EL COLEGIO DE MÉXICO
CENTRO DE ESTUDIOS ECONÓMICOS

MAESTRÍA EN ECONOMÍA

TRABAJO DE INVESTIGACIÓN PARA OBTENER EL GRADO DE MAESTRO EN ECONOMÍA

THE IMPACT OF EMISSION TAXES ON THE ADOPTION OF POLLUTION-REDUCING TECHNOLOGIES IN A DUOPOLY

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PROMOCIÓN 2014-2016

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JULIO 2016

Agradecimientos

Me gustaría primero agradecer a mi asesora de tesis, Dra. Adriana Gama Velázquez, por su paciencia, dedicación y motivación en cada una de las etapas de esta tesina. Sus consejos y recomendaciones resultaron invaluables para la culminación de este trabajo.

También quiero agradecer a todos los profesores que han formado parte de mi vida académica, sus enseñanzas son los pilares que sostienen esta tesina.

Finalmente, quiero agradecer a mi familia por habérmelo dado todo. Hubiera sido imposible concluir este proyecto sin su apoyo y guía.

The Impact of Emission Taxes on the Adoption of Pollution-Reducing Technologies in a Duopoly

El Colegio de México

This draft: July 5, 2016

Abstract

Emission taxes are widely used by governments to reduce emissions and encourage investment in cleaner technologies. We show that in a duopoly with strategic substitutes a higher price of emissions does not necessarily lead to the adoption of cleaner production methods or lower emissions. In fact, the emissions-to-output is a U-shaped function of the strictness of policy and firms may find it optimal to invest into cleaner technologies in order to credibly commit themselves to higher production levels in the future, which may offset the reduction in emission intensity. The main conclusion is that emission taxes are significantly limited in their ability to provide incentives that spur both technology adoption and pollution reduction, proving that one must refrain from claiming that stricter environmental policy is always beneficial for the environment.

JEL Classification: L130, Q520, Q580.

Keywords: environmental regulation, oligopoly, technology adoption.

Contents

1 Introduction

Now that ecological crises are becoming more frequent, governments face the overwhelming task of appropriately designing environmental policies that induce the adoption of less pollution-intensive technologies. Our immediate intuition might suggest higher emission taxes, as firms would then have an incentive to invest in cleaner production processes in order to reduce compliance costs. Indeed, there is a large amount of literature that provides a theoretical justification for this positive relationship and it is commonly assumed in empirical tests of induced innovation hypothesis (Perino & Requate, 2012).[1] However, a recent strand of literature has questioned this monotonic relationship between environmental regulation stringency and adoption incentives.[2] The intuition behind this skepticism can be summarized as follows: firms first respond to an increase in policy stringency by investing more in environmental R&D and by reducing output; however, this decrease in output reduces firms' incentives to invest in cleaner production technologies. This reasoning thus reveals a mixed picture for the effectiveness of emission taxes in inducing the adoption of cleaner production methods.

Perino and Requate (2012) found that the relationship between policy stringency and the rate of technology adoption in an industry is non-monotonic and, if firms are symmetric, is inverted U-shaped. In other words, the number of firms that adopt a cleaner technology is initially increasing in the tax rate but is eventually decreasing once policy becomes sufficiently strict. Nevertheless, the authors assume that there is a continuum of small firms choosing between two alternative production technologies and do not model the output market explicitly. Bréchet

[1] See Requate (2003) for a survey.

[2] For a synthesis of this literature, see Calel (2011).

and Meunier's (2014) analysis shows that this result is robust to the introduction of the output market.

Earlier studies on technology adoption in oligopolistic markets with a continuous technology choice have emphasized the strategic role of R&D in the presence of environmental regulation, as it can be used by firms to influence market equilibrium. Unfortunately, these considerations make the analysis quite complex and the results are seldom clear. For example, Carlsson (2000) and Ulph (1997) found that, in such a setting, the effectiveness of tax emissions in inducing the adoption of cleaner production technologies is ambiguous. By specifying linear functions, Dijkstra and Gil-Molto (2011) are able to use Ulph's (1997) two-stage model to study the relationship between emission intensity, determined by the production technology, and the emission tax. The authors find that, although this relationship can be U-shaped, this is not necessarily the case as emission intensity can also be monotonically declining in the tax. In a more recent article, Dijkstra and Gil-Molto (2014) show that their results hold in general when firms choose their emission intensity and output levels simultaneously. Thus, their findings suggest that the U-shaped relationship in Perino and Requate (2012) and Bréchet and Meunier (2014) might not always carry over to the case of imperfect competition with a continuous choice of technology.

