Climate Policy and Innovation in the Absence of Commitment *

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Abstract

We compare the effect of price and quantity instruments, (an emissions tax and a quota with tradable permits,) on the incentive to innovate to reduce the cost of an emission-free (green) technology. We assume that the government cannot commit to the level of a policy instrument before R & D occurs, but sets the level to be optimal after the results of R & D are realized. We suppose the government can subsidize or tax R & D in conjunction with either of the instruments mentioned above.

We show that the slope of the marginal cost of the dirty technology relative to the slope of the marginal benefit of energy is crucial for determining which instrument is to be preferred. Let i denote an index of the unit cost of R & D. If the relative slope of the marginal cost is high enough, then a tax induces R & D for a wider range of i than a quota. Furthermore, if the relative slope of the marginal cost is high enough, then a tax weakly dominates a quota in terms of social welfare.

Ex-ante commitment to the level of the tax or quota can improve welfare relative to no commitment, but not by as much as the use of an R & D subsidy or tax.
Keywords: Climate, innovation, policy instruments, emissions tax, tradable permits, R & D, commitment.

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1 Introduction

Avoiding dangerous climate change and ocean acidification involves a halt to, and possibly even a reversal of, the build-up of carbon dioxide in the atmosphere. It is, therefore, clear that energy technologies that replace those emitting carbon dioxide are a necessary part of any solution. This makes technological advance to reduce the cost of carbon-free energy an important target of climate policy.

In order to induce investment in research and development, incentive-based instruments such as emissions taxes and carbon cap and trade have to be expected to be in place *after* the new technology comes to market. This can be several years after the decision to invest in R & D is made. Policies announced or put in place today can be changed. To put it simply, there is a commitment problem. This commitment problem does not apply to policies put in place today that lower the cost of R & D, such as subsidies or complementary investments by public-sector entities. We compare the effect of an emissions tax with that of an emissions quota with tradeable permits on a firm's incentive to conduct R & D in the absence of commitment by the government. We ask whether a subsidy to R & D can improve welfare when either of these instruments is in place. We also ask whether the government's ability to commit *ex-ante* to the level of the tax or quota can substitute for an R & D subsidy. Finally, we compare the tax and quota in welfare terms.

While there is a considerable literature on the role of emission-reducing R & D, (see, for example, Kneese and Schulze (1975), Marin (1978), Downing and White (1986), Milliman and Prince (1989), Jung et al. (1996), Denicolo (1999), Innes and Bial (2002), Montero (2002), Amacher and Malik (2002), Fischer et al. (2003), Tarui and Polasky (2005), Greaker and Hoel (2011)), most of it concerns technologies that reduce the rate of emissions. This approach is suited to the study of end-of-pipe abatement technologies, or others where emissions rates can be reduced by changing the quality of fuel. It is of limited applicability in studying carbon dioxide emissions, the most significant contributor to climate change. Of greater significance in the climate context are technologies that replace carbon-based fuels with an entirely different source of energy, such as solar, wind, or nuclear energy. In recent years, Montgomery and Smith (2005) studied the commitment problem in climate policy in a framework where innovation leads to development of zero carbon technologies. They concluded that standard market-based environmental policy tools cannot create credible incentives for R & D. A crucial assumption in their paper was that the R & D sector is competitive. Thus, their negative result is a consequence of the non-appropriability of the returns from R & D. In our work, we assume a monopolistic R & D sector so that the returns from R & D are appropriable.[1] We obtain results that are much less pessimistic than

[1] This can serve as a benchmark for future models with more than one firm conducting R & D.

Montgomery and Smith (2005).

An earlier paper by Laffont and Tirole (1996), also models a fall in the cost of an emission-free technology as a result of R & D. They assume that the marginal cost of the dirty technology is constant and point out that if the government can sell any number of permits to pollute *ex-post*, then this undercuts the incentive to conduct R & D. (Our Proposition 1 is very close to their result.) They go on to consider the problems with committing to a pre-specified quota when the outcome of R & D is uncertain. They analyze the role of options to buy permits in this context. Our paper instead maintains the assumption of no pre-commitment to a policy, but compares tax and quota policies. We examine the increasing marginal cost case and show that this changes the first result. We examine the role that subsidies to R & D can play in improving welfare.

It is also instructive to compare our results with those of Denicolo (1999). Like us, Denicolo considers a monopolistic firm that decides how much to invest in R & D on the basis of its expectation about the level of an emissions tax or quota with tradeable permits. Denicolo assumes that the extent of emission reduction per unit of output is an increasing function of the amount invested in R & D but that the private marginal cost of producing a unit of output is unaffected by R & D. In contrast, we assume that R & D is used to reduce the marginal cost of zero-emission technologies. Our assumption is intended to model replacement technologies of the kind mentioned above, while his is better suited to modeling end-of-pipe abatement of a particular kind: one in which there is a sunk cost of abatement (the cost of R & D) but no variable cost of abatement. Denicolo shows that if the government sets the level of the emissions tax or aggregate quota to be optimal ex-post, that is, after the result of R & D is realized, then tax and quota policies are equivalent. They induce the same R & D. In contrast, we show that in our framework in which R & D affects the cost of a zero-emission technology, a tax can never induce R & D while a quota can do so.[2] Scotchmer (2009) uses a framework similar to that of Denicolo and obtains similar results. Kolstad (2010) develops a model without dynamic inconsistency. He models technological progress on the lines of Denicolo (1999) and shows that a single instrument in the form of a tax or an abatement quota can ensure social optimality. In Section 3 below, we explain why our model gives results that are different from those in the end-of-pipe abatement models that are common in the literature.

An R & D subsidy in our model can be a direct transfer to a firm or any government expenditure that lowers the cost to the private sector of conducting R & D. For example,

[2] This result holds only under the assumption (common to Denicolo (1999)) that the marginal cost of the dirty technology is constant.

public-sector R & D that can be used by the private sector, or an increased supply of PhD's in relevant disciplines promoted by government funding. We further ask whether commitment can serve as a substitute for an R & D subsidy.

In Section 3 we analyze the tax regime. We begin with the limiting special case of a constant marginal cost of dirty (emission-producing) energy. We show that in this case, an emissions tax is ineffective in inducing R & D. The reason for this is that a fall in the marginal cost of the emission-free technology as a result of R & D means that a lower tax is sufficient to allow the new technology to compete. Since a higher-than-necessary tax results in a welfare loss by giving the owner of the new technology monopoly power, the government reduces the emissions tax in response to successful R & D. This destroys the incentive to do R & D.

Since fossil fuels are subject to increasing marginal costs of production when harder to reach mineral deposits have to be extracted, it is, of course, more realistic to assume that the supply curve of dirty energy is upward-sloping. We show that when the supply curve is close to flat, then a tax will induce R & D only if the cost of investing in R & D is very low. However, for a sufficiently steep supply curve of dirty energy, it is optimal for the government to *raise* the tax when the marginal cost of green energy falls (up to a limit). This encourages R & D. When the supply curve of dirty energy is sufficiently steep compared to the demand curve for energy, a subsidy to R & D can expand the range of parameter values under which R & D occurs and this can be welfare-improving. That is, a subsidy can induce R & D that would be too expensive to conduct in its absence.

In Section 4, we examine the emissions quota with tradable permits. We show that the government will reduce the quota when the emission-free technology gets less expensive (as long as it remains more costly than the dirty alternative), because the cost of reducing emissions has fallen. This is the case regardless of the steepness of the supply curve of dirty energy. This response induces R & D. As in the case of the tax, a subsidy to R & D investment is welfare-reducing when the supply of dirty energy is flat relative to demand and welfare-increasing when supply is steep relative to demand. We show, both for the quota and for the tax regimes, that while commitment to a stated level of the quota or tax before R & D occurs can substitute for an R & D subsidy or tax as an inducement to R & D, such commitment can never deliver as high a level of welfare as a lack of commitment in conjunction with the R & D subsidy (or tax). We compare tax and quota regimes and show that the former dominates the latter in welfare terms when the marginal cost of dirty energy is sufficiently steep relative to the marginal benefit of energy. Section 5 concludes.

2 The structure of the economy

There is a representative consumer who consumes two goods, energy (e) and the numeraire good (y). The consumer maximizes a quasi-linear utility function

$$U(e) + y = ae - \tfrac{b}{2}e^2 + y \tag{2.1}$$

subject to

$$Pe + y = Y, \tag{2.2}$$

where P is the price of energy and Y is the endowment with the consumer. Solving this problem gives the consumer's inverse demand function for energy

$$P = D^{-1}(e) = \begin{cases} a - be & \text{if} \quad e < \frac{a}{b} \\ 0 & \text{if} \quad e > \frac{a}{b} \end{cases} \tag{2.3}$$

So b is the slope of the marginal social *benefit* of energy.

