Environmental Innovation under Taxes and Permits*

by

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Abstract
This paper presents a theoretical analysis of the incentives to innovate created by pollution permits and pollution taxes in a two sector model. As with many recent results in the literature of environmental innovation, an absolute ranking is not obtained. This paper demonstrates that a government's choice of either taxes or permits in order to illicit a greater level of investment in research and development (R&D) should depend on prevailing circumstances, including the ability of firms to imitate technology. The possibility of technology imitation is shown to lead to a greater preference for the use of pollution permits than in a case of no-imitation.

*Paper presented at the 5th National Honours Colloquium, 17 August 2006, at the University of New South Wales. I would like to thank my advisor Professor John Creedy for his assistance and encouragement
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1. **Introduction**

For many years the potential that technological progress offers environmental outcomes has been an important consideration in environmental policy design. In their paper 'Pollution, Prices and Public Policy', Kneese and Schultz (1978) stated that:

“Over the long haul, perhaps the single most important criterion to judge environmental policies is the extent to which they spur new technology towards the efficient conservation of environmental quality.”

In relation to the challenge of climate change, Stern (2006) more recently commented that:

“Stabilisation of greenhouse gases in the atmosphere will require the deployment of low-carbon and high-efficiency technologies on a large scale… [b]ringing forward a range of technologies that are competitive enough … for firms to adopt is an urgent priority.”

The important role that technology has in achieving environmental outcomes gives rise to two important challenges for the regulator. The first of these is to devise a means by which pollution can be reduced to a socially desirable level. The second is to find a way to increase innovation in green technologies to a socially optimal level. A failure to incorporate the potential for technological progress into any such policy will lead to wasted resources and sub-optimal outcomes.

Given the two externalities, being the pollution externality and the technology externality, standard economic theory states that a socially optimal outcome is achievable through the use of at least two policy instruments, that is, one for each of the externalities. While it is generally accepted that the pollution externality can be efficiently addressed through standard economic instruments, some doubt surrounds the efficiency of instruments designed to encourage innovation. In a scenario where the innovation externality cannot be perfectly corrected, the pollution instrument serves two roles. The first is to discourage polluting activity, while the second is to ‘induce’ innovation. In describing the second role, Hicks explained that “[a] change in the relative price of factors is itself a spur to invention and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive. (Hicks 1932: 124-125)

This paper contributes to the burgeoning literature on environmental policy under technological innovation by comparing the effects of instrument choice and timing on induced innovation and social welfare, within a partial equilibrium framework. The model, which is a modification of that used in Denicoló (1999), comprises two sectors: a perfectly competitive polluting sector and a monopolistic R&D sector. Once an innovation has been made, it is assumed that the new technology is either sold to a licensing firm for a royalty payment or is imperfectly imitated, without cost, by the polluting firms. This approach is intuitively applicable to a number of polluting industries comprising a large number of polluters and very few research firms. The incorporation of imperfect imitation reflects the potential for legal adoption of patented technologies. The regulator can either use taxes or auctioned permits as environmental policy instruments.

This paper supports the result from Denicoló (1999) that there can be no absolute ordering of policy instruments under all scenarios. This paper's introduction of an ability to imitate technology, however, alters the circumstances under which either instrument is to be preferred.

The paper's main results are as follows:

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1. Some recent studies also question the social gains from innovation. See (Parry et al (2003), Nordhaus (1998) and Goulder and Mathai (2000)
2. Orr (1976) also stated that "technological adaptation rather than resource allocation (is) the key to an effective solution of (environmental problems)."
3. These can include taxes, subsidies and permits (both auctioned and free)
4. This is a common approach in the literature. Notably adopted in Fischer et al. (2003) and Parry (1998)
5. This occurs in practice through reverse engineering or the presence of certain non-patentable technologies.
6. In this model firms are required to own permits in order to pollute
(a) if regulation occurs after an innovation has been made (ex-post) taxes and permits are equivalent;  

(b) if the regulator no longer regulates ex-post, this equivalence breaks down; and  

(c) the relative rankings of taxes and permits are different when imitation is possible than when it is not possible.

