Climate Policy and Innovation in the Absence of Commitment

Ashokankur Datta, E. Somanathan

Abstract: We compare the effects 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 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 socially optimal after the results of R&D are realized. The equivalence of price and quantity instruments in inducing innovation that is seen in end-of-pipe abatement models does not hold. When the marginal cost of the dirty technology is constant, then a quota can induce R&D, but a tax is completely ineffective. However, if the marginal cost function of the dirty technology is steep enough, then both a tax and a quota with tradable permits can induce R&D, and the tax will do so in a wider range of circumstances. Furthermore, in this case, an R&D subsidy may induce R&D and raise welfare whether a tax or a quota regime is in place.

JEL Codes: O31, O38, Q54, Q55

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THE IPCC has made it clear that emission reduction is not enough to avoid dangerous climate change. Zero or negative greenhouse gas emissions will be required this century (Edenhofer et al. 2014, chap. 6) to meet a 2-degree target. This puts the focus

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on climate policies that will induce R&D in zero-carbon technologies. Moreover, this has to be achieved in the absence of commitment by future governments to any given level of stringency in a policy. In this paper, 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 examine the conditions under which a subsidy to R&D can improve welfare when either of these instruments is in place.

While there is a considerable literature on the role of emission-reducing R&D (e.g., Kneese and Schulze 1975; Marin 1978; Downing and White 1986; Milliman and Prince 1989; Jung, Krutilla, and Boyd 1996; Denicolò 1999; Amacher and Malik 2002; Innes and Bial 2002; Montero 2002; Fischer, Parry, and Pizer 2003; Tarui and Polasky 2005; Kolstad 2010), 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. But, as noted above, 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 (2007) 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 nonappropriability 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 those of Montgomery and Smith (2007).

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 charge any price 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 the level of a policy but compares tax and quota policies and examines the role that R&D subsidies can play. We examine the increasing marginal cost case and show that this changes the first result—a pollution tax can induce R&D.

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

It is also instructive to compare our results with those of Denicolò (1999), who 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. Denicolò 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. Denicolò 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. This result appears in end-of-pipe abatement models because the production technology is unchanged by R&D. In these models, R&D only shifts the marginal abatement cost curve. In contrast, we show that in our framework, taxes and quotas do not, in general, induce the same level of R&D. In fact, when the marginal cost of the dirty technology is constant (as assumed by Denicolò (1999)), a tax can never induce R&D while a quota can do so. The underlying reason why our results are different is that in our model, ex post there are two targets—emissions and total energy, or equivalently, dirty and clean energy—but only one instrument available. In the standard model there is only one technology in use ex post and one instrument is enough to deal with it.

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, public-sector R&D that can be used by the private sector or an increased supply of PhDs in relevant disciplines promoted by government funding. We ask when an R&D subsidy can improve welfare when either a tax or a quota with tradable permits is in place.

In section 1, we lay out the structure of our model. In section 2, we analyze the limiting special case of a constant marginal cost of dirty (emission-producing) energy. In section 2.1, we show that 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.

In section 2.2, 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 response induces R&D. Perhaps surprisingly, it is impossible for an R&D subsidy to improve welfare, and it may actually reduce it.

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. This is the case taken up in section 3. We find that now both the tax and the quota can induce R&D, with the tax doing so in a wider range of circumstances. 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 with only the incentive of an emissions tax or a quota with tradable permits.

Thus, whether an R&D subsidy is welfare improving depends both on the choice of instrument that is used ex post and on the shape of the cost curve of the dirty technology. In contrast, in an end-of-pipe abatement model, these considerations are irrelevant—an R&D subsidy is welfare improving if the emissions price that yields the socially optimal level of emissions ex post leads to an insufficient incentive to conduct R&D in the first place (Golombek, Greaker, and Hoel 2010).

Section 4 concludes with some implications for further research.

1. 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

$$U(e) + y = ae - \frac{b}{2}e^2 + y, \tag{1}$$

subject to

$$Pe + y = Y, \tag{2}$$

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

$$P = D^{-1}(e) = \begin{cases} a - be & \text{if} \quad e < \frac{a}{b} \\ 0 & \text{if} \quad e > \frac{a}{b} \end{cases}. \tag{3}$$

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.

$$\text{The marginal cost of producing } e_d = ce_d. \tag{4}$$

So c denotes the slope of the dirty technology's marginal cost. In section 2, we analyze the special case $c = 0$ when 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 $t + ce_d$. When $c > 0$ the supply curve of dirty energy is

$$S_d(P) = \frac{P}{c}. \tag{5}$$

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

$$g(I) = \begin{cases} \bar{g} - \left(\frac{I}{i}\right)^{1/2} & \text{if} \quad 0 \leq I < i\bar{g}^2 \\ 0 & \text{if} \ \ I \geq i\bar{g}^2 \quad \text{where} \quad i > 0. \end{cases} \tag{6}$$

Therefore,

$$g'(I) < 0, \quad g''(I) > 0, \quad g(0) = \bar{g} > 0. \tag{7}$$

Equation (6) can also be written as

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

The term $1/i$ 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.[2] After observing the tax rate or the level of the quota, the green firm chooses its price and output. [3]

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 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

$$\Pi = \pi - I,$$

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:

$$w = ae - \frac{b}{2}e^2 + Y - \delta e_d - \frac{c}{2}e_d{}^2 - ge_g. \tag{8}$$

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 $\bar{g}$ is too high for it to be socially optimal to have any production of green energy.[4] These two assumptions can be written as:

2. 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 than the level of emissions, thus restricting the number of margins along which adjustment can take place.

3. 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.

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

Assumption 1:

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

where

$$P_d^*(t) = \frac{ac + bt}{b + c} \tag{9}$$

denotes the equilibrium price of dirty energy when there is no green energy produced and there is an emissions tax of t.

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 1 implies that $\bar{g} > \delta$. If $\bar{g} < \delta$, 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.

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

$$e_d^*(t) \equiv S_d(P_d^*(t) - t) = \frac{a - t}{b + c}. \tag{10}$$

2. HORIZONTAL SUPPLY OF DIRTY ENERGY

Most papers in the literature make the assumption that $c = 0$ (e.g., Laffont and Tirole 1996; Denicolò 1999; Montgomery and Smith 2007). We start with this special case.

2.1. The Tax Regime

The government and the green firm play a sequential game with three stages,

1. The green firm chooses investment I that results in a marginal cost g of green energy.
2. The government chooses an emissions tax rate t.
3. The green firm chooses its price and output.

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 $\bar{g} > \delta$) in the first stage. Then the social marginal cost of green energy is greater than that of dirty energy. 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 $g = \bar{g}$.

If $g \leq \delta$, then the optimal tax is infinitesimally greater than g. 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. QED

We remark that linearity of demand and of the damage from emissions are not required for this argument.

When dirty energy supply is flat, the optimal tax falls with g, wiping out the incentive to do R&D.[5] This is not the case in models of end-of-pipe abatement such as that of Denicolò (1999). Ex post emissions taxation does not eliminate R&D in those models because they 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.

2.2. The Quota Regime

The government and the green firm play a sequential game with three stages,

1. The green firm chooses an investment that results in a marginal cost g of green energy.
2. The government chooses an emissions quota q.
3. The green firm chooses its price and output.

We begin with the third stage in which g and q have been chosen. Suppose $q \geq D(g)$ for some $g \geq 0$. Then the price of tradeable emissions permits will be $D^{-1}(q)$ and the dirty sector can supply energy at a price less than the green firm's cost. Thus the green energy firm will not produce. The price of energy will be $D^{-1}(q)$, and energy produced will be equal to the level of the quota.

Now suppose $q < D(g)$ for $g \geq 0$ (see fig. 1). The green firm faces a residual demand curve of $D(P) - q$ for P in the relevant range $D^{-1}(q) \geq P \geq 0$. It acts as a monopolist in this market and chooses e_g to maximize

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

The gross profit 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

5. It can be shown that the decision of the green firm not to invest in R&D is the limiting case as c gets close to zero. A proof is available from the authors on request.