Energy in the economy can be produced in two ways. There is a competitive industry that produces dirty energy e_d, with a pollutant being emitted as a by-product.

$$\text{The marginal cost of producing } e_d = ce_d. \tag{2.4}$$

So c denotes the slope of the dirty technology's marginal *cost*. In the special case $c = 0$, the private marginal cost of dirty energy is zero for all levels of production. The marginal cost of dirty energy when there is an emissions tax of t is $t + ce_d$. The supply curve of dirty energy implied by (2.4) is

$$S_d(P) = \frac{P}{c}. \tag{2.5}$$

Energy can also be produced without any pollution emissions. The quantity of this green energy is denoted by e_g. The marginal cost of producing green energy depends on the research and development investment made by a monopolist in the period before production occurs. If I is investment measured in units of the numeraire good, then the (constant) marginal cost of green energy that will be realized next period is $g = g(I)$ given by

$$g(I) = \begin{cases} \overline{g} - (\frac{I}{i})^{\frac{1}{2}} & \text{if } 0 \leq I < i\overline{g}^2 \\ 0 & \text{if } I \geq i\overline{g}^2 \quad \text{where} \quad i > 0. \end{cases} \tag{2.6}$$

Therefore,

$$g'(I) < 0, \quad g''(I) > 0, \quad g(0) = \overline{g} > 0 \tag{2.7}$$

Equation (2.6) can also be written as:

$$I : [0, \overline{g}] \to \mathbb{R}^+ \quad \text{where} \quad I(g) = i(\overline{g} - g)^2.$$

$\frac{1}{i}$ measures the impact of investment on the marginal cost of green energy. The lower the value of i, the more sensitive the marginal cost of green energy is to R & D investment.

Emissions produce an externality that is not internalized by the consumer. We choose units so that one unit of dirty energy produces one unit of emissions and we suppose that the damage from emissions is linear so that e_d units of dirty energy result in an external damage of δe_d. Thus δ is the (constant) marginal *damage* of dirty energy.

The sequence of events in the model is as follows: The government inherits from the past the choice of policy instrument: tax or quota. It is assumed that it cannot change this. The government chooses a percentage subsidy for the firm's investment in research and development. Then the green firm chooses its investment in R & D. In the next period, as a result of the green firm's R & D, its marginal cost of production g is realized. The government observes g and then chooses the level of the quota or tax (as the case may be) with the objective of maximizing social welfare. We assume that in the first period the government cannot credibly commit to the level of the quota or to the tax rate it will impose in the second period. However, it *is* committed to the kind of instrument it has inherited, whether that is a tax or a quota. After observing the tax rate or the level of the quota, the green firm chooses its price and output.[3] [4]

In reality, we believe that the choice of quota or tax is made by governments on the basis of their usefulness in the current period. Governments are not looking half a decade, or even several decades ahead at the effects on the technologies that become available. Once this choice is made, an institutional infrastructure is locked in around it, so it is not easily reversible. On the other hand, the effective level of the tax or quota can be altered by future legislatures or governments that react to the then prevailing conditions. This is the motivation for our assumptions above. Since we are interested in the effects of instruments on the incentive to innovate, we do not model production and emissions in the current period.

The green firm's profit net of investment in R & D is denoted by

$$\Pi = \pi - I$$

[3]Even with commitment, a single policy instrument will not be able to achieve the first best. The number of instruments required to achieve a vector of policy targets cannot be less than the number of elements in the vector. Since we have two targets: the level of abatement, given a marginal cost of abatement and the marginal cost of abatement itself, a single instrument is unable to achieve it (Tinbergen, 1964).
In Kolstad (2010), optimality is achieved as he assumes that policy targets abatement rather the level of emissions, thus restricting the number of margins along which adjustment can take place.

[4]The owner of the patent for the green technology, could, of course, license it rather than engaging in production. This does not change the analysis in any way.

where π denotes gross profit in the last stage of the game. Similarly, social welfare net of investment in R & D is denoted by

$$W = w - I$$

where w is the gross social welfare that the government maximizes in the second stage of the game:

$$w = ae - \frac{b}{2}e^2 + Y - \delta e_d - \frac{c}{2}{e_d}^2 - ge_g. \tag{2.8}$$

We assume that in the absence of a green firm, it is socially optimal to produce a positive level of dirty energy, and that the initial marginal cost of the green firm is below the marginal social value of energy at $e = 0$. We also assume that the initial marginal cost of the green technology $\overline{g}$ is too high for it to be socially optimal to have any production of green energy.[5] These two assumptions can be written as:

Assumption 2.1

$$a > \overline{g} > P_d^*(\delta),$$

where

$$P_d^*(t) = \frac{ac + bt}{b + c} \tag{2.9}$$

denotes the equilibrium price of dirty energy when there is no green energy produced and there is an emissions tax of t. The two assumptions above can be written as:

The equilibrium quantity of dirty energy when there is no green sector and there is an emissions tax of t is

$$e_d^*(t) \equiv S_d(P_d^*(t) - t) = \frac{a - t}{b + c}. \tag{2.10}$$

It should be noted that in the special case when $c = 0$, that is, the supply curve of dirty energy is flat, then $P_d^*(\delta) = \delta$, so that Assumption 2.1 implies that $\overline{g} > \delta$. If $\overline{g} < \delta$, it would be optimal to use only the green technology. So the problem facing society would not be one of reducing emissions, but only that of making emission control less expensive.

3 The Tax Regime

Let us start with the special case $c = 0$.[6]

[5] In Datta and Somanathan (2010) we show that the alternative assumption leads to qualitatively similar results.

[6] Most papers discussed in Section 1 make the assumption that $c = 0$, for example Denicolo (1999); Montgomery and Smith (2005); Laffont and Tirole (1996).

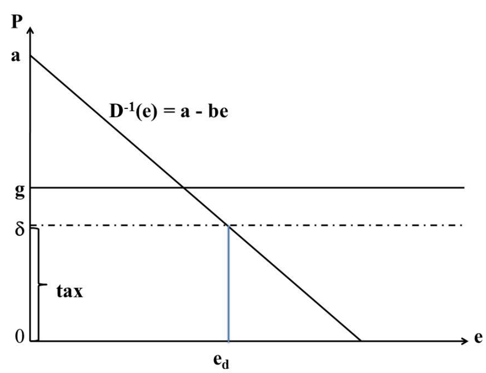
Proposition 1 *If the supply curve of dirty energy is flat, then there will be no investment in research and development under the tax regime.*

Proof: Suppose the firm chooses $g > \delta$ (which can happen only if $\overline{g} > \delta$) in the first stage. Then the social marginal cost of green energy is greater than that of dirty energy (Figure 1 (a)). Thus the optimal tax is δ, the difference between the social and private marginal costs of energy production. The green firm will not produce and so will incur a net loss with $\pi = -I(g) \leq 0$, where equality holds only when $g = \overline{g}$.

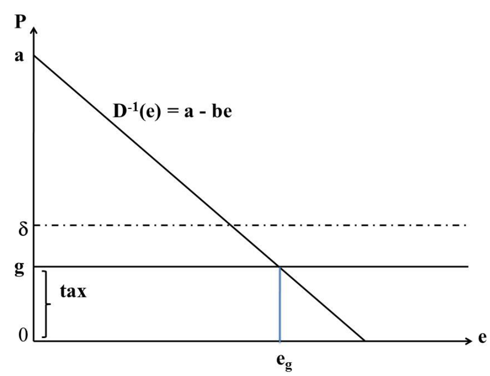
If $g \leq \delta$, then the optimal tax is infinitesimally greater than g (Figure 1 (b)). This is just sufficient to drive the dirty firms out of the market, but not enough to allow the green firm to exercise its monopoly power to restrict output. Now the green firm can only charge the tax, which is just infinitesimally greater than g. Thus the green firm incurs a loss of $-I(g) \leq 0$.

Therefore, the green firm must set $I = 0$ if it is to avoid a loss.

■



(a) Tax Regime with $g > \delta$.



(b) Tax Regime with $g < \delta$.

Figure 1: Tax Regime when $c = 0$.

When dirty energy supply is flat, the optimal tax falls with g, wiping out the incentive to do R & D.[7] However, since fossil fuels can have heterogeneous extraction costs that depend

[7] *Ex-post* emissions taxation does not eliminate R & D in models of end-of-pipe abatement such as that of Denicolo (1999). The reason is that those models allow the innovating firm to choose the emission intensity of its technology from a continuum of possibilities. In equilibrium, the firm chooses an emission intensity far enough from zero so as to prevent the government from setting a very low emissions tax.

on the location and quality of deposits, they can be expected to have an increasing marginal cost of extraction. It can be shown that the decision of the green firm not to invest in R & D is the limiting case as c get close to zero.[8] Figure 2 below depicts the R & D behavior of the green firm for different positive values of c.

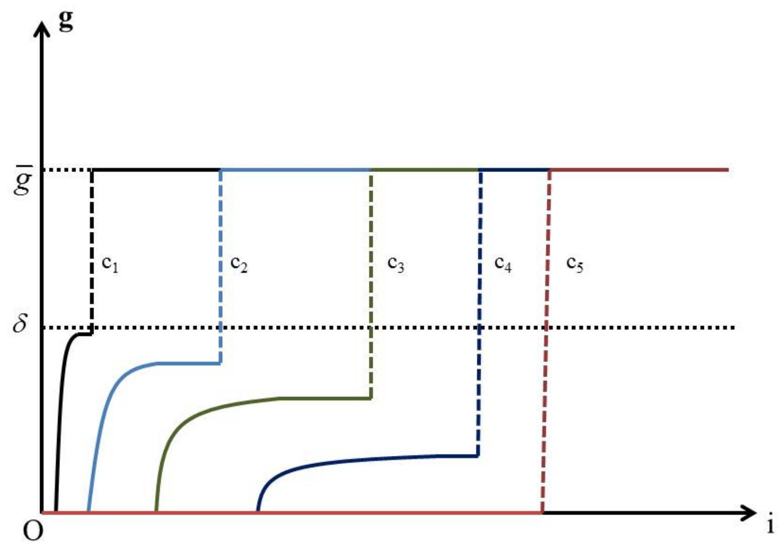


Figure 2: Equilibrium g as a function of i for different values of c $\left(0 < c_1 < c_2 < c_3 < c_4 < \frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)} \leq c_5\right)$.

