ISSN 1745-8587

Birkbeck UNIVERSITY OF LONDON

School of Economics, Mathematics and Statistics

Birkbeck Working Papers in Economics & Finance

BWPEF 1016

How Green Should Environmental Regulators Be?

Anthony Heyes
Royal Holloway, University of London

Sandeep Kapur
Birkbeck, University of London

December 2010

How Green Should Environmental Regulators Be?*

Anthony Heyes
Royal Holloway College
University of London

Sandeep Kapur†
Birkbeck College
University of London

2010

Abstract

The extent to which environmental regulatory institutions are either 'green' or 'brown' impacts not just the intensity of regulation at any moment, but also the incentives for the development of new pollution-control technologies. We set up a strategic model of R&D in which a polluter can deploy technologies developed in-house, or license technologies developed by specialist outsiders. Polluters exert R&D effort and may even develop redundant technologies to improve the terms on which they procure technology from outside. We find that, while regulatory bias has an ambiguous impact on the best-available technology, strategic delegation to systematically biased regulators can improve social welfare.

Keywords: Regulation, innovation, strategic delegation

JEL codes: Q55, K2

*We are grateful to Peth Tuppe, Ron Smith, Bernard Sinclair-Desgagne, and seminar participants at University College London for comments. Errors are ours.

†Corresponding author: Prof S Kapur, Department of Economics, Birkbeck, University of London, Malet St, London WC1E 7HX. *e-mail* s.kapur@bbk.ac.uk.

1 Introduction

Policy choices typically involve balancing one category of costs against another. The standard prescription, in accordance with maximization of social welfare, requires that policy-designers should weight the various categories of costs equally. There are notable exceptions: analyzing the tradeoff between the costs of inflation and unemployment, Rogoff (1985: 1169) pointed out that "Society can often make itself better off by appointing a central banker who does not share the social objective function, but instead places 'too large' a weight on inflation relative to unemployment."

Environmental regulation, in particular, may involve balancing the costs of pollution damage against the costs incurred in emissions reduction. We consider a setting in which, by design, environmental regulators may attach greater or less emphasis on environmental concerns relative to other impact of their policies. The introduction of an attitude parameter allows us to capture how 'green' or 'brown' the regulator is, akin to the 'conservativeness' of Rogoff's central banker.[1] We develop, in this setting, a dynamic model in which the regulatory attitude affects not only the stringency of abatement standards at any moment in time, but also the incentives to develop new pollution-control technologies. In the spirit of Rogoff's conclusion, we show that society can typically make itself better-off by establishing an environmental regulatory regime that appears to *over*- or *under*-weight environmental impacts.

In fact, regulation is often delegated to specialist agencies whose attitudes may well diverge from social preference.[2] While we can view regulators' bias as a taste parameter, in our preferred interpretation such biases are a feature of institutional design, and embodied in agency procedures and practices. In the conduct of cost-benefit analyses (CBA), for example, agencies have a plethora of rules and guidelines relating to the methods to be used in the monetization of costs and benefits, discounting practices, the scope of studies, the categories of costs and benefits that are admissible, *etc.*, so the CBA can favor one side of the equation or the other

[1] When the US President nominates an EPA Administrator the 'green' credentials of candidates are debated, often with reference to environmental 'doves' and 'hawks' – see Cohen (2001) for such assessment of President Bush's prospective appointees.

[2] In the broader literature on regulation a number of authors refer to pro-industry versus pro-consumer regulators – see, for example, Arocena et al. (2002), and Moita and Paiva (2006).

(Adler and Posner (1999), Gayer and Hahn (2005)). For example, Driesen (2006: 335) has argued that CBA practices at the US Environmental Protection Agency are 'anti-environmental' in that they under-weight environmental elements relative to a neutral benchmark.

There may be, as Rogoff pointed out, sound reasons to design institutions that depart from the neutral benchmark. In a model of environmental regulation, Amacher and Malik (1996) analyze the case where regulatory standards are set through bargaining between the regulator and the regulated firm. In the context of their model, they find that from a social welfare perspective a regulator who attaches less importance to the firm's compliance costs than it does to environmental damage and enforcement costs may achieve a better outcome than a neutral regulator. In other words, their 'ideal regulator' is one who is biased in favor of environmental concerns.

We seek to characterize the ideal environmental regulator in a model where the regulatory bias affects, among other things, the degree of innovation in pollution control technologies. In our model the regulatory attitude is captured by a parameter γ, which refers to the weight that the regulatory agency places on environmental benefits relative to the direct costs imposed by regulation. This is similar in spirit to that used in Amacher and Malik (1996), though we do not have enforcement costs. The value $\gamma = 1$ corresponds to a 'neutral' or unbiased regulator; values larger than unity describe regulators who are relatively 'green' and lower values refer to those who are 'brown'. This 'greenness' parameter affects the choice of regulatory standards directly and, through that, affects the incentives to invest in R&D that leads to new abatement technologies.

Our model explores a setting in which the regulator is unable to commit (or can commit only imperfectly) to any regulatory standard in advance of the innovation process. If so, R&D is carried out anticipating the impact that development of innovative technologies will have on the calibration of future regulatory standards. There is a potential time-inconsistency problem if the chosen regulatory standard aims not only to correct the static pollution externality but also to induce the socially-optimal level of innovation. In general the ex-post (after innovation has occurred) optimal regulatory policy deviates from the ex-ante optimal when effects on R&D incentives are taken into account. In such situations credible delegation to a biased regulator can mitigate the time-inconsistency problem.[3]

How green or brown should our ideal environmental regulator be? We find that the direction and the extent of the bias is sensitive to the innovation process. We depart from the existing literature in allowing for two potential sources of innovation: (a) the polluters themselves, who can develop in-house technologies to reduce the cost of complying with pollution abatement regulations, and (b) specialist outside firms, who are not engaged in polluting activity themselves but develop technologies that they license to polluting firms. The existing literature assumes that R&D is done *either* by the polluting industry *or* by outside firms engaged in supplying pollution-control technologies, but never both.[4] This is unsatisfactory since in most real settings we could expect to find significant R&D efforts exerted *both* by the polluting sector itself and by outsiders. Lanjouw and Mody (1999) estimate that worldwide 80% of patents for pollution control technologies are taken out by outsiders, 20% by insiders. Jaffe and Palmer (1997), Brunnermeier and Cohen (2003) and others evidence the outlays on pollution-control R&D made by polluting firms and the environmental services sector.

Consistent with these stylized facts, and in a marked departure from the existing literature, we assume that new abatement technologies emerge from the competitive R&D choices of the regulated polluting firm ('insider') and a specialist entrepreneur ('outsider'). The outsider conducts R&D in order to obtain a patent and license the abatement technology to the insider. The insider invests in R&D to develop better technologies for its own use, or to strengthen its bargaining position with respect to the outsider thereby reducing the license fee it must pay. The R&D choices of the two firms are inter-dependent and the strategic interaction between them – absent by assumption from all existing analyzes of environmental R&D – is central to our

[3]We discuss our modeling specification below, but note that it fits the trend – in environmental economics and more widely – towards emphasizing the need for time-consistent policies. See Melumad and Mookherjee (1989) for a seminal treatment of the more general literature on strategic delegation.

