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The strategic use of innovation to influence regulatory standards

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Abstract

This paper investigates the welfare consequences of strategic behavior by firms to affect the amount of environmental regulation they face. Environmental regulation often attempts to force an industry to develop cleaner technology, but the regulator may have no means to commit to a specific standard. This lack of regulatory commitment induces firms to choose innovation strategically. It is well-known that firms have incentives to suppress innovation to induce the regulator to ratchet down the standard, and this strategic behavior lowers welfare. This paper explores a countervailing incentive. In oligopoly settings, firms have heightened incentives to innovate so as to increase regulation and raise rivals costs. In equilibrium, the incentive to raise rivals cost can mitigate the welfare loss arising from no regulatory commitment. Also, a regulator who is unable to commit ex ante to the stringency of a regulatory standard can induce *more* clean technology than a regulator with a commitment mechanism.

Keywords: Environmental regulation; Innovation; Rules versus discretion

1. Introduction

Government regulation is the impetus for many innovations in environmentally cleaner technology. In a common regulatory scenario, the regulator imposes a standard because clean technology has yet to be developed and the regulator seeks to spur innovation. However, because no cost-effective technology is initially available to meet the standard, the regulator must rely on the industry's innovation to make the regulation welfare-improving. If for some reason the industry does not innovate, the regulator would have an incentive to ratchet down the regulation to avoid imposing an expensive policy on society. This will create incentives for the firms in the industry to behave strategically with the regulator when choosing innovation. This paper analyzes incentives to innovate in cleaner technology when firms are not "regulation-takers".

In oligopoly settings, firms face countervailing incentives to innovate relative to exogenous regulation. If the regulator cannot commit to a standard, firms have lower incentives to innovate because the regulator has an ex post incentive to ratchet up regulation and expropriate gains from cost-reducing innovation. In anticipation of expropriation, firms face dampened incentives to innovate. However, oligopoly firms face another incentive as well. A firm may innovate and encourage regulation if the firm has a cost advantage over competitors in

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complying with the regulation. Therefore, the incentive to influence the regulatory standard depends on the relative sizes of the "ratchet" and "raise rivals cost" effects. I model the incentives to innovate and address whether the incentive to raise rivals cost induces welfare improving innovation. This paper analyzes whether "rules are better than discretion" in regulation of oligopoly firms.

Many examples of environmental, health, safety and product quality regulation involve strategic incentives for firms to use innovation to influence the regulatory standard. In some cases, the impetus is to ratchet down subsequent regulation. Analysts have claimed that auto emission standards were held up for several years in the 1970s due to auto manufacturers footdragging in innovation to holdup the Environmental Protection Agency.[1] In 1990, California adopted zero emission vehicle requirements, but the schedule was rolled back several times because few vehicles meeting the standard were commercially feasible. Finally, advocates of electric vehicle regulation have contended that auto manufacturers suppressed fuel cell technology in order to discourage regulation.

In other cases, the raise rivals cost effect appears to dominate. In the case of energy efficiency regulation of household appliances, Whirlpool Corporation invested heavily in designing more efficient refrigerators and then lobbied for stronger regulation to gain a competitive advantage over less innovating rivals. To quote a competitor, "They (Whirlpool) believe government regulations can be used to their competitive advantage".[2] In regulations to impose fuel economy standards (CAFE) in the 1980s, U.S. automakers had different positions on increasing the standard. GM and Ford generally opposed the 27.5 mpg standard while Chrysler favored a higher standard because it had eliminated much of its large car segment in the early 1980s [27]. However, the 27.5 mpg standard has been maintained, despite fuel-saving technologies that appear to have been utilized to increase performance rather than boost fuel economy [3]. In international regulation to reduce destruction of the ozone layer, DuPont, a leading developer of CFC alternatives, planned to phase-out CFC production ahead of schedule in what some analysts claim was the hope of accelerating regulation and hurting rivals who did not possess viable CFC alternatives.[3] Even regulation less in the public spotlight such as power tool regulation boasts stories of some firms in the industry innovating and encouraging regulation, while other firms do not innovate and press regulators for less stringent standards.[4] Most recently, this effect is present in Unocal's research into reformulated gasoline and its efforts to influence the California Air Resources Board's (CARB) cleaner-burning gasoline standards. In the future, one might expect to observe similar examples of strategic behavior in energy and environmental regulation. As electricity generating firms follow different strategies for developing renewable and cleaner-burning sources of new energy, these firms may lobby for regulations that mandate specific types of renewable portfolios or CO_2 capture.

This paper models the strategic interaction between a regulator and oligopoly firms to investigate the role of strategic innovation on the equilibrium levels of innovation, regulation, and welfare. The strategic interaction is captured by a simple model of a stage game between a welfare-maximizing regulator and profit-maximizing firms. The regulator chooses an initial standard, the firms innovate to reduce regulatory compliance costs, the regulator observes innovation and updates the standard, and the firms compete in the output market. I find that in a monopoly setting in which there is only a ratchet effect, the lack of regulatory commitment lowers welfare. This result is consistent with much of the literature that has focused on a monopolist's incentives to suppress innovation. However, this paper shows that a countervailing incentive can mitigate the incentive to reduce innovation. In oligopoly settings, competition in the output market creates incentives to raise rivals costs (and avoid having their own costs raised) which induces firms to innovate.

These results have implications for the design of environmental policy. Policymakers often believe that the inability to establish rules and limit future regulatory discretion is detrimental for implementing optimal environmental regulation. This is not necessarily the case. I find that, in oligopoly settings, the lack of regulatory commitment may not reduce welfare. Moreover, a regulator without a commitment mechanism can induce more clean-technology innovation than one with commitment by exploiting the raise rivals cost effect. Rules are not necessarily better than discretion in environmental policy.

[1]See, for example, White [34], Yao [36], Bresnahan and Yao [5], and Gerard and Lave [10].

[2]Doug Horstmann, Maytag Corporation Vice-President Quintanilla [31].

[3]See Murphy [28].

[4]Wall Street Journal Lifsher [19].

This paper contributes to the literature on the effect of regulatory policy on innovation. Previous research has analyzed firms' strategic behavior to influence the regulatory standard.[5] In settings with a single firm, the strategic incentive is to suppress innovation to induce the regulator to ratchet down the standard.[6] Several papers analyze the incentives to innovate into cleaner technology when the firm is a monopolist or the firms in the industry are modeled as a single decisionmaker. Yao [36] models technology-forcing regulation where the regulator cannot commit to a standard ex ante. He shows that industry *jointly* choosing investment has incentives to underinvest if the regulator has incomplete information on the industry's innovative potential. Policies to correct for suppressed incentives to innovate include administrative procedures to solve the time-inconsistency problem [18]. In this strand of the literature, firm behavior is modeled in a way that precludes a raise rivals cost effect.

In oligopoly settings, there is an added strategic motive to induce higher regulation—the raise rivals cost effect, discussed in a general setting by Salop and Scheffman [32].[7] This paper is complementary to Innes and Bial [14] who propose an optimal combination of Pigouvian taxes and discriminatory pollution standards to take advantage of incentives to raise rivals' costs and obtain first-best innovation. In contrast to Innes and Bial, I focus on the most common form of environmental regulation used in practice—the case where the regulator chooses a common standard that all firms must meet, and the regulator may not have the means to commit to the standard. In many if not most regulatory settings, the regulator does not have a commitment mechanism because regulators have limited ability to restrict their future behavior or that of future regulators.[8] The major distinction between this paper and the existing literature is that the model allows for a raise rivals cost effect and considers the strategic incentives to innovate when the regulator cannot commit to a standard.

