^1 - \int_0^1 \kappa (c_e(e(\kappa), 1) - c_e(e(\kappa), 0)) \frac{de^*}{d\kappa} d\kappa - \\
&\quad \left(c(e(1), 1) - c(e(0), 0) - \int_0^1 g(\kappa) \frac{de^*}{d\kappa} d\kappa \right) = \\
&= c(e(0), 0) - c(e(1), 0) + \int_0^1 c_e(e(\kappa), 0) \frac{de^*}{d\kappa} d\kappa = \\
&= c(e(0), 0) - c(e(1), 0) + \int_{e(0)}^{e(1)} c_e(e(\kappa), 0) de = 0.
\end{aligned}$$

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