[4]Much of the related literature, including most seminal papers, assume R&D is done internally. For the latter approach see Parry (1995), Requate (2005b) and an excellent recent paper by Greaker and Rosendahl (2008). The extensive literature exploring the relationship between environmental policy and innovation is surveyed by Jaffe and Stavins (2002). In the more general literature on environmental policy (not R&D) the existence of an upstream 'environmental services' industry selling compliance-solutions to polluters has been acknowledged: see, for instance, the excellent paper by David and Sinclair-Desgagne (2005).

analysis. We show that R&D effort of the insider is *increasing* in the R&D efforts of the outsider, whilst the efforts of the latter are *decreasing* in the efforts of the former.

We examine the equilibria of this R&D game. Our primary focus is on equilibria in which both parties engage in inventive activity, but it is the outsider who develops the best technology (that is, one with lowest unit abatement cost), and it is this technology that is used for pollution abatement. We also describe equilibria in which a high level of R&D by the insider induces the outsider to abandon innovation altogether. Our model contributes to the understanding of the relationship between environmental institutions and green R&D and, to the best of our knowledge, is the first to model a scenario where innovations may come from within the polluting industry or from outside.

We analyze the impact of changes in the regulatory attitude parameter γ upon (a) the terms of the strategic interaction between the two parties in the R&D game; (b) the equilibrium 'mix' of in-house versus out-sourced R&D activity; (c) the new technologies that emerge, including the best-available technology; (d) the licence fees paid by polluters for pollution-control technologies; (e) expected environmental quality and, most importantly, (f) social welfare. We find that the strategic interaction matters in that it can lead to R&D effort that exceeds or falls short of the socially-optimal level.

The analysis allows us to characterize the optimal γ, and therefore to talk about the optimal corrective 'bias' that a welfare-motivated polity should wish to embody in its regulatory institutions. In contrast with the existing literature – notably Amacher and Malik (1996) – we can identify circumstances where the ideal regulator should be 'brown' relative to the neutral benchmark. To that extent, our analysis offers an alternative efficiency interpretation to the perceived regulatory capture interpretation of agency practices.

Whilst the focus of this paper is theoretical we point to consistency with stylized facts. Section 2 sets-up the model and characterizes equilibria in the R&D game, market for technology and regulatory decisions. Section 3 explores the question of the ideal regulator. Section 4 concludes and identifies potential extensions.

2 The Model

A firm generates pollution as a by-product of its business activity. Absent regulation, its level of pollution is X. The regulator must choose some level of abatement a, in order to reduce pollution level to $(X - a)$.[5]

The abatement standard a chosen by the regulator will vary with his greenness – the relative weight γ he attaches to abatement benefits relative to abatement costs. We assume that γ is common knowledge and credible. It could be that γ is simply announced and believed. But given the incentive here for cheap talk, in real-world settings policy actors have credibly to establish their reputation through, say, the manner in which they respond in a sequence of decision contexts. An appointee may 'import' a reputation for a particular set of attitudes from their previous activities. Recall that our preferred interpretation of γ is as being embodied in regulatory institutions and practices – the way in which cost-benefit analysis is conducted, for example – in which case knowledge of γ can be assumed through observation of those practices.

For any γ, the choice of the regulatory standard also varies with abatement cost, which depends on the state of available technologies. An abatement technology is characterized by constant marginal abatement cost c, so that the total cost of achieving target abatement level a equals ac. The marginal abatement cost can be lowered by investment in new technologies. We assume that R&D can be carried out in-house by the polluting firm ('insider') or by an external entrepreneur ('outsider'). R&D expenditure r leads to a technology with marginal abatement cost $c(r)$, where $c' < 0$ (higher R&D spending generates technologies with lower marginal abatement

[5] We focus on quantitative standards because of their prevalence: as Hueth and Melkonyan (2006) point out, "The regulation of environmental risk remains dominated by the use of standards. Although performance incentives (e.g. Pigovian taxes and emissions-trading programs) are sometimes employed, standards remain the core component." This is the case even with relatively recent European legislation, where examples of quantitative restrictions include: (a) The London Airports Noise Restrictions Notice (February 2007) places an upper bound on the noise from aircraft allowed to land at London's Heathrow and Gatwick airports; (b) UK's Environment Agency sets limits on air and water pollutant levels that power stations can emit; (c) The Waste Incineration Directive (2000/76/EC) places non-tradable quantitative limits on emissions of heavy metals from incinerators; (d) The EC Battery Directive (2001/338/EC) limits the cadmium content of batteries. We argue later that we could arm our regulator with a different instrument without disturbing the essential insights.

cost) and $c'' > 0$ (there are diminishing returns to effort in research). Once a technology is developed and patented, its parameters cannot be readily adjusted: in reality, many technologies take considerable time to develop with only limited possibilities of adjustment.

Our model incorporates two further simplifying assumptions. One, the innovation process is deterministic. The return to R&D effort can be made stochastic without varying our qualitative insights. Two, we assume that the outsider and insider are equally adept at research, so that the innovation function $c(r)$ is common to them. We could extend our model to allow for different research capabilities, and the advantage could plausibly go either way. On the one hand, the polluting firm might benefit from its 'inside' knowledge of production practices and product design to better develop an abatement technology. On the other hand, the outsider might have higher generic innovative capability by virtue of its being a specialist research and engineering firm, equipped for, and with experience of, designing pollution-control solutions across varied settings. Our assumption of common innovation capability provides a useful benchmark since it ensures that any predicted differences in research levels are *not* driven by differences in research capability.

In our model, the outsider invests in R&D in order to obtain a patent and license its technology to the regulated firm. The insider invests either because it expects to use its proprietary abatement technology or because investment strengthens its bargaining position with respect to the outsider's innovation, lowering the royalty it must pay to the outsider. Thus, our innovation process is competitive: we ignore the possibility of collaborative research between the insider and outsider, whilst acknowledging the significance of research joint ventures (RJVs) in some real world settings – see, for example Hackett (1995).[6] The market for technology is assumed to be efficient: if the outsider develops a lower-cost technology the surplus from adopting that technology is shared between the two firms, so the insider has an incentive to adopt it.

It is well-known that the assumed order of moves can have a significant impact on outcomes in models of this sort. Amacher and Malik (2002) make a compelling

[6]The game of vertical RJV formation would be an interesting one to consider in future research, with the returns to each party from participation in such a scheme being sensitive to regulatory attitude. We are grateful to a referee for pointing this out.

argument that in any particular case the most realistic sequencing of instrument-calibration by regulators and technology-choice by firms is likely to vary according to setting, and provide examples. In the model here we have the additional complication of an R&D stage. It is helpful, then, to be explicit about the assumed sequence of events:

- Stage 1: Principal installs a regulator/puts in place regulatory institutions - in effect choosing γ, how green the regulatory regime should be. The chosen γ is common knowledge.
- Stage 2: (R&D game) The regulated firm (insider) and a specialist entrepreneur (outsider) invest independently in developing pollution-abatement technologies. Once developed, their technologies are patented and common knowledge.
- Stage 3: (Regulation) The regulator observes the set of available technologies and sets the abatement standard.
- Stage 4: (Market for technology) The regulated firm chooses between using its in-house technology or licensing the outsider's technology for a fee.

Some key elements of our model's structure merit emphasis. One, the choice of γ is assumed to be credibly fixed: this fits with the interpretation of it being descriptive of regulatory institutions and practices. It may be feasible to change such institutions ex post, but such changes might be expected to be slow or face practical hurdles.

Two, the regulator is assumed, in stage 3, to set standards after observing the technologies that have been developed. A sufficient – though demanding – assumption for this would be that the regulator can observe R&D efforts directly. In fact, the weaker assumption that the regulator is able to observe patents suffices. Regulation is conditioned only on the characteristics of the best-available technology which, in the equilibrium of interest, 'belongs' to the outside innovator who will always benefit from patenting to prevent free adoption of his technology.[7]

[7]In theory an *insider* could choose not patent his superior in-house innovation if, for example, deploying an outsider's inferior technology allowed for weaker regulation. In the model here, however, this is never the case.

