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Chapter Author(s): Charles D. Kolstad

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Regulatory Choice with Pollution and Innovation

Charles D. Kolstad

4.1 Introduction

Probably the most fundamental issue in climate change is the role of innovation and invention in helping find a solution to the climate change problem. It is clear that many are depending on innovation to find cheaper ways to mitigate emissions and adapt to impacts. Governments around the world are trying to spur innovation. But nobody really knows how to efficiently induce innovation. No one knows what kinds of policies are effective in promoting the necessary amount of innovation. It is also unclear how the different approaches to regulating greenhouse gas emissions perform in inducing innovation. There is a sense that it is important to place a price on carbon, directly or indirectly, to send better signals to innovators. But how that carbon price translates into abatement-cost-reducing innovation is poorly understood.

In this chapter, we examine how environmental regulations work when there is an innovator with perfect property rights (perfect in the sense of a perfect patent with no spillovers). The innovator does not engage in pollution abatement but instead specializes in reducing the cost of pollution abatement, through innovation (which is then sold/licensed to polluters).

Charles D. Kolstad is professor of economics at the University of California, Santa Barbara, a university fellow of Resources for the Future, and a research associate of the National Bureau of Economic Research.

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The two questions we ask are: (a) do different types of environmental regulations perform differently in inducing innovation and abatement, and (b) do regulations differ in terms of how the gains from innovation are appropriated?

We develop a simple model, involving no uncertainty, in which we compare the performance of a cap-and-trade system (marketable permits) and an emissions tax system. Although other authors have examined this question, most authors use a highly simplistic representation of the innovation process. In this chapter, we focus more on the innovation process and less on other aspects of the economic environment.

As one might expect, given a lack of uncertainty, either regulatory policy is able to implement the first-best outcome. However, innovators clearly do better under a cap-and-trade system, capturing all of the rents from their innovation. Under a tax system, gains are split between the polluters and the innovators. Nevertheless, marginal conditions are such that efficiency is obtained.

4.2 Background

Innovation is at the core of dynamic economics. Hicks ([1932] 1966) put forward the idea that when relative prices of input factors shift, technical change will focus on saving the factor that has become relatively more expensive (the induced innovation hypothesis). One of the insights of the Solow model of growth is the so-called "Solow residual," which is the difference between growth in output and growth in input. It is attributable to technical change. This is a natural precursor to the more recent literature on endogenous growth (Romer 1994).

In the 1960s, a number of economists turned their attention to innovation, beginning with a seminal paper of Arrow (1962) and culminating in a host of papers including the classic papers by Scherer (1967) and Kamien and Schwartz (1968), the latter of which provides a theoretical model of induced innovation.

None of these papers deals with environmental externalities or regulation. That literature began to emerge in the 1970s, with a paper by Smith (1972). A common theme in the environmental literature is the comparative performance of different regulatory structures in terms of fostering innovation. Magat (1978) follows the common approach at that time of examining technical change through the lens of factor/output augmenting technical change (as did Kamien and Schwartz [1968]), within the context of optimal growth. He finds little difference between prices and quantities within this framework. Milliman and Prince (1989) compare a wide variety of environmental regulations (command-and-control, subsidies, taxes, free permits, auctioned permits) with a simple representation of regulation, cost-reducing innovation and diffusion, and then regulatory response to postinnovation costs. The focus is on who captures rents from innovation in a multiagent context, rather than on providing an explicit model of the innovation process. Fischer, Parry, and Pizer (2003) take this further by explicitly representing the process of innovation (making innovation endogenous). Abatement costs are $C(a, k)$ where a is the level of abatement and k is the level of technology, which results from research and development (R&D) at cost $F(k)$. The presence of the possibility of imitations of the innovated technology allows spillovers and thus diffusion to occur, which limits licensing fees. They do find differences among the different environmental regulations examined, though no clear regulatory approach dominates in terms of performance.