The purpose of this paper is twofold. First, it aims at showing that the reversal of Perino and Requate (2012) and Bréchet and Meunier's (2014) U-shaped relationship is not as conceivable as they state. The model in this paper shows that a monotonically declining emissions-to-output ratio arises only if, as is assumed in Dijkstra and Gil-Molto (2014), positive production with zero emissions is possible. This assumption, of course, is highly unrealistic. Second, the paper generalizes Dijkstra and Gil-Molto's (2011) two-stage linear example since, contrary to their static generalization, a dynamic model both allows for strategic commitment and better reflects the long-run nature of investments in cleaner technology.

Whether emission intensity is U-shaped or monotonically declining in the emissions tax rate is not only of theoretical importance, but has significant implications for policy as well. If policymakers wish to reduce environmentally harmful impacts at the source, by inducing firms to substitute or modify their less clean technologies, a stricter policy may be counterproductive if emission intensity is U-shaped in the emission tax. Thus, by discarding the possibility of a monotonically declining emission-to-output ratio misleading policy recommendations may be avoided.

It is important to note that this paper focuses on investment into cleaner production technologies rather than on innovation. In order to motivate the assumptions behind the model, we will make this distinction clear. Requate (2005) subsumes a paper under a model of innovation if it contains either a stochastic element, a patenting system or spillovers. As our model contains neither one of these, it is one of technology adoption. However, it does not abstract from the innovation process altogether, as firms take the findings of previous R&D activities as given and decide whether to implement them or not. Furthermore, we can assume that these discoveries are the result of R&D on firm-specific techniques and, hence, do not entail spillovers or patents. These assumptions are plausible and consistent with empirical work. For example, Frondel, Horbach, and Rennings (2004) found that internal environmental audits and the preparation of environmental reports are particularly important for the implementation and operation of cleaner technologies, as these instruments identify both the environmental impacts and the saving potentials at each stage of the production process. These observations also motivate Mabrouk, Kurtyka, and Llerena's (2015) model, in which a monopolist can either invest to develop a process integrated clean technology or bargain with external eco-industry to use an end-of-pipe technology.

The rest of this article is organized as follows. We set up the model in Section 2. In Section 3 we characterize the behavior of emission intensity, output and total emissions with respect to the tax rate. Section 4 contains an illustrative example using linear demand and quadratic installation costs. Section 5 concludes.

2 The Model

Let us set out our simple model of technology adoption in a duopolistic market. While it is a generalization of Dijkstra and Gil-Molto's (2011) specification, it modifies it in one important aspect: firms cannot eliminate emissions completely, except by ceasing production altogether.

Consider two profit-maximizing firms subject to an emissions tax t. Each firm i, $i=1,2$, produces q_i and sells its output at market price $P(Q)$, where $Q \equiv q_1+q_2$ is industry output. We shall assume that the inverse demand function $P(Q)$ is downward sloping and is not too convex. In other words, it satisfies $P'(Q)<0$ and

$$P'(Q)+P''(Q)q_i \leq 0. \tag{1}$$

Assumption (1) ensures that goods are strategic substitutes and, hence, that firms are competing rivals. In addition, it guarantees stability and uniqueness of the Cournot equilibrium (Gaudet and Salant, 1991).

The production activities of the firms generate pollution. Firm i's emissions e_i are given by

$$e_i = (1+\varepsilon_i)q_i, \tag{2}$$

where $\varepsilon_i \in [0,\alpha]$ denotes the type of technology the firm has installed which, in turn, emits $1+\varepsilon_i$ pollutants per unit of output. If the firm did not invest in abatement, $\varepsilon_i = \alpha$. On the other hand, if the firm acquired the cleanest technology available, $\varepsilon_i = 0$. The latter implies that a firm cannot reduce its emission intensity below one effluent per unit of output, reflecting the fact that perfectly clean production is impossible.