Three, the regulator is unable to commit to a regulatory standard before the innovation outcome is known, As such our model fits into the "regulatory ratchet" part of the literature – Puller (2006) provides a recent example – rather than the "technology-forcing" part in which the regulator moves first with the intention of influencing R&D programs. It should become obvious that if the regulator is allowed to move before the R&D game and with commitment, then the strategic delegation element of the setting is lost and principal can never do better than appoint a regulator sharing his tastes (that is, an unbiased one).

As usual, we solve the model backwards.

2.1 The market for technology

Let the innovation expenditures for the insider and outsider be r_i and r_o, resulting in abatement technologies that have unit costs $c(r_i)$ and $c(r_o)$ respectively. We make no *a priori* assumptions about the level of r_i relative to r_o but distinguish between two kinds of outcomes. With deterministic innovation when $r_i \geq r_o$ the polluting firm's in-house technology has lower costs: we have $c(r_i) \leq c(r_o)$, so that the insider uses his own technology. If so, the outsider gets no revenue.

In contrast, when $r_o > r_i$ the outsider's technology has lower abatement costs. Both firms can potentially gain if the polluter licenses the outsider's technology in preference to using his own technology. For any required abatement level a, the saving in total abatement costs from switching to the outsider's technology is

$$a[c(r_i) - c(r_o)].$$

We assume the market for technology is efficient and the above surplus is split between the outsider (technology licensor) and the insider (licensee) in proportions β and $(1-\beta)$ respectively.[8] So whenever $r_o > r_i$ the insider adopts the outsider's

[8] This is the usual bargaining solution in bilateral monopoly models: Mas-Colell et al. (1995) provide a textbook treatment of such 'cake-sharing' games. Here $0 < \beta < 1$ captures relative bargaining power, and may be related to the degree of patience in an alternate-offer bargaining game (Rubinstein, 1982), or the degree of protection afforded by the intellectual property rights regime.

technology in return for a license fee equal to

$$a\beta[c(r_i) - c(r_o)].$$

This fee is increasing in the cost advantage of the outsider's over the insider's technology, in the relative bargaining power β of the outsider, and in the stringency of the regulatory standard a. We summarize the outcome in the market for technology as follows:

Remark 1 *(Market for technology) If $c(r_o) \geq c(r_i)$ the polluting firm adopts its in-house abatement technology. If $c(r_o) < c(r_i)$ it adopts the outsider's abatement technology and pays license fee $a\beta[c(r_i) - c(r_o)]$.*

2.2 Regulation

The regulator's choice of abatement level a is based on his evaluation of the weighted environmental benefits and financial costs of abatement activity. Abatement costs depend, as detailed above, on the pollution-control technology used. Regulation is forward-looking and – since R&D effort is already sunk – when evaluating abatement costs the regulator takes the state of technology as given. It it important to emphasize that he does not impose a technology to be used, but sets a standard anticipating that the best-available technology will be adopted (in other words, he understands Remark 1). Given innovation expenditures r_o and r_i, define $\hat{r}(r_i, r_o) = \max\{r_i, r_o\}$ and $c_{min} = c(\hat{r})$. The choice of regulatory standard a will call for expenditure ac_{min} on abatement.

The environmental benefits of abatement are given as a smooth function $b(a)$. We make the usual assumption that environmental damage is increasing in pollution at an increasing marginal rate, implying that abatement benefits increase with abatement level but at a decreasing rate: $b' > 0$ and $b'' < 0$.

A regulator with bias γ chooses abatement standard a to maximize the difference between weighted benefits and costs

$$\gamma b(a) - ac_{min}. \tag{1}$$

Let a^* maximize expression (1). Assuming an interior solution exists, it is implicitly defined by

$$\gamma b'(a^*) = c_{min}. \tag{2}$$

Given our assumption that $b'' < 0$, the sufficient second-order condition for a maximum is satisfied. The regulator sets the abatement standard at a level where the weighted marginal benefit of abatement equals the marginal cost of abatement using the best-available technology. This chosen standard is functionally dependent on $\hat{r}$ and γ, so that we write the regulatory stringency function as $a^* = a(\hat{r}, \gamma)$.

Our assumptions about the costs and benefits of abatement imply that

$$\frac{\partial a}{\partial \gamma} = -\frac{b'(a^*)}{\gamma b''(a^*)} > 0, \tag{3}$$

and

$$\frac{\partial a}{\partial \hat{r}} = \frac{c'(\hat{r})}{\gamma b''(a^*)} > 0. \tag{4}$$

In words, other things being equal, stricter standards will result when the regulator is greener or when higher R&D expenditure leads to cheaper abatement technologies. Also, for analytical tractability, we make the following assumption on the regulatory choice function:

Assumption 1 *A greener regulator is no less responsive to better pollution control technologies, that is,* $\frac{\partial^2 a}{\partial \hat{r} \partial \gamma} \geq 0$.

This assumption warrants some discussion. Differentiating (3) with respect to $\hat{r}$ we get

$$\frac{\partial^2 a}{\partial \hat{r} \partial \gamma} = -\frac{1}{\gamma} \frac{\partial a}{\partial \hat{r}} \left[\frac{b''b'' - b'b'''}{b''b''} \right].$$

Assumption 1 then amounts to the restriction that $b''b'' - b'b''' \leq 0$ at the regulatory optimum. While the concavity of benefit function is standard (that is, $b' > 0$ and $b'' < 0$), restrictions on third derivatives are – as ever – *ad hoc*. Nonetheless, it is straight-forward to verify that the condition holds for commonly-used concave functional forms, for example the logarithmic form $b(a) = \ln a$, or the exponential function $b(a) = a^k$ where $k \in (0, 1)$. While we invoke this assumption at various places, where relevant we note how altering this assumption affects our results.

2.3 The green R&D game

We turn now to the R&D choices of the insider and outsider at the innovation stage. Firms recognize that their payoff varies with their own choice and the choice made by the other firm. Their payoffs, and hence their choices, also depend on the anticipated regulatory response, $a(\hat{r}, \gamma)$.

Our primary focus is on the case where both the insider and outsider choose positive level of R&D. However, for completeness we also consider the case where the outsider chooses to drop out of the innovation stage because it is not profitable.

Recall that the regulatory policy is conditioned on the best available pollution-control technology which depends on $\hat{r} = \max\{r_i, r_o\}$. Significantly, note that $a(\hat{r}, \gamma)$ does not vary with r_i for ranges where $r_o > r_i$, and does not vary with r_o when $r_i > r_o$. With slight abuse of notation we write $a(., .)$ as a function directly of r_i and r_o, and denote the partial derivatives of this function with respect to innovation expenditures as a'_i and a'_o, depending on the context.[9]

2.3.1 The outsider's choice

The outsider chooses r_o to maximize the revenue from licensing its technology net of the costs of R&D. This is given as

$$\Pi(r_i, r_o, \gamma) = \begin{cases} -r_o & \text{if } r_o \leq r_i \\ a(r_o, \gamma)\beta[c(r_i) - c(r_o)] - r_o & \text{otherwise.} \end{cases}$$

To understand this, note that if $r_o \leq r_i$, the outsider's technology is no better than the insider's, so generates no revenue.