A parallel component of the rent-seeking literature models the equilibrium levels of innovation and regulation as the outcome of a political economy game between the regulator and firm(s). Early work by Maloney and McCormick [22] shows that incumbent firms can benefit from environmental regulations that prevent entry or by raising some firms' costs more than others. Other work builds upon Stigler–Peltzman–Becker political economy models. Hackett [13] models the incentives to innovate when pollution regulation is determined through a political influence game. In his model, firms can innovate individually or jointly through a research joint venture (RJV). Under individual innovation, the successful innovators have incentives to lobby for regulation in order to gain a cost advantage over rivals. Maxwell et al. [23] model regulation as a political influence game in which firms reduce pollution in order to preempt government action. The authors find empirical evidence consistent with such ''self-regulation'' using data on toxic chemical releases.[9] My paper differs from this literature in two main dimensions—I explicitly model the actions of a welfare-maximizing regulator in a strategic regulator-firm game, and I compare the equilibrium level of innovation when regulation is both endogenous and exogenous to firm investment.

Section 2 develops a simple model that captures the coutervailing incentives to innovate in oligopoly settings. The model is general and allows for various forms of product market competition. In Section 3, I find the equilibrium for a specific model of competition and illustrate the effect of the raise rivals' cost effect on equilibrium innovation, welfare, and regulation. Section 4 discusses specific regulatory examples in which the model may apply. Section 5 suggests how the basic model extends to other incentive-based policy instruments, and Section 6 concludes.

[5] A well-developed literature analyzes the effect of various policy instruments on innovation when the policy is exogenous to individual firm behavior. See, for example, Milliman and Prince [26], Biglaiser and Horowitz [4], Jung et al. [15] and Fischer et al. [8].

[6] The ratchet effect is discussed in other regulatory settings in Freixas et al. [9] and Dalen [6].

[7] Several other papers analyze similar welfare issues surrounding firm-regulator interaction but do not discuss the possibility of raising rivals' costs. Wilson [35] analyzes the effects of technology-forcing regulation on market structure. Gersbach [11] models strategic behavior between firms and the regulator and proposes a scheme to avoid the firms holding-up the regulator.

[8] See Kleit [18] for how administrative procedures may create some degree of commitment. In a slightly different context, Lutz et al. [20] study the role of a firm's first-mover advantage in a strategic game between firms and a regulator to set quality standards.

[9] A series of interesting papers also analyzes the incentives to self-regulate including Arora and Gangopadhyay [2], Lyon and Maxwell [21], Neilson and Kim [29], and Anton et al. [1]. Other work related to raising rivals' costs in a political economy context include Salop and Scheffman [33] and Farzin and Zhao [7].

2. Model of innovation under endogenous regulation

2.1. Stage game

I model the incentives to innovate in regulatory compliance technology by firms faced with potentially endogenous regulation. The process of innovation and regulation is a stage game of complete and perfect information between a welfare maximizing regulator and profit maximizing firms. The components of welfare—the profit, consumer surplus, and externality cost functions—are common knowledge to all players and there is no uncertainty in the economic environment. One could extend the model to include private information and uncertainty, but this simple model illustrates that the regulator's lack of commitment can have important welfare consequences *even without private information.*

In period 1, the regulator chooses a future performance-based standard that is uniformly applied to all firms in the industry. The standard is a mandated improvement in each firm's product or production process to which consumers are indifferent, but which reduces external costs. This standard can be thought of as a reduction in emissions for each unit of output (e.g. a 10% reduction in nitrogen oxide (NO_x) emissions per gallon of gasoline). The standard increases each firm's marginal production cost and therefore affects the surplus in the output market. At the time of the initial regulation, the standard may be too costly to be socially beneficial, so the firms in the industry are expected to invest in research and development to reduce the cost of compliance.

In period 2, firms choose a level of independent innovation to reduce the cost of complying with the standard. Firms can meet any regulatory standard at a sufficiently high marginal cost of output, but may wish to innovate to reduce compliance cost.[10] Innovation only serves to reduce the cost of complying with the regulation. I assume innovative output to be a deterministic function of R&D expenditures.

In period 3, the regulator reviews the success of innovation, evaluates the cost of the regulation, and has the option to modify the standard to maximize welfare. This updating also can be seen as a failure to commit to the period 1 standard. As discussed in the introduction, regulators are often unable to restrict the ability of future regulators from changing the standard. In this period of the game, the regulator has an incentive to increase or decrease the original standard based upon the amount of period 2 innovation.

In period 4, firms observe the final regulatory standard and their resulting costs, and compete in the output market. Firms with different levels of innovation will have asymmetric costs of production. In my general formulation of the game, I allow for various forms of competition (e.g. Bertrand, Cournot). In Section 3, I illustrate the incentives under Cournot competition.

2.2. Notation

Assume the industry consists of N (not necessarily identical) firms with marginal cost that is constant in output. Firm i's reduced-form profit π_i from competing in a particular market is a function of its marginal cost c_i and the marginal cost $\mathbf{c}_{-i}$ of the $(N-1)$ other firms in the industry: $\pi_i(c_i, \mathbf{c}_{-i})$. This formulation allows for various forms of product market competition including Bertrand, Cournot, markets with product differentiation, and the threat of import competition.[11]

A firm's marginal cost is a function of the regulatory standard (x), its own independent innovation to reduce the cost of compliance (I_i), and the innovation that spills over to firm i from other firms ($\sigma_i(\mathbf{I}_{-i})$). Spillovers can be viewed as a lack of perfect intellectual property protection. This suggests the following form for marginal cost: $c_i(T_i, x)$ where $T_i = T_i(I_i, \sigma_i(\mathbf{I}_{-i}))$ is the pollution abatement technology possessed by firm i. Assume $c_x > 0$ and $c_T \leqslant 0$. Marginal cost is increasing in regulation because regulation increases the cost of producing every unit of the good. Marginal cost is weakly decreasing in abatement technology because the

[10] For example, a refrigerator manufacturer may be able to switch to very costly refrigerants to temporarily satisfy energy efficiency standards until more cost effective refrigerants are phased in. Alternatively, regulations such as the CAFE fuel economy standards contain a penalty for non-compliance which is a function of the number of cars sold.

[11] For example, with two Bertrand competitors facing demand $D(p), \pi_i(c_i, c_{-i}) = \mathbf{1}(c_i < c_{-i}) \cdot (c_{-i} - c_i)D(c_{-i})$. For a Cournot duopolist facing linear demand $P = a - bQ$ under non-drastic innovation, $\pi_i(c_i, c_{-i}) = \frac{(a-2c_i+c_{-i})^2}{9b}$.

technology strictly reduces marginal cost so long as compliance costs are positive, but pollution abatement technology cannot reduce marginal cost below the unregulated level. Spillovers $\sigma_i(\cdot)$ are weakly increasing in the innovation by the other firms in the industry. Finally, abatement technology is increasing in own innovation and spillovers from other firms. Total profit Π_i is the reduced form profit π_i net of the research and development cost of innovation ($R_i(I_i)$ with $R_I > 0$). Therefore, total profit is represented as: $\Pi_i = \pi_i(c_i, \mathbf{c}_{-i}) - R_i(I_i)$.

In order to determine the behavior of the regulator, I need to specify the other components of welfare—consumer surplus and externality costs—as a function of output. Equilibrium output depends upon the marginal production costs and how firms compete (e.g. Cournot or Bertrand competition). For a given model of competition, demand and the marginal costs of all N firms determines output and consumer surplus, so I represent consumer surplus in reduced-form: $CS(\mathbf{c}(\mathbf{T}, x))$.[12] Externality costs are a function of the amount of output and the "pollution" per unit of output (e.g. gallons of gasoline sold and the emissions per gallon). The regulatory standard affects externality costs directly by reducing the level of pollution per unit output and indirectly by raising marginal cost and reducing output. I represent reduced-form externality costs as $EC(\mathbf{c}(\mathbf{T}, x), x)$.[13] Total welfare is the sum of producer and consumer surplus net of externality costs and is given by: $\sum_i(\pi_i(c_i, \mathbf{c}_{-i}) - R_i(I_i)) + CS(\mathbf{c}(\mathbf{T}, x)) - EC(\mathbf{c}(\mathbf{T}, x), x)$. Note that this definition of the social welfare function, in contrast to some previous work, explicitly allows for the regulatory standard to affect welfare through effects on the output market—regulation affects each firm's marginal cost which determines equilibrium output.