The firm's production cost function is $C(q_i)$ with $C'(0) = 0$, $C' > 0$ for $q_i > 0$, and $C'' > 0$. Furthermore, for production to be profitable in the absence of taxes we impose

$$P(0) > C'(0). \tag{3}$$

In order to avoid scenarios in which firms find it optimal to produce nothing and sell this nothing at an infinite price, we assume that

$$\lim_{q\to 0} \left[P(2q) + P'(2q)q - C'(q)\right] \text{ is finite.}^3 \tag{4}$$

Changing the production process is, of course, costly. If a firm wants to reduce its emissions-to-ouput ratio to $1+\varepsilon_i$, it must spend $F(\varepsilon_i)$ in order to make the necessary modifications. This abatement cost function satisfies $F(\alpha) = F'(\alpha) =$

[3] This problem is known to arise with isoelastic demand functions. See Tramontana, Gardini, & Puu (2010).

0, $F'(\varepsilon_i) < 0$ for ε_i in $[0, \alpha)$, and $F'' > 0$. In other words, the cost of reducing emission intensity is continuous, positive and strictly convex for $\varepsilon_i < \alpha$.

The model is a two-stage game. In the first period, firms simultaneously choose their technology types and make the necessary modifications to their production processes. In the second stage, after observing the emission-to-output ratios, firms compete in quantity. As is usual, we will only focus on symmetric subgame perfect equilibria.

Firm i's profits π_i can be written as

$$\begin{aligned}\pi_i &= P(Q)q_i - C(q_i) - t(1+\varepsilon_i)q_i - F(\varepsilon_i)\\ &= \pi_i^o(q_i, q_j) - te_i - F(\varepsilon_i),\end{aligned} \tag{5}$$

where $\pi_i^o(\cdot)$ denotes firm i's profits before taxes and payments to capital.

3 Adoption and Emission Taxes

3.1 No Emission Taxes

Let us begin by considering the case with no emission taxes, i.e., $t = 0$. Although the results of this section are intuitive and fairly obvious, they will prove useful in deriving the non-monotonic relationships of section 3.2.

In the last stage of the game, firm i maximizes its profit with respect to q_i and takes ε_i, ε_j, and q_j as given, where $j \neq i$. That is, it solves

$$\max_{q_i \geq 0} P(Q)q_i - C(q_i) - F(\varepsilon_i). \tag{6}$$

Assumption (3) implies that firm i's first-order condition with respect to q_i is given by

$$P(Q) + P'(Q)q_i = C'(q_i). \tag{7}$$

From (1) it follows that the second-order condition for profit maximization

$$2P'(Q) + P''(Q)q_i - C''(q_i) \leq 0 \tag{8}$$

is satisfied.

Since ε_i does not appear in either firm's first-order condition, it is clear that neither q_1 or q_2 depend on ε_i. Thus,

$$\frac{\partial q_i}{\partial \varepsilon_i} = \frac{\partial q_j}{\partial \varepsilon_i} = 0. \tag{9}$$

Anticipating that its choice of ε_i will not affect the outcome of the second-stage of the game, firm i faces the following maximization problem in the first-period

$$\max_{\varepsilon_i \in [0,\alpha]} P(Q)q_i - C(q_i) - F(\varepsilon_i). \tag{10}$$

Differentiating (10) with respect to ε_i yields first-order condition

$$-F'(\varepsilon_i) = 0. \tag{11}$$

The second-order condition for profit maximization is that

$$-F''(\varepsilon_i) \leq 0, \tag{12}$$

which is true by assumption.

Given our assumptions on $F(\cdot)$, first-order condition (11) implies that $\varepsilon_i = \alpha$. In other words, the firm does not modify its production process.

3.2 Positive Emission Taxes

With positive emission taxes, firm i's second-period profit function now becomes

$$P(Q)q_i - C(q_i) - t(1+\varepsilon_i)q_i - F(\varepsilon_i). \tag{13}$$

The first-order condition with respect to q_i is

$$\frac{\partial \pi_i^o(q_i, q_j)}{\partial q_i} = t(1+\varepsilon_i). \tag{14}$$

where $\pi_i^o(\cdot)$ is defined as before. As can be easily verified, the second-order condition for profit maximization is the same as in the zero tax case.