Denicolò (1999) focuses on innovation rather than diffusion and explicitly models the innovation process separately from the abatement process. He assumes the preinnovation emissions-output ratio is α (a constant) and the postinnovation ratio is β (a variable chosen by the innovator), with $\beta < \alpha$. The R&D cost of achieving that innovation is $C(\beta)$. The innovator licenses its innovation for a fee. With this simple structure of innovation, he shows that emission fees and marketable permits perform identically when the regulator moves first and commits to not change regulations postinnovation. When the regulator cannot so commit, the two instruments perform differently, though it is not possible to conclude that one regulatory approach dominates the other. Krysiak (2008) de-emphasizes the innovator as licensing a technology and focuses on how uncertainty might induce a preference for prices versus quantities, in the spirit of Weitzman's (1974) classic analysis. He concludes quantities are more efficient.

Scotchmer (2011) provides one of the most recent analyses of this issue, in the context of regulations for carbon emissions. Because of this, her model explicitly involves producing a good (energy) with an emissions-output ratio that can be reduced through innovation. Rather than focusing on the innovator's decision of how much innovation to undertake (with an explicit cost of innovation), she focuses on the returns to innovation from a specific reduction in the emissions-output ratio. She concludes that an emissions tax provides more innovation incentives than a cap-and-trade system.

The previous discussion concerns theoretical results on innovation. However, one of the key issues that has been of concern in the realm of climate policy and related empirical economics is how to empirically represent the extent of carbon-saving technological change (or, more generally, the rate of technical change for any factor). Although this literature is large, it is appropriate to mention two recent contributions by David Popp. Popp (2002) uses patent data to explicitly model the formation of the knowledge stock, using a perpetual inventory method (much as one would do using investment over time to estimate the capital stock). Using this approach he is able to disentangle the effect on energy consumption of prices as distinct from technological improvements. In Popp (2004) he carries this process further by modifying an optimal growth model commonly used for climate policy (Nordhaus' DICE model) to include endogenous technical change. One of the challenges is to represent private provision of R&D, acknowledging the inefficiencies of its provision, within a representation of the dynamics of economic activity and emissions.

4.3 A Model of Innovation and Abatement

We consider a situation with multiple atomistic firms in a polluting industry. Distinct from the polluting industry, there is one innovating firm, developing technologies to reduce the cost of abating in the polluting industry. The innovating firm conducts research, innovates, patents its innovation, and licenses the innovation to the polluting industry.

Our characterization of the polluting industry is straightforward. If the polluting industry chooses an aggregate amount of abatement a, then $C(a)$ is the cost of abatement incurred by firms in the industry (these costs are preinnovation and exclude the costs of innovating). Furthermore, $B(a)$ is the environmental benefits from abatement, though those benefits do not accrue to the polluting industry. As is customary, C', C'', and $B' > 0$ and $B'' < 0$.

Our characterization of the innovating firm is also straightforward. Assume there is a firm that does not emit pollution but rather engages in innovation and licenses its abatement-cost-reducing innovations to the abating firms. The innovating firm undertakes R&D, which results in a technology that reduces the marginal cost of abatement. In particular, assume the innovator chooses the reduction in the marginal cost of abatement, σ. The cost of achieving this reduction in abatement costs is an R&D cost to the innovator of $R(\sigma)$, with $R' \geq 0$ and $R'' > 0$. Note that the unit of measurement for R is dollars whereas the unit of measurement for σ is dollars per ton (or dollars per unit of pollution abated). The R' is the change in R&D expenditures necessary to achieve a unit decrease in the marginal cost of abatement; R' thus maps dollars per ton into tons. Let the inverse of R' be given by the function S, which maps tons into dollars per ton. The innovating firm licenses its technology to the abating firms for a fee of φ per unit of abatement. This setup is shown in figure 4.1. The postinnovation social marginal cost of abatement is lower but the licensing fee offsets some or all of these cost reductions, from the perspective of the polluting firm. This model is similar to that of Denicolò (1999), though it differs in substantial ways, primarily in the representation of abatement and innovation.

The dynamics of this problem are as simple as possible: a three-period world. In the first period, the regulator acts, setting the level of the environmental regulation. In the second period, the R&D occurs and is licensed. In the third period, firms abate. This does not necessarily involve the actual passage of time but might be three stages to a single regulatory game.