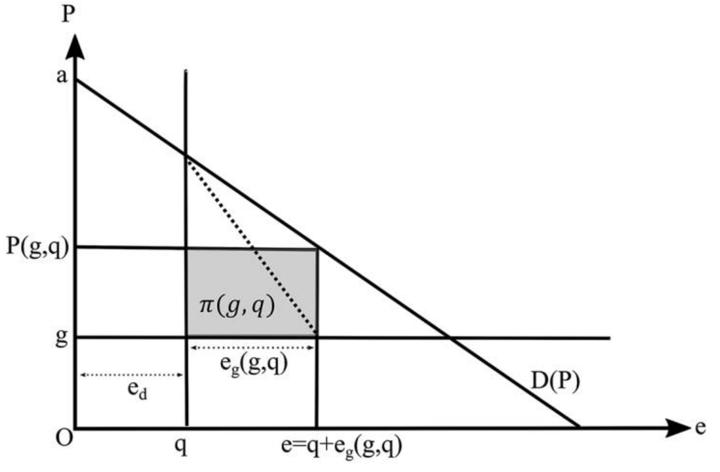

Figure 1. Quota regime: $q < D(g)$

$D^{-1}(q)$. Thus the output of clean energy and total energy, the price of energy, and the profit of the green firm are, respectively:

$$e_g(g,q) = \frac{1}{2}[D(g) - q] = \frac{a - bq - g}{2b}, \tag{11}$$

$$e(g,q) = \frac{1}{2}[D(g) + q] = \frac{a + bq - g}{2b}, \tag{12}$$

$$P(g,q) = \frac{1}{2}(D^{-1}(q) + g) = \frac{a - bq + g}{2}, \tag{13}$$

$$\pi(g,q) = \frac{1}{4}[D(g) - q][D^{-1}(q) - g] = \frac{(a - bq - g)^2}{4b}. \tag{14}$$

Moving one step back in the game, we turn to the government's choice of q. Recall assumption 1, which reduces to $\bar{g} > \delta$ since we are in the case $c = 0$. If $\bar{g} < \delta$, there would be no emissions problem, only a problem of making emission control less expensive.

If in stage 1, the green firm had chosen I so that $g > \delta$, the social marginal cost of green energy would be greater than that of dirty energy, and it would be inefficient to allow the green firm to operate. So the optimal $q \geq D(g)$. Optimality is attained at $q = D(\delta)$ where the marginal social cost of dirty energy equals the marginal social benefit from energy consumption.

Now consider the case $g < \delta$. Now the marginal social cost of green energy is lower than that of dirty energy. While a larger quota brings a welfare gain from higher consumption of energy, it inflicts a welfare loss due to increased emissions. The government chooses the quota taking this trade-off into account.

The net marginal social benefit of increasing the quota is

$$\begin{aligned} &\frac{\partial e}{\partial q}(P(q,g) - g) - (\delta - g) \\ &= \frac{1}{2}\left[\frac{1}{2}(D^{-1}(q) - g)\right] - (\delta - g). \end{aligned} \tag{15}$$

This is depicted in figure 2 for $q = D(\delta)$. $(1/2)(D^{-1}(q) - g)$ ($= KL$ in fig. 2) is the marginal gain in social surplus when energy consumption rises in response to the increase in q while $\delta - g$ ($= IJ$ in fig. 2) is the marginal increase in the social cost of energy as dirty energy replaces clean energy. The net marginal social benefit of increasing the quota is clearly negative at $q = D(\delta)$ and decreasing in q. Thus the optimal $q < D(\delta)$.

Setting the expression (15) equal to zero, we find that the optimal quota is given by

$$q(g) = \begin{cases} D(\delta), & \text{if} \quad g \geq \delta \\ \max\left\{\dfrac{a + 3g - 4\delta}{b}, 0\right\} & \text{if} \quad g < \delta. \end{cases} \tag{16}$$

It is clear from this that if g falls, then q must also fall to restore equality (as long as q remains positive). Thus, in contrast to the tax regime, a fall in g induces a tightening of the emissions quota, thus reinforcing the incentive for the green firm to conduct R&D.

From now on, we ignore corner solutions in q for the sake of simplicity. In other words, we assume that the externality from emissions is not high enough to justify setting a zero quota. It follows from (16) that the required assumption is

Assumption 2: $a > 4\delta$.

Substituting (16) into (12) yields

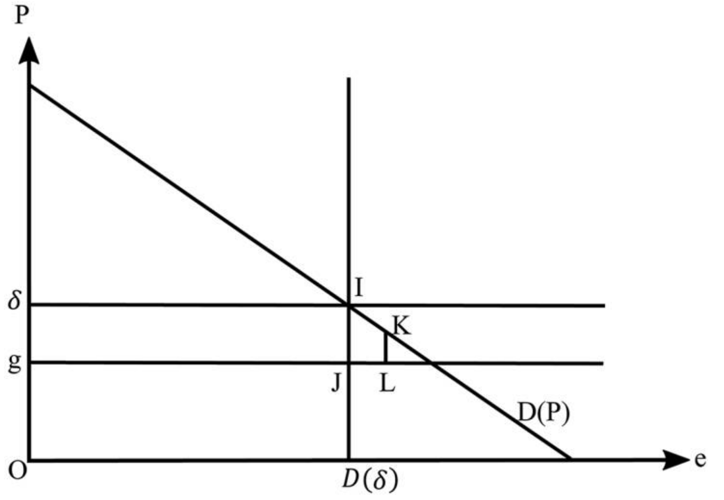

Figure 2. Quota regime: Suboptimality of $q = D(\delta)$ when $g < \delta$

Remark 1: Total energy consumption must fall when g falls below δ.

As will be seen shortly, this fact has important implications for the welfare effects of an R&D subsidy.

We now turn to the first stage of the game, the optimal choice of investment (and marginal cost) by the green firm given the reaction function (16) of the government.

The green firm's net profit function is

$$\begin{aligned}\Pi(g) &= \pi(g, q(g)) - I(g)\\ &= \frac{4}{b}(\delta - g)^2 - i(g - \bar{g})^2 \qquad \text{(using [14] and [16])},\\ &< 0 \qquad \text{at } g = \delta.\end{aligned}$$

Now

$$\Pi'(g) = -\frac{8}{b}(\delta - g) - 2i(g - \bar{g}) > 0 \qquad \text{at } g = \delta.$$

Unless the positive slope of Π at $g = \delta$ is reversed at a lower value of g, investment in R&D is ruled out. Now

$$\Pi''(g) = \frac{8}{b} - 2i.$$

It follows immediately that R&D can take place only if Π is convex and, therefore, if and only if $\Pi > 0$ at $g = 0$. This argument is summarized in

Proposition 2: The quota regime induces R&D with $g = 0$ provided the marginal cost of green energy is sufficiently sensitive to R&D investment, that is, if (and only if) $i < 4\delta^2/b\bar{g}^2$.

This is illustrated in figure 3. Thus, provided investment in R&D is not too costly, the quota regime will induce R&D while the tax regime will not. This last statement will be true even with a nonlinear demand function and a convex damage function. To see this, note that for any g below the intersection of the demand and marginal damage functions, the government will always do better to set a binding quota at this intersection than to set a nonbinding quota. The reason is that, compared to no policy, this unambiguously reduces dirty energy when its marginal damage is greater than its marginal benefit. But such a quota guarantees the green firm a positive gross profit and, hence, also a positive net profit if i is sufficiently small.

2.3. R&D Subsidies and Social Welfare

We now ask whether a government subsidy for R&D would improve social welfare under each regime. When the rate of subsidy is s, the amount the green firm has to

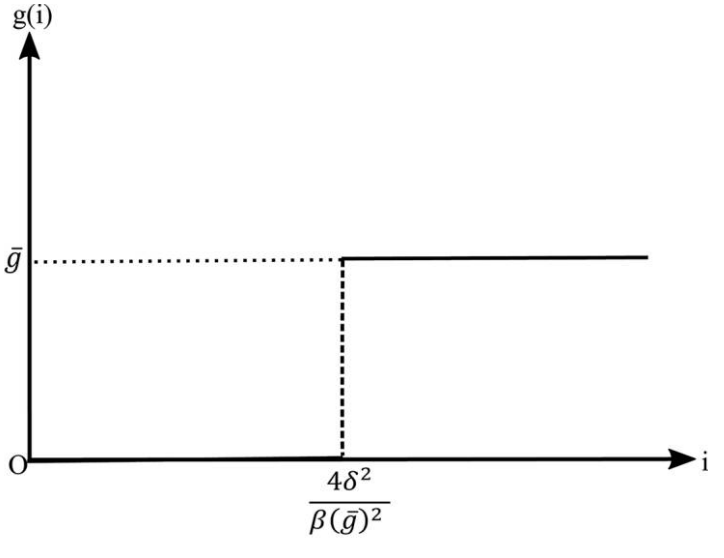

Figure 3. Optimal choice of g in the quota regime

spend on R&D in order to achieve a marginal cost g becomes $(1-s)i(g-\bar{g})^2$. Thus, a subsidy reduces the effective i for the green firm. It can have no effect in a tax regime (as long as $s < 1$ which we assume), since any expenditure at all is sufficient to deter the firm from conducting R&D. In a quota regime, it is clear from proposition 2 that it will have an effect if and only if it moves the effective i for the firm below the threshold $4\delta^2/b\bar{g}^2$. At this threshold value of i, the firm is indifferent between conducting R&D and not doing so. That is $\Pi(0) = \Pi(\bar{g}) = 0$. Therefore, its gross profit if it conducts R&D, $\pi(0)$, must equal $i\bar{g}^2$, the social cost of R&D at the threshold level of i.