2.3. Choice of regulatory standard

The equilibrium concept is subgame-perfect equilibrium for this dynamic policy game so I solve backwards. For the most general formulation, I characterize the equilibrium of the game so that the countervailing incentives can be seen most clearly. In Section 3, I find the equilibrium outcome for specific parameters.

Output in period 4 depends on the nature of competition and marginal costs, and this is already captured by the reduced-form profit function $\pi_i(c_i, \mathbf{c}_{-i})$. In period 3, the regulator chooses the standard x to maximize welfare as a function of the technological capability of the N firms. If all N firms are identical and have equal compliance capability, one expects regulation and innovation to be strategic complements—the regulator increases regulation in response to more innovation. Intuitively, if firms innovate to reduce the marginal social cost of regulation, the regulator has an incentive to raise the standard to reduce externality costs and increase welfare. In the appendix, I show sufficient conditions of the welfare function to ensure that $x^*(\cdot)$ is weakly increasing in innovation.

Regulation and innovation are not necessarily strategic complements under asymmetric equilibria. On one hand, the regulator may find it optimal to ratchet up the standard in response to increased innovation because the marginal cost of compliance by the innovating firm has decreased. On the other hand, if the increased regulation sufficiently increases the marginal cost of other firms in the industry, the regulator may not increase the standard so as to avoid competition concerns. In the extreme, increasing regulation may drive lesser-innovating firms out of the industry and increase market power.[14] I do not derive sufficient conditions for innovation and regulation to be strategic complements under asymmetric equilibria for the most general formulation. However, I assume $\frac{dx^*}{dI_i} \geqslant 0$ and later provide a specific example where the condition holds.

2.4. Industry innovation

In period 2, firms choose innovation to reduce the cost of compliance with any eventual regulation, recognizing that regulation is endogenous. Each firm's equilibrium level of innovation (assuming an interior

[12]For example, if two Bertrand duopolists face demand $D(p)$, then $CS(\mathbf{c}(\mathbf{T}, x)) = \int_{p^*}^{\infty} D(v)\,dv$ where $p^* = \max\{c_1(T_1, x), c_2(T_2, x)\}$.

[13]As in the above example of Bertrand duopolists, if there is a constant externality cost γ per unit of output and regulation x is the mandated fraction reduction in emissions, then $EC(\mathbf{c}(\mathbf{T}, x), x) = \gamma(1 - x)D(p^*)$.

[14]For example in the case of energy efficiency standards set in April 1998 for the superefficient refrigerator, the Department of Energy was concerned that if it required energy efficiency levels of the more efficient firm, then antitrust concerns may arise.

solution) is characterized by the first-order condition:

$$\frac{d\Pi_i}{dI_i} = \frac{\partial \pi_i}{\partial c_i} \cdot \left[\frac{\partial c_i}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i} + \frac{\partial c_i}{\partial x^*} \cdot \frac{dx^*}{dI_i} \right] + \sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \left[\frac{\partial c_j}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i} + \frac{\partial c_j}{\partial x^*} \cdot \frac{dx^*}{dI_i} \right] - \frac{\partial R_i(\cdot)}{\partial I_i} \bigg|_{x^*(I_i^*, I_{-i}^*)} = 0, \tag{1}$$

where the ratcheting up of regulation due to increased innovation is given by

$$\frac{dx^*}{dI_i} = \frac{\partial x^*}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i} + \sum_{j \neq i} \frac{\partial x^*}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i}. \tag{2}$$

Eq. (1) says a firm chooses innovation so that the marginal effect on profits through own and rival costs is zero. Innovation affects all firms' marginal costs through the level of regulation and the technological compliance capability of the firm. Eq. (2) says that innovation by firm i affects the level of regulation by increasing the technological compliance capability of all firms. If innovation and regulation are strategic complements, regulation is increasing in innovation.

I separate Eq. (1) into the factors that determine the major incentives and disincentives to innovate. In the following equation which holds at the equilibrium outcome, the left side represents the ''marginal benefits of innovation'' and the right side represents the ''marginal costs of innovation'':

$$\underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i}}_{\text{cost reduction effect}} + \underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial x^*} \cdot \frac{dx^*}{dI_i}}_{\text{raise rivals cost effect}} = - \left[\underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial x^*} \cdot \frac{dx^*}{dI_i}}_{\text{ratchet effect}} + \underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i}}_{\text{spillover effect}} - \underbrace{\frac{\partial R_i(\cdot)}{\partial I_i}}_{\text{R\&D cost}} \right]. \tag{3}$$

Firms benefit from additional innovation due to two factors: (1) reducing their own marginal costs and (2) raising their rivals' marginal costs by encouraging more regulation.[15] The increased innovation comes with a cost: (1) innovation encourages the regulator to ratchet up the standard, (2) some innovation spills over and reduces the marginal costs of competing firms, and (3) innovation raises R&D costs.

Several special cases commonly found in the literature can be seen in this formulation. First, when there is only one firm in the industry so that there is no raise rivals cost or spillover effects, this formulation reduces to the incentives of a regulated monopolist to innovate. Second, we can compare the innovation incentives of firms facing exogenous regulation to firms faced with regulation that is endogenous to innovation. The classification of incentives to innovate in (3) reduces to the typical incentives for the exogenously regulated firm when the ratchet and raise the rivals cost effects are zeroed out ($\frac{dx^*}{dI_i} = 0$). Therefore, the added element of this model is that the incentives to innovate under endogenous regulation also depend upon the net of the ratchet and raise rivals cost effect.

This model formalizes the notion that firms should not necessarily be modeled as ''regulation-takers'' when faced with environmental regulation. When innovation affects the marginal social benefit of the regulatory standard, the firms have incentives to behave strategically with the regulator and among themselves in choosing innovation. However, the equilibrium level of innovation can be lower or higher than the level of innovation if regulation were exogenous. Firms have heightened incentives to innovate if the increased profits due to raising the marginal costs of rivals counteracts the reduction in profits due to raising own costs. On the other hand, firms have dampened innovation incentives relative to exogenous regulation if the ratchet effect outweighs the raise the rivals cost effect. The net of the ''raise rivals cost'' and ''ratchet'' effects determines the extent to which firms increase or decrease innovation from the ''regulation-taking'' level of innovation.

[15]The concept of raising rivals' costs is developed in Salop and Scheffman [32] for the case of an industry consisting of a dominant firm and a competitive fringe. As an example of raising rivals' costs, Salop and Scheffman suggest that firms may engage in rent-seeking behavior such as encouraging government regulation to raise rivals' relative compliance costs.

3. Examples of equilibrium outcomes

A simple example demonstrates that the raise rivals cost effect interacts with the presence of regulatory commitment in significant ways and can have large impacts on the equilibrium level of welfare and innovation. First, the regulator's lack of a commitment mechanism reduces both welfare and innovation in monopoly industries but not necessarily in oligopoly industries due to the raise rivals cost effect. Second, in an oligopoly setting in which the regulator has no commitment mechanism, a firm with low compliance costs has heightened incentives to innovate to raise rivals cost. Thus, lack of regulatory commitment can lead to higher innovation than commitment when there are modest levels of compliance cost heterogeneity.

3.1. Special case of general model

In order to explicitly characterize the equilibrium of the policy game in Section 2, I need to place restrictions on the nature of competition and functional forms. Even with those restrictions, standard comparative static techniques do not allow for straightforward analytical solutions. I seek to compare the effect of regulatory commitment on equilibrium outcomes, where endogenous regulation is modeled with the firm as the "first-mover" and exogenous regulation is modeled with the regulator as "first-mover".[16] Because I compare equilibrium outcomes under different orders of play, standard analytical techniques (e.g. applying the implicit function theorem to first-order conditions) are not applicable. Therefore, I assume explicit functional forms and solve numerically for the pure strategy equilibrium.