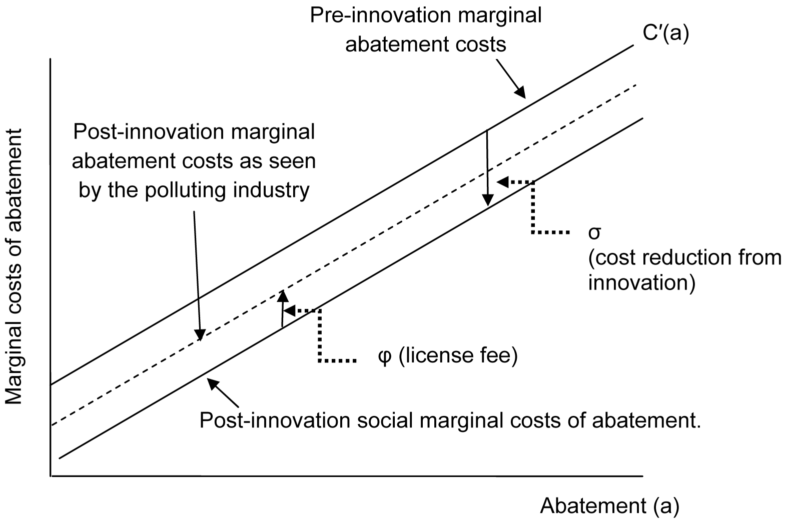

Fig. 4.1 The effect of innovation on marginal abatement costs

Superimposed on these market players is a regulator who is trying to maximize social welfare:

$$W(a, \sigma) = B(a) - [C(a) - \sigma a] - R(\sigma). \tag{1}$$

Although it may seem like equation (1) is the obvious social welfare function, some ambiguity remains. Certainly the cost of R&D is a social cost. However, once the R&D is done, it becomes a sunk cost and abatement costs are forever lowered. Postinnovation, the regulator's objective is to balance $B(a)$ and $C(a)$-σa, without regard to the sunk cost ($R(\sigma)$). Recognizing this, a regulator may act in the first period to ignore $R(\sigma)$ in the social calculus. However, ignoring innovation involves viewing this problem through a different dynamic lens than is assumed here. In our simple structure, no further action occurs after innovation and abatement. This is equivalent to the regulator committing to not change the level of the regulation postinnovation.[1] It is clearly an interesting question as to what will prevail if a more realistic view of the dynamics of innovation is explored.

With exact control over abatement and innovation, the regulator can choose abatement and innovation to maximize welfare:

$$B'(a^*) - C'(a^*) + \sigma^* = 0, \tag{2a}$$

and

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[1] The point about commitment to regulation and the distinction between the preinnovation and postinnovation period is clearly articulated by Denicolò (1999).

$$a^* - R'(\sigma^*) = 0 \qquad \Rightarrow \sigma^* = S(a^*). \tag{2b}$$

However, we are assuming the regulator does not directly control abatement (a) and innovation (σ), but rather uses imperfect regulatory instruments. In particular, the regulator chooses a price instrument (t) or a quantity instrument (a). Polluting firms respond rationally and the innovating firm invests in the privately profit-maximizing amount of innovation and also sets the licensing fee (in dollars per ton abated), φ, accordingly. We are concerned about how much abatement and how much innovation result from an arbitrary price or quantity regulatory instrument and, further, when optimally designed, how these two instruments differ in terms of induced innovation, abatement, or distribution of rewards from innovation.

Quantity instruments. Consider first the case of a quantity instrument, $\hat{a}$, which mandates the amount of abatement that must take place. The abating firm has no choice but to undertake this amount of abatement. The innovator on the other hand, must choose a license fee, $\hat{\varphi}$, and a level of innovation, $\hat{\sigma}$, to maximize profits of the innovator. Since the abating firms have no ability to adjust the amount of abatement (it is mandated), the innovating firm can set the licensing fee to capture all of the rent, $\hat{\varphi} = \hat{\sigma}$. Profits for the innovating firms are then

$$\Pi_I = \sigma a - R(\sigma), \tag{3}$$

which implies a resulting profit-maximizing level of innovation ($\hat{\sigma}$), as a function of the mandated abatement ($\hat{a}$), defined implicitly by the first-order conditions:

$$d\Pi_I \,/\, d\sigma = \hat{a} - R'(\hat{\sigma}) = 0. \tag{4}$$

Equation (4) defines a condition for the amount of innovation that maximizes profit for the innovator: $\hat{\sigma}$ is set so that the marginal cost of reducing abatement costs is equal to the amount of abatement. By totally differentiating equation (4) one obtains an expression that shows how innovation changes as the abatement mandated increases:

$$d\hat{\sigma} \,/\, d\hat{a} = 1/R''. \tag{5}$$

Because of curvature assumptions on R, this equation implies that as required abatement increases, the amount of innovation will also increase.