If $r_o > r_i$ he is able to license his technology for a fee $a(r_o, \gamma)\beta[c(r_i) - c(r_o)]$ that varies with the insider's choice. Then the outsider's optimal choice of R&D level, $r_o^* > r_i$, is given by the first-order condition

$$\Pi_o(r_i, r_o^*, \gamma) \equiv \beta[a'_o(r_o^*, \gamma)[c(r_i) - c(r_o^*)] - a(r_o^*, \gamma)c'(r_o^*)] - 1 = 0, \quad (5)$$

[9] So more fully we would write $a'_i = \frac{\partial a}{\partial \hat{r}} \frac{\partial \hat{r}}{\partial r_i}$ and $a'_o = \frac{\partial a}{\partial \hat{r}} \frac{\partial \hat{r}}{\partial r_o}$.

provided the optimized value of profits $\Pi(r_i, r_o^*, \gamma) \geq 0$. The non-negativity of profits ensures the outsider's participation: if profits were negative, the outsider would prefer to opt out of the innovation stage. Note that it will never make sense for the outsider to exceed the insider's R&D expenditure by only a small amount as license revenue would be too meagre to recoup R&D expenses. Further, the outsider's optimal profit is decreasing in r_i (the envelope theorem provides a formal demonstration) so that, given γ, there exists some r_i – call it $\overline{r}_i(\gamma)$ – such that $\Pi(r_i, r_o^*, \gamma) < 0$ for all $r_i > \overline{r}_i(\gamma)$. Hence, if the insider spends above this critical threshold, it is optimal for the outsider to drop out (or, formally, $r_o^* = 0$ whenever $r_i > \overline{r}_i(\gamma)$).

We summarize the outsider's optimal response to insider's choice r_i as a reaction function $R_o(r_i; \gamma)$. For $r_i > \overline{r}_i(\gamma)$ we have $R_o(r_i; \gamma) = 0$, for reasons described above. If the insider's expenditure is below this threshold, the outsider's optimal choice is positive. To see how the outsider's choice varies with r_i and γ in this range, total differentiation of first-order condition (5) gives us

$$\Pi_{oi} dr_i + \Pi_{oo} dr_o + \Pi_{o\gamma} d\gamma = 0. \tag{6}$$

It is easy to check that $\Pi_{oi} < 0$ and $\Pi_{oo} < 0$: if so, $\partial R_o / \partial r_i = -\Pi_{oi}/\Pi_{oo} < 0$. Further, Assumption 1 is sufficient for $\Pi_{o\gamma} = \beta a''_{o\gamma}[c(r_i) - c(r_o)] - \beta a'_\gamma c'_o$ to be positive, so $\partial R_o / \partial \gamma = -\Pi_{o\gamma}/\Pi_{oo} > 0$. We summarize this as follows:

Proposition 1 *At any configuration in which both the insider and outsider engage in R&D, other things equal*

(a) an increase in the R&D spending of the insider will induce the outsider to decrease his R&D spending;

(b) given Assumption 1, an increase in γ, the greenness of the regulator, will induce the outsider to increase his R&D spending.

2.3.2 The insider's choice

The insider chooses his R&D expenditure r_i to minimize the sum of expected abatement costs and R&D spending. The insider's loss function is

$$I(r_i, r_o, \gamma) = \begin{cases} a(r_i, \gamma)c(r_i) + r_i & \text{if } r_o \leq r_i \\ a(r_o, \gamma)[c(r_o) + \beta[c(r_i) - c(r_o)]] + r_i & \text{otherwise.} \end{cases}$$

The insider's optimal choice varies with r_o and γ, and can be represented by reaction function $R_i(r_o; \gamma)$. For the case where the outsider's technology is inferior the insider falls back on his own technology. In this circumstance, the insider expects the regulatory stringency to vary with his own level of R&D, so the insider must choose r_i to minimize $a(r_i, \gamma)c(r_i)+r_i$. Ignoring the trivial outcome where $r_i^* = 0$, an interior minimum for this case is given by

$$I_i(r_i^*; \gamma) = a_i'(r_i^*, \gamma)c(r_i^*) + a(r_i^*, \gamma)c'(r_i^*) + 1 = 0. \tag{7}$$

The solution r_i^* to this equation defines the insider's optimal reaction to $r_o = 0$,[10] and can be denoted as $R_i(0, \gamma)$. It is easy to check that $I_{ii} > 0$ at the optimum, but the sign of $I_{i\gamma}$ is ambiguous. Notably $I_{i\gamma} < 0$ whenever the cross-partial $a_{i\gamma}''$ is relatively small, in which case $R_i(0, \gamma)$ is increasing in γ.[11]

Next, for configurations where $r_i < r_o$, the outsider's technology is superior. In this range, the insider's costs are given as

$$I(r_i, r_o, \gamma) = a(r_o, \gamma)[c(r_o) + \beta[c(r_i) - c(r_o)]] + r_i.$$

Here abatement standards and costs are driven by the superior technology, and marginal changes in r_i have no direct impact on the regulatory intensity.[12] R&D is

[10]We do not have to consider $r_i > r_o > 0$. As already established it is better for the outsider to choose $r_o = 0$ than a response in the above range. In other words, when looking for equilibria, we can restrict attention to the cases where $r_o = 0$ and $r_o > r_i$.

[11]The other case, where $a_{i\gamma}''$ is positive and large, amounts to one where a greener regulator is very responsive to innovation. Higher γ then lead the isolated insider to cut back on innovation to avoid ratcheting of regulation.

[12]Bear in mind that we are dealing with partial derivatives here. In the equilibrium comparative statics that we present below changes in r_i will alter regulatory choices by influencing r_o.

costly but improves payoff by reducing the license fees paid to the outsider. Assuming the insider's problem has an interior solution in the interval $r_i \in (0, r_o)$, it must satisfy the first-order condition[13]

$$I_i(r_i^*, r_o, \gamma) = a(r_o, \gamma)\beta c'(r_i^*) + 1 = 0. \tag{8}$$

Thus, the insider invests in R&D up to the point where its marginal cost equals the marginal reduction in expected license payments. In this case the insider engages in positive levels of R&D even though he recognizes that he will, ultimately, procure abatement technology from outside. The technology he develops constitutes a fall-back position and any improvement in that strengthens the bargaining position with the outsider, reducing license fees. This is similar in spirit to the role of R&D by incumbents in the 'creative gale of destruction' model of Gans and Stern (2000).

To identify the characteristics of the reaction function, $R_i(r_o; \gamma)$ in the range where both firms innovate, we differentiate (8) to get

$$I_{ii}dr_i + I_{io}dr_o + I_{i\gamma}d\gamma = 0, \tag{9}$$

where $I_{ii} = a\beta c'' > 0$, $I_{io} = a_o'\beta c' < 0$, and $I_{i\gamma} = a_\gamma'\beta c' < 0$. It follows directly that

$$\frac{\partial R_i}{\partial r_o} = -\frac{I_{io}}{I_{ii}} > 0, \quad \frac{\partial R_i}{\partial \gamma} = -\frac{I_{i\gamma}}{I_{ii}} > 0.$$

These effects are intuitive. Higher values of r_o or γ translate into more stringent regulation, increasing the license fee paid to the outsider: in response, the insider increases R&D to economize on these payments. In summary:

Proposition 2 *At any configuration in which both the insider and outsider engage in R&D, other things equal*

(a) an increase in the R&D spending of the outsider will induce the insider to

[13] An interior solution results if $a\beta c'(0)+1 < 0$ and $a\beta c'(r_o)+1 > 0$, which holds for r_o sufficiently large. Note that the second-order condition for a maximum is necessarily satisfied since $c'' > 0$. The corner solutions are as follows: If $I_i(r_i, r_o, \gamma)$ is positive at $r_i = 0$, it is optimal for the insider to invest nothing. If on the other hand, $I_i(r_i, r_o, \gamma)$ is negative everywhere in the interval $[0, r_o]$ then it is optimal for the insider to match $r_i = r_o$.

increase his R&D spending;

(b) an increase in γ, the greenness of the regulator, will induce the insider to increase his R&D spending.