The rest of this paper is structured as follows: Section 2 places this paper within the existing literature; Section 3 introduces the theoretical model; Section 4 investigates model outcomes under ex-ante regulation; Section 5 investigates model outcomes under ex-post regulation; Section 6 compares the incentives to innovate under taxes and permits; Section 7 considers potential extensions to the model; and section 8 concludes the paper.

2. Relation to the literature

There is currently a rapidly expanding body of literature regarding pollution-reduction and resource-saving technological progress. Recent research can be placed into two major categories. The first involves macroeconomic endogenous growth models designed to address the dynamic aspects of the accumulation of pollution. The second incorporates microeconomic partial equilibrium models which analyses the incentives to reduce pollution and to invest in technology. These models, with very few exceptions, do not address the dynamic nature of many pollutants. This paper is of the partial equilibrium variety.

The economically intuitive result that market based policy instruments\textsuperscript{8} dominate ‘command and control’ instruments in inducing innovation was established in Zerbe (1970). The focus then moved to a comparison of the various market based instruments. The earliest attempts to rank policy instruments included studies by Milliman and Prince (1989), Downing and White (1986) and Malueg (1989). These studies also do not specifically model the output market and assume industry wide adoption of the new technology. Using graphical arguments Milliman and Prince conclude that emissions taxes and abatement subsidies are superior to both free permits and emissions standards but are inferior to auctioned permits. Comparison was made of the aggregate cost savings incurred by industry in adopting a new technology and there was no treatment of the process of innovation, only adoption of a given technology.

Since these early contributions a wide variety of models which endeavour to rank market based policy instruments have emerged. These have addressed issues such as timing of regulation (Requate (1995) and Kennedy and Laplante (1999)), imperfect competition in the output market (Carraro and Soubeyran (1996)) and uncertainty (Laffont and Tirole (1996) and Kennedy (1999)) amongst others. None of the above explicitly models the decision to innovate.

Parry (1995) and Biglaiser and Horowitz (1995) were the first to explicitly model the innovation decision. Following these contributions, a number of models have emerged which explore the response of firm’s innovation decisions to environmental regulation. Variations in assumptions in these models include: The timing of regulations, the nature of R&D, the shape of the marginal environmental damage function and the treatment of R&D and output markets. The relative instrument rankings of these so-called ‘innovation and diffusion’ models vary depending on model assumptions, however there remains a clear preference for market based instruments over command and control.

Of the innovation and diffusion models, the paper which most closely resembles this one is that of Denicoló (1999). Denicoló (1999) pays special attention to the polluting market, incorporating an upstream monopolistic R&D firm and a perfectly competitive downstream polluting sector. The polluting sector produces with constant returns to scale and each unit of output produces a proportional level of emissions. The proportion depends on the level of technology the firms use; a smaller proportional

\textsuperscript{7} This is an important property of pollutants such as CO\textsubscript{2}, whose cumulative effect can last for many decades.  

\textsuperscript{8} Taxes subsidies and permits are all examples of market based instruments.
emission is associated with higher technology. R&D is modelled non-stochastically and the level of
technology available increases with the amount of investment by the monopolistic R&D firm. Both ex-
te ante (before the R&D firm innovates) and ex-post (after innovation) regulation using taxes and permits
are analysed. Denicoló achieves three main results: firstly, that taxes and permits are completely
equivalent under ex-post regulation, secondly, that this equivalence breaks down for ex-ante regulation
and thirdly, under ex-ante regulation if the regulator commits to the second best level of the instruments
taxes dominate permits for low social costs of pollution and permits dominate taxes for higher social costs
of pollution.

Unlike Denicoló (1999) this paper includes the potential for (imperfect) imitation of any technology
developed. The approach adopted is similar to that of Fischer et al. (2003), Parry (1995) and Parry (1998).
Fischer et al. (2003) assume that firms decide between paying a royalty to use any new technology or can
imitate the same technology without cost. The imitation is assumed to be less effective than adopting
the technology by royalty payment. Fischer et al. find that emission taxes dominate permits if imitation is
easy and are inferior to permits if imitation if difficult. Similarly to Denicoló, they find that for a steeper
marginal damage curve permits will dominate a tax. Notably, Parry (1998) also indicates that the
inclusion of imitation does not imply significant inefficiency in the market for innovation.