Price instruments. Now consider the more complex case of a price instrument. Compared to quantities, the price instrument sends a more indirect signal to both abaters and innovators. The regulator sets a price, t, for abatement (a payment for extra abatement is of course conceptually equivalent to charging a fee for unabated pollution). Profits for the polluting industry are given by

$$\Pi_P = ta - C(a) + (\sigma - \varphi)a. \tag{6}$$

Profit maximization implicitly defines the abatement level, $\tilde{a}$, in response to a price $\tilde{t}$:

$$\tilde{a}: d\Pi_I / da = \tilde{t} - C'(\tilde{a}) + (\sigma - \varphi) = 0 \Leftrightarrow \tilde{t} = C'(\tilde{a}) - (\sigma - \varphi). \tag{7}$$

We now turn to the innovator's behavior. First, we totally differentiate equation (7), keeping t constant to determine how changes in σ and φ influence $\tilde{a}$:

$$0 = C'' d\tilde{a} - d\sigma + d\varphi \Rightarrow, \tag{8a}$$

$$d\tilde{a} / d\sigma = 1/C'', \tag{8b}$$

and

$$d\tilde{a} / d\varphi = -1/C''. \tag{8c}$$

The innovator's profit is

$$\Pi_I = \varphi\tilde{a} - R(\sigma). \tag{9}$$

The innovator must choose both σ and φ to maximize profits in equation (9), resulting in first order conditions

$$\partial\Pi_I / \partial\sigma = \hat{\varphi} d\tilde{a} / d\sigma - R'(\tilde{\sigma}) = 0, \tag{10a}$$

and

$$\partial\Pi_I / \partial\varphi = \hat{\varphi} d\tilde{a} / d\varphi + \tilde{a} = 0, \tag{10b}$$

which implicitly define $\tilde{\sigma}$ and $\hat{\varphi}$ as functions of $\tilde{a}$ which in turn depends on $\tilde{t}$:

$$\tilde{\sigma} : R'(\tilde{\sigma}) = \tilde{a} \Rightarrow \tilde{\sigma} = S(\tilde{a}), \tag{11a}$$

$$\hat{\varphi} : \hat{\varphi} = \tilde{a}C''(\tilde{a}). \tag{11b}$$

In essence, the three equations, (7), (11a), and (11b) implicitly define $\tilde{a}$, $\tilde{\sigma}$ and $\hat{\varphi}$, as functions of t.

Socially optimal instruments. First-best levels of abatement (a^*) and innovation (σ^*) are defined by equation (2). If a quantity regulation is set such that $\hat{a} = a^*$, then innovation, $\hat{\sigma}$, will be set according to equation (4). Thus $\hat{\sigma} = \sigma^*$. A price regulation must be set (if possible) so that the same outcome prevails. In particular, set $\tilde{t}$ according to:

$$\tilde{t} = C'(a^*) - S(a^*) + a^* C''(a^*). \tag{12}$$

It is easy to see that $\tilde{a} = a^*$ and $\tilde{\sigma} = \sigma^*$ satisfy equations (7) and (11), and thus a first-best outcome is supported by this level of the price instrument.

Equation (12) is intuitive, if somewhat more complicated than for the optimal quantity instrument. At an efficient level of abatement, a^*, and an efficient level of innovation, σ^*, the marginal costs will be reduced by $S(a^*)$ but then the license fee will increase the marginal cost seen by polluters by $a^*C''(a^*)$. This results in marginal costs equal to the right-hand side of equation (12). Setting the price instrument equal to that marginal cost, evaluated at a^*, supports the first-best outcome. Note that the optimal price instrument will be less than would prevail absent innovation. Similarly, the optimal quantity instrument will be more than would prevail absent innovation (since absent innovation, the σ^* would be missing from equation [2]).