By Proposition 1, when $c = 0$, the equilibrium $g(i)$ curve is a horizontal line at a height of $\overline{g}$. For values of c that are positive but close to zero, the equilibrium $g(i)$ curve has a discontinuity with zero and positive segments. As c increases, the green firm generally invests more in R & D.[9] For values of c above the cut-off level of $\frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)}$, the equilibrium g curve is a step function. We now discuss the logic behind the shape of the different curves in Figure 2 in some detail.

After the choice of R & D investment has been made by the green firm, a social welfare-maximizing government faces a trade-off in setting the tax. When g is higher than $P_d^*(\delta)$, the trade-off is relatively simple. The government chooses a tax equal to the marginal damage from emissions and allows only the dirty sector to operate. Green energy is too costly to be

[8] A formal proof is available from the authors on request, and the intuition is discussed below.

[9] Note that the left hand limit of g (at the point of discontinuity) falls as c increases.

produced.

The trade-off becomes more interesting when $g < P_d^*(\delta)$. Suppose the tax is set at such a high level that the dirty sector is wiped out and only the green firm produces energy. Then the absence of competition from the dirty sector gives the green firm monopoly power, resulting in a high price of energy, low total energy output and low consumer surplus. On the other hand if the government sets a low tax that allows the dirty sector to produce, there is a welfare loss from pollution damage. The government's choice between these two evils, depends crucially on the amount of R & D investment in Period 1, which determines the marginal cost g achieved by the green firm in Period 2. If g is sufficiently low, then it can be welfare-maximizing for the government to wipe out the dirty sector as a lower g tilts the trade-off in favour of the green firm. This is due to two factors: Firstly, a lower g reduces the difference in the private marginal costs of green and dirty energy, thus reducing the cost of imposing a higher tax. Secondly, for a fixed tax level, a lower g implies higher production of green energy. Thus a lower g reduces the loss of consumer surplus from reduced energy consumption. Let g_H be the highest value of g for which it is socially optimal to eliminate the dirty sector. For all values of $g \leq g_H$, the welfare-maximizing government wipes out the dirty sector by choosing a tax that is high enough. In Figure 2, g_H is the left-hand limit of g at the point of discontinuity of the curves labelled c_1 through c_4. For a given tax rate, a higher c implies greater monopoly power for the green firm. Thus g has to be low enough to ensure that it is welfare-maximizing for the government to wipe out the dirty sector. This is why g_H falls as c rises. When $c = 0$, g_H is equal to δ. When c increases beyond $\frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)}$, g_H becomes negative. When dirty energy supply is relatively flat ($c < \frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)}$), the green firm has little scope to price high, so it conducts R & D only if the dirty sector is eliminated.[10]

Now we consider the case in which c is high enough ($c > \frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)}$) to ensure that g_H is less than zero. This assumption can be written as:

Assumption 3.1 $\delta(b + 2c)^2 - ac^2 < 0$.

Now it is not welfare-maximizing to set a tax high enough to wipe out the dirty sector for any positive level of g. For any value of $g < P_d^*(\delta)$, let $t_H(g)$ be the highest tax rate that lets the dirty sector survive. It is never optimal for the government to choose a tax above $t_H(g)$. This is because choosing $t > t_H(g)$ raises the price of energy, and so reduces energy consumption and consumer surplus, but is unable to achieve any welfare gain through reduced emissions since emissions are already zero. Given Assumption 3.1, the government never chooses $t_H(g)$ either.

[10]Proofs of the claims above are available from the authors on request.

For $g < P_d^*(\delta)$, let $t_L(g)$ be the lowest (non-negative) tax that keeps the green firm viable. The government never chooses a tax less than $t_L(g)$ for the following reason. A reduction in the tax from $t_L(g)$ increases the production of energy (all of which is dirty energy) which is already higher than what is optimal.[11] Thus when $g < P_d^*(\delta)$, the government chooses an optimal tax from the segment $[t_L, t_H)$. Optimality is achieved when the marginal gain from reduced emissions when the tax is increased equals the marginal loss from the reduction in consumer surplus.

Figure 3 explains the choice of optimal tax and the green firm's response to the imposition of such a tax. Suppose the government imposes a tax of $t \in (\delta, t_H)$. Note that $\delta > t_L$. As $g < P_d^*(t)$ the green firm has a price-setting role to play in the post-tax stage of the game. For any given price P, the dirty sector produces $\frac{P-t}{c}$, while the remaining demand is served by the green firm. While a higher price ensures a higher profit per unit of green energy produced, it reduces the green energy produced. The green firm balances these two effects and chooses the optimal price at $P(g)$, which (it is easy to show) is the average of g and $P_d^*(t)$. Dirty and green energy produced are $e_d(g,t)$ and $e(g,t) - e_d(g,t)$ respectively. The green firm's gross profit π is shown by the rectangle shaded in grey in Figure 3.

Summarizing, we can say that for any $g \geq P_d^*(\delta)$, $P(g, t(g)) = P_d^*(\delta)$ and energy production is given by: $e_d = e_d^*(\delta)$ and $e_g = 0$.

For $g \in [0, P_d^*(\delta))$ and $t \in [t_L(g), t_H(g))$,

$$P(g,t) = \frac{1}{2}[g + P_d^*(t)], \tag{3.1}$$

$$e(g,t) = \frac{1}{2}[e_d^*(t) + D(g)], \tag{3.2}$$

$$e_d(g,t) = \frac{1}{2}[e_d^*(t) + S_d(g-t)], \tag{3.3}$$

$$e_g(g,t) = \frac{1}{2}[D(g) - S_d(g-t)], \tag{3.4}$$

$$\pi(g,t) = \frac{b+c}{4bc}[P_d^*(t) - g]^2, \tag{3.5}$$

where $S_d(P)$ denotes the supply curve of the dirty sector in the absence of a tax.

[11] This is because, by definition, $t_L(g) < \delta$.

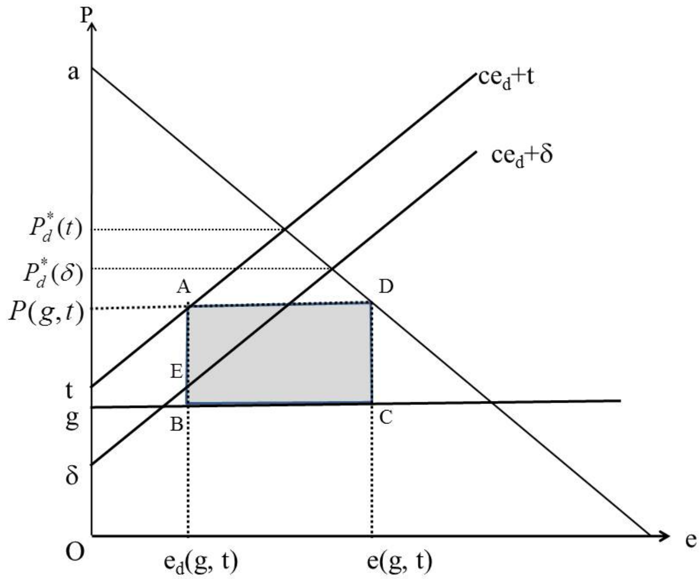


Figure 3: Price determination in a tax regime.

The government chooses the optimal t by equating the social marginal benefit (SMB) and social marginal cost (SMC) of changing the tax by a unit.

$$\begin{aligned}
\text{The SMB of increasing the tax} &= |\frac{\partial e_d}{\partial t}| * \text{SMB of replacing dirty with clean energy} \\
&= |\frac{\partial e_d}{\partial t}| * (\delta + ce_d - g) \\
&= |\frac{\partial e_d}{\partial t}| * EB \quad \text{(refer to Figure 3)}, \\
\text{and the SMC of increasing the tax} &= |\frac{\partial e}{\partial t}| * \text{SMC of reducing energy consumption} \\
&= |\frac{\partial e}{\partial t}| * (a - be - g) \\
&= |\frac{\partial e}{\partial t}| * DC \quad \text{(refer to Figure 3)}.
\end{aligned}$$

From 3.2 and 3.3, we see that $|\frac{\partial e_d}{\partial t}| > |\frac{\partial e}{\partial t}|$. Thus, to equate the marginal benefit and cost of the tax, the marginal social benefit from replacing dirty with clean energy must be less than the marginal social cost of reducing energy consumption. Since $t_L < \delta$, this shows, looking at Figure 3, that t_L cannot be an optimal tax. Hence, the optimal tax is in (t_L, t_H) and satisfies:

$$(a - be)\frac{\partial e}{\partial t} = (\delta + ce_d)\frac{\partial e_d}{\partial t} + g\frac{\partial e_g}{\partial t}, \tag{3.6}$$

where

$$\frac{\partial e_d}{\partial t} = -(\frac{1}{2(b+c)} + \frac{1}{2c}),$$
$$\frac{\partial e_g}{\partial t} = \frac{1}{2c},$$
$$\frac{\partial e_d}{\partial t} + \frac{\partial e_g}{\partial t} = \frac{\partial e}{\partial t}.$$

From these expressions we obtain the government's reaction function:

$$t(g) = \begin{cases} \frac{ac-(b+c)g+2\delta(b+2c)}{b+4c}, & \text{if} \quad g \in [0, P_d^*(\delta)], \\ \delta, & \text{if} \quad g > P_d^*(\delta). \end{cases} \tag{3.7}$$

Remark 1 *Assumption 3.1* $\implies t'(g) < 0$. *When the supply curve of dirty energy is steep enough, then the government* increases *the emissions tax when g falls.*

Unlike in the case when $c \to 0$, the dirty sector has not been wiped out, so a lower g reduces the welfare cost of a given tax by allowing cheaper substitution of green for dirty energy. So the policy-maker's response reinforces the incentive to conduct R & D instead of attenuating it.