Assumption (1) implies that, for every (ε_i, ε_j) chosen in the first-period, the equilibrium outcome of the second-stage is unique and given by $[q_i(t,\varepsilon_i,\varepsilon_j), q_j(t,\varepsilon_i,\varepsilon_j)]$.

Furthermore, this equilibrium vector must satisfy the system of equations

$$\frac{\partial \pi_i^o[q_i(t,\varepsilon_i,\varepsilon_j),q_j(t,\varepsilon_i,\varepsilon_j)]}{\partial q_i} = t(1+\varepsilon_i) \tag{15}$$

$$\frac{\partial \pi_j^o[q_i(t,\varepsilon_i,\varepsilon_j),q_j(t,\varepsilon_i,\varepsilon_j)]}{\partial q_j} = t(1+\varepsilon_j). \tag{16}$$

Totally differentiating (15) and (16) with respect to ε_i yields (the arguments of q_i and q_j will often be dropped for the sake of clarity.)

$$\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial q_i}{\partial \varepsilon_i} + \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial \varepsilon_i} = t \tag{17}$$

$$\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial \varepsilon_i} + \frac{\partial^2 \pi_j^o}{\partial q_j^2}\frac{\partial q_j}{\partial \varepsilon_i} = 0. \tag{18}$$

Solving for $\partial q_i/\partial \varepsilon_i$ and $\partial q_j/\partial \varepsilon_i$ we find

$$\frac{\partial q_i}{\partial \varepsilon_i} = \frac{t\frac{\partial^2 \pi_j^o}{\partial q_j^2}}{\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial^2 \pi_j^o}{\partial q_j^2} - \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}} \leq 0 \tag{19}$$

$$\frac{\partial q_j}{\partial \varepsilon_i} = \frac{-t\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}}{\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial^2 \pi_j^o}{\partial q_j^2} - \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}} \geq 0. \tag{20}$$

It can be shown that if assumption (1) holds, then the denominator of both derivatives is positive (proof in Appendix). This assumption also implies that the numerator of (20) is positive. Thus, q_j is increasing in ε_i. Since $\pi_j^o(\cdot)$ is concave by (8), we can conclude that q_i is decreasing in ε_i. These results are fairly intuitive. Given a positive emissions tax, a larger ε_i means that firm i faces a higher marginal cost and, consequently, it must produce less. Since q_i and q_j are strategic substitutes by (1), firm j increases its output in response to said reduction.

Totally differentiating equations (15) and (16) with respect to t yields the following system of equations

$$\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial q_i}{\partial t}+\frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial t}=(1+\varepsilon_i) \tag{21}$$

$$\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial t}+\frac{\partial^2 \pi_j^o}{\partial q_j^2}\frac{\partial q_j}{\partial t}=(1+\varepsilon_j). \tag{22}$$

Solving for $\partial q_i/\partial t$ obtains

$$\frac{\partial q_i}{\partial t}=\frac{(1+\varepsilon_i)\frac{\partial^2 \pi_j^o}{\partial q_j^2}-(1+\varepsilon_j)\frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}}{\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial^2 \pi_j^o}{\partial q_j^2}-\frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}}. \tag{23}$$

This expression cannot be signed unambiguously. Whereas the denominator, as mentioned above, is positive, the numerator can be either positive or negative. In fact, if firm i's emission intensity is considerably lower than that of its rival, its output can actually rise with an increase in the emissions tax. The intuition behind this result is better understood in terms of the firms' reaction curves. As can be seen in Figure 1, a higher tax rate shifts both curves to the left, as production is now more expensive. However, if firm 2's emissions-to-output ratio exceeds that of its rival, it could be the case that firm 2's reaction curve shifts so far to the left that the new equilibrium occurs at point B. In this case, firm 1 would end up increasing its production after the tax hike.