3. The basic model

In order to analyse the relationship between climate policy instrument choice, technological innovation,
enmissions abatement and regulation timing, a number of simplifying assumptions have been made.

The model incorporates an upstream innovating firm which is assumed to be a monopolist and a
downstream polluting sector which is perfectly competitive. The polluting sector comprises a large
number of identical firms. The innovating firm maximises profits by developing an environmental
technology which reduces the amount of pollution per unit of output in the polluting sector. Prior to
R&D the level of pollution per unit of output is denoted a. Expenditure on research creates a technology
which will reduce this to b. All stochastic aspects of the R&D process have been ignored. I simply
assume that greater expenditure on R&D will lead to a lower value of b. R&D is undertaken at a cost of
\( C(b) \). Once a new technology is developed it is immediately patented.

We assume \( C(a) = 0; C'(b) < 0; C'(a) = 0; C'(0) = -\infty; C''(b) > 0 \), refer to figure 1.

The polluting sector produces output at a cost of c per unit of output. Demand for the output is \( X(P) \)
and is assumed to be linear in price, with corresponding inverse demand function \( P(X) \). Firms in the polluting
sector can either pay a royalty to use the new technology once it has been developed or they can adopt a
poorer quality imitation without cost.\(^9\) We will see that in equilibrium all firms adopt the technology, however the threat of imitation means that the innovating firm cannot extract the full benefit of its
innovation.

3.1 Taxes

Let \( t \) denote the tax per unit of pollution and \( v \) the royalty fee per unit of production to use the new
technology. If polluters use the new technology the cost per unit of output is \( c + bt \). If an imitation is
used the cost per unit of output is \( c + at - \theta(a - b)t \geq c + bt; 0 \leq \theta \leq 1 \). The term \( \theta(a - b)t \) can be
interpreted as a reduction in tax cost from using the imitation. It is assumed that the reduction brought
about by imitation is a proportion, \( \theta \), of the innovation size \( (a - b) \). Higher values of \( \theta \) indicate that
imitation is relatively more effective. A value of \( \theta = 1 \) can be interpreted as a innovation which is a pure

\(^9\) This assumption reflects the imperfect nature of property rights protection. Legal imitation of technology can arise
in a number of cases. For instance some discoveries are not patentable and even if a technology does receive a
patent it can be hard to enforce in which case reverse engineering can legally occur. Studies on non-environmental
innovations have shown that imitation rates vary considerably between innovations with an average rate of
approximately 50%. (Grilliches (1980) and Nadiri (1993))
public good, while a value of $\theta = 0$ indicates that no imitation is possible and therefore indicates that the innovation is a pure private good.

The innovating firm seeks to maximise profits. Given that all polluting firms are identical and perfectly competitive the maximum royalty price will be one which leaves polluting firms indifferent between imitating and paying the royalty. In addition we assume innovation is non-drastic\(^{10}\). This means that any strategy, by the innovator, of pricing lower than the above specified maximum in order to increase quantity of royalty sales will lead to a lower profit for the innovator:

We can therefore express the royalty price as

$$v = c + \left[ a - \theta(a - b) \right] t - \left( c + bt \right) = (a - b)(1 - \theta)t$$

From this we also know that in the perfectly competitive polluting market firms will make zero profit. Therefore the equilibrium price of output will be the sum of production cost, tax cost and royalty payment:

$$P = c + bt + (a - b)(1 - \theta)t$$

$$= c + \left[ a - \theta(a - b) \right] t$$

From this we can express the equilibrium market quantity as

$$X \left\{ c + \left[ a - \theta(a - b) \right] t \right\}$$

and the innovator’s total revenue as

$$V' = (a - b)(1 - \theta) t X \left[ c + \left[ a - t(a - b) \right] t \right]$$

(3.1)

Please see figure 2 for an illustration.