The green firm chooses its level of R & D by taking the government's reaction function as given when maximizing net profit. As before, the firm never chooses $g \in [P_d^*(\delta), \overline{g})$ as this choice would not allow it to operate in the market in the second period. In the range $[0, P_d^*(\delta))$, the net profit function is obtained by sequentially substituting the firm's second-period reaction function and the government's reaction function into the profit function 3.5 and subtracting the cost of investment in R & D:

$$\Pi(g) = \frac{b+c}{4bc}\left[\frac{ac+bt(g)}{b+c} - g\right]^2 - i(\overline{g}-g)^2. \tag{3.8}$$

Maximizing 3.8 leads to

Proposition 2 *In the tax regime with c large enough (Assumption 3.1 holds), the $g(i)$ curve is a step function with a discontinuity at* $i_T \equiv \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$.

$$g = \begin{cases} 0, & \text{if} \quad i \le i_T, \\ \overline{g}, & \text{if} \quad i \ge i_T. \end{cases} \tag{3.9}$$

Proof: In Appendix A. ■

Unlike in the case $c = 0$, the green firm will undertake R & D if its cost of doing so is not too large. The steepness of the dirty sector supply curve generates monopoly power for the green firm, thus creating the incentive for R & D when it is inexpensive to conduct (i is low enough).[12] As explained above, the policy response re-inforces this incentive.

Figure 4 shows the optimal choice of g by the green firm.

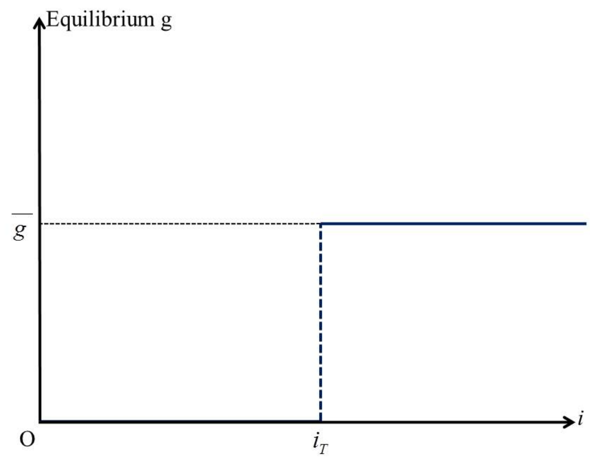


Figure 4: Equilibrium green marginal cost g as a function of i in the tax regime.

Note that in the equilibrium, emissions and energy output are not at their socially optimal levels *ex-post*, that is, after the result of R & D is realized. The reason is that the government has only a single instrument at its disposal to meet two targets, emissions and energy output, or equivalently, dirty and green energy. This is in contrast to the end-of-pipe abatement model of Denicolo (1999) in which emissions are at their first-best level when the government sets the emissions tax *ex-post*. This is because the marginal cost curve of the lower-emission technology in the end-of-pipe abatement model is simply that of the old technology minus a (tax-dependent) constant. So only the low-emission technology is used in equilibrium, and hence one instrument is sufficient to achieve the first-best. In the end-of-pipe model, the new technology strictly dominates the old one; given any positive emissions price, it costs less than the old technology at every level of output. It is, of course, the same technology with a lower emissions intensity. It is this fact that also generates the equivalence of tax and quota regimes in Denicolo (1999) since either can be used to generate the

[12] Reversing Assumption 2.1 that $\overline{g} > P_d^*(\delta)$ implies a smoothly increasing $g(i)$ function for i large enough (see Proposition 9 in Datta and Somanathan (2010)).

emissions price that delivers the desired level of output. In our model, the green technology has a different marginal cost curve since it is not dependent on fossil resources.

We now turn to the role of a subsidy to R & D. A subsidy rate of s $(0 < s < 1)$ implies that when the green firm incurs an investment cost of I, the government pays sI to the firm. Thus when the subsidy is s, the amount the green firm has to spend on R & D in order to achieve a marginal cost g becomes $(1-s)i(g-\overline{g})^2$. Thus, a subsidy reduces the effective i for the green firm. It can have no effect when the marginal cost of the dirty sector is flat $(c = 0)$, since any expenditure at all is sufficient to deter the firm from conducting R & D. However, under Assumption 3.1 ($c > \frac{b(2\delta+\sqrt{a\delta})}{(a-4\delta)}$), when $i > i_T$, a large enough subsidy can reduce the effective i, i.e. $(1-s)i$ below i_T. In this case, a subsidy to R & D is effective in inducing R & D. Under what conditions will it improve welfare?

By Proposition 2, at $i = i_T$, $\Pi(\overline{g}) = \Pi(0)$, so $\pi(0) = i\overline{g}^2$. Therefore, a welfare-improving subsidy will exist for i greater than and sufficiently close to i_T if $W(0) - W(\overline{g}) > 0$ at $i = i_T$. The last condition will be met if, at $i = i_T$,

$$\begin{aligned} w(0) - i\overline{g}^2 - w(\overline{g}) \quad &> 0, \\ \text{or} \quad w(0) - w(\overline{g}) \quad &> \pi(0). \end{aligned}$$

To find the conditions under which this will be true, first note that by 3.7,

$$t(0) = \frac{ac + 2\delta(b+2c)}{(b+4c)} > \delta,$$

and by 3.1 and 2.9,

$$\begin{aligned} P(0, t(0)) \quad &= \quad \frac{(ac+b\delta)(b+2c)}{(b+c)(b+4c)} \\ &= \quad \frac{(b+2c)}{(b+4c)} P_d^*(\delta) \\ &< \quad P_d^*(\delta). \end{aligned}$$

This situation is depicted in Figure 5. $\pi(0)$ is given by the rectangle $EGLK$. Gross welfare when there is R & D and $g = 0$ is

$$w(0) = ADJC + DKLG$$

If there is no R & D, $w(\overline{g}) = \triangle ABC$. Therefore,

$$w(0) - w(\overline{g}) = JKLGB \quad \text{(shaded in grey)}.$$

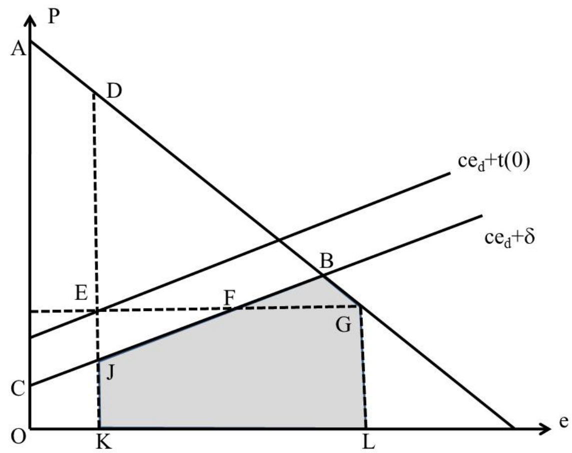


Figure 5: The welfare consequences of an R & D subsidy.

Therefore,

$$w(0) - w(\overline{g}) - \pi(0) = \triangle FGB - \triangle EFJ.$$

Now $\triangle FGB > \triangle EFJ$ if and only if $4c^2 - bc - b^2 > 0$ i.e $c > \frac{1+\sqrt{17}}{8}b$ (see B). Thus if $c < \frac{1+\sqrt{17}}{8}b$, there can be no welfare-improving subsidy.

At the threshold i_T, even a tiny subsidy is sufficient for improving welfare when $c > \frac{1+\sqrt{17}}{8}b$. For higher i, a larger subsidy is needed, and the welfare gain from R & D shrinks.[13] In Appendix B, we show that $\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$ is the maximum value of i for which a subsidy can induce R & D and still increase welfare. We summarize these conclusions in

Proposition 3 *When $c = 0$, a subsidy to R & D is totally ineffective in a tax regime. When assumption 3.1 is satisfied, then an R & D subsidy will induce investment* and *increase welfare if and only if $c > \frac{1+\sqrt{17}}{8}b$ and $i \in [i_T, \frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}]$.*

Figure 5 provides some intuition for why it is the slope of the marginal cost of dirty energy relative to the slope of the marginal benefit of energy that determines whether an R & D subsidy is welfare-improving. A decrease in b rotates the demand curve outward and the first-order effect of this is to increase consumer surplus and thus the area of $\triangle FGB$. Note that the area of $\triangle FGB$ is positively related to the welfare gain from the green technology minus the profit gain from the green technology while the area of the other triangle is negatively related to this difference.[14] Similarly, an increase in c rotates the supply curve upward

[13]Of course, the shrinking of the welfare gain is not due to the subsidy *per se*, which is just a transfer, but because of the greater cost of investment.

[14]The price line is monotonic in g.

whose first-order effect is also to increase the size of $\triangle FGB$ and reduce that of $\triangle EFJ$. The effect of these changes on the price of energy goes in the opposite direction, but that is smaller as the calculations show.