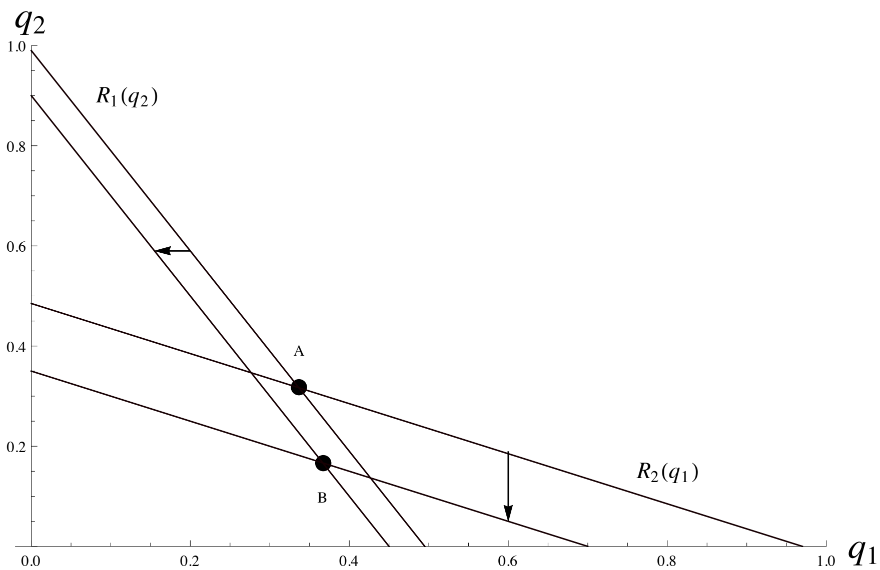


Figure 1: Firms reaction functions before and after a tax increase

If firms are symmetric - i.e., have a common emissions-to-output ratio ε - then (23) reduces to

$$\frac{\partial q_i}{\partial t} = \frac{(1+\varepsilon_i)}{\frac{\partial^2 \pi_i^o}{\partial q_i^2} + \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}} \leq 0, \tag{24}$$

where the inequality follows from (1) and (8).

In the first stage of the game, firms perfectly anticipate how their technology choices will affect second period behavior. Firm i thus solves

$$\max_{\varepsilon_i \in [0,\alpha]} \pi_i^o[q_i(t,\varepsilon_i,\varepsilon_j), q_j(t,\varepsilon_i,\varepsilon_j)] - t(1+\varepsilon_i)q_i(t,\varepsilon_i,\varepsilon_j) - F(\varepsilon_i), \tag{25}$$

where $\pi_i^o(\cdot)$, $q_i(t,\varepsilon_i,\varepsilon_j)$, and $q_j(t,\varepsilon_i,\varepsilon_j)$ are defined as above.

As shown in the Appendix, it follows from (14) that the first-order condition with respect to ε_i is

$$\left[P'(Q)\frac{\partial q_j}{\partial \varepsilon_i} - t\right] q_i - F'(\varepsilon_i) = 0. \tag{26}$$

Rearranging yields

$$\left[P'(Q)\frac{\partial q_j}{\partial \varepsilon_i} - t\right] q_i = F'(\varepsilon_i). \tag{27}$$

The intuition behind (27) is straightforward. Notice that investments in cleaner production methods have two positive effects on a firm's profit margin. On the one hand, a reduction in the firm's emissions-to-output ratio leads to a contraction in its rival's output and, hence, increases the price of its current output. On the other hand, a cleaner production process allows a firm to pay less taxes per unit of output. First-order condition (27) tells us that, at the optimum, the revenue increase resulting from a reduction in emission intensity must equal its marginal cost.

The second order condition in the first period is given by

$$\left[\frac{\partial^2 \pi_i^o}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial \varepsilon_i} + \frac{\partial^2 \pi_i^o}{\partial q_j^2}\frac{\partial q_j}{\partial \varepsilon_i}\right]\frac{\partial q_j}{\partial \varepsilon_i} + \frac{\partial \pi_i^o}{\partial q_j}\frac{\partial^2 q_j}{\partial \varepsilon_i^2} - t\frac{\partial q_i}{\partial \varepsilon_i} - F''(\varepsilon_i) \leq 0. \tag{28}$$

Note that the term in square brackets and $\frac{\partial^2 q_j}{\partial \varepsilon_i^2}$ cannot be signed without ambiguity. The sign of the former clearly depends on the curvature of both the demand and the cost function, whereas that of the latter will depend on their third derivatives. Nevertheless, we know that the firm's second order condition is satisfied when $t = 0$. Hence, if $\pi(\cdot)$ is a smooth function, it follows from (12) that the sum of the first three terms in (28) is small relative to $F''(\varepsilon)$ for low t. Consequently, second order condition (28) will be satisfied as long as we assume that the diseconomies of abatement $F''(\cdot)$ are large relative to the emissions tax rate. This assumption seems plausible.