Consider Cournot duopolists i and j who face inverse market demand for output of $P(Q) = 1 - Q$. Assume each firm's marginal cost of output absent any regulatory standard is $\tilde{c}_i = \tilde{c}_j = 0$. Regulation and pollution abatement technology shift marginal cost.[17] Firms i and j innovate into compliance cost technology I_i and I_j, and I assume no spillovers so that $T_i = I_i$. Assume that regulation increases marginal cost at an increasing rate and that abatement technology reduces linearly the marginal cost of compliance with any regulatory standard. Therefore, for firm i, the marginal cost of output is[18]

$$c_i(x, I_i) = \tilde{c}_i + \alpha_i \cdot x + \lambda \cdot x^2 - \phi \cdot x \cdot I_i, \tag{4}$$

where α_i, λ, and ϕ are positive parameters. Marginal cost is similarly defined for firm j.

Let externality costs be linear in both market output and the regulatory standard: $EC(x, Q) = \gamma \cdot (1 - x) \cdot Q$, where $\gamma > 0$. For example, in the electric vehicle case, the amount of externality cost from air pollution (EC) is falling in the percent of new vehicles required to be electric (x), but rising in the total number of vehicles sold (Q). Assume that innovation exhibits rising average costs: $R(I) = \frac{1}{2} \cdot \delta \cdot I^2$, where $\delta > 0$.

Finally, it is important to recognize that the regulator faces competition concerns in the output market when choosing the level of regulation. If one firm innovates significantly more than another, then imposing high regulation could raise the low innovator's marginal cost to a sufficiently high level that the regulator effectively creates a monopoly for the high innovator. More precisely, if the monopoly price of the high innovating firm $p_i^{\text{monop}}(c_i(\cdot))$ is less than the marginal cost of the low innovating firm $c_j(\cdot)$, the industry will be a monopoly. Otherwise, it will be a duopoly. Therefore, welfare is given by

$$welfare(x) = \begin{cases} \text{duopoly welfare} & \text{if } p_i^{\text{monop}}(c_i(\cdot)) \geqslant c_j(\cdot), \\ \text{monopoly welfare} & \text{if } p_i^{\text{monop}}(c_i(\cdot)) < c_j(\cdot). \end{cases}$$

I calculate the outcome under endogenous and exogenous regulation. The endogenous regulation equilibrium corresponds to the outcome of the game described in Section 2.1. Each firm anticipates the regulator's welfare-optimizing response to each possible level of industry innovation and simultaneously

[16]In my model, exogenous regulation corresponds to the regulator committing to the period 1 standard and not re-optimizing in period 3.

[17]For example, if refrigerator manufacturers are required to adopt a higher efficiency standard, a single refrigerator will cost more to produce. However, the cost to produce the refrigerator under the standard will fall if the firm has innovated to produce more effective (less costly) refrigerants.

[18]Note that $\frac{\partial c_i}{\partial I_i} = 0$ when $x = 0$ so innovation only reduces compliance costs.

Table 1
Equilibrium outcomes under commitment and no commitment

	Regulation (x^*)	Innovation (I^*)	Welfare	% of maximum welfare gain
Monopoly				
Status quo	0	0	0.175	–
Social planner	0.93	0.18	0.230	–
Commitment	0.90	0.12	0.229	98%
No commitment	0.77	0.00	0.221	83%
Cournot Duopoly				
Status quo	0	0	0.178	–
Social planner	0.99	0.11	0.266	–
Commitment	0.98	0.10	0.266	100%
No commitment	0.97	0.08	0.265	99%

Parameters for this calculation are: $\alpha = 0.15, \lambda = 0.09, \phi = 0.25, \sigma = 0.00, \gamma = 0.40, \delta = 0.80$.

chooses the profit-maximizing level of innovation. The exogenous regulation game in which the regulator can commit to an initial standard is simply the game described in Section 2.1 in which period 3 is removed (i.e. regulator chooses the standard, firms simultaneously choose innovation and then compete as Cournot firms). I numerically calculate the equilibrium outcomes under "regulator as first-mover" and "firms as first-movers".

3.2. *Value of regulatory commitment: monopoly vs. oligopoly*

First, I show that the regulator's lack of commitment to the period 1 standard may significantly reduce welfare in monopoly but not oligopoly settings. Table 1 displays equilibrium outcomes under regulatory commitment and lack of commitment for a monopolist and Cournot duopolists.[19] In addition, I show equilibrium outcomes under two benchmarks—the status quo of no regulation and the social planner's outcome where the regulator chooses both innovation and regulation.

In the status quo, a monopolist competing on normalized linear demand with the assumed externality cost function generates welfare $W = 0.175$. The social planner's solution is to reduce 93% of per unit externality costs ($x^* = 0.93$) and for the monopolist to innovate at $I^* = 0.18$, generating welfare of $W^{SP} = 0.23$, or a 31% increase in welfare over the status quo.

A monopolist facing a regulator without commitment to the period 1 standard has no incentives to innovate whereas a committed regulator can induce innovation. This can be seen in Fig. 1. The firm and regulator best response functions indicate that innovation and regulation are strategic complements. The regulator ratchets up regulation beyond a baseline level for any positive level of innovation. Because it is the first-mover, the firm can choose the location on the regulator's best response function that maximizes profit. In equilibrium, the firm does not innovate and the regulator chooses a lower level of regulation $x^*(0) = 0.77$. At these levels of regulation and innovation, the regulator only achieves 83% of the potential efficiency gain over the status quo.

However, a regulator with a commitment mechanism can achieve an outcome closer to the social planner's solution. The equilibrium under exogenous regulation is regulation $x^* = 0.90$ to which the monopolist responds with innovation of $I^*(0.90) = 0.12$. The regulator with commitment can achieve 98% of the potential improvement in welfare. Therefore, the lack of regulatory commitment in a monopoly setting creates a ratchet effect that reduces the welfare benefits of regulation by 15%.

In a duopoly setting, the lack of commitment does not substantially decrease welfare as seen in Table 1. Status quo duopoly welfare is 0.178 while first-best welfare is 0.266. As in the duopoly case, a regulator with a commitment mechanism can nearly achieve first-best. However, a regulator without commitment also can induce levels of innovation and regulation just below first-best levels and achieve 99% of potential welfare gains. The reason that lack of commitment does not substantially reduce welfare is that the individual firms do

[19]For this simulation, I use parameter values: $\alpha = 0.15, \lambda = 0.09, \phi = 0.25, \gamma = 0.40, \delta = 0.80$.