We have assumed all along that the government cannot commit to a tax rate before the firm conducts R & D. It is now easy to see that if such a commitment were possible, then it would be welfare-improving under conditions similar to those required for an R & D subsidy to be welfare-improving under no commitment. Suppose Assumption 3.1 is satisfied, and that $c > \frac{1+\sqrt{17}}{8}b$. When i is only slightly greater than i_T, the firm needs only a small increase in prospective profit after R & D to push it over the threshold and induce it to conduct R & D. Thus, by committing to a tax just a little higher than the optimal tax under no commitment, the government could push the firm over the threshold, induce it to conduct R & D, and improve welfare. Note, however, that this option is dominated by the no commitment case if the government avails of the option of subsidizing R & D. This is, of course, because changing the tax from its *ex-post* optimal level inflicts a welfare loss that is avoided by using the R & D subsidy instead.

4 Quota Regime

As before, the model is a sequential game between the government and the green firm with three stages,

1. The green firm choosing investment.
2. The government choosing an emissions quota q.
3. The green firm choosing its price and output.

We use backward induction to solve it.

If $g > P_d^*(\delta)$, it is clear that the optimal quota is $e_d^*(\delta)$ and the green firm is shut out of the market. Energy consumption is $e_d^*(\delta)$ and its price is $P_d^*(\delta)$.

Now consider the case $P_d^*(0) \leq g \leq P_d^*(\delta)$, depicted in Figure 6. The green firm chooses its output to maximize its profit given the residual demand curve for energy after the dirty sector has produced q.[15]

[15]It is clear that the quota must be less than $D(g)$, then the green firm would be shut out of the market. So $q = e_d^*(\delta)$ would yield higher welfare.

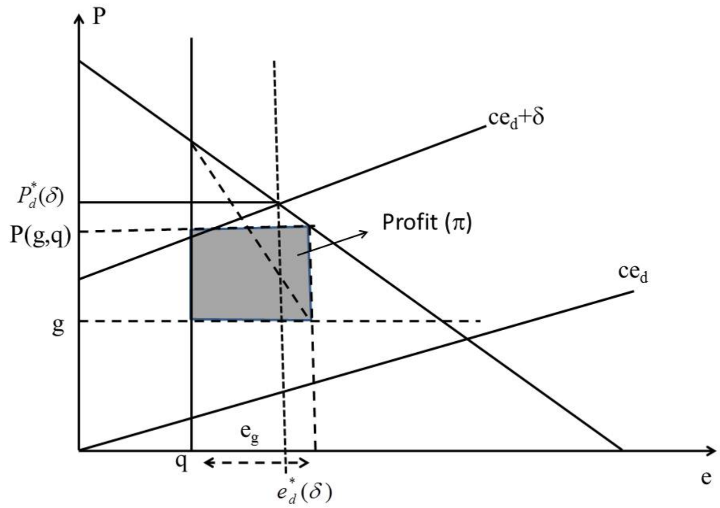


Figure 6: Choice of green energy output when $P_d^*(0) \leq g \leq P_d^*(\delta)$.

The profit function of the green firm is :

$$\begin{aligned} \pi &= e_g[D^{-1}(e_g + q) - g] \\ &= e_g[a - b(q + e_g) - g]. \end{aligned}$$

π is concave in e_g and there is no corner solution. The monopoly price is the average of marginal cost and the highest point of the residual demand curve $D^{-1}(q)$. Thus the output of clean energy and total energy, the price of energy and the profit of the green firm are respectively (Refer to Figure 6):

$$\begin{aligned} e_g(g, q) &= \frac{1}{2}[D(g) - q] \\ &= \frac{a - bq - g}{2b} \end{aligned} \tag{4.1}$$

$$\begin{aligned} e(g, q) &= \frac{1}{2}[D(g) + q] \\ &= \frac{a + bq - g}{2b} \end{aligned} \tag{4.2}$$

$$\begin{aligned} P(g, q) &= \frac{1}{2}(D^{-1}(q) + g) \\ &= \frac{a - bq + g}{2} \end{aligned} \tag{4.3}$$

$$\pi(g,q) = \frac{1}{4}[D(g)-q][D^{-1}(q)-g] = \frac{(a-bq-g)^2}{4b}. \tag{4.4}$$

Next, consider the case $g < P_d^*(0)$. It is straightforward to show that in the absence of government intervention, that is, if there were no quota set for dirty energy, then profit maximization by the green firm would lead to an energy price $P = \frac{1}{2}[P_d^*(0)+g]$ and dirty energy production $e_d = \frac{1}{2c}[P_d^*(0)+g]$. The government can always achieve this outcome by setting a large enough quota; any $q \geq e_d^*(0)$ will do. We note that the government may, under some parameter configurations and values of g, actually choose to set such a non-binding quota. The reason is that setting a quota slightly less than $\frac{1}{2c}[P_d^*(0)+g]$ gives the green firm monopoly power. The resulting high energy price restricts total energy output so much that it is preferable to set a non-binding quota and allow $e_d = \frac{1}{2c}[P_d^*(0)+g]$. Having said this, we now assume, for ease of exposition, that the government does in fact commit to a *binding* quota in the first period, that is, $q(g) \leq \frac{1}{2c}[P_d^*(0)+g]$. The remaining propositions in the paper, Propositions 4 and 5, remain qualitatively unchanged when this assumption is dropped.[16]

To avoid a proliferation of cases, we assume below (Assumptions 4.1 and 4.2) that the government's choice of q from the interval $\left[0, \frac{1}{2c}(P_d^*(0)+g)\right]$ has an interior optimum. Hence, optimal green energy production, total energy production, the price of energy, and the gross profit of the green firm are given by (4.1), (4.2), (4.3) and (4.4) respectively.

When $0 \leq g \leq P_d^*(\delta)$, the gross welfare function is

$$w(g,q) = a(\frac{a+bq-g}{2b}) - \frac{b}{2}(\frac{a+bq-g}{2b})^2 - \delta q - \frac{cq^2}{2} - g(\frac{a-bq-g}{2b}) \tag{4.5}$$

The marginal social benefit from tightening the quota is, as in Section 3, the reduction in social cost when dirty energy is replaced by green energy, while the marginal welfare loss arises from the reduction in net welfare from energy consumption. The first-order condition from maximizing 4.5 with respect to q can, therefore, be written as

$$cq + \delta - g = \frac{1}{2}[\frac{a-bq-g}{2}] \tag{4.6}$$

provided the solution is interior, which we assume. It is easy to see that the assumption needed to rule out a zero quota is[17]

[16] The proof is available from the authors on request.

[17] At $q = 0$,

$$\frac{\partial w}{\partial q} = \frac{a}{4} + \frac{3g}{4} - \delta.$$

To rule out the corner solution, we need $a + 3g - 4\delta > 0, \quad \forall g \geq 0$. This requires $a - 4\delta > 0$.

Assumption 4.1 $a - 4\delta > 0$.

The next assumption ensures that it is optimal to set $q < \frac{1}{2c}[P_d^*(0) + g]$.[18]

Assumption 4.2 $\frac{b-2c}{2(b+c)}a - 4\delta < 0$.

Given Assumptions 4.1 and 4.2, it follows easily from 4.6 that the government's reaction function is:

$$q(g) = \begin{cases} e_d^*(\delta) & \text{if} \quad g > P_d^*(\delta) \\ \frac{a+3g-4\delta}{b+4c} & \text{if} \quad g \leq P_d^*(\delta) \end{cases} \tag{4.7}$$

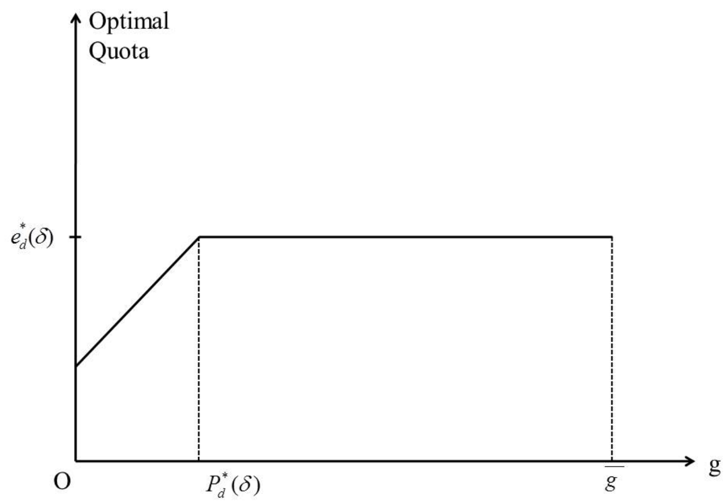


Figure 7: The government's reaction function $q(g)$.

Remark 2 $q'(g) > 0$. *The optimal quota falls when g falls.*

The policy response to R & D reinforces the incentive to do R & D. When green energy gets cheaper, the welfare cost of capping the dirty sector falls, since substituting green for dirty energy is cheaper. So the policy maker sets a stricter quota. Unlike in the tax regime,

[18]Evaluating $\frac{\partial w}{\partial q}$ at the right end-point $\frac{1}{2c}[P_d^*(0) + g] = \frac{1}{2c}\left[\frac{ac}{b+c} + g\right]$, we get

$$\frac{\partial w}{\partial q} = \frac{a}{4} - \delta - \frac{a(b+4c)}{8(b+c)} - \frac{g}{8c}(b-2c).$$

For an interior solution, this expression has to be negative. If $b > 2c$, then it is decreasing in g, so we require it to be negative at $g = 0$. This forces $\frac{b-2c}{2(b+c)}a - 4\delta < 0$. If $b < 2c$, then the expression above is increasing in g. So we need it to be negative at $g = P_d^*(0)$, which is always true.

this is true regardless of the steepness of the marginal cost of dirty energy (recall the discussion following Proposition 2).