Comparing Propositions 1 and 2, we note that an increase in the greenness parameter γ induces both the insider and outsider to increase their innovation activity. They react differently to changes in each other's R&D expenditure: an increase in the insider's R&D induces the outsider to *decrease* his R&D (the outsider's reaction function is downward sloping) while an increase in the outsider's R&D induces the insider to *increase* his activity (reaction function is upward-sloping.)

2.3.3 Equilibrium of the R&D game

For any given γ, a Nash equilibrium of the R&D game is a pair $[r_i^*(\gamma), r_o^*(\gamma)]$ such that $r_i^*(\gamma) = R_i(r_o^*; \gamma)$ and $r_o^*(\gamma) = R_o(r_i^*; \gamma)$.

Two kinds of equilibria can arise depending on the parameter values (we ignore the possibility of mixed-strategy equilibria). First, we may obtain equilibrium configurations in which r_i^* and r_o^* are both positive – the insider and outsider both engage in R&D. Such an outcome is illustrated in Figure 1.

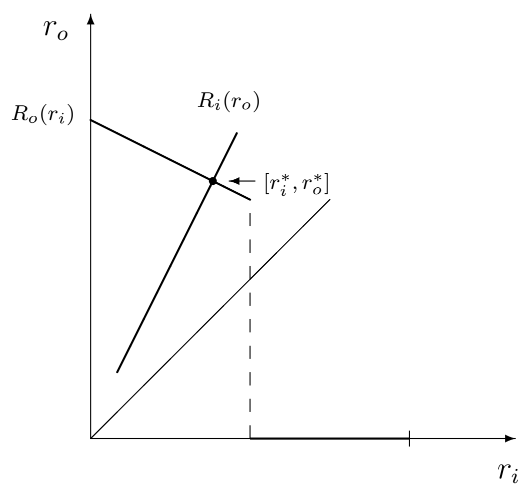

Figure 1: **Equilibrium when both innovate**

Second, recall that the outsider chooses $R_o(r_i;\gamma) = 0$ for $r_i \geq \overline{r}_i(\gamma)$. Then, if $R_i(0;\gamma) > \overline{r}_i(\gamma)$, we get an equilibrium in which the outsider drops out ($r_o^* = 0$) and the insider chooses $r_i^* = R_i(0;\gamma) > 0$. This is illustrated in Figure 2.

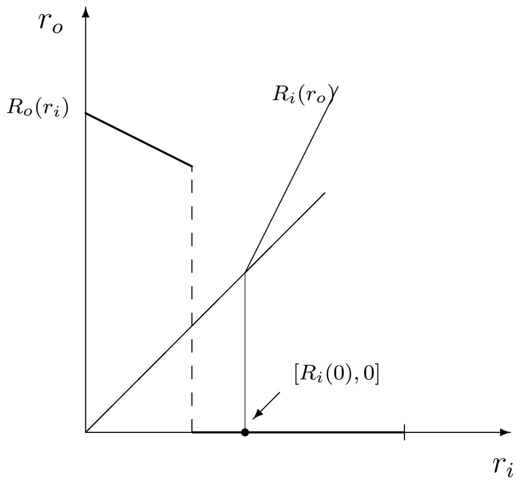

Figure 2: **Equilibrium when outsider drops out**

2.3.4 Comparative statics: the impact of varying γ

In this sub-section we explore the impact of varying the greenness parameter γ on the equilibrium outcome.

For equilibria in which the outsider drops out, the effect of varying γ is straightforward to analyze but potentially ambiguous. Higher values of γ raise the threshold $\overline{r}_i(\gamma)$ beyond which the outsider drops out but, as noted earlier, the isolated insider's response $R_i(0;\gamma)$ is increasing in γ as long as the cross-partial $a''_{i\gamma}$ is relatively small.

Equilibria in which both firms innovate offers analytically interesting possibilities. Total differentiation of the relevant first-order conditions (5) and (7) gives, in compact notation,

$$\begin{bmatrix} I_{ii} & I_{io} \\ \Pi_{oi} & \Pi_{oo} \end{bmatrix} \begin{bmatrix} \frac{dr_i^*}{d\gamma} \\ \frac{dr_o^*}{d\gamma} \end{bmatrix} = \begin{bmatrix} -I_{i\gamma} \\ -\Pi_{o\gamma} \end{bmatrix}.$$

Using Cramer's rule, we can check that

$$\frac{dr_i^*}{d\gamma} = \frac{\begin{vmatrix} -I_{i\gamma} & I_{io} \\ -\Pi_{o\gamma} & \Pi_{oo} \end{vmatrix}}{\begin{vmatrix} I_{ii} & I_{io} \\ \Pi_{oi} & \Pi_{oo} \end{vmatrix}} > 0 \quad \text{and} \quad \frac{dr_o^*}{d\gamma} = \frac{\begin{vmatrix} I_{ii} & -I_{i\gamma} \\ \Pi_{oi} & -\Pi_{o\gamma} \end{vmatrix}}{\begin{vmatrix} I_{ii} & I_{io} \\ \Pi_{oi} & \Pi_{oo} \end{vmatrix}} \gtrless 0.$$

Under Assumption 1, which implies $\Pi_{o\gamma} > 0$, a higher value of γ increases the insider's equilibrium investment in R&D, while the impact on the outsider's choice of R&D is ambiguous.[14] Figure 3 helps with intuition. Appointing a greener regulator – setting a higher value of γ – shifts both reaction curves to the right. This, combined with the upward slope of the insider's reaction function leads to an unambiguous increase in the insider's equilibrium R&D level. For the outsider, higher γ has a positive direct impact on R&D. But higher γ also stimulates the insider's R&D activity, which discourages the outsider's R&D, so that the indirect effect pushes in the opposite direction. The net effect could go either way.

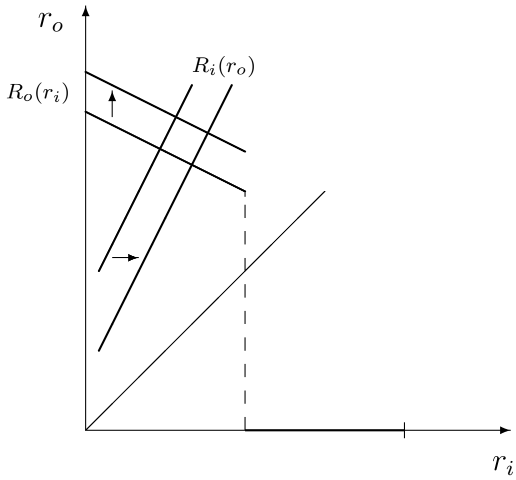

Figure 3: **Equilibrium impact of higher γ when both firms innovate**

Recalling that it is the outsider's technology that is used when both firms inno-

[14]Note sign $\left(\frac{dr_i^*}{d\gamma}\right) = \text{sign}\frac{\begin{vmatrix} + & - \\ - & - \end{vmatrix}}{\begin{vmatrix} + & - \\ - & - \end{vmatrix}} > 0$, while sign $\left(\frac{dr_o^*}{d\gamma}\right) = \text{sign}\frac{\begin{vmatrix} + & + \\ - & - \end{vmatrix}}{\begin{vmatrix} + & - \\ - & - \end{vmatrix}}$ is ambiguous.

vate, we have the following proposition.