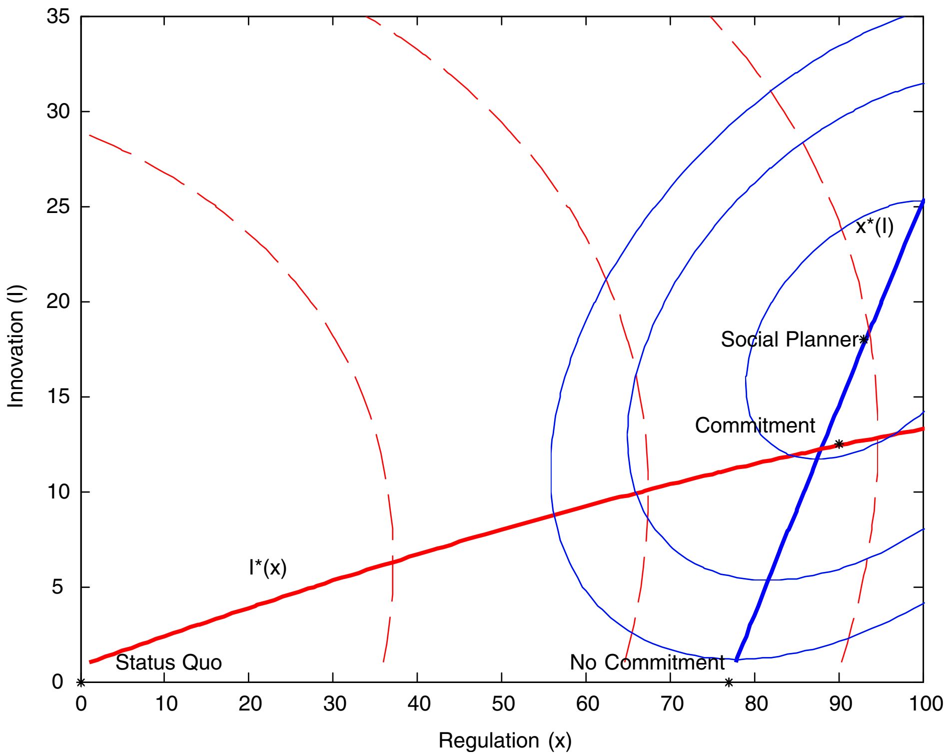

Fig. 1. Strategic outcome for monopoly case. *Note*: $I^*(x)$ is the firm's best response innovation function for a given level of regulation (x). $x^*(I)$ is the regulator's best response regulation function. Iso-profit level sets are shown with the dashed lines—profit is increasing toward the origin which represents zero regulation and zero pollution abatement innovation. Iso-welfare level sets are shown with the solid lines.

Table 2
Effect of technological spillovers in oligopoly when regulation is endogenous

Fraction of technology spilled over (σ)	Regulation (x^*)	Innovation (I^*)	Welfare
0	0.97	0.08	0.265
0.2	0.96	0.06	0.266
0.4	0.95	0.04	0.265
0.6	0.93	0.02	0.262
0.8	0.90	0	0.258
1	0.90	0	0.258

Note: This table contains equilibrium outcomes for a Cournot duopoly when regulation is endogenous (the regulator has no commitment mechanism) and both the raise rivals cost and ratchet effects are in play, as described in Section 3.2. Other than the spillover parameter σ, all parameters are the same as in Table 1.

not face unilateral incentives to suppress innovation. If one firm suppresses innovation, the other firm could increase innovation and raise its rival's cost. In equilibrium, innovation and regulation are nearly identical to their levels under regulatory commitment. The raise rivals cost effect greatly mitigates the ratchet effect.[20]

It is noteworthy that the raise rivals cost effect relies on the innovator being able to appropriate the majority of the benefits of innovative effort. If rival firms can easily imitate the innovator's technology, the raise rivals cost effect is diminished. To see this, assume that in the above example, technology from one duopolist spills over to the other firm. Let $T_i = I_i + \sigma I_j$ for $0 \leqslant \sigma \leqslant 1$. Table 2 shows equilibrium outcomes when the regulator

[20]These results are robust to variation in the cost per unit of R&D (δ). A higher δ leads to less innovation and less regulation, however, the raise rivals cost effect still greatly mitigates the ratchet effect.

has no commitment mechanism. The first row with $\sigma = 0$ corresponds to the duopoly outcome earlier in this section. As spillovers rise (and the raise rivals cost effect decreases), both firms have fewer incentives to innovate which induces the regulator to ratchet down the standard. For large spillovers, firms have no

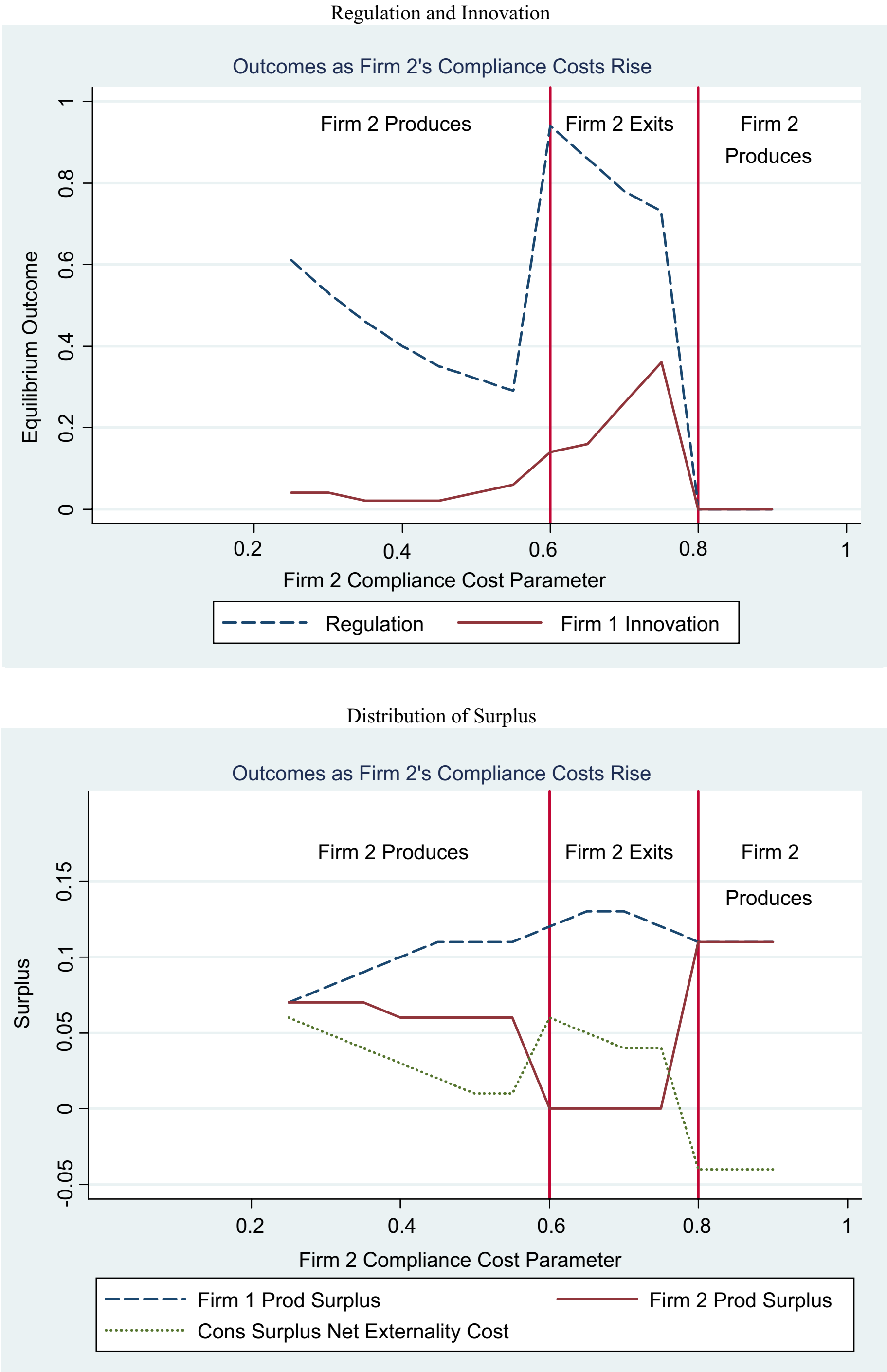

Fig. 2. No regulatory commitment: equilibrium under cost asymmetries. *Note*: Firm 1 compliance cost parameter $= \alpha_1 = 0.25$.

incentive to innovate and equilibrium welfare is reduced. This suggests that a lack of regulatory commitment in an oligopoly setting can reduce welfare in the absence of strong intellectual property protection.

3.3. Effect of compliance cost asymmetries on innovation

Next, I show that lack of regulatory commitment strengthens the raise rivals cost effect and induces firms to increase innovation. This can lead to a high level of regulation and innovation in equilibrium. I illustrate this by introducing cost asymmetries so that Firm 1 has lower regulatory compliance costs than Firm 2. Firm 1's compliance cost parameter α_1 is fixed at $\alpha_1 = 0.25$ and Firm 2's parameter varies in the interval $\alpha_2 = \{0.25, 0.90\}$. I calculate equilibrium outcomes for different values of α_2.

