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Environmental regulation with technology adoption, learning and strategic behavior

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Abstract

We analyze a model of environmental regulation with learning about environmental damages and endogenous choice of emissions abatement technology by a polluting firm. We compare environmental policy under discretion, in which policy is updated upon learning new information, versus under rules, in which policy is not updated. When investment in abatement technology is made prior to the resolution of uncertainty, neither discretion nor rules with either taxes or standards achieve an efficient solution except in special cases. When there is little uncertainty, rules are superior to discretion because discretionary policy gives the firm an incentive to distort investment in order to influence future regulation. However, when uncertainty is large, discretion is superior to rules because it allows regulation to incorporate new information. Taxes are superior to standards under discretion regardless of the relative slopes of marginal costs and marginal damages for the case of quadratic abatement costs and damages.

JEL: H23; Q2

Keywords: Environmental regulation; Emissions taxes and standards; Rules versus discretion; Technology adoption

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1. Introduction

Environmental policy issues often have important temporal dimensions as well as significant uncertainty. Environmental regulations are periodically adjusted based on updated understanding or new circumstances. Over time, new scientific findings generate additional information that may cause a change in our understanding of how much damage is likely to be caused by emissions of various pollutants. For example, EPA revised its standard for particulate matter ($PM_{2.5}$) after new scientific evidence linked $PM_{2.5}$ to serious health problems.[1] Similarly, investment in research and development or investment in new plant and equipment may change how costly it is to abate emissions. Once ARCO showed the feasibility of producing "reformulated gasoline with fewer smog-forming and toxic ingredients" in the early 1980s, EPA and the California Air Resources Board "required all oil companies to develop and sell even cleaner gasoline."[2]

Because environmental regulations may be adjusted through time to reflect updated understanding or new circumstances, there may be scope for strategic behavior. On the one hand, a regulator should anticipate how regulations affect not only current emissions levels, but also the effect on investment in R&D or new plant and equipment by regulated firms. In the long-run, the dynamic effects of policy on incentives to innovate may be of greater importance than the static effects of policy on emissions. On the other hand, regulated firms should anticipate how their investment in R&D or new plant and equipment affects not only costs given current regulations, but also how investment might influence future regulation. In other words, a firm may have an incentive to alter investment in a strategic fashion in order to induce favorable shifts in future environmental policy. Such strategic investment can occur when regulated firms are large in the sense of producing a significant share of emissions (e.g., large automobile companies, electric power generators, or oil companies). Such firms regularly lobby governments to influence environmental policy. These firms also have incentives to influence future regulations through their choice of investment strategies. DuPont's successful R&D efforts to find substitutes for chlorofluorocarbons (CFCs) was a major factor in changing the Montreal Protocol from calling for a 50% reduction of CFC production by 1999 to a complete production ban. DuPont profited by shifting demand from CFCs to substitutes where Dupont held patents [16].

In this paper, we analyze an environmental regulation game of symmetric but imperfect information between a regulator and a single regulated firm in which there is learning about environmental damages and investment in abatement technology. One question we investigate is whether it is better for a regulator to commit to an emissions policy prior to learning about the environmental damage function and investment decisions by the firm (rules), or whether it is better to adjust policy after learning about the environmental damage function and investment decisions by the firm (discretion). In a game where investment occurs prior to learning about the damage function, the first best solution cannot in general be achieved under either rules or discretion. Rules are not first best because regulation may not reflect actual benefits or costs of abatement after investment and uncertainty about damages is resolved. As in Kydland and

[1]Cited from http://www.epa.gov/ttn/oarpg/t1/fact_sheets/pmfdsp_fs.pdf, "August 2003 Draft Staff Paper for Particulate Matter."

[2]Cited from http://www.aqmd.gov/monthly/aprilcov.html, "The Southland's War on Smog: Fifty Years of Progress Toward Clean Air."

Prescott [14], discretion is not first best because of the strategic nature of the game. The firm will distort its investment decision in order to influence regulation. We find that, when uncertainty about damages is relatively small, rules are preferred to discretion because avoiding distortion of investment incentives is more important than adjusting policy in light of new information. On the other hand, with relatively large uncertainty about damages, discretion is preferred to rules.

A second question we investigate is whether simple (linear) taxes or standards are preferable. When the regulator commits to a rule, taxes and standards yield exactly the same outcome. The regulator sets regulation such that expected marginal benefits of abatement equal expected marginal costs (post investment). This outcome can be accomplished with either taxes or standards. On the other hand, with discretionary policy, taxes and standards generate different outcomes. Knowing that regulations will be changed to reflect future conditions, regulated firms can invest strategically to change future regulation [2,12,18]. With standards that adjust, the firm has a strategic incentive to reduce investment because investment lowers the abatement cost function resulting in tighter emissions standards. With taxes that adjust, the firm has a strategic incentive to increase investment because a lower abatement cost function causes the regulator to set a lower tax rate. Assuming quadratic cost and benefit functions, we find with discretionary policy that taxes are preferred to standards regardless of the slopes of marginal cost and marginal benefit. This result contrasts with other findings in the literature where the superiority of price or quantity mechanisms depends upon circumstances, such as the cost of innovation, the slope and level of marginal benefits of abatement, the ability of firms to imitate innovation, and the number of firms [5], or the slopes of marginal benefit and marginal cost [24].

There is a growing literature on dynamic environmental regulation that includes aspects of investment in new technology and learning (see Jaffe et al. [7] for a recent survey). Early papers analyzing the incentives to adopt new technology assumed that environmental regulation was fixed, as in our paper with rules (e.g., [3,17]). More recent work on incentive to adopt new technology has assumed that regulation changes if new technology is adopted, as in our paper with discretion (e.g., [12]). Biglaiser et al. [2] consider both rules and discretion. Another strand of literature analyzes environmental regulation with learning by the regulator about abatement costs or damages. Several papers characterize optimal policy with learning and irreversibilities [13,23,10,21,22]. Papers more closely related to the current paper analyze equilibrium solutions in a game where the regulator learns about the damage function or the cost function through time [1,6,8,9,11,18,20]. In some cases with technology adoption and learning first best outcomes can be achieved in equilibrium, such as with non-strategic firms and constant marginal damages [11] or with non-linear taxes [2]. With strategic firms and non-constant marginal damages, however, simple linear taxes or standards generally will not yield first best outcomes. In these cases, comparisons of relative efficiency of taxes and standards are of interest. Karp and Zhang [9] find that the relative efficiency of taxes over standards increases as the regulator has more opportunities for learning in a model with a stock pollutant and non-strategic firms. Moledina et al. [18] analyze a model with strategic firms and a naïve regulator and compare results under taxes and tradable permits. Prior literature has not solved for equilibrium in cases where both the regulator and the regulated firm are strategic, which is the central focus of this paper.

In Section 2, we describe the game with investment in technology adoption and learning about the damage function. We define alternative policy schemes that we consider, rules and discretion, taxes and standards, and find subgame perfect equilibrium under each policy. We then characterize welfare consequences of the equilibrium under each policy. In Section 3, we compare welfare consequences assuming quadratic abatement cost and damage functions. Section 4 contains concluding remarks and comments on potential future research.