There is an interesting relationship between the green firm's choice of g and subsequent energy output. This can be shown as follows:

$$\begin{aligned} \frac{de}{dg} &= \frac{\partial e}{\partial g} + \frac{\partial e}{\partial q}.\frac{dq}{dg} \\ &= -\frac{1}{2b} + \frac{1}{2}\frac{3}{(b+4c)} \\ &= \frac{(b-2c)}{b(b+4c)}. \end{aligned}$$

Thus, if $c < \frac{b}{2}$, then energy consumption falls when g falls. We will see below that in this case a welfare-improving subsidy to R & D does not exist.

We now turn to the green firm's choice of R & D investment. The firm never chooses $g \in [P_d^*(\delta), \overline{g})$. This is because while such cost reduction from $\overline{g}$ is costly, it does not allow the firm to operate in the market in the second period. In the range $[0, P_d^*(\delta))$, the net profit function (obtained by substituting the government's reaction function (4.7) into the profit function (4.4) and subtracting the investment cost) is

$$\begin{aligned} \Pi(g) &= \frac{4}{b(b+4c)^2}[ac + b\delta - (b+c)g]^2 - i(\overline{g}-g)^2 \\ &= \frac{4(b+c)^2}{b(b+4c)^2}[P_d^*(\delta) - g]^2 - i(\overline{g}-g)^2. \end{aligned} \tag{4.8}$$

Maximizing 4.8 yields

Proposition 4 *Under Assumptions 2.1, 4.1, and 4.2, in the quota regime the $g(i)$ curve is a step function with a discontinuity at $i_Q \equiv \frac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2}$.*

$$g(i) = \begin{cases} 0, & \textit{if} \quad i \leq i_Q, \\ \overline{g}, & \textit{if} \quad i \geq i_Q. \end{cases} \tag{4.9}$$

Moreover, $i_Q < i_T$.

This result is depicted in Figure 8 and the proof is in Appendix C.[19] The monopoly power created by the quota ensures that the green firm can get a return on its investment in R & D. It avails of the opportunity if R & D is not too expensive.

[19]As with Proposition 2, reversing Assumption 2.1 that $\overline{g} > P_d^*(\delta)$ implies a smoothly increasing $g(i)$ function for i large enough. Moreover, the equilibrium level of $g(i)$ is lower in a tax regime as compared to a quota regime for i large enough (see Proposition 9 in Datta and Somanathan (2010)).

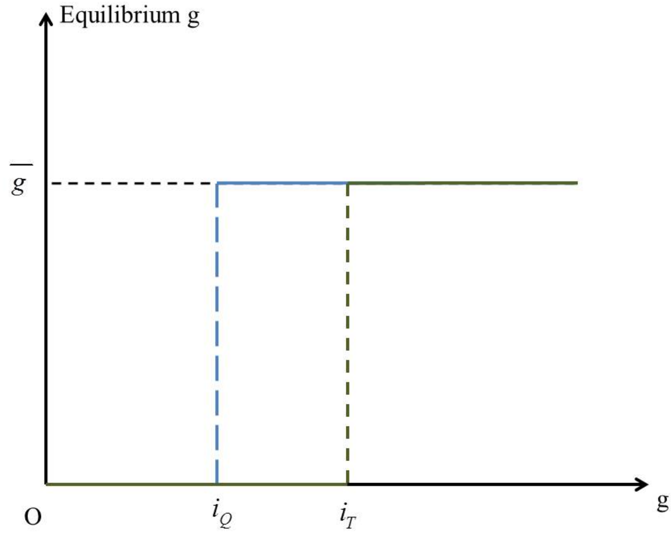


Figure 8: Equilibrium g as a function of i in tax and quota regimes.

The Role of an R & D Subsidy

We remarked above that total energy output will be smaller when there is a green firm than in its absence if and only if the marginal cost of dirty energy is sufficiently flat relative to the marginal benefit of energy, that is, $c < \frac{b}{2}$. If $c < \frac{b}{2}$, then for i below the threshold, the situation would be as depicted in Figure 9.

Would it be welfare-improving to subsidize R & D if i is just slightly greater than i_Q? This would be the case if the welfare gain from conducting R & D, $w(0) - w(\overline{g})$ were greater than the cost of R & D, $i_Q\overline{g}$. But, at $i = i_Q$, the green firm is indifferent between conducting R & D and not doing so, so that $i_Q\overline{g} = \pi(0)$. Thus, an R & D subsidy can be welfare-improving only if $w(0) - w(\overline{g}) > \pi(0)$. Referring to Figure 9, gross welfare when there is R & D and $g = 0$ is

$$w(0) = \text{ the area of } aIGH + \text{ the area of } IBCD.$$

If there is no R & D, then

$$w(\overline{g}) = \text{ the area of } \triangle aEH.$$

So the increase in welfare from conducting R & D is

$$w(0) - w(\overline{g}) = \text{ the area of } GFCD - \text{ the area of } \triangle BEF.$$

But this has to be *less* than $\pi(0)$ = the area of the rectangle ABCD. Thus, it is clear that when $e_d < e_d^*(\delta)$, which, as we remarked above is true when $c < b/2$, then there can be no welfare-improving subsidy. In fact,

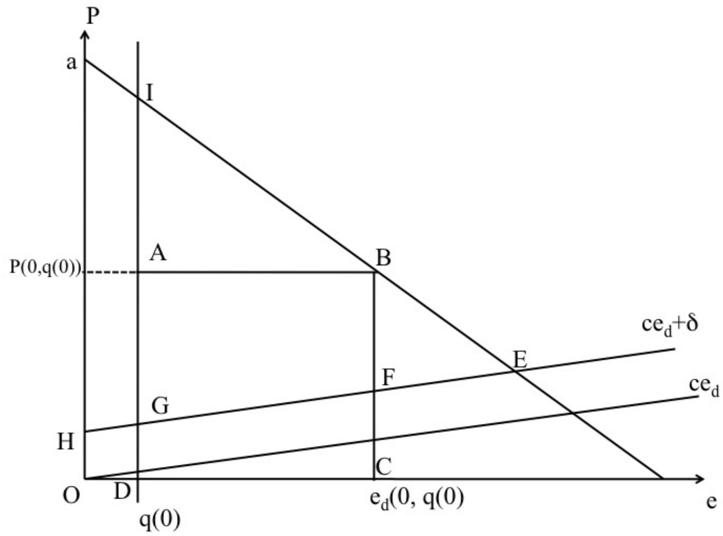


Figure 9: The welfare consequences of an R & D subsidy when $c < \frac{b}{2}$.

Proposition 5 *If $c < \frac{5}{4}b$, then there can be no welfare-improving subsidy to R & D in the quota regime. If $c > \frac{5}{4}b$, then an R & D subsidy can improve investment and welfare if the marginal cost of green energy is sufficiently sensitive to R & D, that is for $i \in [i_Q, \frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)\overline{g}^2}]$.*

The proof is similar to that of Proposition 3 and is in Appendix D. The intuition for this proposition is very similar to that given for Proposition 3.

As in the tax regime, if the government can commit to a level of the quota before R & D takes place, then this can be potentially welfare-improving relative to no commitment and no R & D subsidy. In the light of the foregoing discussion, the reason for this is easy to see. When $c > \frac{5}{4}b$, and $i \geq i_Q$, inducing R & D would improve welfare discretely. This can be done by committing to a lower level of the quota relative to no commitment. Since the welfare loss from tightening the quota is continuous in the quota, commitment can be welfare-improving for i close enough to i_Q. Again, as in the tax regime, notice that the commitment route is in general worse than no commitment in conjunction with an R & D subsidy, since the latter avoids the *ex-post* distortion associated with a sub-optimal quota.

We now ask which regime, the tax or the quota, delivers higher welfare in the absence of commitment. In the following discussion, we maintain Assumption 3.1, ruling out near-zero values of c. First, we remark that when the cost of investment in R & D is low enough that both regimes induce R & D ($i < i_Q$), then the greater monopoly power that the green firm has in the quota regime means that welfare is lower than in the tax regime. To see this, suppose that in a tax regime, the tax t is set so that the resulting level of dirty energy is $q(0)$, the level that would be produced in a quota regime in which the quota is set optimally when $g = 0$. This is depicted in Figure 10. The resulting price of energy would then be one-half of $P_d^*(t)$, the price at which the demand curve and the resulting supply curve of dirty energy intersect (3.1). However, in the quota regime, the price of energy would be one-half of the intersection of the demand curve with the vertical quota line (4.3), and so would be higher. The quota gives the green firm more monopoly power than the tax. Since dirty energy and emissions are the same in the two cases, total energy produced, and, therefore, welfare, must be higher under the tax. So welfare would be even higher (or at least no lower) if the tax were set optimally.

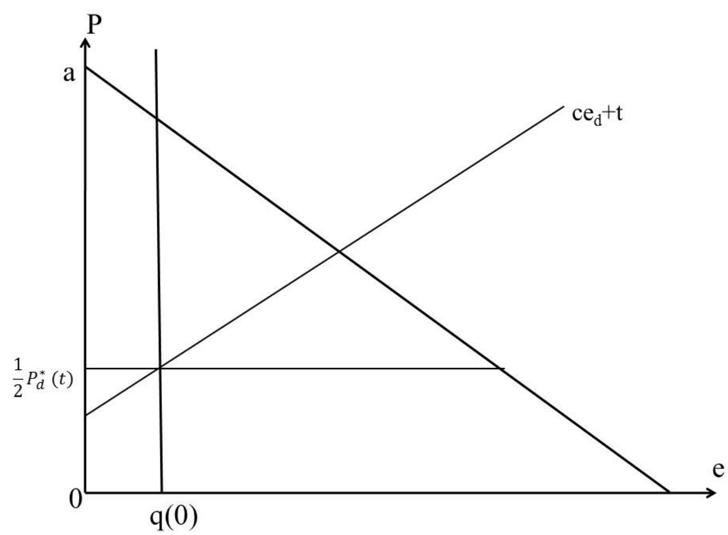


Figure 10: Welfare Comparison between the tax regime and the quota regime.