Hence, welfare will be raised by inducing the firm to conduct R&D if and only if the social return to R&D, $w(0) - w(\bar{g})$, exceeds $\pi(0)$, the private return to R&D.

These two quantities are easily compared in figure 4. In drawing this figure with $e(0)$, the total energy supplied when $g = 0$, being less than the total energy supplied when $g = \bar{g}$, we make use of remark 1. In figure 4, $\pi(0)$ is the area of the rectangle $ADIH$. The expression $w(0) - w(\bar{g})$ is the social surplus from dirty energy (area $aBE\delta$) plus the social surplus from green energy (area $BDIH$) less the social surplus from dirty energy when there is no R&D (area of $\Delta aG\delta$). This equals area $EFIH$—the area of ΔDFG which is clearly less than $\pi(0)$. We conclude that

Proposition 3: In a tax regime, an R&D subsidy is ineffective (has no impact on R&D). Under a quota regime, an R&D subsidy is either ineffective or, if effective, reduces welfare.

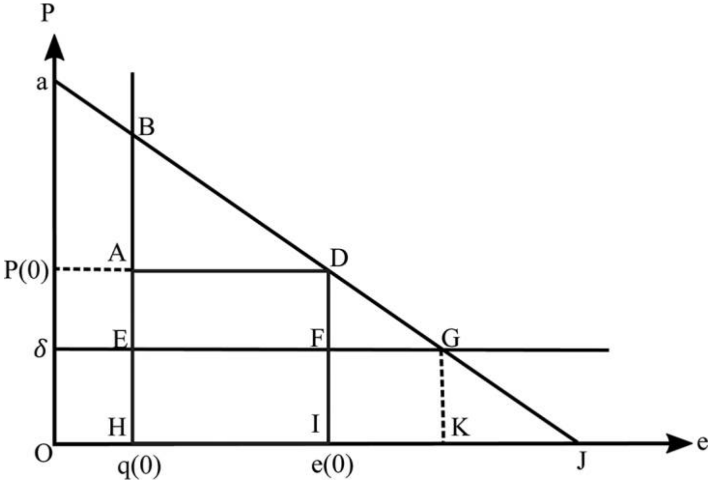

Figure 4. Welfare analysis of tax and quota regimes

It is clear from this argument that if i is only slightly less than the threshold value given in proposition 2, then R&D will occur under a quota regime despite it being welfare reducing. This is a consequence of the government's inability to commit itself to not imposing a quota once g has been chosen. As discussed in the introduction, we believe this is realistic. If the government could commit to a particular $q(g)$ for each possible value of g, then many more outcomes become implementable. Exploring this further is beyond the scope of this paper.

Finally, one may ask whether social welfare is indeed higher under the quota regime than under the tax regime when R&D is sufficiently cheap (that is, i is sufficiently small). The answer is yes and we record this as

Proposition 4: A quota regime that induces R&D results in higher welfare than a tax regime (that never induces R&D) provided the marginal cost of green energy is sufficiently sensitive to R&D investment, that is, if

$$i < \frac{3}{2}\frac{\delta^2}{b\bar{g}^2}.$$

If

$$\frac{3}{2}\frac{\delta^2}{b\bar{g}^2} < i < \frac{4\delta^2}{b\bar{g}^2},$$

then welfare is lower in the quota regime than in the tax regime.

Proof: Welfare is higher under the quota regime than under the tax regime iff the area *EFIH*—the area of ΔDFG in figure 4 is positive. It is easily checked using (11)–(13) and (16), that this is the case iff

$$i < \frac{3}{2}\frac{\delta^2}{b\bar{g}^2}.$$

QED

As an aside, if we suppose that the government is not committed even to the choice of instrument, then it is easy to see, looking at figure 4, that it will always choose a tax if R&D occurs. But this, of course, would guarantee that R&D would not occur.

3. STEEP MARGINAL COST OF DIRTY ENERGY

We turn to the more realistic case when $c > 0$.

3.1. Tax Regime

In the previous section, we saw that if the green firm's marginal cost g ever falls below the marginal social damage of emissions δ, then it is optimal for the government to set a tax that eliminates the dirty sector. Whether or not to eliminate the dirty sector is an all-or-nothing choice in the tax regime when $c = 0$. As we will see in this section, with $c > 0$, the government can, by its choice of the tax rate, determine how much of the dirty sector will survive. In fact, for c large enough, it is never optimal for the government to set a tax high enough to eliminate the dirty sector entirely. This is the case we now discuss. It is shown in appendix A that the required assumption is

Assumption 3:

$$c > \frac{b(2\delta + \sqrt{a\delta})}{(a - 4\delta)}.$$

Referring to figure 5, $P_d^*(\delta)$ is the price of energy that would prevail if there were no green firm and emissions were optimally taxed by setting $t = \delta$. Clearly, for any $g > P_d^*(\delta)$ the optimal tax is just δ, and the green firm will not produce. So let us consider a value of $g < P_d^*(\delta)$ as in the figure. Suppose the tax is then set at some t as in the figure.

The green firm can get a positive market share by pricing its energy anywhere between g and $P_d^*(t)$. For any given price P, the dirty sector produces $(P - t)/c$ denoted by $e_d(g, t)$ in figure 5, 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

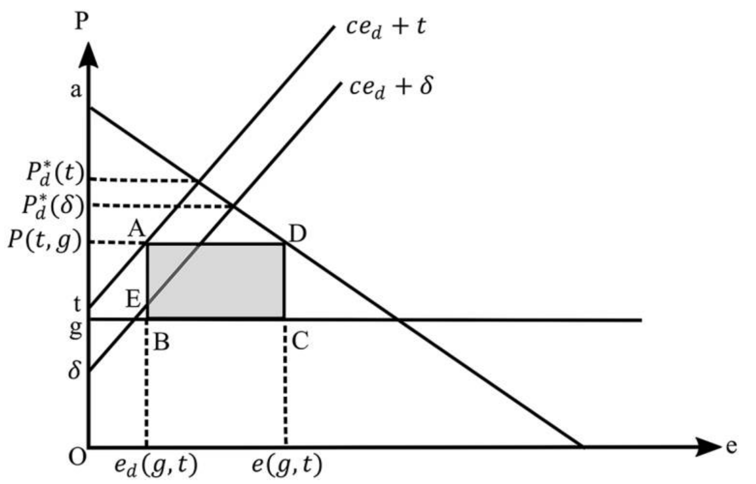

Figure 5. Price determination in a tax regime

profit-maximizing price $P(g, t)$, which (it is easy to show) is the average of g and $P_d^*(t)$. Green energy produced is $e(g, t) - e_d(g, t)$. The green firm's gross profit π is shown by the rectangle shaded in gray.

Turning to the government's choice of t, we note that raising the tax results in a higher energy price. This shrinks total energy consumption and so also consumer surplus from energy consumption. However, a higher tax also results in less dirty energy produced.[6] The government sets the optimal tax by trading off these two effects. Unlike in section 2 in which the optimal tax chases g downward, it can be shown that here the government's optimal tax actually increases as g falls.

One can now see why R&D in the tax regime can occur in equilibrium. Suppose the green firm chooses $g < P_d^*(0)$. The worst possible tax from the green firm's point of view is $t = 0$. But even this will result in a positive gross profit. So if i is low enough, this will mean a positive profit net of the cost of R&D. Of course, when the tax is set to maximize social welfare, R&D will occur for a larger range of i. Clearly, this conclusion does not depend on the linearity of marginal benefit, marginal cost, and damage functions.

Proposition 5: In the tax regime with c large enough (assumption 3 holds), the marginal cost chosen by the green firm is

$$g = \begin{cases} 0, & \text{if} \quad i \le i_T, \\ \bar{g}, & \text{if} \quad i \ge i_T, \end{cases} \tag{17}$$

where

$$i_T \equiv \frac{(b + 2c)^2(ac + b\delta)^2}{bc\bar{g}^2(b + c)(b + 4c)^2}.$$

Proof: In appendix A. QED

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).[7] As explained above, the policy response reinforces this incentive. Figure 6 shows the optimal choice of g by the green firm.