2. The model

2.1. Model environment

We describe a game-theoretic model of pollution regulation with endogenous technology adoption and learning involving a regulator and a single polluting firm. We model the order of moves in a game between the regulator and the firm based on the ease or speed with which a variable or decision can change, starting with the most difficult/slowest decision in the first stage and progressing to the easiest/fastest decision. We assume that the most difficult decision to change in a short period of time is the form of the regulatory regime. The regulatory regime is typically based on environmental statutes or administrative procedures that require concerted effort to change. In our model, the regulatory regime determines whether regulation occurs via emissions taxes or emissions standards and whether regulation is fixed (rules), or may change based on new information (discretion). If the regulatory regime is one of rules, then regulatory policy is chosen in the first stage (with discretionary policy, the level of taxes or of standards is chosen later).

In the next stage of the game, the firm chooses investment in adoption of emissions abatement technology. Let $e \geqslant 0$ represent the level of emissions by the firm, $k \geqslant 0$ represent investment, and $r > 0$ represent the unit cost of investment. The firm's emissions abatement cost is given by $C(e,k)$. We assume that the emissions abatement cost function is twice continuously differentiable, decreasing in emissions and abatement investment ($C_e < 0$, $C_k < 0$) and convex ($C_{ee} > 0, C_{kk} > 0, C_{ee}C_{kk} - C_{ek}^2 \geqslant 0$). We also assume that marginal abatement cost, $-C_e$, is decreasing in investment, $C_{ek} > 0$.[3]

Emissions of pollution by the firm cause damages that are external to the firm. Initially there is uncertainty about the damage function. Let S represent the set of possible states and let $D(e;s)$ represent damages caused by emissions in state $s \in S$. Let $\pi(s)$ be the probability that state s occurs. Uncertainty about which state will occur is resolved after the firm has chosen investment. We assume that the damage function is increasing and convex ($D_e > 0, D_{ee} < 0$). We also assume that the damage uncertainty is non-degenerate: $D_e(e;s) > D_e(e;s')$ for all $e \geqslant 0$ for some states $s, s' \in S$ with $\pi(s), \pi(s') > 0$. We assume there is no information asymmetry between the regulator and the firm. Neither the regulator nor the firm know damages prior to the resolution of uncertainty, and the regulator is fully informed about the firm's abatement cost.

After uncertainty about damages is resolved, the regulator sets the tax or standard if they are in a discretionary policy regime (otherwise taxes or standards are fixed in the initial stage and cannot be changed). The firm then chooses emissions. Finally payoffs to the firm and the regulator are realized. Payoffs to the firm under standards are

$$-rk - \sum_{s \in S} \pi(s) C(e(s), k)$$

[3] C_i is the first-order partial derivative of C with respect to $i(\in \{e,k\})$. C_{ij} is the second-order derivative of C with respect to $i,j(\in \{e,k\})$.

with $e(s) = e$, a constant not conditioned on s, under rules. Payoffs to the firm under taxes are

$$-rk - \sum_{s \in S} \pi(s)[C(e(s), k) + \tau(s)e(s)]$$

with both $e(s) = e$ and $\tau(s) = \tau$ under rules. The regulator is assumed to care about minimizing the social cost of pollution (abatement cost plus damages):

$$-rk - \sum_{s \in S} \pi(s)[C(e(s), k) + D(e(s); s)].$$

The complete sequence of moves for the game is summarized in Fig. 1. In Fig. 1(a), we show the sequence of moves for the discretionary policy game. Fig. 1(b) shows the sequence of moves for the rules game. The difference between discretion and rules is that the tax or standard is selected in the initial move in the rules game, but is chosen after investment and uncertainty is resolved in the discretionary game.

2.2. The first-best outcome and policies

The optimal (socially least cost) investment/emissions plan $(k^*, \{e^*(s)\}_{s \in S})$ is given by a solution to the following problem:

$$\min_{k, \{e(s)\}_{s \in S}} \quad rk + \sum_{s \in S} \pi(s)[C(e(s), k) + D(e(s); s)]$$
$$\text{s.t.} \quad k \geqslant 0 \text{ and } e(s) \geqslant 0 \text{ for all } s \in S.$$

Given convexity assumptions, the following first-order conditions are necessary and sufficient for an interior solution:

$$C_e(e^*(s), k^*) + D_e(e^*(s); s) = 0 \quad \text{for all } s \in S, \tag{1}$$

$$r + \sum_{s \in S} \pi(s) C_k(e^*(s), k^*) = 0. \tag{2}$$

Throughout the paper, we assume that the optimal solution is interior.

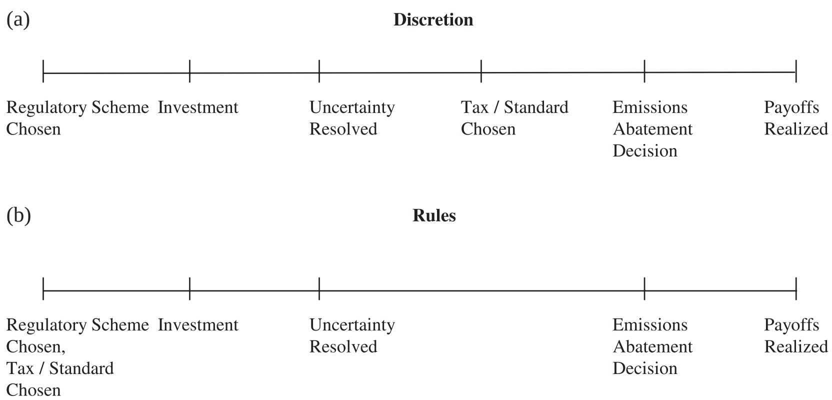

Fig. 1. Order of moves.

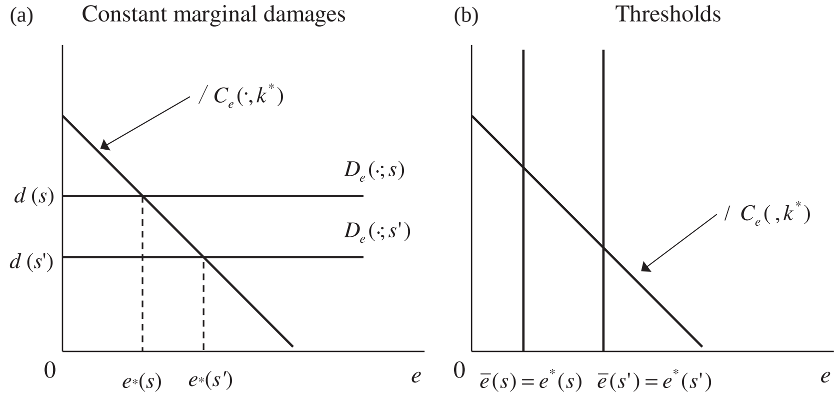

Fig. 2. Constant marginal damages and thresholds.

The regulator can implement the optimal investment/emissions plan if the regulator can choose taxes that are contingent only on the realized state.