Proposition 3 *Given Assumption 1, an increase in γ, the greenness of the regulator, has an ambiguous impact on the quality of the best-available technology.*[15]

3 How green is the 'ideal' regulator?

We begin by examining the social planner's problem. Social welfare is the (unweighted) sum of the environmental benefits of abatement activity minus abatement costs and R&D expenditures:

$$W(a, r_i, r_o) = b(a) - ac(\hat{r}) - r_i - r_o. \tag{10}$$

How would a social planner maximize welfare if it can choose a, r_i and r_o directly? In our setting with deterministic innovation there should be no duplication of R&D, so at the first-best outcome one of r_i or r_o should equal 0. Without loss of generality we can set $r_i = 0$ so that $r_o = \hat{r} = r$. The social planner's problem reduces to: choose a and r to maximize

$$b(a) - ac(r) - r, \tag{11}$$

with first-order conditions for an interior maximum[16]

$$W_a = b'(a) - c(r) = 0 \tag{12}$$

$$W_r = -ac'(r) - 1 = 0 \tag{13}$$

In words, at the first-best outcome all R&D effort is exerted by one firm to avoid wasteful duplication.[17] The regulatory standard is set such that the marginal cost and benefit of abatement are equalized, taking technology as given. R&D effort is

[15] If alternative restrictions entail $\Pi_{o\gamma} < 0$, the sign of $\frac{dr_i^*}{d\gamma}$ is ambiguous, while the sign of $\frac{dr_o}{d\gamma}$ is unambiguously *negative*. For this case appointing a greener regulator unambiguously weakens the best-available technology.

[16] A sufficient second-order condition for this to be a maximum is that $W_{aa} = b'' < 0$ and $W_{aa}W_{rr} - (W_{ar})^2 = -ab''c'' - (c')^2 \geq 0$.

[17] This follows from our assumption that the R&D process is deterministic. With a stochastic element the first-best might involve splitting a given R&D 'pot' between the two parties.

exerted up to the point at which the marginal savings in abatement costs equal the marginal cost of R&D.

In our framework the social planner does not have direct control of r_i and r_o. Those R&D choices are, however, sensitive to the regulatory regime. In appointing a regulator or designing regulatory institutions, then, our planner faces a second-best problem. The choice of γ impacts regulatory decisions both directly (that is for any *given* pattern of technologies available) and indirectly (through influencing R&D choices and therefore the pattern of technologies that emerge in equilibrium).

Denoting the choice of regulatory standard $a(\hat{r}(\gamma), \gamma) = \tilde{a}(\gamma)$ we can express social welfare as a function of γ,

$$W(\gamma) = b(\tilde{a}(\gamma)) - \tilde{a}(\gamma)c(\hat{r}(\gamma)) - r_i^*(\gamma) - r_o^*(\gamma). \tag{14}$$

An interior, second-best, choice of regulatory parameter γ requires

$$\frac{dW(\gamma)}{d\gamma} = [b'(\tilde{a}) - c(\hat{r})] \left(\frac{d\tilde{a}}{d\gamma}\right) - \tilde{a}c'(\hat{r})\frac{d\hat{r}}{d\gamma} - \frac{dr_i^*}{d\gamma} - \frac{dr_o^*}{d\gamma} = 0, \tag{15}$$

where $\frac{d\tilde{a}}{d\gamma} = \left(\frac{\partial a}{\partial \gamma} + \frac{\partial a}{\partial r}\frac{d\tilde{r}}{d\gamma}\right)$. Let γ^* denote the value that optimizes $W(\gamma)$. The expression above allows us to identify the trade-offs involved in choosing γ^*, with the terms capturing the welfare impact of marginal changes in γ through changes induced in equilibrium values of a, r_i and r_o.

The first composite term in (15) relates static efficiency to choice of γ. To see this observe that if we take technology as exogenous by imposing $\frac{dr_i}{d\gamma} = \frac{dr_o}{d\gamma} = 0$ then this equation reduces to

$$\left.\frac{dW}{d\gamma}\right|_{\frac{dr_i}{d\gamma} = \frac{dr_o}{d\gamma} = 0} = [b'(\tilde{a}) - c(\hat{r})] \frac{\partial a}{\partial \gamma} = 0, \tag{16}$$

which holds only if $[b'(\tilde{a}) - c(\hat{r})] = 0$. This is the simple case in which regulatory stringency $\tilde{a}$ equates the marginal benefit of abatement with its marginal cost. Comparing this condition with condition (2), the regulatory process in our model will deliver this outcome only at $\gamma^* = 1$. In other words, if technology development is exogenous then the welfare-motivated social planner should delegate to an unbiased regulator. This is intuitive, and consistent with the often-stated conventional wisdom that regulatory institutions should be unbiased. If green technical change were not sensitive to the regulatory setting then our analysis endorses the conventional wisdom.

However, more generally in our setting innovation is *not* exogenous but, rather, is influenced by the regulatory attitude. Improvement of dynamic efficiency, by creating the incentives for the right level of innovation, provide a reason to bias the regulatory attitude. Rearranging (15) gives

$$b'(\tilde{a}) - c(\hat{r}) = \left(\tilde{a}c'(\hat{r})\frac{d\hat{r}}{d\gamma} + \frac{dr_i^*}{d\gamma} + \frac{dr_o^*}{d\gamma}\right) \Big/ \left(\frac{d\tilde{a}}{d\gamma}\right) \tag{17}$$

The expression on the right includes some terms whose signs are, in general, ambiguous. However, whenever the right-hand side is non-zero, optimal γ will depart from unity. Since $b(a)$ is concave, if the expression on the right is positive, optimally chosen $\gamma^* < 1$: the social planner will wish to design regulatory institutions that apparently *under*-weight environmental concerns. Conversely, if the expression on the rights is negative optimal regulatory institutions should *over*-weight environmental concerns.

Proposition 4 *If the regulatory environment affects the innovation activity in the regulated industry, unbiased regulatory institutions (that is, those embodying $\gamma = 1$) will not in general be socially optimal.*

While the arguments here are made in the context of a specific model, the underlying intuition is quite general. Nonetheless does our model allow us to say more about the direction of departure from unbiased regulatory institutions? The normative recommendation turns out to vary with the nature of the equilibria of the innovation game, so we consider the two categories of equilibria separately.

3.1 Equilibria at which only insider innovates

We consider, first, equilibria where the outsider drops out ($r_o^* = 0$), and the technology in use is the one developed by the insider ($\hat{r} = r_i^*$). This delivers the most straightforward prescription.

Comparing the insider's choice of R&D, as given by equation (7), with the optimality condition (13), we find that the insider *under*-invests in R&D relative to first-best. As in Puller (2006), it is rational for the polluter to under-invest because this reduces the extent to which standards ratchet up in response to innovation. Substituting from (7) in (17), we get

$$b'(\tilde{a}) - c(\hat{r}) = \left(-a_i' c(r_i) \frac{dr_i^*}{d\gamma}\right) \Big/ \left(\frac{d\tilde{a}}{d\gamma}\right). \tag{18}$$

Recall that comparative-static analysis of condition (7) for the insider's R&D choice shows that, in general, the sign of $dr_i^*/d\gamma$ is ambiguous. But whenever the insider's optimal choice is increasing in γ (this happens as long as the cross-partial $a_{i\gamma}''$ is not too large), this expression is positive so that $\gamma^* > 1$.