6. $e_d(g, t) = (P - t)/c$ and P rises at a slower rate than t. This can be seen from figure 5. Consider a tax increase from δ to t as shown. Then $P_d^*(t) - P_d^*(\delta)$ is less than the tax increase, and since P is the average of $P_d^*(t)$ and g, it rises at half the rate that $P_d^*(t)$ does.

7. Reversing assumption 1 that $\bar{g} > P_d^*(\delta)$ implies a smoothly increasing $g(i)$ function for i large enough (see proposition 9 in Datta and Somanathan [2010]).

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 many end-of-pipe abatement models from Downing and White (1986) onward 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 these models since either can be used to generate the 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. As seen in section 2.3, 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 (17) ($c > [b(2\delta + \sqrt{a\delta})]/(a - 4\delta)$), when $i > i_T$, a large enough subsidy can reduce the effective i, that is, $(1 - s)i$ below i_T. In this case, a subsidy to R&D is effective in inducing R&D. Under what conditions will it improve welfare? The next proposition shows that it will do so when the supply curve of dirty energy is steep enough and R&D is not too expensive.

Proposition 6: In the tax regime, when assumption 3 is satisfied, then an R&D subsidy will induce investment and increase welfare if and only if $c > [(1 + \sqrt{17})/8]b$ and

$$i \in \left[i_T, \frac{(b + 3c)(ac + b\delta)^2}{2bc\bar{g}^2(b + c)(b + 4c)} \right].$$

Proof: See appendix B. QED

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 is satisfied and that $c > [(1 + \sqrt{17})/8]b$. 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

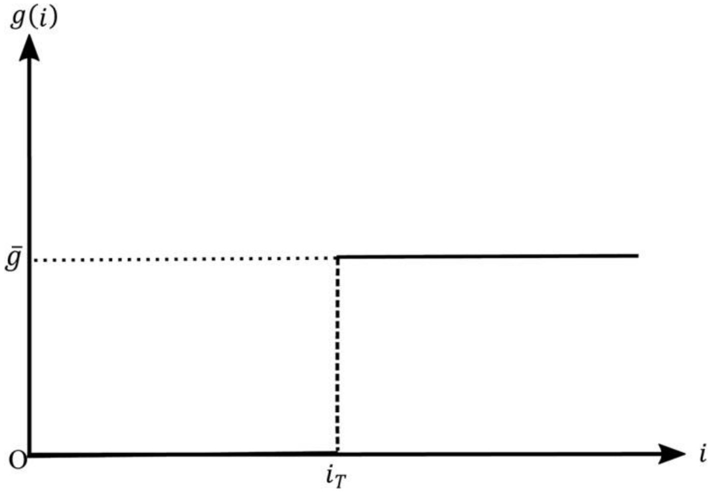

Figure 6. Equilibrium green marginal cost g as a function of i in the tax regime

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 itself 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.[8]

3.2. Quota Regime

The analysis of the quota regime when $c > 0$ is qualitatively similar to that in the case $c = 0$ except in two respects. First, when the supply curve of dirty energy is upward sloping, it is possible for the green firm to make a positive gross profit by choosing $g < P_d^*(0)$ even if there is no quota, or equivalently, if the quota is set high enough to be nonbinding. Hence, it can make a profit net of the cost of R&D if i is small enough.

Second, it is now possible for an R&D subsidy to increase welfare by inducing R&D when it would otherwise have not occurred. This is true when c is sufficiently large.

8. If the government could commit to any tax rate for each possible g, then it could induce the optimal g and ex post optimal t by the use of a trigger strategy. If the firm were to choose any g other than the one desired by the government, it would face a zero tax. We do not believe this is an interesting model.

Proposition 7: If $c > (5/4)b$, then there exists a range of i for which an R&D subsidy is welfare improving in the quota regime. The maximum value of i for which R&D takes place in the quota regime is less than i_T. For large enough c (that is, when assumption 3 holds), the tax regime induces at least as much R&D as the quota regime for every value of i.

Proof: See appendix C. QED

Figure 7 illustrates the set of (c, i) pairs (the region shaded in light gray) for which the tax regime delivers higher welfare than the quota regime, when there is no R&D subsidy. In this simulation, the other parameters have been set at the following values: $a = 100,\ b = 1,\ \bar{g} = 75,\ \delta = 10$. For these parameter values, the tax regime not only induces R&D for a larger set of the $(c,\ i)$ combinations, it also delivers higher welfare for a larger set of $(c,\ i)$ pairs than the quota regime. The threshold value of c above which assumption 3 holds is about 0.86.

In the white region, no R&D investment is made in either of the two regimes, so that welfare is equal in the two. Below the solid black curve, R&D occurs in the tax regime, and below the dashed black curve, it occurs in the quota regime. The solid

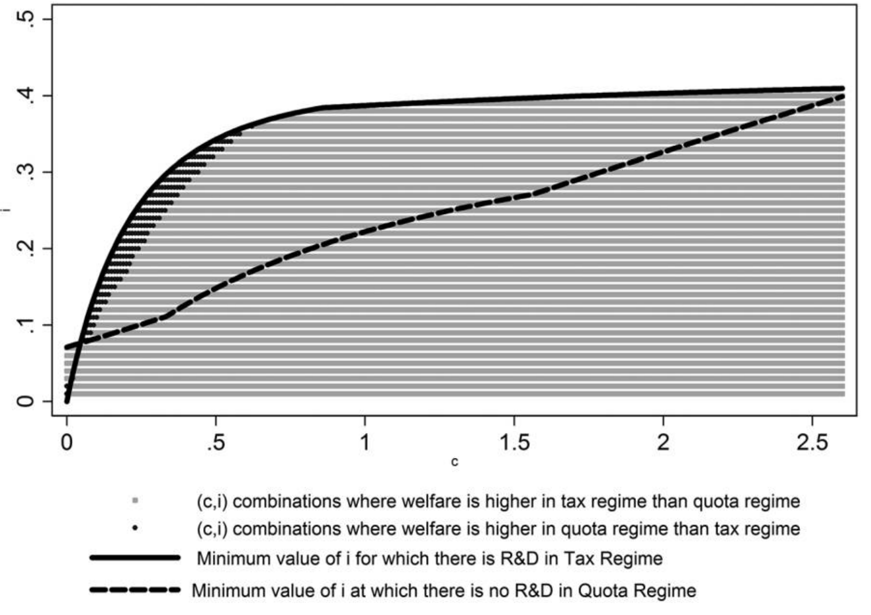

Figure 7. Tax and quota regimes compared

curve passes through the origin illustrating proposition 1 that there can be no R&D in the tax regime when $c = 0$. The dashed line has a positive vertical intercept in accordance with proposition 2, which states that R&D occurs in the quota regime in the flat supply case if i is small enough.

The region shaded in dark gray refers to (c, i) pairs for which welfare is higher in the quota regime than in the tax regime. It should be noted that the vertical axis is shaded in dark gray close to the origin, but not up to the cutoff value above which there is no R&D in the quota regime. This illustrates proposition 4—in the flat supply case, R&D in the quota regime lowers welfare unless the marginal cost of green energy is sufficiently sensitive to R&D investment.

4. 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.

Our results differ dramatically from those in end-of-pipe abatement models. In those models, the innovator chooses the reduction in emissions intensity of the dirty technology by investing in R&D. In the flat supply case, this means that the innovator will always choose an emissions intensity far enough from zero to ensure that the socially optimal tax is bounded away from zero. Thus, R&D will occur in the tax regime. Further, the fact that the new technology strictly dominates the old technology means that only the new technology will be used. Therefore, ex post, the government has only one target to meet with one instrument. It can, therefore, implement the first-best conditional on the existence of the new technology, and either a price or a quantity instrument will do. In our framework, since there are two technologies with different cost curves, there are two targets—emissions and energy output, and only one instrument available ex post. Thus, the first-best cannot be implemented and the instruments are not equivalent.

We have shown that when the slope of marginal cost c of the dirty technology is 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.

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 gives 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 innovator's 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. Since the welfare implications of the choice between a tax and a quota regime are related to the extent of market power the innovator gets, allowing for oligopoly may have implications for this choice. Finally, careful modeling of political economy and lobbying in the context of rents in both dirty and green industries would be interesting.

APPENDIX A

Proof of Proposition 5

Suppose the choice of R&D investment has been made by the green firm. If $g > P_d^*(\delta)$, the government chooses a tax equal to the marginal damage from emissions ($t = \delta$) and allows only the dirty sector to operate. Green energy is too costly to be produced.

Now suppose $g < P_d^*(\delta)$. Let $t_L(g)$ be the lowest (nonnegative) 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.[9] 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. Thus when $g < P_d^*(\delta)$, the government's optimal tax must lie in the interval $[t_L,\ t_H]$.