Fact 1. *A state-contingent and investment-independent tax plan* $\{\tau(s)\}_{s\in S}$ *achieves the socially minimum cost if* $\tau(s) \equiv D_e(e^*(s); s)$ *for all* $s \in S$ *where* $e^*(s)$ *denotes the optimal emissions in state s. Similarly, a state-contingent standard scheme achieves the socially minimum cost if, for all* $s \in S$*, the emissions standard* $q(s)$ *in state s is equal to* $e^*(s)$*, the optimal emissions in state s.*[4]

(See the appendix for the proof.) A state-contingent, investment-independent scheme allows taxes (or standards) to be adjusted to reflect actual conditions allowing marginal abatement costs to equal marginal damages. However, since taxes (standards) are not a function of investment, there is no scope for the firm to manipulate policy through its investment decision. Given the order of moves in the game, specifically that investment occurs prior to resolution of uncertainty, the optimal taxes or standards in Fact 1 are not available to the regulator. If the regulator sets taxes or standards after resolution of damage uncertainty, as necessary to be ex post optimal, the regulator necessarily sets taxes or standards after the firm's technology choice. Once the regulator makes its choice state-dependent, a time-consistent regulator cannot make the policy independent of the firm's investment choice, giving rise to strategic incentives to manipulate investment to affect policy.

Even with investment prior to resolution of uncertainty, special cases exist whereby discretionary regimes can achieve the first best outcome (the minimum social cost of emissions).[5] Fig. 2(a) describes the case where marginal damage is constant: $D_e(e; s) = d(s) > 0$ for each state $s \in S$. If the socially optimal investment level is given by k^*, then the optimal emission levels and the marginal damage costs are given by $e^*(s)$, $d(s)$ in state s, and $e^*(s')$, $d(s')$ in state s'. With tax rates equal to $\tau(s) = d(s)$ in state s and $\tau(s') = d(s')$ in state s', discretionary taxes can achieve the first best. Because such taxes depend only on s, and are independent of the investment choice by the firm, the firm's strategic choice of investment does not influence the regulator's choice of tax

[4] As a referee pointed out, we need continuity and convexity of the investment cost function to show that the taxes $\tau(s) \equiv D_e(e^*(s); s)$ achieve the socially minimum cost. As in the proof, the standards $e^*(s)$ achieve the first best without these assumptions.

[5] We thank the referees for pointing out these cases.

rates. In this case, taxes fully internalize damages and the firm faces the correct investment incentives. Fig. 2(b) describes a case where there is a damage threshold. The marginal damage $D_e(e;s)$ is zero for emission levels $e \leqslant \bar{e}(s)$ and is prohibitively large for emission levels $e > \bar{e}(s)$. The regulator can achieve the first best by setting standards equal to $\bar{e}(s) = e^*(s)$ in state s and $\bar{e}(s') = e^*(s')$ in states$'$.[6] Since the threshold depends only on s and is independent of investment, there is again no incentive to distort investment choices. The firm faces the full costs of meeting the standard and will choose investment optimally. Throughout the rest of the paper we assume that marginal damages are strictly increasing in emissions, ruling out both the thresholds and constant marginal damage costs.

With marginal damage costs strictly increasing in emission levels, the optimal level of emissions and the marginal damage at the optimal emissions level in each state depends on the marginal abatement cost schedule. The marginal abatement cost schedule depends on the firm's choice of investment. If the regulator could impose a non-linear tax schedule that coincides the marginal damage cost schedule in each state, then the regulator could achieve the first best because all external damages would be internalized and the firm would face the correct set of incentives. Such non-linear tax schedules are not available in many practical situations, and regulators are often constrained to use simple linear taxes or standards. In such cases, the firm can choose investment strategically in order to affect the level of taxes or standards chosen by the regulator.

2.3. Emissions taxes

Here we describe subgame perfect equilibrium and the welfare properties of equilibrium outcomes with taxes under both rules and discretion.

2.3.1. Tax under rules

Given a tax τ on emissions, the firm solves

$$\min_{e,k \geqslant 0} rk + C(e,k) + \tau e.$$

The necessary and sufficient conditions for an interior solution are

$$r + C_k(e,k) = 0, \quad C_e(e,k) + \tau = 0.$$

Denote the solution by $e(\tau), k(\tau)$. Given $e(\tau), k(\tau)$, the regulator solves

$$\min_{\tau \geqslant 0} rk(\tau) + \sum_{s \in S} \pi(s)[C(e(\tau), k(\tau)) + D(e(\tau); s)].$$

A subgame perfect equilibrium is given by a tax rate τ^{RT} chosen by the regulator and the firm's investment and emissions plan $(k^{\mathrm{RT}}(\tau), (e^{\mathrm{RT}}(\tau))_{\tau \geqslant 0})$ that solve the above optimization problems by the firm and the regulator. (Superscript RT denotes the rules tax scheme.)

The following proposition states that a tax rule fails to achieve the efficient solution.

[6]If the marginal damage costs are non-zero (constant or increasing) below threshold levels, then both taxes and standards may be second best and the ranking of them may be ambiguous. Depending on the location of the marginal emissions abatement cost curve (relative to the marginal damage cost schedules), the marginal damage cost curve may or may not be horizontal at the target emission levels. In this case, the regulator may want to use taxes in one state and standards in another.

Proposition 2. *The equilibrium tax rate under rules does not achieve the socially minimum cost.*

Proof. A state-independent tax induces the firm to choose the same amount of emissions across different states. As long as the marginal cost function varies across states, the optimal emissions will differ across states. Hence, a tax scheme where the tax rate is uniform across states does not achieve the optimal outcome. □

2.3.2. Taxes under discretion

With discretionary taxes, the regulator chooses a state- and investment-dependent tax plan. Given investment $k \geqslant 0$, state $s \in S$, and tax τ, the firm chooses the level of emissions to solve

$$\min_{e \geqslant 0} C(e,k) + \tau e.$$

Denote the solution by $e(k,\tau)$. Given the firm's emissions plan (as functions of taxes and investment) $(e(k,\tau))_{k,\tau \geqslant 0}$, the regulator solves

$$\min_{\tau \geqslant 0} C(e(k,\tau),k) + D(e(k,\tau);s)$$

for all $s \in S$ given investment k. Denote the solution by $\{\tau(k,s)\}_{k \geqslant 0, s \in S}$, given which the firm solves

$$\min_{k \geqslant 0} rk + \sum_{s \in S} \pi(s)[C(e(k,\tau(k,s)),k) + \tau(k,s)e(k,\tau(k,s))].$$

A subgame perfect equilibrium is given by the regulator's investment- and state-contingent tax plan $\{(\tau^{\mathrm{DT}}(k,s))_{k \geqslant 0}\}_{s \in S}$ and the firm's investment and state- and tax-dependent emissions plan $(k^{\mathrm{DT}}, \{(e^{\mathrm{DT}}(\tau,s))_{\tau \geqslant 0}\}_{s \in S})$ that solve the above optimization problems by the firm and the regulator. (Superscript DT denotes the discretionary tax scheme.)