\(^{10}\) A non-drastic innovation is one in which the monopoly price of output associated with the new cost level $c+bt$ is higher than the old price $c+at$. This means that the innovator has no incentive to restrict technology allocation to maximise profits.
3.2 Permits

We now address a situation in which the government issues N pollution permits. Each permit allows one unit of pollution to be emitted. We assume that $P(N/a) > c$, this means that all permits will be used in equilibrium\(^{11}\). We know that after the innovation the market price of output will be $P(N/b)$ and the market quantity will be $X = \frac{N}{b}$. We can then obtain the permit value $z$ and the royalty fee $v$ by solving the following simultaneous equations:

\begin{align*}
   P(N/b) - c - v - bz &= 0 \quad (3.2) \\
   P(N/b) - c - (a - \theta(a-b))z &= 0 \quad (3.3)
\end{align*}

Equations (3.2) and (3.3) state that, at equilibrium, polluting firms will make zero profit and the innovating firm will charge a royalty which will make them indifferent between adopting the new technology for a royalty and using an imitation.

Combining (3.2) and (3.3) we get

\[ v = \left[ (a - \theta(a-b)) - b \right] z = (a-b)(1-\theta)z \]

From (3.3) we know can solve for $z$

\[ z = \frac{1}{(a - \theta(a-b))} \left( P(N/b) - c \right) \]

\(^{11}\) This simply assumes that the government will not allocate more permits than there is pollution.
This is simply the price-cost margin multiplied by the amount of pollution a firm can produce if it uses the imitation technology. Using this value for \( z \) we can show that

\[
v = (a - b)(1 - \theta) \frac{1}{(a - \theta(a - b))}(P(N/b) - c)
\]

We can therefore conclude that the innovator’s revenue will be

\[
v^p = vX = \frac{N}{b}(a - b)(1 - \theta) \frac{1}{(a - \theta(a - b))}(P(N/b) - c)
\]

(3.4)

4. Equivalence of taxes and permits under ex-post regulation

In this section we analyse a situation in which the government regulates ex-post. The innovator will therefore anticipate the government’s policy and select its level of R&D expenditure accordingly.

We begin by defining a social damage function \( \alpha D(bX) \) which represents the monetary value of pollution caused by output of \( X \) units when using technology \( b \). We can then define a social welfare function as follows:

\[
W(b, X) = \int_0^X P(s)ds - cX - \alpha D(bX) - C(b)
\]

(4.1)

Social welfare is equal to consumer surplus minus production costs, social damage and research costs. Given that the government regulates ex-post we can take \( b \) as given. This then becomes a maximisation problem with respect to \( X \).

We have the following first order condition

\[
W_X(b, X) = P(X) - c - b\alpha D_X(bX) = 0
\]

\[
\therefore P(X) = c + b\alpha D_X(bX)
\]

(4.2)

The government will increase \( X \) to the point at which price is equal to the sum of production cost and marginal environmental damage.

This expression gives us an optimal value of \( X \) for each different value of \( b \), \( X^*(b) \). The government will then choose the level of permits or the tax level which produces this socially optimal outcome.

In the case of permits the government sets the number of permits so that output is optimal given \( b \)

\[
N^* = bX^*(b)
\]

(4.3)

In the case of taxes the government will set the level of the tax to make the post innovation output price equal to the socially optimal price (see equation 4.2)

\[
c + (a - \theta(a - b))t^* = c + b\alpha D_X(bX^*(b))
\]

\[
\therefore t^* = \frac{b\alpha D_X(bX^*(b))}{(a - \theta(a - b))}
\]

(4.4)

Subbing (4.4) into (3.1) we get an expression for the innovator’s revenue under socially optimal taxation
Environmental Innovation under Taxes and Permits
John Feddersen – University of Melbourne

\[ V' = (a - b)(1 - \theta) \frac{b\alpha D_x \left(bX^+(b)\right)}{\left(a - \theta(a - b)\right)} X^+(b) \]  

(4.5a)

repeating the process for permits we have

\[ V^p = (a - b)(1 - \theta) \frac{b\alpha D_x \left(bX^+(b)\right)}{\left(a - \theta(a - b)\right)} X^+(b) \]  

(4.5b)

Thus taxes and permits induce the same level of innovator profit and R&D. This demonstrates that if the government acts to ensure the socially welfare maximising level of production under a situation of ex-post regulation, taxes and permits will be equivalent.