Proposition 5 *If a regulated firm uses its in-house abatement technology, unbiased regulation results in socially sub-optimal levels of R&D. Second-best regulation calls for a* ***pro-environment bias*** *($\gamma^* > 1$) whenever the firm's R&D expenditure is increasing in γ.*[18]

3.2 Equilibria at which both firms innovate

Consider, next, equilibria where both insider and outsider engage in R&D. Here $r_o^* > r_i^*$, so that the outsider's technology is used ($\hat{r} = r_o^*$). At this equilibrium the R&D spending of the insider is redundant from the social point of view: the insider only engages in it to drive down the license fees it anticipates having to pay to the outsider for the use of its technology. As that fee is simply a transfer and so does not affect aggregate welfare, the real resources incurred in the insider's R&D activity reduce welfare. Other things being the same, policies that reduce the insider's R&D expenditure can increase welfare.

The distortion of R&D incentives also depends on the parameter β that measures

[18]If the cross-partial effect dominates such that r_i^* is decreasing in γ then the corrective bias must be applied in the other direction.

the division of surplus between the technology-supplier and the regulated firm.[19] Higher values of β correspond to higher license revenue and spur the outsider towards higher levels of R&D. Comparing condition (5) for the outsider's R&D choice with the social planner's choice (13), we can see that when β is sufficiently close to 1, the outsider *overinvests* relative to the social optimum: on the margin innovation leads to ratcheting up of regulatory standards, increasing the profitability of innovation for the outsider. In aggregate, the excess of R&D is even higher because the outsider's expenditure also causes the insider to escalate his expenditure to reduce license fees.

In this case the second-best outcome would call for a regulatory climate that, on the margin, *discourages* R&D. Once again, whether this is achieved through a regulatory regime biased in favor or against the environment depends on how r_o^* varies with γ. Substituting from (5) in (17) while setting $\hat{r} = r_o^*$, we get

$$b'(\tilde{a}) - c(\hat{r}) = \frac{[\beta a_o'(c(r_i) - c(r_o)) + (1-\beta)a(r_o)c_o'] \frac{dr_o^*}{d\gamma} + \frac{dr_i^*}{d\gamma}}{\frac{d\tilde{a}}{d\gamma}}. \quad (19)$$

The terms in the numerator are positive except for c_o' (which is negative) and $dr_o^*/d\gamma$ (whose sign, recall, is ambiguous). We can assess optimal policy in various cases. Consider the case where $dr_o^*/d\gamma$ is positive at $\gamma = 1$. Then, for relatively large β the right hand side of (19) is positive, and to achieve the second-best outcome we must discourage over-investment in R&D by setting $\gamma^* < 1$.

Proposition 6 *Where a regulated firm uses an abatement technology supplied by an outsider with strong bargaining power, unbiased regulation results in socially excessive levels of R&D. Second-best regulation calls for a* ***bias against the environment*** *($\gamma^* < 1$) whenever the outsider's R&D expenditure is increasing in γ.*

Contrast this with the previous proposition: even though the best-available technology is assumed to respond positively to γ in both cases, the required corrective bias in regulatory attitude differs in direction. The former case calls for a regulator

[19] Throughout we treat β as an exogenous characteristic of the market for technology. The analysis could be extended to make β something amenable to policy influence through direct regulatory intervention in the market for compliance technologies, or through design of intellectual property rights. If the regulator were able to control both γ and β first-best becomes implementable.

who is green relative to the neutral benchmark, the latter for one who is relatively brown.

The case in which the term in square brackets in front of $dr_o^*/d\gamma$ in expression (19) is zero offers an interesting possibility. Here equations (5) and (13) are equivalent and the outsider has the incentive to engage in what would be, for an isolated firm, the socially-optimal level of R&D. Nonetheless the outcome involves socially-wasteful duplication by the insider as it *over*-invests in order to reduce the fee it anticipates having to pay to the outside innovator. In this case regulatory institutions should have a bias *against* the environment.[20]

Once again, other – in our view less natural – assumptions about how R&D responds to γ could deliver contrary recommendations. For example, if $dr_o^*/d\gamma < 0$ the desirable dampening of socially-excessive R&D would require setting $\gamma^* > 1$ (a pro-environment bias). But this only reinforces our central contention: while the second-best entails choosing biased regulators, the direction of the optimal bias is sensitive to the specificities of the innovation process. But in a significant departure from the literature, we can find circumstances that justify bias in either direction.

4 Conclusions

Environmental regulation aims to correct static market failures due to externalities but also to provide incentives for innovation and adoption of better abatement technologies. Given the potential role of technological improvements in mitigating environmental problems, the latter objective is important in practice. We provide what we believe to be a fairly robust argument that institution of an unbiased regulatory regime – one who pursues social welfare as an objective function – will not be efficient.

While the case for diverging from unbiased regulation is quite general, the direction of the bias – whether the ideal regulator should be relatively green or brown – depends on the specificities of the innovation process. In the conventional setting which assumes that innovation is carried out by the polluting firms themselves,

[20] We are grateful to a referee for pointing out the interpretation in this special case.

firms tend to under-invest in R&D in order to dampen the ratcheting up of regulation in response to innovation. If a pro-environment bias in the regulatory regime spurs innovation, appointing a green regulator can correct this tendency towards under-investment.

We extended the existing literature on regulation and environmental innovation to allow – in a manner consistent with observation – for R&D activity from both the polluting sector and from specialist outsiders such as engineering companies. In this setting the R&D effort of the polluting industry may be redundant from a social point of view, but yet rational for the polluters if it improves the terms on which they license the technology developed by the outsider. When innovation outcome depends on the strategic interaction between insiders and outsiders, the welfare outcome and policy prescription are potentially more complicated: duplication of R&D efforts, and especially the escalation of insider's innovation to reduce the cost of licensing the outsider's technology, can lead to over-investment in R&D. This may call for an anti-environment bias whenever it serves to temper this excessive innovation. Failing to account for the underlying regulatory distortions induced in the market for innovation can lead to misinterpretation of observed behavior and to inadequate policy prescription.

While the current paper reports an essentially theoretical exercise, it sheds light on how the optimal bias varies with actual context. For instance, if compliance technologies are already believed to be mature – in the sense of there being little scope for their improvement – the optimal value of γ converges to one. The prescription can be suitably modified for other scenarios, say, to countries where domestic polluters rely on foreign-developed pollution control technologies, or settings where the polluting sector has – for whatever reason – no innovation capability.

We could extend our model in a number of ways. For tractability, we resorted to the simplifying assumption that there exists a single insider and a single outsider. We can outline how our findings might differ for alternative structures in the market for innovation. We could allow for multiple upstream entrepreneurs (effectively an "environmental services" industry) competing to supply abatement technologies to a monopolistic polluting firm.[21] With multiple outsiders the polluter would expect,

[21] In a static setting without R&D, David and Sinclair-Desgagne (2005) emphasize the importance

other things being equal, to pay lower license fees to use any particular technology: in crude form, we could capture this in lower value of the appropriability parameter β. This would reduce the outsiders' incentive to innovate, and in so doing, the strategic motivation for innovation by the insider too. In contrast, a structure in which a single upstream outsider offers his environmental services to multiple polluters would display strong incentives for the outsider to innovate: license revenue would be boosted both by the number of downstream potential licensees and possibly through improved bargaining power with respect to any one of them. Higher innovation by the outsider would prompt more R&D expenditure by insiders too, which would be duplicative and therefore socially wasteful.