It can be seen from (25) that the symmetric equilibrium ε will be a function only of t. Totally differentiating (27) with respect to t and imposing symmetry yields the following solution for $\frac{d\varepsilon}{dt}$

$$\frac{d\varepsilon}{dt} = -\frac{\left\{\left[\frac{\partial^2 \pi_i^o}{\partial q_i \partial q_j} + \frac{\partial^2 \pi_i^o}{\partial q_j^2}\right]\frac{\partial q_j}{\partial \varepsilon_i} - t\right\}\frac{\partial q_i}{\partial t} + \frac{\partial \pi_i^o}{\partial q_j}\frac{\partial^2 q_j}{\partial t \partial \varepsilon_i} - q_i}{\frac{\partial Q}{\partial \varepsilon_i}\left\{\left[\frac{\partial^2 \pi_i^o}{\partial q_i \partial q_j} + \frac{\partial^2 \pi_i^o}{\partial q_j^2}\right]\frac{\partial q_j}{\partial \varepsilon_i} - t\right\} + \frac{\partial \pi_i^o}{\partial q_j}\left[\frac{\partial^2 q_j}{\partial \varepsilon_i^2} + \frac{\partial^2 q_j}{\partial \varepsilon_j \varepsilon_i}\right] - F''(\varepsilon_i)}, \tag{29}$$

where

$$\frac{\partial Q}{\partial \varepsilon_i} = \frac{\partial q_i}{\partial \varepsilon_i} + \frac{\partial q_j}{\partial \varepsilon_i}. \tag{30}$$

We are now ready to characterize the industry's equilibrium level of abatement ε as a function of the emissions tax rate t.

Proposition 1. In the symmetric equilibrium,

i When the emissions tax rate t is low, emission intensity $1+\varepsilon$ is decreasing in t.

ii Emission intensity $1+\varepsilon$ can be either increasing or decreasing in the emissions tax t for intermediate values of t.

iii When the emissions tax rate t is high, emission intensity $1+\varepsilon$ is increasing in

t.

The proof is given in the Appendix. The intuition behind Proposition 1 is as follows. When the tax rate t is small, production levels are relatively high and, consequently, a lower emissions-to-output ratio leads to a substantial increase in revenue. Since it is relatively inexpensive to reduce emission intensity when the the emissions-to-output ratio is large, firms initially respond to tax hikes by investing in cleaner production methods. As t continues to increase, however, one of the following two scenarios will eventually arise. In the first scenario, the marginal cost of reducing emission intensity becomes so high as to exceed the corresponding revenue increase. In this case, firms will actually find it optimal to adopt a more pollution-intensive production method and cutback on production. In the second scenario, it is profitable to adopt the cleanest technology available, so that emission intensity is equal to one effluent per unit of output. Since it is not possible to reduce emission intensity any further, firms have no other alternative than to contract output in response to additional tax hikes. However, the revenue loss from increasing emission intensity decreases as output falls, so that it is eventually profitable to disinvest from cleaner technologies.

Although this result is quite similar to that in Dijkstra and Gil-Molto (2014), it differs in one important aspect: whereas their model allows for a monotonically decreasing emissions-to-output ratio, Proposition 1 shows that this can never be the case in ours. The reason is that, contrary to what is assumed here, it is possible for a firm to adopt a nonpolluting technology at a finite cost in their model. Therefore, firms might actually find it profitable to invest in ever cleaner technology, constantly pay lower emission taxes and monotonically increase production as t rises. However, Proposition 1 tells us that if emission intensity cannot fall below some predetermined ratio then the emissions-to-output ratio cannot be monotonically declining in the tax rate. Since our assumption is a better description of reality, our result shows that the non-monotonicity relationships derived in Perino and Requate (2012) and in Bréchet and Meunier (2014) are robust to the introduction of the output market and the assumption of a continuous technology choice.