Fig. 2 illustrates outcomes when there is no regulatory commitment. As Firm 2's compliance costs rise above those of Firm 1 (α_2 rises above 0.25), Firm 1 has virtually no incentives to increase innovation because the regulator finds it welfare-maximizing to ratchet down the standard to make the output market more competitive. However, if Firm 2's compliance costs are very high, Firm 1 has incentives to substantially increase innovation in order to ratchet up regulation and drive Firm 2 out of the market. For $0.6 \leqslant \alpha_2 < 0.8$, the regulator finds it optimal to set a very high standard even if it increases Firm 2's costs above Firm 1's monopoly price. In this range, the higher levels of innovation and regulation increase consumer surplus and reduce externality costs (see bottom panel). However, eventually as Firm 2's compliance costs become very large, the regulator finds it optimal not to regulate at all. As a result, both firms operate with the same marginal cost and earn substantial producer surplus, and there is a high level of pollution (low consumer surplus net of externality costs). This illustrates that asymmetries in compliance costs can have significant (and sometimes non-monotonic) effects on the level of regulation as well as the allocation of surplus.

Fig. 3 illustrates the outcomes when the regulator is the first-mover and can commit to the period 1 standard. As with the previous case, asymmetries in compliance costs can induce the low cost firm to substantially

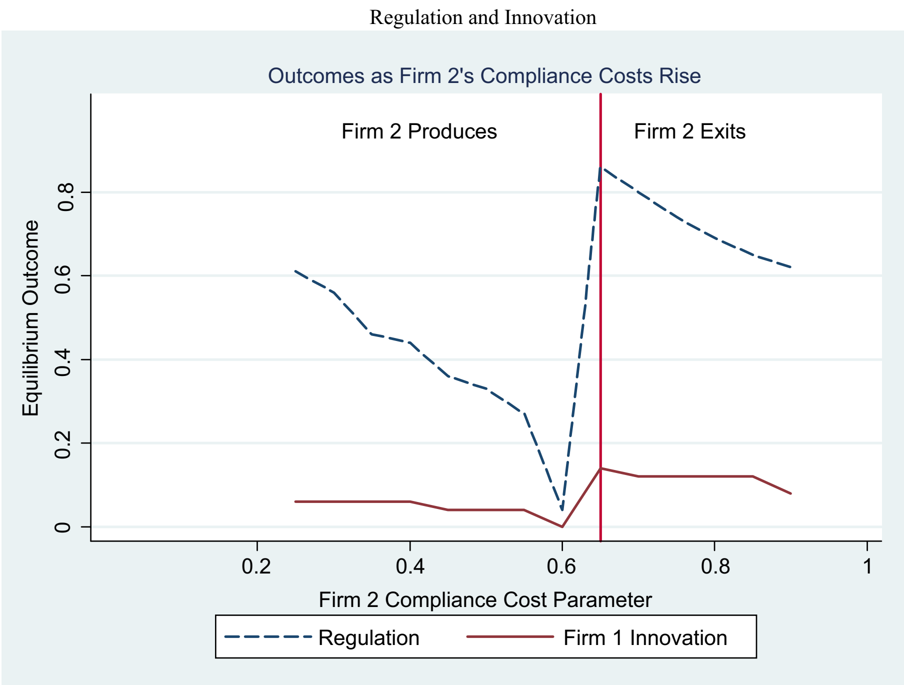

Fig. 3. Regulatory commitment: equilibrium under cost asymmetries. *Note*: Firm 1 compliance cost parameter = $\alpha_1 = 0.25$.

increase innovation so as to ratchet up regulation. For large asymmetries, it is welfare-maximizing for the regulator to significantly increase regulation even if doing so makes the output market less competitive.

One result is particularly noteworthy—lack of regulatory commitment can lead to cleaner technology than commitment. By comparing Figs. 2 and 3, I find that the equilibrium level of innovation can be higher when the regulator cannot commit to a period 1 standard. For modest levels of compliance cost asymmetry ($\alpha_1 = 0.25$ and $\alpha_2 \in [0.55, 0.75]$), innovation is larger when there is no regulatory commitment. Clearly, the raise rivals cost effect can create strong incentives to innovate in oligopoly settings when any ratcheting up of regulation causes rival costs to rise faster than own costs. This effect does not manifest itself when the regulator commits to the initial standard.

These two examples illustrate that the raise rivals cost effect can create strong incentives to innovate when regulation is endogenous. The results arise from a specific assumption about the nature of competition and very simple functional forms. For more general demand and cost functions, the net effect of strategic behavior (Eq. (3)) depends upon the relative size of the ratchet and raise rivals cost effects and can vary in complex ways.[21] In this paper, I do not attempt to generalize the results because the results are sensitive to the specific functional forms and parameters. Moreover, it is difficult to match a specific industry to a specific set of functional forms. Nevertheless, the insight is that the raise rivals cost effect can have important welfare implications in oligopoly settings.

4. Discussion: regulatory examples of raising rivals costs

The existing literature on the strategic incentives to *suppress* innovation has documented several examples including innovation on automobile emission reduction equipment, fuel cells for electric vehicles, and more fuel efficient vehicles. To illustrate the countervailing incentive, this section discusses two examples in which the strategic incentive to raise rivals costs may have *increased* innovation.

4.1. Reformulated gasoline and Unocal

Beginning in the late 1980s, Unocal conducted independent research to develop formulations of gasoline that reduce the emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons. In December 1990, Unocal filed for the first of five patents. At the same time, the California Air Resources Board (CARB) was conducting a rulemaking proceeding to develop new cost-effective standards for reformulated ‘‘summer-time’’ gasoline. The proceeding involved consumer and environmental groups as well as participants from the automobile and oil refining industries. CARB relied upon the refining industry to demonstrate whether various reformulated gasolines were cost effective. In June 1991, Unocal presented internal study results to CARB to indicate that certain properties of gasoline could be altered relatively inexpensively in order to reduce emissions. In November 1991, CARB adopted reformulated gasoline standards that overlapped with critical elements of the Unocal patent. In 1992, Unocal amended an existing patent application for reformulated gasoline to resemble the CARB standard and was granted the patent in 1994. However, at the time of the CARB rulemaking, Unocal did not inform CARB or other industry participants of its pending patents or its intent to exercise proprietary rights on the new gasoline formulations. This lack of disclosure became a source of an FTC complaint against Unocal in 2003.[22]

The FTC argued that Unocal did not reveal its intent to patent so as to induce CARB to base the new reformulated gasoline standards on the Unocal specifications. During the rulemaking period, Unocal officials allegedly discussed internally how their research could be used to induce CARB to mandate standards that overlapped with the patents. Unocal knew that most of its patent claims would be granted by the patent office by 1992, but did not announce its patent and intent to collect royalties until January 1995, just a year and a half before the standard took effect. Other refiners were faced with the possibility they could not work around

[21]One reason for the complexity is that the comparison is essentially between a stage game in which two agents simultaneously move followed by a single agent's move, and another stage game in which the order of play is reversed.

[22]For details, see filings for FTC Docket no. 9305. The Federal Trade Commission's 2003 complaint against Unocal was dismissed under the Noerr-Pennington doctrine that shields from antitrust liability a firm's misrepresentations in political lobbying.

the patent and sued to invalidate the Unocal patent. Courts ruled that Unocal could collect 5.75 cents per gallon from other refiners that infringed its patent. The Unocal research and regulation based upon that innovation afforded Unocal a competitive advantage over rival refiners. This illustrates that Unocal was able to use innovation to increase regulation that raised the marginal production costs of its rivals.[23]

4.2. The Montreal Protocol and DuPont

The Montreal Protocol called for a phaseout of chlorofluorocarbons (CFCs) over the 1990s in order to reduce the depletion of stratospheric ozone. CFCs were used in styrofoam, cleaning fluids, propellants, and as cooling agents in refrigerators and air conditioners. Historically, DuPont had been a very large player in the world market since the introduction of Freon in 1930. However, the market was becoming increasingly competitive with lower prices due to the entry of smaller manufacturers into the CFC market.