It can be shown that for $g \in [0,\ P_d^*(\delta))$ and $t \in [t_L(g),\ t_H(g))$, the optimal choice of price, energy consumption and gross profit by the firm is given by the following equations:

$$P(g,\ t) = \frac{1}{2}[g + P_d^*(t)], \tag{A1}$$

$$e(g,\ t) = \frac{1}{2}[e_d^*(t) + D(g)], \tag{A2}$$

$$e_d(g,\ t) = \frac{1}{2}[e_d^*(t) + S_d(g - t)], \tag{A3}$$

$$e_g(g,\ t) = \frac{1}{2}[D(g) - S_d(g - t)], \tag{A4}$$

$$\pi(g,\ t) = \frac{b + c}{4bc}[P_d^*(t) - g]^2, \tag{A5}$$

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

Substituting (A3) and A4) in (8), we obtain an expression for gross welfare in terms of t. It is not optimal for the government to choose $t = t_H$ if

$$\left.\frac{\partial w}{\partial t}\right|_{t=t_H} < 0 \quad \text{or} \quad g < \frac{\delta(b + 2c)^2 - ac^2}{(b + c)(b + 3c)}. \tag{A6}$$

We define $g_H \equiv [\delta(b + 2c)^2 - ac^2]/[(b + c)(b + 3c)]$. Assumption 3 ensures that $g_H < 0$. Thus t_H cannot be an optimal tax.

9. This is because, by definition, $t_L(g)$ must be less than δ.

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.

$$\begin{aligned}\text{The SMB of increasing the tax} &= \left|\frac{\partial e_d}{\partial t}\right|{}^{*}\text{SMB of replacing dirty with clean energy}\\ &= \left|\frac{\partial e_d}{\partial t}\right|{}^{*}(\delta + ce_d - g)\\ &= \left|\frac{\partial e_d}{\partial t}\right|{}^{*}EB \text{ (refer to fig. 5)},\end{aligned}$$

$$\begin{aligned}\text{and the SMC of increasing the tax} &= \left|\frac{\partial e}{\partial t}\right|{}^{*}\text{SMC of reducing energy consumption}\\ &= \left|\frac{\partial e}{\partial t}\right|{}^{*}(a - be - g)\\ &= \left|\frac{\partial e}{\partial t}\right|{}^{*}DC \quad \text{(refer to fig. 5)}.\end{aligned}$$

From (A2) and (A3), we see that $|\partial e_d/\partial t| > |\partial e/\partial t|$. 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 5, that t_L cannot be an optimal tax. Hence, the optimal tax is in $(t_L,\ t_H)$ and satisfies

$$(a - be)\frac{\partial e}{\partial t} = (\delta + ce_d)\frac{\partial e_d}{\partial t} + g\frac{\partial e_g}{\partial t}, \tag{A7}$$

where

$$\begin{aligned}\frac{\partial e_d}{\partial t} &= -\left(\frac{1}{2(b + c)} + \frac{1}{2c}\right),\\ \frac{\partial e_g}{\partial t} &= \frac{1}{2c},\\ \frac{\partial e_d}{\partial t} + \frac{\partial e_g}{\partial t} &= \frac{\partial e}{\partial t}.\end{aligned}$$

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

$$t(g) = \begin{cases} \dfrac{ac - (b + c)g + 2\delta(b + 2c)}{b + 4c}, & \text{if} \quad g \in [0,\ P_d^*(\delta)],\\[2ex] \delta, & \text{if} \quad g > P_d^*(\delta). \end{cases} \tag{A8}$$

The green firm chooses its level of R&D by taking the government's reaction function as given when maximizing net profit. The firm never chooses $g \in [P_d^*(\delta), \bar{g})$ 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 (A5) and subtracting the cost of investment in R&D:

$$\Pi(g) = \frac{b+c}{4bc}\left[\frac{ac+bt(g)}{b+c} - g\right]^2 - i(\bar{g}-g)^2. \tag{A9}$$

Differentiating (A9) with respect to g,

$$\frac{d\Pi(g)}{dg} = \frac{(b+c)}{2bc}\left[\frac{ac+bt}{b+c} - g\right]\left[\frac{b}{b+c}\frac{dt(g)}{dg} - 1\right] + 2i(\bar{g}-g),$$
$$\text{where} \quad \frac{dt(g)}{dg} = -\frac{b+c}{b+4c}. \tag{A10}$$

Substituting, we get

$$\frac{d\Pi(g)}{dg} = -\frac{2(b+c)(b+2c)^2}{bc(b+4c)^2}[P_d^*(\delta) - g] + 2i(\bar{g}-g), \tag{A11}$$

and

$$\frac{d^2\Pi(g)}{dg^2} = \frac{2(b+c)(b+2c)^2}{bc(b+4c)^2} - 2i. \tag{A12}$$

Note that

$$\left.\frac{d\Pi(g)}{dg}\right|_{g=P_d^*(\delta)} > 0. \tag{A13}$$

If the net profit curve is concave, inequality (A13) 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 nonnegative net profits is $\bar{g}$. Thus $\bar{g}$ 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 $\bar{g}$.

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

$$\Pi(0) = 0,$$
$$\text{or,} \quad i = \frac{(b+2c)^2(ac+b\delta)^2}{bc\bar{g}^2(b+c)(b+4c)^2} \tag{A14}$$

$$\equiv i_T \quad \text{(say)}. \tag{A15}$$

Hence, in equilibrium,

$$g = \begin{cases} 0, \text{ if} & i \leq i_T \\ \bar{g}, \text{ if} & i \geq i_T. \end{cases} \tag{A16}$$

APPENDIX B

Proof of Proposition 6

By proposition 5, at $i = i_T$, $\Pi(\bar{g}) = \Pi(0)$, so $\pi(0) = i\bar{g}^2$. Therefore, a welfare-improving R&D subsidy will exist for i greater than and sufficiently close to i_T if $W(0) - W(\bar{g}) > 0$ at $i = i_T$. The last condition will be met if, at $i = i_T$,

$$w(0) - i\bar{g}^2 - w(\bar{g}) > 0, \text{ or} \quad w(0) - w(\bar{g}) > \pi(0).$$

To find the conditions under which this will be true, first note that by (A8),

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

and by (A1) and A9,

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

This situation is depicted in figure B1. The expression $\pi(0)$ 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, $w(\bar{g}) = \Delta ABC$. Therefore,

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

Therefore,

$$w(0) - w(\bar{g}) - \pi(0) = \Delta FGB - \Delta EFJ.$$

Hence, a welfare-improving R&D subsidy will exist for i greater than and sufficiently close to i_T iff $\Delta FGB - \Delta EFJ > 0$. We now show that $\Delta FGB > \Delta EFJ$ in figure B1 iff $4c^2 - bc - b^2 > 0$. Consider figure B1.

$$\begin{aligned}\Delta EFJ &= \frac{1}{2}.(EJ).(EF)\\ &= \frac{1}{2}.[P(0,t(0)) - (\delta + ce_d(0,t(0)))].\left[\frac{P(0,t(0))-\delta}{c} - e_d(0,t(0))\right]\\ &= \frac{1}{2}.\frac{ac+b\delta}{b+4c}.\frac{ac+b\delta}{c(b+4c)}\\ &= \frac{1}{2c}\left(\frac{ac+b\delta}{b+4c}\right)^2.\end{aligned} \tag{B1}$$

$$\begin{aligned}\Delta FGB &= \frac{1}{2}.FG.[\text{Perpendicular distance of edge FG from B}]\\ &= \frac{1}{2}.\left[D(P(0,t(0))) - \frac{P(0,t(0))-\delta}{c}\right].\left[P_d^*(\delta) - P(0,t(0))\right]\\ &= \frac{1}{2}.\frac{2(ac+b\delta)}{b(b+4c)}.\frac{2c(ac+b\delta)}{(b+c)(b+4c)}\\ &= \frac{2c}{b(b+c)}\left(\frac{ac+b\delta}{b+4c}\right)^2.\end{aligned} \tag{B2}$$

Therefore,

$$\Delta FGB - \Delta EFJ = \left(\frac{ac+b\delta}{b+4c}\right)^2.\left[\frac{2c}{b(b+c)} - \frac{1}{2c}\right]. \tag{B3}$$

Thus, $\Delta FGB - \Delta EFJ$ is positive iff $4c^2 - bc - b^2 > 0$, or, $c > [(1+\sqrt{17})/8]b$.

Therefore, a welfare-improving subsidy to R&D exists for i greater than and sufficiently close to i_T iff $4c^2 - bc - b^2 > 0$. Now suppose, $4c^2 - bc - b^2 > 0$. In this case, $w(0) - w(\bar{g}) > \pi(0) = [(b+2c)^2(ac+b\delta)^2]/[bc\bar{g}^2(b+c)(b+4c)^2]$.