This leads to the following result:

PROPOSITION 1. *Given the earlier structure and assumptions, price and quantity instruments are equivalent in implementing the first-best amount of abatement and innovation.*

Note, however, that the private return to the innovator from innovation differs for the two instruments. For the quantity instrument, all returns to innovation are captured by the innovator (the licensing fee is equal to the cost reduction from the innovation). In the case of the price instrument, only part of the marginal gains are captured by the innovator. As the licensing fee is raised from zero, direct revenue from the license obviously increases. However, an increased licensing fee increases the cost of abatement to the polluter and thus reduces abatement (see equation [8c]) and thus, indirectly, revenue to the innovator. So a tradeoff between raising the fee and lowering the fee implies there is some happy medium with the license fee strictly greater than 0 but strictly less than σ. Thus the polluter captures some of the gain from innovation in the form of reduced costs and the innovator also captures some of the gain. Of course, who captures the gain does not matter to efficiency in this case since the marginal conditions are such that innovation is the same with the two regulatory instruments.

4.4 Conclusion

Innovation is clearly a core issue for modern environmental regulation. Climate change is a case in point. Significantly regulating greenhouse gas emissions will be expensive, and innovation is the primary way of reducing costs (after regulatory efficiency gains have been exhausted). In fact, due to the long lag times of turning emissions reductions into temperature reductions, one of the primary reasons for implementing carbon regulation now is to spur innovation on reducing abatement costs in the future (when we get really serious about emissions). Thus the question of which environmental regulations tend to spur the most innovation is highly relevant.

A related question is how to represent the process of innovation, which is not well understood empirically. A better empirical understanding will help design better policies to encourage innovation and abatement.

This chapter provides a small step forward in terms of representing the process of innovation on abatement costs, though there is a considerable literature on this issue. One conclusion is that price instruments (e.g., a carbon tax) can be designed to induce the same amount of innovation and abatement as a quantity instrument (e.g., cap and trade). Although the two instruments can provide the same marginal incentives to innovators and abaters, the inframarginal rents from innovation differ in the two cases. In fact, the innovators appropriate all of the gains from innovation in the case of a quantity instrument, whereas innovators and abaters share the rents in the case of a price instrument.

The results reported here are suggestive more than definitive. In particular, most types of regulation lead to a first-best level of innovation, though different levels of rents to the innovators. What are the implications of this? Can a more realistic representation, perhaps with some uncertainty, lead to sharper distinctions between the two regulatory approaches? This chapter raises these issues but does not come close to resolving them.

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Comment V. Kerry Smith

If we could rely on technological innovation to dramatically reduce the costs of mitigating greenhouse gases, then climate policy would be easy. All the analyses of the design and impacts of climate policy can agree with this point. Nordhaus (2008), for example, finds the present value of abatement costs would be about one-fourth that of his optimal approach if we could assume a low-cost backstop technology was available to replace fossil fuels when carbon's price reached five dollar a ton (in 2005 dollars). The Stern (2006) report makes exceptionally optimistic assumptions about technological advance, assuming abatement costs will decline by sixfold by 2050. Thus, the focus of Charles Kolstad's chapter is especially important. He notes that serious theoretical analysis to understand the effects of different climate policies on technical change needs to "unpack" the internal structure of the innovation process. He examines the interactions between three parties—the regulator, the firm facing environmental regulation and needing to control its emissions, and the firm offering new abatement technologies to reduce incremental abatement costs. In a stylized model that abstracts from uncertainty and the effects of regulatory policy in output markets, he finds that price and quantity instruments for regulating pollution can be made equivalent in terms of realizing the first-best (efficient) amount of abatement and innovation. However, the total return to innovation is not the same for these two instruments and the distribution of returns between the polluting firm and the innovating firm is also different. Innovators appropriate all the

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V. Kerry Smith is the Regents' Professor, W. P. Carey Professor of Economics, and Distinguished Sustainability Scientist at the Global Institute of Sustainability at Arizona State University; a university fellow at Resources for the Future; and a research associate of the National Bureau of Economic Research.

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