When $i > i_T$, there is no R & D under either regime, so welfare is the same in both. Now, let $i \in (i_Q, i_T)$. First, suppose $c > \frac{1+\sqrt{17}}{8}b$. Then welfare under the tax regime (using the subscripts T for the tax regime, and Q for the quota regime) is

$$\begin{aligned} w_T(g=0) - i\overline{g}^2 &> w_T(g=0) - i_T\overline{g}^2 \\ &> w_T(g=\overline{g}) \quad \text{(by Proposition 3)} \\ &= w_Q(g=\overline{g}) \end{aligned}$$

which is welfare under the quota regime.

So the tax regime is preferable whenever the slope of marginal cost is sufficiently high relative to the slope of marginal benefit.

Now we turn to the case when $i < i_T$ and $c < \frac{1+\sqrt{17}}{8}b$. By using the reasoning behind Proposition 3, it is clear that for i sufficiently near i_T, a tax on R & D just sufficient to deter the firm from conducting R & D would be welfare-improving. Let $\underline{i_T}$ denote the cut-off value of i below which there is no tax on R & D that is welfare-increasing. Let $i \in (\underline{i_T}, i_T)$. Then, welfare under the tax regime is

$$\begin{aligned} w_T(g=0) - i\overline{g}^2 &< w_T(g=0) - \underline{i_T}\overline{g}^2 \\ &= w_T(g=\overline{g}) \quad \text{(by definition of } \underline{i_T}) \\ &= w_Q(g=\overline{g}) \end{aligned}$$

which is welfare under the quota regime.

Putting this together with the fact noted above that welfare under the tax regime is higher than in the quota regime for $i < i_Q$, we conclude that $i_Q < \underline{i_T}$. Now let $i \in (i_Q, \underline{i_T})$. Then, welfare under the tax regime is

$$\begin{aligned} w_T(g=0) - i\overline{g}^2 &> w_T(g=0) - \underline{i_T}\overline{g}^2 \\ &> w_T(g=\overline{g}) \quad \text{(by definition of } \underline{i_T}) \\ &= w_Q(g=\overline{g}) \end{aligned}$$

which is welfare under the quota regime.

Notice that the only case in which the quota regime delivers higher welfare is when $i \in (\underline{i_T}, i_T)$ and $c < \frac{1+\sqrt{17}}{8}b$. In this case, there is R & D under the tax but not under the quota regime. But R & D in the tax regime can be prevented simply by taxing R & D sufficiently. This will render welfare under the tax regime the same as under the quota regime. We conclude that under all parameter values social welfare is higher, or at least no lower, in the tax regime than in the quota regime:

Proposition 6 *Suppose Assumption 3.1 holds. When $c > \frac{1+\sqrt{17}}{8}b$ and $i < i_T$, or when $c < \frac{1+\sqrt{17}}{8}b$ and $i < \underline{i_T}$, then social welfare is higher in the tax regime than in the quota regime. In all other cases, assuming that R & D is appropriately taxed or subsidized, social welfare is the same in the two regimes.*

This proposition suggests that the tax regime (weakly) dominates the quota regime in welfare terms, but this conclusion does not follow if Assumption 3.1 is dropped. Consider the limiting case $c = 0$. We know from Proposition 1 that there cannot be R & D in the tax regime, while from Proposition 4 we know that there will be R & D in the quota regime for $i < i_Q$. Applying an argument similar to the proof of Proposition 5, it is easy to see that there exists a threshold level of i, call it $\underline{i_Q}$ $(< i_Q)$, below which the occurrence of R & D with $g = 0$ is welfare-superior to there being no R & D. For $i < \underline{i_Q}$, the quota regime thus delivers higher welfare than the tax regime. Thus, for $c = 0$, the quota regime weakly dominates the tax regime in welfare terms.

5 Conclusion

Technological innovation in the energy sector is clearly of central importance in any strategy to avoid too much climatic change. In this respect, the climate problem is distinct from many environmental problems in that it is probably more feasible to replace existing technologies entirely than to reduce their emission intensity. Accordingly, we have departed from most of the literature on innovation in environmental economics and modeled the incentive to conduct R & D to lower the cost of such replacements. We have done this in a context in which the government is unable to commit to the future level of any policy instrument (although it is committed to the choice of instrument). This is quite a realistic assumption, given the fairly long delay to be expected between the decision to conduct R & D and the arrival of the resulting technology in the market. We consider a single innovator. This model can be thought of as a benchmark from which various extensions with more than one innovator can be explored in future research.

We find that when the slope of marginal cost c of the dirty technology is zero, then an emissions tax can never induce R & D because the innovator's profit is wiped out by the tax being reduced to the level of the innovator's marginal cost. A tax can be effective in inducing R & D only if c is positive so that the innovator has some monopoly power *ex-post*. Since an emissions quota with tradeable permits does give the innovator monopoly power, it can induce R & D even for $c = 0$. However, for large enough c, a tax may induce R & D in circumstances in which a quota will not. This can happen when it is somewhat costly to use R & D expenditure to lower the marginal cost g of the green technology.

For c large enough relative to the slope of inverse demand b, subsidies to R & D can be welfare-improving in conjunction with either a tax or a quota. An interesting finding is that committing to a particular level of a tax or a quota is inferior to subsidizing (or taxing) R & D and not committing. Of course, this may not be true if the deadweight losses from financing the subsidy are sufficiently large.

An emissions tax gives the innovator less monopoly power than an emissions quota with tradable permits. Thus, the tax leads to higher social welfare provided c is large enough for the innovator to get enough monopoly power in the tax regime to be induced to innovate.

There are two factors not considered in this paper that strengthen the case for R & D subsidies. First, since increasing marginal extraction costs in fossil fuel industries give rise to rents, it is to be expected that rentiers will lobby to protect their rents. This introduces uncertainty about whether there will be any climate policy when the results of R & D are realized. Datta and Somanathan (2010) show that in the presence of such uncertainty, a subsidy to R & D, because it takes effect in the present rather than the future, becomes a more attractive policy instrument. Second, since this paper was focusing on the environmental externality, the externalities from research and development were not modeled. Standard theory suggests that taking this public-good nature of R & D into account makes R & D subsidies more attractive, for example, in the form of basic research that lowers the innovators cost of research.

The paper has considered only a single final good - energy. There are, of course, several forms of energy services that are sometimes complementary and sometimes substitutes. In this context, the game between innovators during the R & D stage and market structure in the output markets remains to be studied. The role of R & D spillovers between innovators in green technologies is another area for further research. Finally, careful modeling of political economy and lobbying in the context of rents in both dirty and green industries would be interesting.

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APPENDICES

A Proof of Proposition 2.

Differentiating 3.8 with respect to g,

$$\frac{d\Pi(g)}{dg} = \frac{(b+c)}{2bc}\left[\frac{ac+bt}{b+c} - g\right]\left[\frac{b}{b+c}\frac{dt(g)}{dg} - 1\right] + 2i(\overline{g} - g), \tag{A.1}$$

$$\text{where} \quad \frac{dt(g)}{dg} = -\frac{b+c}{b+4c}.$$

Substituting, we get:

$$\frac{d\Pi(g)}{dg} = -\frac{2(b+c)(b+2c)^2}{bc(b+4c)^2}[P_d^*(\delta) - g] + 2i(\overline{g} - g), \tag{A.2}$$

$$\text{and} \quad \frac{d^2\Pi(g)}{dg^2} = \frac{2(b+c)(b+2c)^2}{bc(b+4c)^2} - 2i. \tag{A.3}$$

Note that:

$$\left.\frac{d\Pi(g)}{dg}\right|_{g=P_d^*(\delta)} > 0. \tag{A.4}$$

If the net profit curve is concave, inequality (A.4) ensures that in the range $[0, P_d^*(\delta)]$, $g = P_d^*(\delta)$ gives the lowest net loss. Thus, when $\Pi(g)$ is concave, the only choice of g that can give non-negative net profits is $\overline{g}$. Thus $\overline{g}$ is the global optimum.

If the net profit curve is convex, then in the range $[0, P_d^*(\delta)]$, there are two candidates for a maximum: 0 and $P_d^*(\delta)$. We know that at $g = P_d^*(\delta)$, net profit is negative. Thus, we are left with just two candidates for maximum: 0 and $\overline{g}$.

$\overline{g}$ is preferred iff i is greater than the level of i at which

$$\begin{aligned} \Pi(0) &= 0, \\ \text{or,} \quad i &= \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \qquad \text{(A.5)} \\ &\equiv i^T \qquad \text{(A.6)} \end{aligned}$$

Hence, in equilibrium,

$$g = \begin{cases} 0, & \text{if} \quad i \leq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2} \\ \overline{g}, & \text{if} \quad i \geq \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}. \end{cases} \tag{A.7}$$

B Proof of Proposition 3.