Now, an R&D subsidy can be welfare improving if $i \geq i_T$ and $w(0) - i\bar{g}^2 \geq w(\bar{g})$. The last inequality can be rewritten as $i \leq [w(0) - w(\bar{g})]/\bar{g}^2$.

Now,

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

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

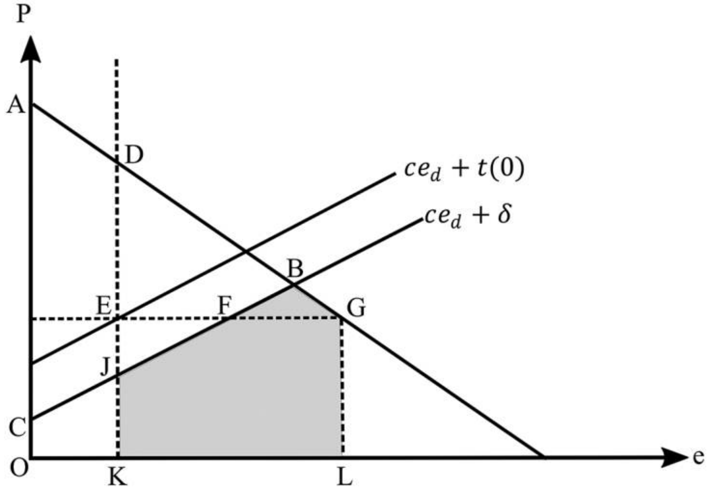

Figure B1. The welfare consequences of an R&D subsidy

APPENDIX C
Proof of Proposition 7

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 C1. The green firm chooses its output to maximize its profit given the residual demand curve for energy after the dirty sector has produced q.[10]

The profit function of the green firm is:

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

The profit 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 given by (11), (12), (13), and (14), respectively (refer to fig. C1).

10. It is clear that the quota must be less than $D(g)$. If not, then the green firm would be shut out of the market. So $q = e_d^*(\delta)$ would yield higher welfare.

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 $P = (1/2)[P_d^*(0) + g]$ and dirty energy production $e_d = (1/2c)[P_d^*(0) + g]$. 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 nonbinding quota. The reason is that setting a quota slightly less than $(1/2c)[P_d^*(0) + g]$ gives the green firm monopoly power. The resulting high energy price restricts total energy output so much that it is preferable to set a nonbinding quota and allow $e_d = (1/2c)[P_d^*(0) + g]$.

If $g < P_d^*(0)$ and the government's choice of q is from the interior of the interval $[0, (1/2c)(P_d^*(0) + g)]$, then the quota is binding, and optimal green energy production, total energy production, the price of energy, and the gross profit of the green firm are given by (11), (12), (13), and (14), respectively.

When $g \leq P_d^*(\delta)$ and the government is choosing a binding quota the gross welfare function is

$$w(g, q) = a\left(\frac{a + bq - g}{2b}\right) - \frac{b}{2}\left(\frac{a + bq - g}{2b}\right)^2 - \delta q - \frac{cq^2}{2} - g\left(\frac{a - bq - g}{2b}\right). \tag{C1}$$

The marginal social benefit from tightening the quota is, as in section 2.1, 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 (C1) with respect to q can, therefore, be written as

$$cq + \delta - g = \frac{1}{2}\left[\frac{a - bq - g}{2}\right], \tag{C2}$$

provided the solution is interior, which we assume. It is easy to see that the assumption needed to rule out a zero quota is $a > 4\delta$.[11]

If the government is restricted to choose a quota from the interval $(0, [1/2c](P_d^*(0) + g))$, it follows easily from (C2) that the government's reaction function is:

11. At

$$q = 0,$$

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

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

$$q(g) = \begin{cases} e_d^*(\delta) & \text{if } g > P_d^*(\delta) \\ \dfrac{a + 3g - 4\delta}{b + 4c} & \text{if } g \le P_d^*(\delta) \end{cases}. \tag{C3}$$

However, if the government is not committed to a binding quota and g is low enough, it could flood the markets with permits, so that the green firm is forced to choose

$$P = \frac{1}{2}[P_d^*(0) + g]. \tag{C4}$$

Emissions would then equal the business-as-usual emissions

$$e_d = \frac{1}{2c}[P_d^*(0) + g], \tag{C5}$$

and energy consumption would be

$$e = \frac{a - \frac{1}{2}[P_d^*(0) + g]}{b}. \tag{C6}$$

By substituting equations (C5) and (C6) in the gross welfare function

$$w = ae - \frac{b}{2}e^2 - \delta e_d - \frac{c}{2}e_d^2 - g(e - e_d),$$

we obtain the gross welfare when a nonbinding quota is chosen. Let us denote this welfare level by w^{nb}.

On the other hand, if the government chooses the binding quota given by equation (C3), gross welfare is obtained by substituting equation (C3) in equation (C1). Let us denote this welfare level by w^b.

When is it optimal for the government to flood the market with permits ($q > P_d^*(0)$) rather than to choose a binding quota? Comparing the welfare levels for optimal binding and nonbinding quotas shows that the government chooses a large nonbinding quota if and only if

$$\begin{aligned} & w^{nb} > w^b, \\ \text{or} \quad & g < \frac{c(a - 4\delta)}{b + c} \equiv g_b. \end{aligned} \tag{C7}$$

When $g = g_b$, the welfare level from choosing a quota given by equation (C3) is equal to the welfare level from the government choosing a nonbinding quota. We assume that the government chooses a binding quota (given by eq. [C3]) when $g = g_b$.[12]

12. The reason for this assumption is the following. Suppose it did not hold. Let the government choose the best binding quota with probability p and the nonbinding quota with prob-

We now turn to the green firm's choice of R&D investment. The firm never chooses $g \in [P_d^*(\delta), \bar{g})$. This is because while such cost reduction from $\bar{g}$ is costly, it does not allow the firm to operate in the market in the second period. In the range $[g_b, P_d^*(\delta))$, the net profit function is obtained by substituting the government's reaction function (C3) into the profit function (14) and subtracting the investment cost. For $g < g_b$, the net profit as a function of g is obtained by substituting equations (C4), (C5), and (C6) in the net profit function

$$\pi = (P - g)(e - e_d) - i(\bar{g} - g)^2.$$

Thus the net profit function is

$$\Pi(g) = \begin{cases} -i(\bar{g} - g)^2 & \text{if } P_d^*(\delta) < g \le \bar{g}, \\ \dfrac{4}{b(b + 4c)^2}[ac + b\delta - (b + c)g]^2 - i(\bar{g} - g)^2 & \text{if } g_b \le g \le P_d^*(\delta), \\ \dfrac{b + c}{4bc}\left[\dfrac{ac}{b + c} - g\right]^2 - i(\bar{g} - g)^2 & \text{if } g < g_b. \end{cases} \tag{C8}$$

Consider values of g in the range $[g_b, P_d^*(\delta)]$. Differentiating $\Pi(g)$ with respect to g,

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

$$\text{So} \quad \left.\frac{d\Pi}{dg}\right|_{P_d^*(\delta)} = 2i(\bar{g} - P_d^*(\delta)) > 0, \tag{C9}$$

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

Now suppose the net profit curve is concave in the range $[g_b, P_d^*(\delta))$. Expression (C9) implies that $P_d^*(\delta)$ maximizes net profit in this range. We know that net profit is negative at $P_d^*(\delta)$. Thus $\bar{g}$ is the profit-maximizing level of g in the range $[g_b, P_d^*(\delta))$ when the profit function is concave.

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

ability $(1 - p)$, $0 \le p < 1$. Since choosing a nonbinding quota reduces the profits of the green firm compared to the binding quota scenario, the net profit function experiences a discontinuous jump at $g = g_b$. As a result, the green firm never chooses $g = g_b$, since choosing g higher than g_b by an infinitesimal amount leads to a strictly higher profit.

In the range $[0, g_b)$, differentiating the net profit function, we get:

$$\frac{d\Pi}{dg} = -\frac{b+c}{2bc}\left[\frac{ac}{b+c} - g\right] + 2i(\bar{g} - g), \quad \frac{d^2\Pi}{dg^2} = \frac{b+c}{2bc} - 2i.$$

When $i < (b+c)/4bc$, the profit function is convex. In this case, the maximum can either be 0 or g_b. When $i > (b+c)/4bc$, the profit function is concave. Note that $\lim_{g \to g_b^+}(d\Pi g/dg) > 0$ if $i > [\delta(b+c)]/[b((b+c)\bar{g} - c(a-4\delta))]$. Now $[\delta(b+c)]/[b((b+c)\bar{g} - c(a-4\delta))] < (b+c)/4bc$ because $\bar{g} > P_d^*(\delta) = (ac + b\delta)/(b+c)$. Thus, the net profit curve is positively sloped in the neighborhood of g_b whenever it is concave. Hence, an interior solution is ruled out in the concave case as well.