Analysts claim that DuPont saw the Montreal Protocol as an opportunity to reclaim a large share of the market. Two of the largest producers, DuPont and ICI, invested heavily in CFC alternatives that possessed many of the same chemical properties but did not break down in the upper atmosphere and destroy ozone molecules [25]. DuPont alone invested more than $400 million to develop products to replace various CFCs [24]. Other smaller CFC manufacturers were far behind in developing CFC alternatives, so the Montreal Protocol represented a large increase in their costs. DuPont supported the Montreal Protocol limits on worldwide CFC emissions and, in 1994, actually announced a plan to begin the phaseout one year *early*. According to the United Nations Environment Programme executive director, DuPont's motivation was to gain a compliance cost advantage over other firms: "The difficulties in negotiating the Montreal Protocol had nothing to do with whether the environment was damaged or not. It was all who was going to gain an edge over who; whether DuPont would have an advantage over the European companies or not" (for more details of the case, see [28]). Some policy analysts contend that DuPont sought to encourage a worldwide ban so that the new product market for alternatives was more concentrated and differentiated than the existing CFC market.

5. Extensions to other policy instruments

The model of countervailing incentives to innovate in Section 2 assumes that regulation takes the form of a uniform standard of emissions reduction. As discussed in Section 4, a uniform standard appears to match several prominent examples of environmental regulation in which firms face both ratchet and raise rivals costs effects. However, I can briefly describe extensions of the model under other policy instruments—emissions taxes and tradeable pollution permits.[24] For each of these policy instruments, the endogeneity of regulation also creates countervailing incentives to innovate.

5.1. Emissions tax

An emissions tax can be modeled with some slight modification of the model in Section 2. The order of play remains the same, however, the notation is modified. Suppose the regulator imposes a tax per unit of emissions τ. Firm i has an emission rate of $e_i(T_i)$ tons per unit of output, and this emission rate is decreasing in the amount of the firm's pollution abatement technology T_i. Let marginal cost of output be given by $c_i(T_i, \tau)$. For example, the marginal cost of output could be given by $c_i(T_i, \tau) = \tilde{c}_i + \tau e_i(T_i)$—the marginal production cost plus the marginal emissions tax. As with the model above, reduced-form profit is given by $\pi_i(c_i, \mathbf{c}_{-i})$. After incurring the cost of innovation, total firm profit is given by $\Pi_i = \pi_i(c_i, \mathbf{c}_{-i}) - R_i(I_i)$. As in Section 2, let reduced-form consumer surplus be given by $CS(\mathbf{c}(\mathbf{T}, \tau))$. Let externality costs be given by

[23]For further details of the case, see http://www.ftc.gov/os/2003/03/unocalcmp.htm, http://www.unocal.com/rfgpatent, and other filings for FTC Docket no. 9305.

[24]As noted above, see Milliman and Prince [26] and subsequent work for analyses of the effect of policy instruments on innovation when regulation is *exogenous*.

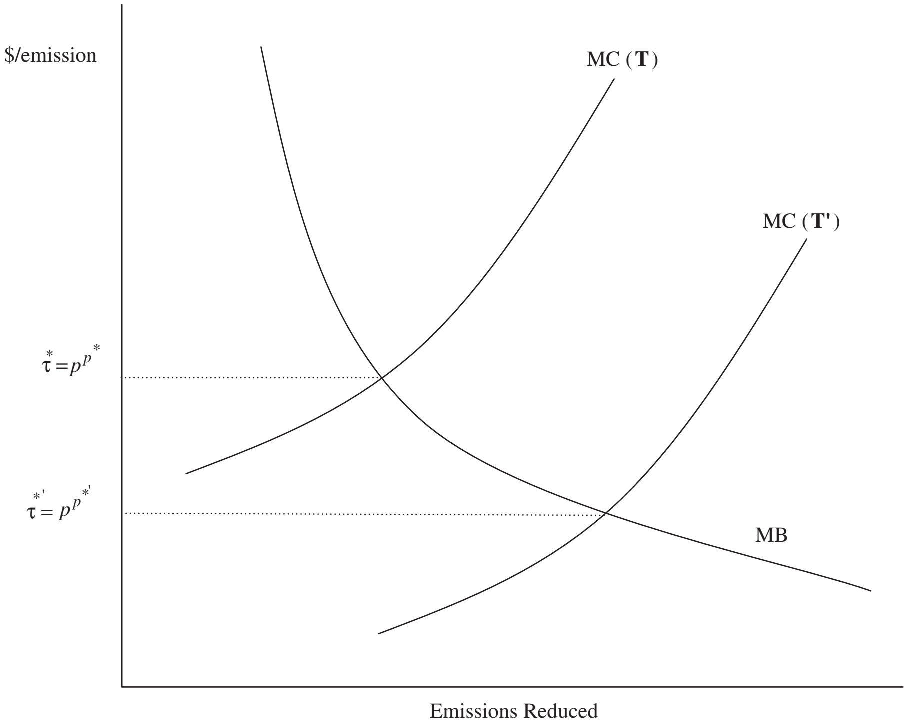

Fig. 4. Regulator's response to increased innovation under an incentive-based policy. *Note*: The shift in aggregate marginal cost of abatement results from an increase in the vector of firm pollution abatement technology from $\mathbf{T}$ to $\mathbf{T}'$. These represent the costs of emission reductions including output market effects on producer and consumer surplus.

$EC(\mathbf{c}(\mathbf{T},\tau),\mathbf{e}(\mathbf{T}(\tau)))$—the emissions tax affects externality costs through marginal cost by affecting output and by determining the emissions per unit of output.

As with the uniform standard model, I restrict the direction of regulatory response to higher levels of innovation. Assume the regulator responds to higher firm innovation by reducing the emission tax ($\frac{d\tau^*}{dI_i} \leqslant 0$). The intuition is easiest to see in the case of symmetric firms. If abatement technology improves, it is optimal for total emissions to decrease and the optimal tax to decrease.[25] This can be seen in Fig. 4 which was used in the analysis by Milliman and Prince [26]. In the figure, marginal benefits of emissions reductions represent all benefits from reducing externality costs of emissions, and marginal costs represent the marginal costs of emission reductions which includes output market effects on producer and consumer surplus. An increase in abatement technology shifts out the aggregate marginal cost of abatement and results in a lower optimal emissions tax τ^*.

As in Section 2, I solve backwards. In period 4, firms observe the emissions tax and choose output to maximize profit, and the equilibrium profit is represented by the reduced-form profit function. In period 3, the regulator observes innovation and chooses the tax, with the restriction that $\frac{d\tau^*}{dI_i} \leqslant 0$. In period 2, firms choose innovation to reduce emission tax payments but recognize that the tax is endogenous. Each firm's equilibrium innovation is characterized by the first-order condition:

$$\begin{aligned}\frac{d\Pi_i}{dI_i} &= \frac{\partial\pi_i}{\partial c_i}\cdot\left[\frac{\partial c_i}{\partial T_i}\cdot\frac{\partial T_i}{\partial I_i}+\frac{\partial c_i}{\partial\tau^*}\cdot\frac{d\tau^*}{dI_i}\right]\\ &\quad+\sum_{j\neq i}\frac{\partial\pi_i}{\partial c_j}\cdot\left[\frac{\partial c_j}{\partial T_j}\cdot\frac{\partial T_j}{\partial\sigma_j}\cdot\frac{\partial\sigma_j}{\partial I_i}+\frac{\partial c_j}{\partial\tau^*}\cdot\frac{d\tau^*}{dI_i}\right]-\left.\frac{\partial R_i(\cdot)}{\partial I_i}\right|_{\tau^*(I_i^*,\,I_{-i}^*)}=0,\end{aligned} \tag{5}$$