We now show that the discretionary taxes fail to achieve an efficient outcome. We use the following lemma as a first step to prove that discretionary policy will be inefficient.

Lemma 1. *Equilibrium discretionary tax rates are decreasing functions of k.*

(See the appendix for the proof.) The logic of this result is described in Kennedy and Laplante [12] and Moledina et al. [18]. Because the regulator will choose a lower tax rate if higher investment is observed, the firm will have an incentive to increase investment in order to manipulate the regulator into setting a lower tax. This is the source of inefficiency in discretionary policies.

Proposition 3. *In equilibrium, the discretionary tax scheme does not achieve the efficient solution (socially minimum cost). The equilibrium investment in a discretionary-tax subgame k^{DT} is larger than the optimal investment k^*.*

Proof. Given investment k, a realized state $s \in S$ and a tax τ, the firm chooses emissions to solve $\min_{e \geqslant 0} C(e,k) + \tau e$. The necessary and sufficient condition for an interior solution is

$$C_e(e,k) + \tau = 0. \tag{3}$$

Let $e(k,\tau)$ represent the emissions level that solves this problem. At the investment stage, the firm's objective function is

$$F_{\mathrm{DT}}(k) = rk + \sum_{s\in S} \pi(s)[C(e(k,\tau(k,s)),k) + \tau(k,s)e(k,\tau(k,s))].$$

The subscript DT stands for discretionary taxes. The derivative of F_{DT} is

$$\begin{aligned}F'_{\mathrm{DT}}(k) &= r + \sum_{s\in S} \pi(s)\left[C_e(e(k,\tau(k,s)),k)\left\{\frac{\partial e}{\partial k} + \frac{\partial e}{\partial \tau}\frac{\partial \tau}{\partial k}\right\} + C_k(e(k,\tau(k,s)),k)\right.\\ &\quad \left. + \frac{\partial \tau(k,s)}{\partial k}\, e(k,\tau(k,s)) + \tau(k,s)\left\{\frac{\partial e}{\partial k} + \frac{\partial e}{\partial \tau}\frac{\partial \tau}{\partial k}\right\}\right]\\ &= r + \sum_{s\in S} \pi(s)\left[C_k(e(k,\tau(k,s)),k) + \frac{\partial \tau(k,s)}{\partial k}\, e(k,\tau(k,s))\right].\end{aligned}$$

The social cost as a function k is given by

$$F(k) = rk + \sum_{s\in S} \pi(s)[C(e^*(k,s),k) + D(e^*(k,s);s)]$$

and the first-order derivative is

$$F'(k) = r + \sum_{s\in S} \pi(s)[C_e(e^*(k,s),k)].$$

As in the proof of Lemma 1, the regulator will set taxes such that $\tau(k,s) = D_e(e^*(k,s);s)$. It follows that $e(k,\tau(k,s)) = e^*(k,s)$. From Lemma 1, we have $\frac{\partial \tau(\cdot,s)}{\partial k} < 0$ for all s and hence $F'(k) > F'_{\mathrm{DT}}(k)$ for all $k > 0$. Therefore, any solution k^{DT} to $F'_{\mathrm{DT}}(k) = 0$ must be larger than the first best level k^*. □

2.4. Emissions standards

Here we describe subgame perfect equilibrium and the welfare properties of equilibrium outcomes with an emissions standard. With emissions standard $q(s) \geqslant 0$ in state s, the firm is restricted to choose emissions $e(s)$ so that $e(s) \leqslant q(s)$. Alternatively, one could assume that $e(s)$ can exceed $q(s)$ but that this would invoke a large fine such that the firm would never find it optimal to choose $e(s) > q(s)$.

2.4.1. Emissions standard under rules

Under rules, there is a single standard, q, that does not depend on state. Given a standard q, the firm solves

$$\begin{aligned}\min_{e,k\geqslant 0} \quad & rk + C(e,k)\\ \text{s.t.} \quad & 0 \leqslant e \leqslant q.\end{aligned}$$

Given that the emissions abatement cost is decreasing in emissions, the firm will choose $e = q$. Denote the solution to investment choice by the firm given q as $k(q)$. Given the firm's choices, the regulator solves

$$\min_{q\geq 0} rk(q) + \sum_{s\in S} \pi(s)[C(q,k(q)) + D(q;s)].$$

A subgame perfect equilibrium is given by the regulator's choice of a standard q^{RS} and the firm's investment and emissions plan $(k^{\mathrm{RS}}(q), e^{\mathrm{RS}}(q))_{q\geq 0}$ that solves the above optimization problems by the regulator and the firm. (Superscript RS denotes the rules standard scheme.)

As with taxes, emissions standards under rules are suboptimal. When standards are set prior to the resolution of uncertainty, the standard set may not achieve an efficient result given the realized damage function.

2.4.2. Emissions standards under discretion

Given investment $k\geq 0$ and state $s\in S$, under standard $q(k,s)$ the firm chooses the level of emissions $e(k,s) = q(k,s)$. Given the firm's emissions plan, the regulator solves

$$\min_{q\geq 0} C(q,k) + D(q;s)$$

for all $s\in S$ given investment k. Denote the solution by $\{q(k,s)\}_{k\geq 0, s\in S}$, given which the firm solves

$$\min_{k\geq 0} rk + \sum_{s\in S} \pi(s)[C(q(k,s),k)].$$

A subgame perfect equilibrium is given by the regulator's state- and investment-contingent standards plan $\{(q^{\mathrm{DS}}(k,s))_{k\geq 0}\}_{s\in S}$ and the firm's investment and emissions plan $(k^{\mathrm{DS}}, \{(e^{\mathrm{DS}}(q,s))_{q\geq 0}\}_{s\in S})$ that solves the above optimization problems by the regulator and the firm. (Superscript DS denotes the discretionary standard scheme.)

If the standard is contingent on both the state and the investment by the firm, then the regulator cannot achieve efficiency. To show this, first we prove that the regulator has an incentive to strengthen the standard if a higher level of investment is observed (Lemma 2).

Lemma 2. *Equilibrium discretionary emissions standards are decreasing functions of* k.

(See the appendix for the proof.) Given Lemma 2, the firm has an incentive to reduce investment to face a more lenient standard. This result leads to the following proposition.

Proposition 4. *The equilibrium discretionary emissions standards do not achieve the socially minimum cost. The equilibrium investment in a discretionary-standard subgame* k^{DS} *is smaller than the optimal investment* k^*.

(See the appendix for the proof.) It is worthwhile noting that discretionary taxes and discretionary standards are both suboptimal, but they are suboptimal in different ways. The discretionary emissions tax results in over-investment whereas the discretionary emissions standard causes the firm to under-invest relative to optimal investment.

3. Comparison of alternative regulatory regimes

3.1. Taxes versus standards

In the previous section we found that taxes and standards under both rules and discretion are suboptimal. Here we compare the relative efficiency of taxes versus standards under both rules and discretion. We begin by comparing taxes and standards under rules.