Thus in the range $[0, g_b]$, there are two candidates for the equilibrium level of g: 0 & g_b. Globally, there are three candidates for an equilibrium: 0, g_b, and $\bar{g}$.

The choice among $g = 0$, $g = g_b$, and $g = \bar{g}$:

If the gross profit of the green firm at $g = g_b$ is higher than that at $g = 0$, the same holds true for the net profit as well. Thus, if $\pi(0) < \pi(g_b)$, then $\Pi(0) < \Pi(g_b)$. Using (C8),

$$\pi(0) < \pi(g_b)$$
$$\text{if and only if} \quad \delta^2 > \frac{a^2 c}{16(b+c)}. \tag{C10}$$

Thus, when $\delta^2 > a^2c/[16(b+c)]$, then $\Pi(0) < \Pi(g_b) \quad \forall i$.

Now we have two cases:

Case 1:

$$\delta^2 > \frac{a^2 c}{16(b+c)}.$$

The two candidates for a maximum are: g_b and $\bar{g}$. Substituting these two values of g in the profit function (C8), we identify the cut-off value of i at which the firm is indifferent between $g = g_b$ and $g = \bar{g}$.

$$\Pi(\bar{g}) < \Pi(g_b)$$
$$\Leftrightarrow 0 < \frac{4\delta^2}{b} - i\frac{((b+c)\bar{g} - c(a-4\delta))^2}{(b+c)^2} \tag{C11}$$
$$\Leftrightarrow i < \frac{4\delta^2(b+c)^2}{b((b+c)\bar{g} - c(a-4\delta))^2} \equiv i_Q^1.$$

Thus,

$$g(i) = \begin{cases} g_b, & \text{if } i \le i_Q^1, \\ \bar{g}, & \text{if } i \ge i_Q^1. \end{cases} \quad \text{(C12)}$$

Let

$$i_Q = \frac{4(ac + b\delta)^2}{b(b + 4c)^2\bar{g}^2}.$$

Note that

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

Now,

$$\begin{aligned} & i_Q^1 < i_Q \\ \Leftrightarrow \quad & \frac{4\delta^2(b + c)^2}{b((b + c)\bar{g} - c(a - 4\delta))^2} < \frac{4(ac + b\delta)^2}{b(b + 4c)^2\bar{g}^2} \\ \Leftrightarrow \quad & \frac{\delta(b + c)}{(b + c)\bar{g} - c(a - 4\delta)} < \frac{ac + b\delta}{(b + 4c)\bar{g}} \quad \text{because} \quad \bar{g} > \frac{ac + b\delta}{b + c} > \frac{ac - 4\delta c}{b + c} \quad \text{(C13)} \\ \Leftrightarrow \quad & c(a - 4\delta)(ac + b\delta) < c(b + c)(a - 4\delta)\bar{g} \\ \Leftrightarrow \quad & \frac{ac + b\delta}{b + c} < \bar{g}. \end{aligned}$$

Thus, $i_Q^1 < i_Q$ because $\bar{g} > P_d^*(\delta)$. So $i_Q^1 < i_T$ because $i_Q < i_T$. The equilibrium $g(i)$ curve for case 1 is depicted in figure C2.

Case 2:

$$\delta^2 < \frac{a^2 c}{16(b + c)}.$$

Since inequality (C10) is not satisfied, $g = 0$ maximizes profit for values of i very close to zero. We know that at $i = i_Q^1$,

$$\Pi(g_b) = \Pi(\bar{g}) = 0.$$

Case 2a: If, at $i = i_Q^1$,

$$\Pi(0) > \Pi(g_b)$$

$$\text{so that} \quad \delta^2 < \frac{a^2 c}{16(b+c)}\left[\frac{(b+c)\bar{g} - c(a-4\delta)}{(b+c)\bar{g}}\right]^2, \tag{C14}$$

then there are just two candidates for the equilibrium g: 0 and $\bar{g}$. Solving the equation $\Pi(0) = \Pi(\bar{g})$, we get $i = a^2c/[4b\bar{g}^2(b+c)] \equiv i_Q^3$. Thus if the inequality (C14) holds, the equilibrium g is given by:

$$g(i) = \begin{cases} 0, & \text{if } i \le i_Q^3, \\ \bar{g}, & \text{if } i \ge i_Q^3. \end{cases} \tag{C15}$$

We now show that $i_Q^3 < i_Q$. It is easily checked graphically that when $g = 0$, gross profits are higher if the government chooses a binding quota (given by the second part of equation [C3]) rather than choosing an large nonbinding quota. When $g = 0$, let π_0^B and π_0^{NB} denote the gross profits attained when a binding quota (given by substituing $g = 0$ in the second part of equation [C3]) and a large nonbinding quota are chosen respectively. Thus, $\pi_0^B > \pi_0^{NB}$. By definition of i_Q^3 and i_Q,

$$\begin{aligned} \pi_0^{NB} - i_Q^3\bar{g}^2 &= \Pi(\bar{g}) = 0 \\ \text{or} \quad i_Q^3 &= \frac{\pi_0^{NB}}{\bar{g}^2} \end{aligned} \tag{C16}$$

$$\begin{aligned} \pi_0^{B} - i_Q\bar{g}^2 &= \Pi(\bar{g}) = 0 \\ \text{or,} \quad i_Q &= \frac{\pi_0^{B}}{\bar{g}^2}. \end{aligned} \tag{C17}$$

Since $\pi_0^B > \pi_0^{NB}$, therefore $i_Q^3 < i_Q$.

Case 2b: Inequality (C14) does not hold. In this case,

$$\frac{a^2 c}{16(b+c)}\left[\frac{(b+c)\bar{g} - c(a-4\delta)}{(b+c)\bar{g}}\right]^2 < \delta^2 < \frac{a^2 c}{16(b+c)}.$$

By (C11), we know that $g = \bar{g}$ is not an equilibrium for any $i < i_Q^1$. Solving

$$\Pi(0) = \Pi(g_b),$$

we get the cut-off level of i below which $g = 0$ is the profit-maximizing choice for the green firm. The cut-off level is denoted by

$$i_Q^2 = \frac{(b+c)(a^2c - 16\delta^2(b+c)}{4bc(a-4\delta)(2(b+c)\bar{g} - c(a-4\delta))}.$$

Thus, in case 2b the equilibrium value of g is

$$g(i) = \begin{cases} 0, & \text{if } i \le i_Q^2, \\ i \le i_Q^2, & \text{if } i \le i_Q^2, \\ i \le i_Q^2, & \text{if } i \ge i_Q^1. \end{cases} \tag{C18}$$

Moreover, $i_Q^1 < i_Q$ because $\bar{g} > P_d^*(\delta)$. Therefore, $i_Q^1 < i_T$. The equilibrium $g(i)$ curve in case 2b is depicted in figure C3.

This discussion has shown that in all the three cases 1, 2a, and 2b, the tax regime ensures more R&D than the quota regime. For the remaining values of i, the amount of R&D is equal in the two regimes.

C.0.1 Conditions under which a subsidy to R&D is welfare improving

Consider case 1 and case 2b. In these two cases, if $i > i_Q^1$, then there is no R&D in the absence of a subsidy. As in the paper, a subsidy can ensure R&D only if it takes the effective i, that is, $(1-s)\,i$ below i_Q^1. Suppose i is infinitesimally higher than i_Q^1. A small subsidy then pulls the effective i below the cut-off i_Q^1. The equilibrium g is then g_b. By substituting the value of g_b from equation (C7) into the second part of the optimal quota function (C3),

$$\begin{aligned} q(g_b) &= \frac{a + 3g_b - 4\delta}{b+4c} \\ &= \frac{a + 3\left(\frac{c(a-4\delta)}{b+c}\right) - 4\delta}{b+4c} \\ &= \frac{a(b+c) + 3c(a-4\delta) - 4\delta(b+c)}{(b+c)(b+4c)} \\ &= \frac{a(b+4c) - 4\delta(b+4c)}{(b+c)(b+4c)} \\ &= \frac{a-4\delta}{b+c} \\ &= \frac{g_b}{c}. \end{aligned} \tag{C19}$$

$$P(g_b, q(g_b)) = \frac{(2(b+c)(ac+b\delta) - c(b-2c)(a-4\delta))}{(b+c)(b+4c)}. \tag{C20}$$

Now, it can be shown that $P(g_b, q(g_b)) > P_d^*(\delta)$ iff $c < b/2$. Thus, we consider two cases:

Case a:

$$c < \frac{b}{2}.$$

Refer to figure C4. When $i = i_Q^1$,

$$\Pi(g_b) = \Pi(). \text{ So } \quad \pi(gb) = i.$$

In figure C4,

$$\begin{aligned} w(g_b) - w(\bar{g}) &= [IBDC + aIGH] - \Delta aEH \\ &= GFDC - \Delta BEF \\ &= ABCD - (ABFG + \Delta BEF) \\ &< ABCD = \pi(g_b) = i(\bar{g} - g_b)^2. \end{aligned}$$

$$\text{So} \quad w(g_b) - i(\bar{g} - g_b)^2 < w(\bar{g}),$$

$$\text{or} \quad W(g_b) < W(\bar{g}).$$

Thus, when $c < b/2$, R&D subsidies are not welfare improving.