5. Non-equivalence under ex-ante regulation

Under ex-ante\(^{12}\) regulation the equivalence breaks down. In this section it is assumed that the government sets its policy (level of a tax or number of permits) prior to the innovation decision and does not change it thereafter. The innovating firm therefore takes this policy as given. The government is assumed to have perfect knowledge of the innovator’s R&D cost function \(C(b)\).

Under taxes the innovator will maximise profit with respect to \(b\)

\[ \max_b V' - C(b) \]

under a tax this can be expressed as

\[ \max_b (a - b)(1 - \theta) tX \left[c + (a - (a - b)\theta) t\right] - C(b) \]

which has first order condition (by product rule)

\[ (1 - \theta) tX \left[c + (a - (a - b)\theta) t\right] - (a - b)(1 - \theta) tX_b \left[c + (a - (a - b)\theta) t\right] + C'(b) = 0 \]  

(5.1)

We can interpret the first term as the marginal change in innovator revenue caused by a greater difference between the pollution per unit when using the imitation compared to the new technology\(^{13}\). The second term reflects the increase in revenue brought about by the higher quantity traded as \(b\) decreases (technology improves)\(^{14}\) the final term is the marginal cost of reducing \(b\). Thus, the innovator maximises profits by increasing \(b\) to the point where the cost of increasing \(b\) is equal to the increase in royalty revenue.

Under permits the profit maximisation is as follows

\[ \max_b V^p - C(b) \]

which can be expressed as

\(^{12}\) Ex-ante regulation refers to regulation before R&D has been undertaken by the innovating firm.

\(^{13}\) This equates to a greater height of the innovator revenue box in figure 1.

\(^{14}\) This equates to a greater width of the innovator box in figure 1. Note that \(X_b \left[c + (a - (a - b)\theta) t\right]\) is negative.
\[
\max_b \frac{N}{b} (a - b)(1 - \theta) \frac{P\left(\frac{N}{b}\right) - c}{a - \theta(a - b)} - C(b)
\]

this yields the following first order condition for the maximisation
\[
= \frac{(1 - \theta) N}{b(a - (a - b)\theta)} \left\{ \frac{(a - b)N}{b^2} P\left(\frac{N}{b}\right) + \left( P\left(\frac{N}{b}\right) - c \right) + \frac{(a - b)}{b} \left[ P\left(\frac{N}{b}\right) - c \right] + (a - b)\theta \frac{P\left(\frac{N}{b}\right) - c}{a - \theta(a - b)} \right\} + C'(b) = 0
\]  

(5.2)

To compare the two regulatory instruments we assume that the government regulates to ensure that a fixed output level of \(X\) is produced after innovation. With taxes, post innovation output becomes \((a + (a - \theta(a - b))\theta)\). Therefore the government sets the tax rate according to
\[
\bar{t} = \frac{P\left(\bar{X}\right) - c}{a - \theta(a - b)}
\]  

(5.3)

Under permits to ensure post innovation production is equal to \(X\) the government sets
\[
\bar{N} = b\bar{X}
\]  

(5.4)

Subbing (5.3) into (5.1) we have the innovator’s first order condition under taxes
\[
(1 - \theta) \frac{P\left(\bar{X}\right) - c}{a - \theta(a - b)} \bar{X} + (a - b)(1 - \theta) \left[ P\left(\bar{X}\right) - c \right] ^2 \theta \bar{X} \left[ P\left(\bar{X}\right) \right] + C'(b) = 0
\]  

(5.5)

Subbing (5.4) into (5.2) we have the innovator’s first order condition under permits
\[
= \frac{(1 - \theta)}{a - (a - b)\theta} \left[ \frac{(a - b)}{b} \left[ \bar{X} P\left(\bar{X}\right) + P\left(\bar{X}\right) - c \right] + \left( P\left(\bar{X}\right) - c \right) \left[ \frac{a}{a - (a - b)\theta} \right] \right] + C'(b) = 0
\]  

(5.6)