To complete the proof in the text, we now show that $\triangle FGB > \triangle EFJ$ in Figure 5 iff $4c^2 - bc - b^2 > 0$. Consider Figure 5.

$$\begin{aligned}
\triangle EFJ &= \frac{1}{2}.(EJ).(EF) \\
&= \frac{1}{2}.[P(0,t(0)) - (\delta + ce_d(0,t(0)))].\left[\frac{P(0,t(0)) - \delta}{c} - e_d(0,t(0))\right] \\
&= \frac{1}{2}.\frac{ac+b\delta}{b+4c}.\frac{ac+b\delta}{c(b+4c)} \\
&= \frac{1}{2c}\left(\frac{ac+b\delta}{b+4c}\right)^2. \qquad \text{(B.1)}
\end{aligned}$$

$$\begin{aligned}
\triangle FGB &= \frac{1}{2}.FG.[\text{Perpendicular distance of edge } FG \text{ from } B] \\
&= \frac{1}{2}.\left[D(P(0,t(0))) - \frac{P(0,t(0)) - \delta}{c}\right].[P_d^*(\delta) - P(0,t(0))] \\
&= \frac{1}{2}.\frac{2(ac+b\delta)}{b(b+4c)}.\frac{2c(ac+b\delta)}{(b+c)(b+4c)} \\
&= \frac{2c}{b(b+c)}\left(\frac{ac+b\delta}{b+4c}\right)^2. \qquad \text{(B.2)}
\end{aligned}$$

$$\text{Therefore,} \quad \triangle FGB - \triangle EFJ = \left(\frac{ac+b\delta}{b+4c}\right)^2.\left[\frac{2c}{b(b+c)} - \frac{1}{2c}\right]. \qquad \text{(B.3)}$$

Thus, $\triangle FGB - \triangle EFJ$ is positive iff $4c^2 - bc - b^2 > 0$, or, $c > \frac{1+\sqrt{17}}{8}b$.

So, the arguement made in the text leading upto Proposition 2 shows that a welfare improving subsidy exists iff $4c^2 - bc - b^2 > 0$. Now suppose, $4c^2 - bc - b^2 > 0$. In this case, $w(0) - w(\overline{g}) > \pi(0) = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}$.

Now, an R & D subsidy can be welfare improving if $i \geq i_T$ and $w(0) - i\overline{g}^2 \geq w(\overline{g})$. The last inequality can be re-written as $i \leq \frac{w(0)-w(\overline{g})}{\overline{g}^2}$.

Now,

$$\begin{aligned} w(0)-w(\overline{g}) &= \text{Area of } \quad EKLG + \text{Area of } \triangle FGB - \text{Area of } \triangle EFJ \\ &= P(t(0),0).e_g(t(0),0) + \text{Area of } \triangle FGB - \text{Area of } \triangle EFJ \\ &= \frac{(ac+b\delta)^2(b+2c)^2}{bc(b+c)(b+4c)^2} + \left[\left(\frac{ac+b\delta}{b+4c}\right)^2 \cdot \left[\frac{2c}{b(b+c)} - \frac{1}{2c}\right]\right] \\ &= \frac{(b+3c)(ac+b\delta)^2}{2bc(b+c)(b+4c)}. \end{aligned}$$

Thus, $\frac{(b+3c)(ac+b\delta)^2}{2bc\overline{g}^2(b+c)(b+4c)}$ is the highest level of i for which a subsidy that encourages R & D can be welfare-improving.

C Proof of Proposition 4.

Differentiating 4.8 with respect to g,

$$\frac{d\Pi}{dg} = -\frac{8(b+c)}{b(b+4c)^2}[P_d^*(\delta)-g] + 2i(\overline{g}-g),$$

$$\text{So} \quad \frac{d\Pi}{dg}\Big|_{P_d^*(\delta)} = 2i(\overline{g}-P_d^*(\delta)) > 0 \tag{C.1}$$

$$\frac{d^2\Pi}{dg^2} = \frac{8(b+c)}{b(b+4c)^2} - 2i.$$

Now suppose the net profit curve is concave in the range $[0, P_d^*(\delta))$. (C.1) implies that $P_d^*(\delta)$ maximizes net profit in this range. We know that net profit is negative at $P_d^*(\delta)$. Thus $\overline{g}$ is the profit-maximizing level of g when the profit function (4.8) is concave.

If the net profit curve is convex in the range $[0, P_d^*(\delta))$, there are two candidates for a maximum in the range $[0, P_d^*(\delta))$: 0 and $P_d^*(\delta)$. We know that net profit is negative at $P_d^*(\delta)$. Thus $\overline{g}$ and 0 are the two candidates for a global maximum.

We know that net profit is zero when $g = \overline{g}$. The net profit at $g = 0$ is as follows:

$$\begin{aligned} \Pi(0) \quad &= \quad \frac{4(ac+b\delta)^2}{b(b+4c)^2} - i\overline{g}^2 \geq 0 \\ \text{if} \quad i \quad &\leq \tfrac{4(ac+b\delta)^2}{b(b+4c)^2\overline{g}^2} \equiv i_Q. \end{aligned}$$

By Proposition 2,

$$i^T = \frac{(b+2c)^2(ac+b\delta)^2}{bc\overline{g}^2(b+c)(b+4c)^2}.$$

$$\text{Therefore,} \frac{i^T}{i^Q} = \frac{(b+2c)^2}{4c(b+c)} > 1.$$

D proof of Proposition 5

Figure 11 depicts the case $c > \frac{b}{2}$. As in the proof of Proposition 3, a welfare-improving subsidy exists for i greater than and sufficiently close to i_Q iff $w(0) - w(\overline{g}) - \pi(0) > 0$. An examination of the figure reveals that $w(0) - w(\overline{g}) - \pi(0) > 0$ iff $\triangle LIF > \triangle ALB$. We now show that $\triangle LIF > \triangle ALB$ iff $c > \frac{5}{4}b$. Note that

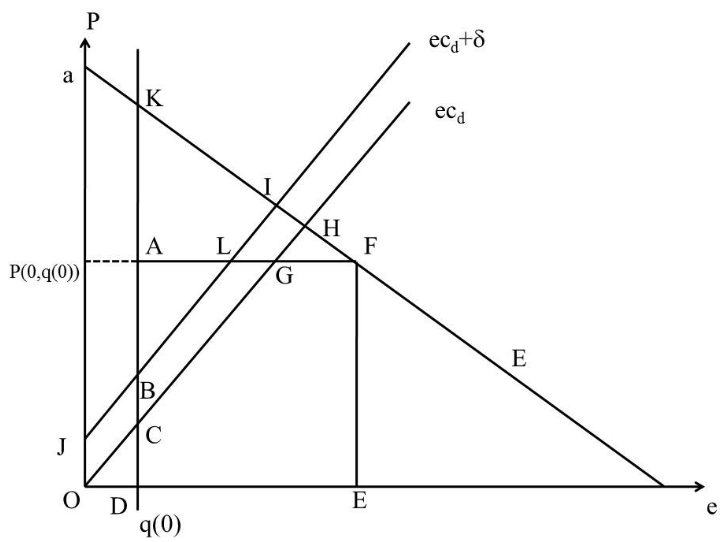

Figure 11: Government's reaction Function

$$P(g, q(g)) = \frac{2(ac + b\delta) - (b - 2c)g}{b + 4c}.$$

The marginal social cost of producing $q(0)$ units of dirty energy is

$$\begin{aligned} c\,(q(0)) + \delta &= c\left(\frac{a - 4\delta}{b + 4c}\right) + \delta \\ &= \frac{ac + b\delta}{b + 4c} \\ &= \frac{1}{2}P(0, q(0)). \end{aligned}$$

Now,

$$P_d^*(\delta) - P(0, q(0)) = \frac{(2c-b)(ac+b\delta)}{(b+c)(b+4c)} > 0.$$

$$\begin{aligned}
\text{The area of } \triangle ALB &= \frac{1}{2}AB.AL \\
&= \frac{1}{2}[P(0,q(0)) - (c\,(q(0)) + \delta)].[S_1(P(0,q(0)) - \delta) - q(0)] \\
&= \frac{1}{2c}\left(\frac{ac+b\delta}{b+4\delta}\right)^2.
\end{aligned}$$

$$\begin{aligned}
\text{The area of } \triangle LIF &= \frac{1}{2}FL.[\text{Perpendicular distance from vertex I}] \\
&= \frac{1}{2}[D(P(0,q(0))) - S_1(P(0,q(0)) - \delta)].[P_d^*(\delta) - P(0,q(0))] \\
&= \frac{(ac+b\delta)^2(2c-b)^2}{2bc(b+c)(b+4c)^2}.
\end{aligned}$$

Therefore, $\triangle LIF < \triangle ALB$ iff $c < \frac{5}{4}b$. Thus, if $c < \frac{5}{4}b$, there can be no welfare-improving subsidy.

Let $c > \frac{5}{4}b$. An R & D subsidy can be welfare improving if $i \geq i_Q$ and $w(0) - i\overline{g}^2 \geq w(\overline{g})$. The last inequality can be re-written as $i \leq \frac{w(0)-w(\overline{g})}{\overline{g}^2}$.

Now,

$$\begin{aligned}
w(0) - w(\overline{g}) &= BDEF \\
&= AFED + \triangle LIF - \triangle ALB \\
&= \frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)}
\end{aligned}$$

Thus, $\frac{3(ac+b\delta)^2}{2b(b+c)(b+4c)\overline{g}^2}$ is the highest level of i for which a subsidy that ensures $g = 0$ is welfare improving.