Proposition 5. *Under rules, the equilibrium standard and the equilibrium tax result in the same equilibrium choice of emissions and investment and the same expected social cost in equilibrium.*

(See the appendix for the proof.) Under rules, the same equilibrium outcome can be attained via a tax or a standard. Because the regulator has committed to a policy (tax or standard), the firm faces no uncertainty when it makes its choice of investment and emissions level. Further, note that the firm's investment choice will satisfy $r + C_k(e,k) = 0$ under both the tax and the standard, which is also the optimal investment choice given emissions. As long as the emissions level is equal under two rules, the investment will be equal. The regulator sets the tax or the standard such that the expected marginal damage equals marginal abatement cost given optimal investment. Therefore, the regulator can induce the firm to choose the ex ante optimal investment and emissions choice via either a standard or a tax. Note that this result is not ex post optimal because in fact the firm's emissions choice should reflect the true state of damages rather than expected damages.

Next, we compare the relative performance of taxes versus standards under discretionary policy. Because investment levels differ under taxes and standards, causing differences in resulting regulatory policy and emissions, comparing performance is complicated. To simplify the task, we restrict attention for the following proposition to a case with quadratic abatement costs and damage functions. Suppose the emissions abatement cost function is given by

$$C(e,k) = \tfrac{1}{2}c(\bar{e} - e - ak)^2 \quad \text{for } e,k \text{ such that } 0 \leqslant e \leqslant \bar{e} - ak,\ k \geqslant 0, \tag{4}$$

where $c, \bar{e}$ and a are positive scalars. Suppose the damage function is given by

$$D(e;s) = \frac{de^2}{2} + f(s)e \quad \text{for } e \geqslant 0, \tag{5}$$

where $d > 0$ and $f(s) \geqslant 0$ for all $s \in S$, where the mean of $f(\cdot)$ is $\sum_{s\in S} \pi(s)f(s) = f > 0$ and the variance is $\sum_{s\in S} \pi(s)[f(s) - f]^2 = \sigma^2 > 0$. These functions satisfy all of the properties assumed for the cost and damage functions.[7]

Proposition 6. *Suppose the abatement cost and the damage cost are given by* (4) *and* (5), *and assume the equilibrium solution is interior under each regulatory regime. Under a discretionary policy regime, the expected social costs are lower in equilibrium with emissions taxes compared to the expected social costs in equilibrium with emissions standards.*

(See the appendix for the proof). This result contrasts with other findings in the literature where the superiority of price or quantity mechanisms depends upon circumstances (e.g. [5,24]). To gain

[7]Function C defined in (4) satisfies the assumptions for the cost function on the domain specified in (4).

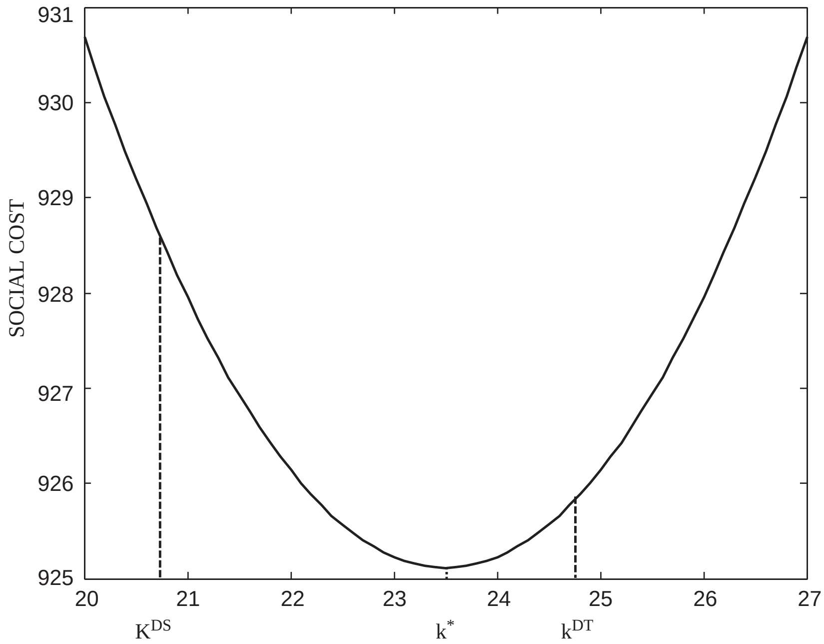

Fig. 3. Total cost as a function of investment.

some intuition for this result, note that the expected social cost as a function of k, assuming an optimal choice of emissions for given k and s, $e(k, s)$, which will be the case under discretion, is

$$TC(k) = rk + \sum_{s \in S} \pi(s)[C(k, e(k, s)) + D(e(k, s); s)].$$

With a quadratic abatement cost function, $TC(k)$ is symmetric about the first-best investment level k^*. Fig. 3 shows an example of function TC under specific parameter values. The relative efficiency of alternative policy instruments then depends on the difference between k^* and the equilibrium investment level under each policy instrument. With quadratic cost and damage functions defined in (4) and (5), the difference between investment under the tax, k^{DT}, and k^* is smaller than the difference between investment under the standard, k^{DS}, and k^*: $k^* - k^{\mathrm{DS}} - (k^{\mathrm{DT}} - k^*) = \frac{(c+d)(adf+2cr)}{a^2d^2(2c+d)} > 0$. Because the bias in investment under standards is larger than the bias under taxes, discretionary taxes are always preferred to discretionary standards.

3.2. Rules versus discretion

Here we compare equilibrium social costs under rules and discretion. The following proposition characterizes the rankings of rules versus discretion.

Proposition 7. *Suppose that the abatement cost function and the damage functions are given by* (4) *and* (5), *and the equilibrium solutions are interior. The equilibrium social cost under rules is smaller*

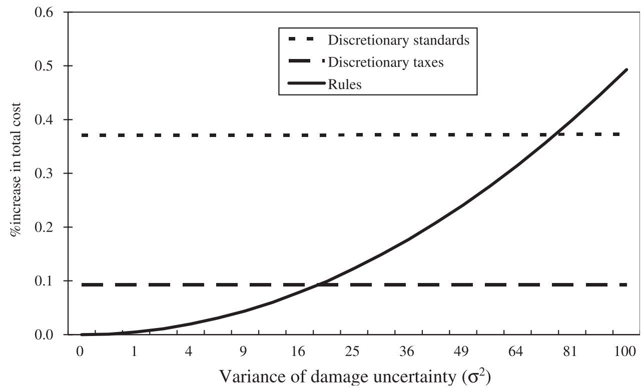

Fig. 4. Rules versus discretion.