We see that (5.5) and (5.6) are different (in general) and inspection reveals that these will not always lead to the same level of \(b\). It can be shown however that profit will be equal for both instruments:

Subbing (5.3) into (3.1) and (5.4) into (3.4) we have:
\[
V' = V^p = (a - b)(1 - \theta) \frac{P\left(\bar{X}\right) - c}{a - \theta(a - b)} \bar{X}
\]

This is explained by the fact that R&D investment (and therefore the level of \(b\)) is determined by the marginal profit and not the absolute profit of the innovator. In the case of ex-ante innovation, profit will be equal under taxes and permits for a given market output \(\bar{X}\), however the marginal profit will be different for the respective instruments.
6. Comparative statics

In this section I evaluate the differences between the level of R&D induced by taxes and permits under ex-ante regulation. A simulation is used to compare the policy instrument choice in a situation where imitation occurs to that in Denicoló (1999), in which there is no imitation.

Denicoló (1999) finds that:

“If $\bar{X} > X^M$, R&D investment under taxes is higher than under permits that lead to the same post-innovation output. If $\bar{X} < X^M$, the incentive to innovate is higher under permits. Only when $\bar{X} = X^M$ the two policy instruments lead to the same equilibrium R&D investment.”

Where $X^M$ is the zero-tax monopoly output in the polluting sector.

The following simulation evaluates the relative incentive to innovate under permits and taxes:

The following specifications were used:

$$C(b) = \frac{1}{b} + \frac{b}{a^2} - \frac{2}{a} X(P) = 10 - P, \ c = 1, \ a = 1, \ \theta = 0.7 \text{ and } X^M = 4.5$$

Figure 3. Post innovation equilibrium under taxes and permits

Figure 3. shows the level of innovation (b) for which the innovator maximises profit given a level of output $\bar{X}$ under both taxes and permits. Taxes and permits lead to equivalent levels of b at three points. When there is no market output neither taxes nor permits can induce innovation and we have a situation of no innovation (b=a). When the market quantity is at a point where equilibrium price=c there is no incentive to innovate and b=a. There is a third point where $\bar{X} > X^M$ at which taxes and permits yield equivalent levels of b.

It becomes immediately obvious that the result from Denicoló (1999) does not extend to the case where imitation is possible. The point at which $\bar{X} = X^M$ no longer determines which instrument induces more R&D investment. Permits dominate (achieve a lower level of b) for a larger range of values of X than under a situation of no imitation. This result is consistent with that of Fischer (2003), in a situation in which imitation is possible, permits induce a larger level of R&D than if no imitation is possible.
7. Extensions and expectations

There are a number of possible extensions to the current paper.

7.1 Comparative statics

The most obvious would be a more complete comparative static analysis of the level of R&D induced under ex-ante regulation. While imitation leads to a greater preference for permits in the comparative static analysis in section 6 this gives no indication of the parameters influencing this superiority or even if this superiority holds under all conditions. A broader range of simulation values and functional forms would give greater insight into the nature of this superiority. An analysis of the effect of changing the imitation parameter $\theta$ would be of interest.

7.2 Welfare ranking

The above instrument comparison is on the basis of the level of induced R&D rather than social welfare. It can be shown in a no-imitation setting that both taxes and permits will result in under provision of R&D when compared to the social optimal and hence that greater levels of innovation do induce greater levels of social welfare. An extension of this result to the imitation case would allow a ranking based on welfare rather than on the level of induced R&D.

8. Conclusion

This paper presents a theoretical analysis of the incentives to innovate under pollution permits and taxes. Similar to many recent results no absolute ranking is obtained. Under different circumstances either taxes or permits can illicit a greater level of R&D.

In a setting of an upstream monopolistic innovation market and a downstream perfectly competitive polluting market with constant returns to scale we have shown three results. (i) Both taxes and permits are equivalent (induce the same level of R&D and same innovator profit) if the government regulates ex-post. (ii) This equivalence breaks down if the government regulates ex-ante. (iii) The relative ordering of taxes and permits when imitation is possible is different to that when imitation is not possible with permits being preferred in a greater number of situations.
9. Bibliography