We can now use Proposition 1 to study the behavior of output as a function of the emissions tax. Let us denote the equilibrium output of the game by q, which is a function only of t. The total change in q due to an increase in t is given by

$$\begin{aligned}\frac{dq}{dt} &= \frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial t} + \frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial \varepsilon_i}\frac{d\varepsilon_i}{dt} + \frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial \varepsilon_j}\frac{d\varepsilon_j}{dt} \\ &= \frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial t} + \left[\frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial \varepsilon_i} + \frac{\partial q_i(t,\varepsilon_i,\varepsilon_j)}{\partial \varepsilon_j}\right]\frac{d\varepsilon}{dt},\end{aligned} \tag{31}$$

where the last equality results from imposing symmetry and $q_i(t,\varepsilon_i,\varepsilon_j)$ and $q_j(t,\varepsilon_i,\varepsilon_j)$ are defined as before.

Note that an increase in the emissions tax rate t has both a direct and an indirect effect, as shown by the first- and second-terms in (31), respectively. As a direct consequence, an increase in taxes causes a firm's marginal costs to rise and, thus, leads to lower output. Nevertheless, a firm may respond to this increase by investing in abatement that, in turn, lowers marginal costs and increases output. As shown in Corollary 1, these two opposing effects may cause q to behave non-monotonically in t.

Corollary 1. In the symmetric equilibrium of the game,

i. Output q is decreasing in the emissions tax rate t when t is either very high or very low.

ii. For intermediate values of the emissions tax rate t, output q can be either increasing or decreasing in t.

The proof is shown in the Appendix. Nevertheless, the intuition behind Corollary 1 is straightforward. Since emission intensity cannot fall below one pollutant per unit of output, firms must start making tax payments once the emissions tax rate t becomes positive. In other words, when t=0, a small increase in t causes a firm's marginal costs to rise and its output to contract. As mentioned above, however, firms eventually find it optimal to adopt more pollution-intensive technologies and cutback on production.

The assumption that the emissions-to-output ratio cannot be reduced to zero plays an important role in Corollary 1. Without this assumption, an arbitrarily large tax rate t could actually induce firms to invest in a nonpolluting production process and, hence, production would eventually be increasing in t. In fact, this phenomenon arises in (Dijkstra & Gil-Molto, 2011, 2014) and it is the reason why output can be a U-shaped function of the emissions tax rate in that model.

Having characterized the behavior of q and ε, we can now analyze the relationship between firm emissions e and the emissions tax rate t. Given that we are focusing on symmetric equilibrium only, the behavior of industry emissions $E = e_1 + e_2$ is identical. Totally differentiating (2), which is a function only of t, yields

$$\frac{de}{dt} = \frac{d\varepsilon}{dt} q + (1+\varepsilon) \left\{ \frac{\partial q_i(t, \varepsilon_i, \varepsilon_j)}{\partial t} + \left[\frac{\partial q_i(t, \varepsilon_i, \varepsilon_j)}{\partial \varepsilon_i} + \frac{\partial q_i(t, \varepsilon_i, \varepsilon_j)}{\partial \varepsilon_j} \right] \frac{d\varepsilon}{dt} \right\}$$

$$= \frac{d\varepsilon}{dt} q + (1+\varepsilon) \frac{dq}{dt}, \tag{32}$$

where $\frac{dq}{dt}$ is as defined in (31).

Once again, we can only sign (32) when the emissions tax t is either very low or very high. Since both emission intensity $1+\varepsilon$ and output q are decreasing in the tax rate when t is low, it follows that total emissions are declining for small t. We know from Proposition 1 and Corollary 1 that, for sufficiently high tax rates, firms disinvest from cleaner production technologies and reduce output. As a consequence, the revenue loss that would result from a higher emissions-to-output ratio decreases, as output is now lower. This, in turn, causes firms to respond to higher tax rates t with even more disinvestment and output reduction. Thus, output becomes increasingly low as the tax rate continues to rise. As shown in the Appendix, this reduction in output offsets the increase in emission intensity, leading to a decrease in total emissions. Corollary 2 summarizes these results.