than the equilibrium social cost under discretionary standards if and only if

$$\sigma^2 < \frac{cr^2(c+d)^2}{a^2 d^3}. \tag{6}$$

The equilibrium social cost under rules is smaller than the equilibrium social cost under discretionary taxes if and only if

$$\sigma^2 < \frac{c(c+d)^2(r-af)^2}{a^2 d(2c+d)^2}. \tag{7}$$

(See the appendix for the proof).[8] Both conditions (6) and (7) will be satisfied if the degree of uncertainty is small. The less uncertain the future damages caused by emissions, the more likely that rules are preferred to discretion. We also observe in condition (6) that the right-hand side is increasing in $\frac{r}{a}$, the ratio of the unit cost of investment to the effectiveness of abatement per unit of investment. As $\frac{r}{a}$ increases, the firm's incentive to under-invest under discretionary standards increases, which results in a further increase of the equilibrium social costs under discretionary standards. We also note that the right-hand side in condition (6) is increasing in c (the slope of the marginal abatement cost) and decreasing in d (the slope of the marginal damage). Similar statements hold in condition (7). Making the marginal abatement cost steeper or the marginal damage cost flatter makes rules more likely to be preferred to discretion. In Fig. 4 we show the effect of increased uncertainty on the relative efficiency of alternative policy schemes.[9] With no uncertainty ($\sigma^2 = 0$), rules result in an efficient solution. The regulator can set standards or taxes to induce the firm to choose the correct levels of investment and emissions. Discretionary policy, however, does not result in an efficient solution even with no uncertainty. This result occurs because of the distortion in investment incentives. With increasing uncertainty, rules become

[8]From the proof of Proposition 7, we note that $r > af$ must hold for an interior solution. Therefore, $\frac{cr^2(c+d)^2}{a^2d^3} > \frac{c(c+d)^2(r-af)^2}{a^2d(2c+d)^2}$, so that it will never be the case that discretionary standards are preferred to rules when discretionary taxes are not (i.e. discretionary taxes are preferred to discretionary standards as shown in Proposition 6).

[9]The figure is based on the model with Eqs. (4) and (5) where the parameters $c, \bar{e}, a, d, f, \sigma$ and r are chosen so that all the equilibrium solutions are interior.

relatively less efficient. Rules may be set in ways that are far from optimal given actual conditions. On the other hand, the relative inefficiency of discretionary policy is hardly affected by increased uncertainty because policy will be set to reflect actual conditions. Inefficiency arises because of distortion of investment, which is affected little by changes in uncertainty. As in Proposition 7, discretionary policy is preferred to rules for high levels of uncertainty.

4. Discussion

In this paper we compared taxes versus standards under discretion, in which policy is updated upon learning new information, versus under rules, in which policy is not updated. When investment in abatement technology is made prior to the resolution of uncertainty, neither discretion nor rules with either linear taxes or standards achieve an efficient solution. When uncertainty about damages is small, rules are superior to discretion, because discretionary policy schemes give the firm an incentive to distort investment in order to influence future regulation. However, when uncertainty about damages is large, discretion is superior to rules because it allows regulation to incorporate new information. With rules, taxes and standards are equivalent. However, with discretionary policy and quadratic benefits and costs, we find that taxes are always superior to standards. This result contrasts with other findings in the literature where the superiority of price or quantity mechanisms depends upon circumstances, such as the cost of innovation, the slope and level of marginal benefits of abatement [5] or the slopes of marginal benefit and marginal cost [24].

Our focus in this paper was on the comparison of taxes and standards under rules versus discretion. We did not consider other types of environmental policy such as subsidies for abatement or marketable emissions permit (because we have only a single polluting firm). Changes in property rights implicit in a switch from taxes to subsidies, or from grandfathered permits to auctioned permits, cause change in the equilibrium outcome under discretion (but not under rules). When the firm invests and causes a shift in policy, this causes a shift in the value of the property right. So, for example, a subsidy scheme may result in under-investment rather than over-investment as under the tax.[10]

The inefficiency of environmental policy under both rules and discretion is caused by the fact that investment occurs prior to the resolution of uncertainty. If it were possible to reverse the order so that all uncertainty were resolved prior to investment, the regulator could make policy dependent on actual conditions but not dependent upon investment. This would avoid distorting investment incentives while still allowing regulation to reflect actual conditions. This order is not likely to be reversed in practice because investments for technology adoption tend to be long-lived while new information is learned on a fairly frequent basis.

Even with timing fixed as in this model, the inefficiency of environmental policy with learning and innovation under both rules and discretion could be overcome with sufficiently sophisticated regulatory policy. One way to achieve an efficient result is for the regulator to set non-linear taxes. An efficient result will occur if the regulator sets a tax schedule equal to realized marginal damages. In this case, the firm always faces the social costs of its actions and it will choose efficient

[10]We thank a referee for this point.

levels of emissions abatement and investment. By definition, fully internalizing all external costs will correct externalities, but such solutions cannot typically be implemented in practice. In special cases, external costs can be fully internalized by a single linear tax (constant marginal damages) or a standard (threshold).

Another possible route to overcome inefficiency in cases with learning and technology adoption is to consider the introduction of an environmental investment policy in addition to traditional environmental policy targeted to emissions. Innovation policies would need to be coordinated with emissions policy. Under discretionary emissions standards, the firm will tend to invest too little. This distortion could be corrected by subsidizing investment in emissions abatement equipment. On the other hand, under discretionary emissions taxes, the firm will tend to invest too much. Therefore, somewhat paradoxically, with a discretionary emission tax scheme, investment in emissions abatement equipment should also be taxed.

These results also have implications for the policy debate on the effectiveness of technology forcing standards. Technology forcing standards are set at levels that cannot be met by regulated firms with current technology. The idea behind setting strict standards is to stimulate research and development and force technological innovation. Technology forcing standards have been used in North America and Europe to regulate emissions of air pollutants. For example, the U.S. Clean Air Act required a 90 percent reduction in emissions at a time when there did not exist means to achieve the emissions reduction goal [15]. Our results show that committing to standards (rules) when there is large uncertainty can lead to large expected losses. In such cases, discretionary policy is preferable, and with discretion, taxes are preferred to standards (at least for quadratic costs and benefits).

We assumed there is only one polluting firm in our model to highlight the strategic aspects of the regulator-regulated firm interaction. At the other extreme, a large number of small firms might each believe that their own actions have no influence on future regulation. In this case, there would be no distortion of investment incentives and discretionary policy would be the optimal approach. In the more interesting intermediate case with a small number of strategic firms, each firm must consider the effect of their investment on rival firms as well as on the regulator opening up numerous possible results. In addition, having more than one firm raises the issue of appropriability of rents from successful innovation among firms and the possibility of oligopoly competition in output markets (see [5,19] for analysis of these issues).

We considered a model in which the firm chooses a technology from a menu of available existing technologies. In the model, larger investment leads to lower abatement costs with certainty. In practice, the return to investment on technology is stochastic. Firms choose expenditures on research and development for technology innovation, where greater investment results in a larger probability of finding a new technology with lower abatement costs. Stochastic returns to investment in R&D add another source of uncertainty to the model and make discretion preferable to rules.

In this model we focused on symmetric uncertainty about damages in the model. An alternative formulation of the model would be to assume that the results of technology adoption or innovation are private information to the firm, which would then make the model one of regulation under asymmetric information. In addition to firms' private information about costs, the regulator's type may be another source of asymmetric information. For example, perhaps the commitment to rules is somewhat less than categorical. The firm may be uncertain whether a regulator really can or cannot commit to rules. The firm will form a belief on the regulator's type (the ability of the regulator to commit rules) and the firm's response will depend on such beliefs. We leave analysis of asymmetric information models for future research.