For the purposes of this paper we have focused on quantitative environmental standards, in part because these are quite prevalent in the context of environmental regulation. As Brozović (2002: 1) notes: "Our profession's fondness for the use of economic incentives notwithstanding, regulation via direct quantitative control is commonplace in the real world. Diverse consumer and producer activities, from speeds on public thoroughfares to the emissions of pollutants from smokestacks, are controlled using maximum allowable limits." We could have considered other instruments and, indeed, there is a large literature on instrument choice and innovation (see Jaffe and Stavins (2002)). It would be an interesting in future work to consider the performance of other regulatory instruments, in particular market-based instruments, within our framework. Tradeable permits have, for example, taken on an important role in the climate change setting. A substantial literature has sought to investigate the positive and normative implications of tradeable permits and green taxes – Requate (2005a) provides an excellent survey – though never in a setting cohabited by internal and external technology developers. With tradable permits, for example, buying permits to pollute would be a substitute for abatement such that an analysis would require the R&D market and permit market to be in equilibrium simultaneously. An emissions tax might be expected to act in a similar way, giving an external 'price' to units of emissions against which emissions reductions generated by installation of abatement-technologies would have to 'compete'. This would impact the market for technology and so also the research incentives for insiders and

of the degree of competition in the industry supplying pollution control technologies for the optimal regulation of polluters.

outsiders in potentially complex ways.

However, regardless of the chosen instrument, our central insight is durable: with limited instruments, calibrating the instrument to correct the static externality may distort incentives to innovate, and that seemingly biased regulation may be a second-best device to reconcile these objectives. The precise nature of the desired bias will depend on how the policy instrument interacts with innovation and adoption of new technologies but, importantly, could feasibly lie in either direction relative to the standard, neutral case.[22]

A more complex analysis might also model the research and development process itself in a more sophisticated way. In designing the model presented here we deliberately chose the simplest approach to modeling the outputs of R&D, with the 'quality' of pollution-control technology developed being a deterministic function of R&D effort. Of course there are other ways of modeling R&D competition that involve stochastic returns to research effort as, for example, in a patent race. This complicates the analysis of the strategic interaction in the innovation process (innovation outcomes cannot be ordered simply by research effort) and also the welfare evaluation (duplicating R&D is not necessarily wasteful if multiple research units increase the likelihood of at least one successful innovation). The model could also be developed, as we have noted, to take allow for the possibility of research joint ventures, which are observed to be important in some green-technology settings. These extensions add considerably to the complexity of our model but offer valuable seams for future research.

[22]Where multiple instruments can be used in combination, there is a temptation to believe that the inconsistency problem can be circumvented altogether. For instance, static pollution externality could be corrected through quantitative standards, and direct subsidies or taxes can be used to generate the optimal level of R&D. But such regimes may be inherently complex: for instance, where innovation is potentially carried out by outsiders and insiders with differing incentives to innovate, the tax or subsidy regime may need to treat them differently.

References

1. Adler M. and E. Posner (1999) "Rethinking Cost-Benefit Analysis," *Yale Law Journal* 109: 165-247.

2. Arocena P., I. Contin and E. Huerta (2002) "Price Regulation in the Spanish Energy Sectors: Who Benefits?" *Energy Policy* 30(10): 885-895.

3. Amacher, G. and A. Malik (1996) "Bargaining in Environmental Regulation and the Ideal Regulator," *Journal of Environmental Economics & Management* 30(2): 233-53.

4. Amacher, G. and A. Malik (2002) "Pollution Taxes when Firms Choose Technologies,", *Southern Economic Journal* 6(4), 891–906.

5. Brozović, N. (2002) "Prices versus Quantities Reconsidered," Working Paper, Department of Agricultural and Resource Economics, University of California Berkeley.

6. Brunnermeier, S. and M. A. Cohen (2003) "Determinants of Environmental Innovation in US Manufacturing Industries," *Journal of Environmental Economics and Management* 45(3): 278-93.

7. Cohen, B. (2001) "Who Will be the New EPA Administrator?" *Environment News* 1 January 2001: Heartland Institute: Chicago, IL.

8. David, M. and B. Sinclair-Desgagne (2005). "Environmental Regulation and the Eco Industry," *Journal of Regulatory Economics* 28(2): 141-55.

9. Driesen, D. M. (2006) "Is Cost-Benefit Analysis Neutral?" *Colorado Law Review* 72: 335.

10. Environmental Business International (2006) "Global Market Review," *Environmental Business Journal* 19: 5-6.

11. Gans, J. S. and S. Stern (2000) "Incumbency and R&D Incentives: Licensing the Gale of Creative Destruction," *Journal of Economics and Management Strategy* 9(4): 485-511.

12. Gayer T. and R. W. Hahn. (2005) "The Political Economy of Mercury Regulation," *Regulation* 28(2): 26-33.

13. Greaker, M. and K. E. Rosendahl (2008) "Environmental Policy with Upstream Pollution Abatement Technology Firms," *Journal of Environmental Economics and Management* 56(1): 246-59.

14. Hackett, S. C. (1995). "Pollution-Controlling Innovation in Oligopolistic Industries: Some Comparisons Between Patent Races and Research Joint Ventures," *Journal of Environmental Economics and Management* 29(3): 339-56.

15. Hueth, B. and T. Melkonyan (2006) "Standards and the Regulation of Environmental Risk," Working Paper, Department of Agricultural and Resource Economics, University of Maryland, College Park.

16. Jaffe, A.B. and K. Palmer (1997) "Environmental Regulation And Innovation: A Panel Data Study," *The Review of Economics and Statistics*, 79(4), 610-619.

17. Jaffe, A.B. and R. Stavins (2002). "Dynamic Incentives of Environmental Regulations," *Journal of Environmental Economics & Management* 29(3), S43-S63.

18. Lanjouw, J. O. and A. Mody (1999). "Innovation and the International Diffusion of Environmental Responsive Technology," *Research Policy* 25: 549-71.

19. Mas-Collel, A. M. Whinston and J. Green (1995) *Advanced Economic Theory*, Oxford University Press, Oxford, England.

20. Melamud, N. and D. Mookherjee (1989) "Delegation as Commitment," *RAND Journal of Economics* 20(2): 139-63.

21. Moita, R. and C. Paiva (2006) "Political Price Cycles in Regulated Industries: Theory and Evidence," IMF Working Paper WP/06/260: Washington DC.

22. Parry, I. W. H. (1995). "Optimal Pollution Taxes and Endogenous Technological Progress," *Resource and Energy Economics* 17(1): 69-85.

23. Puller, S. L. (2006) "The Strategic Use of Innovation to Influence Regulatory Standards," *Journal of Environmental Economics & Management* 52: 690-706.

24. Requate, T. (2005a) "Dynamic Incentives by Environmental Policy Instruments – A Survey," *Ecological Economics* 54(3): 175-95.

25. Requate, T. (2005b) "Timing and Commitment of Environmental Policy, Adoption of New Technology and Repercussions for R&D," *Environmental and Resource Economics* 31(2): 175-199.

26. Rogoff, K. (1985) "The Optimal Degree of Commitment to an Intermediate Monetary Target," *Quarterly Journal of Economics* 100(4): 1169-1189.

27. Rubinstein, A. (1982) "Perfect Equilibrium in a Bargaining Model," *Econometrica* 50(1): 97-109.