[25]This assumes that innovation reduces the marginal rather than the fixed cost of abatement. Keohane [17] explores the possibility of higher marginal abatement costs.

where the ratcheting down of the emissions tax due to increased innovation is given by

$$\frac{d\tau^*}{dI_i} = \frac{\partial \tau^*}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i} + \sum_{j \neq i} \frac{\partial \tau^*}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i}. \tag{6}$$

The firm's first-order condition in the emissions tax case is analogous to the uniform standard case (Eq. (1)); innovation affects profits through own and rival costs where innovation affects costs by changing the abatement technology possessed by each firm and the tax imposed by the regulator. By comparing Eqs. (1) and (5), one sees that each corresponding term has the same sign *except* the effect of innovation on the regulator's policy instrument. In the case of the uniform standard, higher innovation causes the regulator to *increase* the standard (x^*) which ceteris paribus increases marginal cost. However, in the case of an emissions tax, higher innovation causes the regulator to *decrease* the tax (τ^*) which decreases marginal cost. As a result, the "raise rivals cost effect" and "ratchet effect" from the uniform standard model are *reversed*. Relative to exogenous regulation, firms have larger incentives to innovate so that the emissions tax is reduced.[26] However, firms have smaller incentives to innovate because the lower emissions tax will *lower* rivals costs. Gathering the terms representing the marginal benefits and marginal costs of innovation, I obtain

$$\underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i}}_{\text{cost reduction effect}} + \underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial \tau^*} \cdot \frac{d\tau^*}{dI_i}}_{\text{reverse ratchet effect}} = -\left[\underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial \tau^*} \cdot \frac{d\tau^*}{dI_i}}_{\text{lower rivals cost effect}} + \underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i}}_{\text{spillover effect}} - \underbrace{\frac{\partial R_i(\cdot)}{\partial I_i}}_{\text{R\&D cost}} \right]. \tag{7}$$

These five incentives to innovate under an emissions tax are very similar to the five incentives under a uniform standard (Eq. (3)), except that the two incentives to behave strategically with the regulator are reversed. Therefore, the endogeneity of regulation also creates countervailing incentives to innovate for emission taxes. The net of the "lower rivals cost" and "reverse ratchet" effects determines the extent to which firms increase or decrease innovation from "regulation-taking" levels.

5.2. *Tradable pollution permits*

The innovation incentives under a simple model of permit trading are identical to those under an emissions tax. Assume the permit market is competitive but the output market is an oligopoly (e.g. a national permit market but a local product market). Given an emission rate $e_i(T_i)$, the marginal cost of output is a function of the permit price (p^p) and the abatement technology: $c_i(T_i, p^p)$. An example is $c_i(T_i, p^p) = \tilde{c}_i + p^p e_i(T_i)$. For simplicity, assume that permits are allocated via a competitive auction rather than via endowments; therefore, firm behavior that affects the price of permits does not affect the value of permit holdings.

Under these assumptions, the strategic incentives are identical to the incentives under an emissions tax. The regulator responds to higher innovation by reducing the number of permits (increasing the number of emissions reduced), which results in a lower equilibrium price of permits (see Figure 4).[27] As with the emissions tax, a firm behaving strategically with the regulator will choose innovation to tradeoff the reduction in its own permit costs against the reduction in rivals' permit costs. The balance of these countervailing incentives determines the equilibrium level of innovation.

[26] Milliman and Prince [26] also show that firms can benefit from regulatory adjustment under an emissions tax regime in the context of a perfectly competitive output market.

[27] The timing of the game implicitly assumes that the regulator adjusts the policy instrument immediately following innovation. As a result, there is no important distinction between price and quantity instruments. This abstracts from issues surrounding the speed of regulatory adjustment; in the period between technology adoption and adjustment, the equilibrium price of permits will fall under a permit system while the emissions tax will not be affected.

6. Conclusions

This paper illustrates a simple but important point — the lack of regulatory commitment does not necessarily reduce innovation into "cleaner" technology. Although an endogenous regulatory standard can reduce incentives to innovate and ratchet up the standard, a countervailing raise rivals cost effect can mitigate those low incentives. Rules are not necessarily better than discretion for environmental regulation in oligopoly settings.

This result has implications for regulatory policy when innovation is a critical component of optimal regulation. In particular, regulatory commitment through legislation or bureaucratic procedures is not necessarily critical in oligopoly settings. However, in monopoly settings the incentive to suppress innovation may justify funding for "public interest" research and development.

It would be informative to test for empirical evidence of strategic behavior between firms and regulators that is consistent with this model. The econometric challenge in designing such tests is to identify a set of firms facing both endogenous and exogenous regulation, or regulators with varying degrees of commitment.[28] Future research could explore such evidence.

This paper also suggests that research joint ventures (RJVs) do not necessarily pose dangers as means to collude on low innovation. RJVs are not uncommon in environmental regulation. For example, the major automakers and oil refiners formed a joint reformulated gasoline research project in October 1989, but some members including Unocal and ARCO also conducted their own fuels research. The National Cooperative Research and Production Act relaxes the antitrust treatment of RJVs so that firms can take advantage of economies of joint research and overcome free rider and appropriability problems. However, these joint ventures may serve as a means to suppress innovation if all research is conducted through the RJV. As suggested in Grossman and Shapiro [12] and Katz [16] and by my model, the possibility of pursing independent research in addition to joint research creates strong innovation incentives and may prevent firms from using RJVs to restrict cleaner technology.

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Appendix

Sufficient conditions for regulation to be weakly increasing in innovation for the symmetric equilibrium case: Holding the nature of competition constant, I can write welfare as a function of technology $\mathbf{T}$ and regulation $x : W(\mathbf{T}, x)$ where I do not index by firm because I focus on symmetric equilibria. Welfare is the sum of producer and consumer surplus net of externality costs. Although the pure welfare economist would value all costs and benefits equally, some argue that the regulator is "captured" by the industry while others believe that consumers are the major concern. In order to make the model robust to political economy considerations, I add parameters for the relative weights of each components of the objective function. Accordingly, I can write

$$W(\mathbf{T}, x) = \omega_1 \cdot CS(\mathbf{T}, x) + \omega_2 \cdot \Pi(\mathbf{T}, x) + (1 - \omega_1 - \omega_2) \cdot EC(\mathbf{T}, x).$$

Assuming differentiability, if $W_{x\mathbf{T}} \geqslant 0$, then $W(\mathbf{T}, x)$ is supermodular and Topkis' Monotonicity Theorem says that $x^*(\cdot)$ is weakly increasing in technology. I make assumptions about the signs of the cross-partials of each of the components of welfare: $CS_{x\mathbf{T}} \geqslant 0, \Pi_{x\mathbf{T}} \geqslant 0$, and $EC_{x\mathbf{T}} = 0$.

$CS_{x\mathbf{T}} \geqslant 0$ says that for higher levels of technology, an increase in regulation will have a lower (negative) impact on marginal cost and thus reduce quantity and CS by less. For example, this would be satisfied under

[28] Alternatively, the researcher could utilize exogenous instruments that are predictors of firm-level regulation, and test whether a firm's predicted innovation in response to exogenous regulation explains the observed innovation. See Puller [30] for an example of such an approach using data on emissions from the chemical manufacturing industry.

Cournot competition with marginal cost a second order polynomial of x and I: $c = \tilde{c} + \alpha x + \lambda x^2 - \beta I - \eta I^2 - \phi x I$. $\pi_{x\mathbf{T}} \geqslant 0$ says that for higher levels of technology, an increase in regulation will have a smaller (negative) impact on marginal cost and therefore π. Because $R_{Ix}(\cdot) = 0$, $\Pi_{x\mathbf{T}} \geqslant 0$. Finally, $EC_{x\mathbf{T}} = 0$ says that externality costs are only a function of the regulatory standard and the amount of output, and do not directly depend upon technology. For example, we could specify $EC = \gamma \cdot (1 - x) \cdot Q$, where x is the fraction of external costs which must be eliminated per unit of the good.

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