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Appendix

A.1. Proof of Fact 1

The socially optimal (i.e. least cost) emissions levels and investment are given by the solution to

$$\min_{k,\{e(s)\}_{s\in S}} \quad rk + \sum_{s\in S} \pi(s)[C(e(s),k) + D(e(s);s)]$$
$$\text{s.t.} \quad k \geqslant 0, \; e(s) \geqslant 0 \text{ for all } s \in S.$$

The optimal plan $(k^*, \{e^*(s)\}_{s\in S})$ is characterized in the text by Eqs. (1) and (2).

Under taxes, the firm chooses state-s emissions given investment k and tax rate $\tau(s)$ to solve

$$\min_{e(s)} C(e(s),k) + \tau(s)e(s)$$

for all $s \in S$. The necessary and sufficient conditions are

$$C_e(e(s),k) + \tau(s) = 0 \quad \text{for all } s \in S.$$

Denote the solutions by $\{e(k,s)\}_{s\in S}$. At the investment stage, the firm solves

$$\min_{k\geqslant 0} rk + \sum_{s\in S} \pi(s)[C(e(k,s),k) + \tau(s)e(k,s)].$$

The necessary and sufficient condition for an interior solution is

$$r + \sum_{s\in S} \pi(s)C_k(e(k,s),k) = 0.$$

With $\tau(s) \equiv D_e(e^*(k,s);s)$ for all $s \in S$, the equilibrium emissions and investment are the same as the unique optimal solution.

With standards set equal to the first best levels, the firm will choose emissions $\{e^*(s)\}$. Then, for any investment levels $k \geqslant 0$ we have

$$rk + \sum_{s\in S} \pi(s)C(e^*(s),k) + \sum_{s\in S} \pi(s)D(e^*(s);s) \geqslant rk^* + \sum_{s\in S} \pi(s)C(e^*(s),k^*) + \sum_{s\in S} \pi(s)D(e^*(s);s)$$

by the definition of k^* and $\{e^*(s)\}$. It follows from this inequality that

$$rk + \sum_{s\in S} \pi(s)C(e^*(s), k) \geq rk^* + \sum_{s\in S} \pi(s)C(e^*(s), k^*).$$

Hence, the firm's cost-minimizing investment decision given standards $\{e^*(s)\}$ is k^*, the socially optimal level.

A.2. Proof of Lemma 1

Denote the optimal emissions given investment k and state $s \in S$ by $e^*(k, s)$. The interior optimal emissions satisfy, for all $s \in S$, $C_e(e^*(k, s), k) + D_e(e^*(k, s); s) = 0$. Totally differentiating both sides with respect to investment and emissions, we have

$$\frac{\partial e^*(k, s)}{\partial k} = -\frac{C_{ek}(\cdot, \cdot)}{C_{ee}(\cdot, \cdot) + D_{ee}(\cdot; s)} < 0.$$

The equilibrium tax rate $\tau(k, s)$ given investment k and state $s \in S$ must satisfy $\tau(k, s) = D_e(e^*(k, s); s)$. Differentiating both sides with respect to k, we have

$$\frac{\partial \tau(k, s)}{\partial k} = D_{ee}(e^*(k, s); s) \cdot \frac{\partial e^*(k, s)}{\partial k} < 0$$

for all $k \geq 0$ since $D(\cdot; s)$ is strictly convex in emissions. Hence, the equilibrium discretionary tax rate is strictly decreasing in investment k.

A.3. Proof of Lemma 2

Denote the optimal standard given investment k and state $s \in S$ by $q(k, s)$, which must satisfy

$$C_e(q(k, s), k) + D_e(q(k, s)) = 0.$$

Totally differentiating with respect to investment and emissions yields:

$$\frac{\partial q(k, s)}{\partial k} = -\frac{C_{ek}(\cdot, \cdot)}{C_{ee}(\cdot, \cdot) + D_{ee}(\cdot; s)} < 0$$

for all $k \geq 0$ and $s \in S$. Hence, the equilibrium discretionary standard level is strictly decreasing in investment k.

A.4. Proof of Proposition 4

Given investment k and an emissions standard plan $\{(q(k, s))_{k \geq 0}\}_{s\in S}$, the firm chooses emissions to minimize cost. From Lemma 2, we know that the optimal discretionary standard level is decreasing in investment. At the investment stage, the firm minimizes

$$F_{DS}(k) = rk + \sum_{s\in S} \pi(s)[C(q(k, s), k)].$$

The subscript DS stands for discretionary standards. The first-order derivative is

$$F'_{\mathrm{DS}}(k) = r + \sum_{s \in S} \pi(s) \left[C_e(q(k,s),k) \cdot \frac{\partial q(k,s)}{\partial k} + C_k(q(k,s),k) \right].$$

As in the proof of Proposition 3, the first derivative of the social cost is

$$F'(k) = r + \sum_{s \in S} \pi(s)[C_e(e^*(k,s),k)].$$

The regulator will set standards such that $q(k,s) = e^*(k,s)$. From Lemma 2, we have $\frac{\partial q(k,s)}{\partial k} < 0$ for all k, s and hence $F'(k) < F'_{\mathrm{DS}}(k)$ for all $k > 0$. Therefore, any solution k^{DS} to $F'_{\mathrm{DS}}(k) = 0$ must be smaller than the first best level k^*.

A.5. Proof of Proposition 5

With rules, the regulator sets a single tax or a single standard. The firm faces the same regulation no matter which state $s \in S$ occurs. In the tax case, the firm facing emissions tax τ will choose emissions level and investment satisfying the following equations:

$$r + C_k(e,k) = 0, \quad C_e(e,k) + \tau = 0. \tag{A.1}$$

Denote the solution by $e(\tau), k(\tau)$. The regulator will choose the tax rate in order to minimize social cost knowing the firm's emissions and investment choices as a function of τ:

$$\min_{\tau \geqslant 0} rk(\tau) + C(e(\tau), k(\tau)) + \sum_{s \in S} \pi(s) D(e(\tau); s).$$

The necessary and sufficient condition for solving this minimization problem is

$$rk'(\tau) + C_e e'(\tau) + C_k k'(\tau) + e'(\tau) \sum_{s \in S} \pi(s) D_e(e(\tau); s) = 0.$$

Using condition (A.1) and the fact that $e'(\tau) \neq 0$, we have $C_e(e,k) + \sum_{s \in S} \pi(s) D_e(e;s) = 0$. In the case of standards, the firm will set emissions equal to the standard: $e = q$. The firm will choose investment $k(q)$ to satisfy

$$r + C_k(q, k(q)) = 0. \tag{A.2}$$

The regulator will choose the standard in order to minimize social cost knowing the firm' emissions and investment choices as a function of standard: $\min_{q \geqslant 0} rk(q) + C(q, k(q)) + \sum_{s \in S} \pi(s) D(q;s)$. The necessary and sufficient condition for solving this minimization problem is

$$rk'(q) + C_e(q, k(q)) + C_k(q, k(q)) k'(q) + \sum_{s \in S} \pi(s) D_e(q;s) = 0.$$

Using (A.2) we can simply this equation: $C_e(q, k(q)) + \sum_{s \in S} \pi(s) D_e(q;s) = 0$. Noting that $e = q$, we have the same equilibrium emissions and investment under the tax rule and the standard rule.