Case b:

$$c > \frac{b}{2}.$$

When

$c > \frac{b}{2}$, $P_d^*(\delta) > P(g_b, q(g_b)) >$ the social marginal cost of dirty energy at $q(g_b)$.

In figure C5,

$$\begin{aligned} \pi(g_b) &= AFEC. \\ w(g_b) - w(\bar{g}) - \pi(g_b) &= BCEFI - AFEC \\ &= \Delta IFL - \Delta ALB \\ &= \frac{1}{2}\frac{(2c - b)^2\delta^2}{bc(b + c)} - \frac{\delta^2}{2c}. \end{aligned}$$

Now $w(g_b) - w(\bar{g}) - \pi(g_b) > 0$ requires $c > (5/4)b$. Thus, for the subsidy to be welfare improving, we require $c > (5/4)b$.

Note that in case 2a (refer to eq. [C15]), the green firm is indifferent between choosing $g = \bar{g}$ and $g = 0$ at $i = i_Q^3$. If for some value of i, the firm chooses $g = 0$, the government will not choose a binding quota. Thus in this case the firms choice of price and energy is given by equations (C4) and (C6), respectively. The dirty energy produced (when $g = 0$) is less than $e_d^*(\delta)$ due to assumption 2. Thus it is simple to see that a subsidy is welfare improving provided $i \geq i_Q^3$ but i is not much higher than i_Q^3.

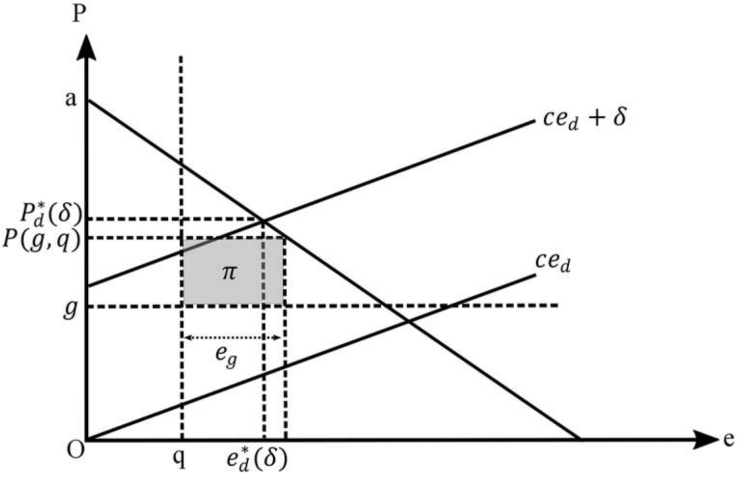

Figure C1. Choice of green energy output when $P_d^*(0) \leq g \leq P_d^*(\delta)$

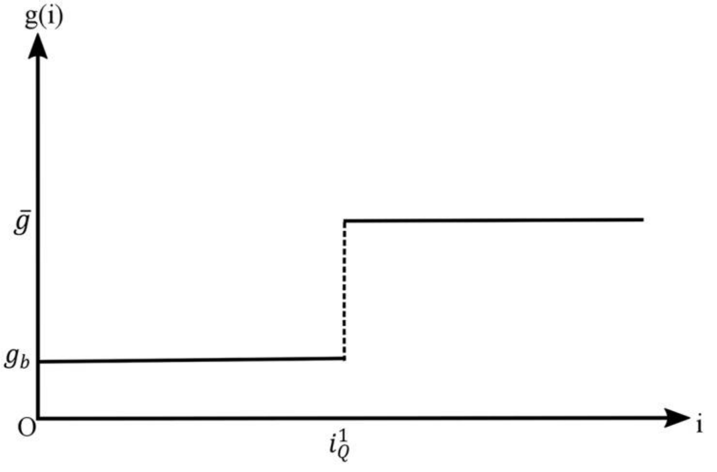

Figure C2. Equilibrium green marginal cost g as a function of i

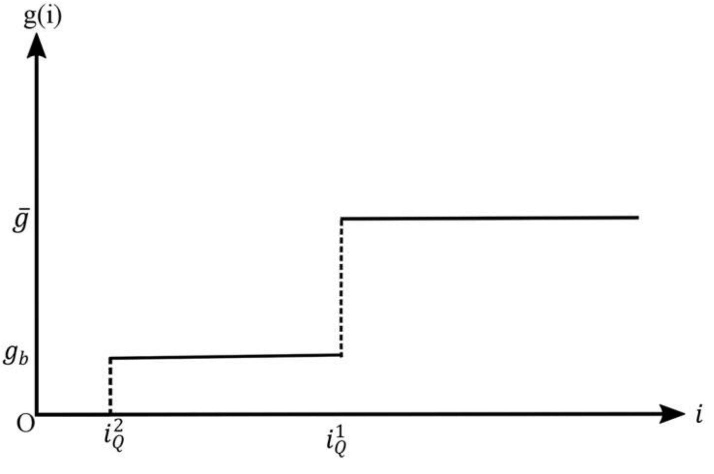

Figure C3. Equilibrium green marginal cost g as a function of i

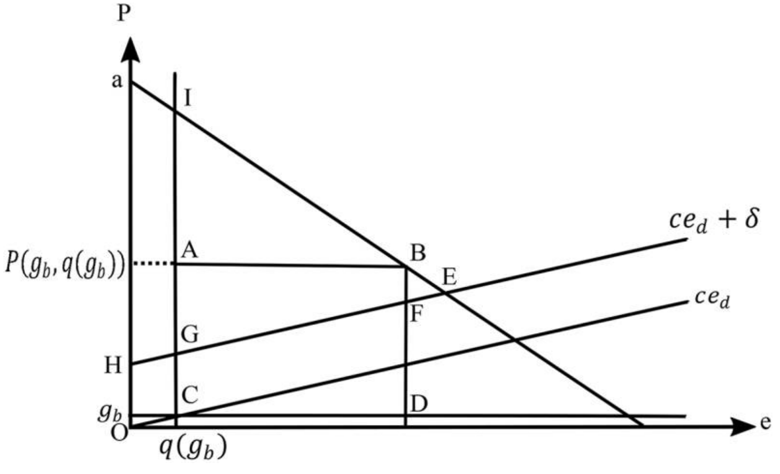

Figure C4. Case a: Role of subsidy

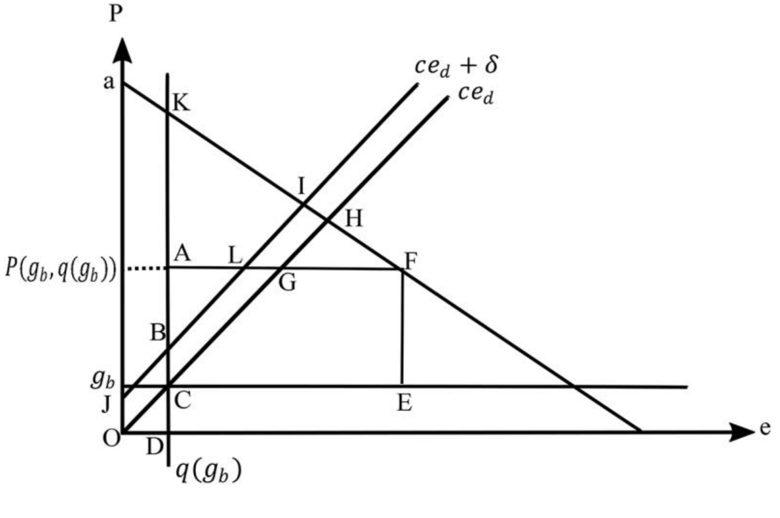

Figure C5. Case b: Role of subsidy

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