A.6. Proof of Proposition 6

Let Δ be the expected total costs in the equilibrium under discretionary standards minus the expected total costs in the equilibrium under discretionary taxes. We want to show that $\Delta > 0$.

First, for discretionary standards, we derive the equilibrium standards and emissions as functions of investment. Then we derive the equilibrium investment under discretionary standards. We follow the same steps for deriving equilibrium tax rates, emissions and investment under discretionary taxes. Then we show that $\Delta > 0$.

(i) *Discretionary standards*: Given state s and investment k, the regulator sets the standard $q(k,s)$ to solve

$$\min_{q \geqslant 0} \frac{c(\bar{e} - ak - q)^2}{2} + \frac{dq^2}{2} + f(s)q.$$

Solving this problem, we obtain $q(k,s) = \frac{c(\bar{e}-ak)-f(s)}{c+d}$. Given standards $\{(q(k,s))_{k \geqslant 0}\}_{s \in S}$, in the investment stage the firm solves

$$\min_{k \geqslant 0} rk + \sum_{s \in S} \pi(s) \frac{c(\bar{e} - ak - q(k,s))^2}{2}.$$

The solution k^{DS} is given by $k^{\mathrm{DS}} = \frac{-r(c+d)^2 + acd(d\bar{e}+f)}{a^2cd^2}$. (Note that $f \equiv \sum_{s \in S} \pi(s)f(s)$.)

(ii) *Discretionary taxes*: In the emissions abatement stage, given investment k and a tax τ, the firm chooses emissions $e(k,\tau)$ to solve

$$\min_{e \geqslant 0} \frac{c(\bar{e} - ak - e)^2}{2} + \tau e.$$

The solution is given by $e(k,\tau) = \frac{c(\bar{e}-ak)-\tau}{c}$. Hence, in state s, given investment k the regulator sets the tax rate $\tau(k,s)$ to solve

$$\min_{\tau \geqslant 0} \frac{c(\bar{e} - ak - e(k,\tau))^2}{2} + \frac{de(k,\tau)^2}{2} + f(s)e(k,\tau).$$

The solution is given by $\tau(k,s) = \frac{cd(\bar{e}-ak)+cf}{c+d}$, and hence $e(k,\tau(k,s)) = \frac{c(\bar{e}-ak)-f(s)}{c+d}$ (note that $e(k,\tau(k,s)) = q(k,s)$). In the investment stage, the firm chooses investment k^{DT} to solve

$$\min_{k \geqslant 0} rk + \sum_{s \in S} \pi(s) \left[\frac{c(\bar{e} - ak - e(k,\tau(k,s)))^2}{2} + \tau(k,s)e(k,\tau(k,s)) \right].$$

The solution k^{DT} is given by $k^{\mathrm{DT}} = \frac{-r(c+d)^2 + acd\bar{e}(2c+d) + ac^2 f}{a^2cd(2c+d)}$.

(iii) *Comparison of equilibrium costs*: Given the equilibrium quantities found above, we have

$$\Delta = rk^{\mathrm{DS}} + \sum_{s \in S} \pi(s) \left\{ \frac{c}{2}\{\bar{e} - ak^{\mathrm{DS}} - q(k^{\mathrm{DS}},s)\}^2 + \frac{d}{2}\{q(k^{\mathrm{DS}},s)\}^2 + f(s)q(k^{\mathrm{DS}},s) \right\}$$
$$- \left[rk^{\mathrm{DT}} + \sum_{s \in S} \pi(s) \left[\frac{c}{2}\{\bar{e} - ak^{\mathrm{DT}} - e(k^{\mathrm{DT}},\tau(k^{\mathrm{DT}},s))\}^2 \right.\right.$$

$$
\left. \left. + \frac{d}{2} \{ e(k^{\mathrm{DT}}, \tau(k^{\mathrm{DT}}, s)) \}^2 + f(s) e(k^{\mathrm{DT}}, \tau(k^{\mathrm{DT}}, s)) \right] \right]
$$

$$
= \left[-r + \frac{ac(d\bar{e} + f)}{c + d} - \frac{a^2 cd(k^{\mathrm{DT}} + k^{\mathrm{DS}})}{2(c + d)} \right] (k^{\mathrm{DT}} - k^{\mathrm{DS}}).
$$

In the last equation, the expression inside the square bracket is

$$
-r + \frac{ac(d\bar{e} + f)}{c + d} - \frac{a^2 cd(k^{\mathrm{DT}} + k^{\mathrm{DS}})}{2(c + d)} = \frac{c(2cr + adf)}{2d(2c + d)} > 0.
$$

We have $k^{\mathrm{DT}} - k^{\mathrm{DS}} > 0$ by Propositions 3 and 4. Hence, we have $\Delta > 0$. We conclude that the expected total cost under taxes is less than the expected total cost under standards.

A.7. Proof of Proposition 7

With the specifications given by (4) and (5), the equilibrium investment and emissions under rules are

$$
k^{\mathrm{R}} = \frac{ac(d\bar{e} + f) - r(c + d)}{a^2 cd}, \quad e^{\mathrm{R}}(s) = \frac{r - af}{ad} \quad \text{for all } s \in S.
$$

Under discretion, the equilibrium investment under taxes (k^{DT}) and under emissions standards (k^{DS}) are given as in the proof of Proposition 6. The equilibrium emissions are $e^J(s) = (c(\bar{e} - ak^J) - f(s))/(c + d)$ for state s under taxes ($J = \mathrm{DT}$) and standards ($J = \mathrm{DS}$). We can compute the equilibrium social cost under each regulatory regime:

$$
TC^J \equiv r^J k^J + \sum_{s \in S} \pi(s) [C(e^J(s), k^J) + D(e^J(s); s)] \quad (J = \mathrm{R}, \mathrm{DT}, \mathrm{DS}.)
$$

The difference between the costs are given by

$$
TC^{\mathrm{R}} - TC^{\mathrm{DS}} = \frac{a^2 d^3 \sigma^2 - cr^2(c + d)^2}{2a^2 d^2 (c + d)^2}, \quad TC^{\mathrm{DT}} - TC^{\mathrm{R}} = \frac{c(c + d)^2 (af - r)^2 - a^2 d\sigma^2 (2c + d)^2}{2a^2 d(c + d)(2c + d)^2}.
$$

Therefore, $TC^{\mathrm{R}} < TC^{\mathrm{DS}}$ if and only if $\sigma^2 < \frac{cr^2(c+d)^2}{a^2 d^3}$ and $TC^{\mathrm{R}} < TC^{\mathrm{DT}}$ if and only if $\sigma^2 < \frac{c(c+d)^2(af-r)^2}{a^2 d(2c+d)^2}$.

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