Corollary 2. In the symmetric equilibrium,

i Total emissions E are decreasing in the emissions tax t when t is either very low or very high.

ii For intermediate values of t, total emissions E can be either increasing or decreasing in t.

This non-monotonic behavior is mainly driven by the dynamic structure of the game, since Dijkstra and Gil-Molto (2014) have already shown that total emissions are monotonically decreasing in the tax rate when firms choose output q and the level of abatement ε simultaneously. The intuition behind Corollary 2 is straightforward. As mentioned above, a firm can increase its output in response to a tax hike if its emissions-to-output ratio is considerably lower than that of its rival. Thus, by adopting a cleaner technology, a firm can credibly commit itself to a higher activity level in the second-stage and pressure its rival into producing less. Anticipating this, the rival firm may find it in its best interest to do the same, since its market share would otherwise shrink. These investments can, in principle, result in an increase in the industry's output that offsets these reductions in emission intensity, thereby leading to an increase in the industry's emissions. Therefore, a higher tax can potentially induce technological improvements that are pollution-increasing.

4 Example

This sections contains an example that closely follows the one provided by Dijkstra and Gil-Molto (2011), with the exception that is not possible to have positive production with zero emissions. Whereas our previous analysis did not characterise emission intensity behavior precisely for intermediate values of t, a simple linear example suffices to obtain the U-shaped relationship found in Perino and Requate (2012).

Consider a duopoly facing inverse demand function

$$P(Q) = a - Q. \tag{33}$$

Marginal costs of production are constant and normalized to zero. The abatement cost function is given by

$$F(\varepsilon_i) = \frac{\gamma}{2}(\alpha - \varepsilon_i)^2. \tag{34}$$

Firm i's profits can thus be written as

$$\pi_i = [a - Q - t(1+\varepsilon_i)]\, q_i - \frac{\gamma}{2}(\alpha - \varepsilon_i)^2. \tag{35}$$

In the second stage of the game, firms maximize profits with respect to output and take everything else as exogenous. Firm i's first-order condition with respect to q_i is

$$q_i = a - Q - t(1+\varepsilon_i). \tag{36}$$

The second order condition is given by

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = -2. \tag{37}$$

As is usual, we can use both firms' first-order conditions to solve for $q_i(t, \varepsilon_i, \varepsilon_j)$ and $q_2(t, \varepsilon_i, \varepsilon_j)$. Thus, given the vector (t, ε_i, ε_j), Cournot equilibrium in the second period of the game is

$$q_i(t,\varepsilon_i,\varepsilon_j) = \frac{1}{3}[a - t(1+2\varepsilon_i - \varepsilon_j)], \quad i = 1,2. \tag{38}$$

In the first stage of the game, each firm engages in abatement in order to influence the resulting Cournot equilibrium. In other words, firm i solves

$$\max_{\varepsilon_i \in [0,\alpha]} \frac{1}{9}[a - t(1+2\varepsilon_i - \varepsilon_j)]^2 - \frac{\gamma}{2}(\alpha - \varepsilon_i)^2 \tag{39}$$

which follows from substituting both $q_i(t,\varepsilon_1,\varepsilon_2)$ and $q_j(t,\varepsilon_1,\varepsilon_2)$ as defined in (38) into (35). Firm i's first-order condition with respect to ε_i, after imposing symmetry, can be written as

$$-\frac{4t\,[a - t(1+\varepsilon)]}{9} + \gamma(\alpha - \varepsilon) = 0. \tag{40}$$

The second order condition with respect to ε_i is

$$\frac{8}{9}t^2 - \gamma \leq 0. \tag{41}$$

As mentioned above, second order condition (41) will be satisfied if the diseconomies of abatement, represented by γ, are large relative to the emissions tax rate t.

Solving (40) for ε yields

$$\varepsilon(t) = \frac{\alpha\gamma - \frac{4}{9}t(a-t)}{\gamma - \frac{4}{9}t^2}. \tag{42}$$

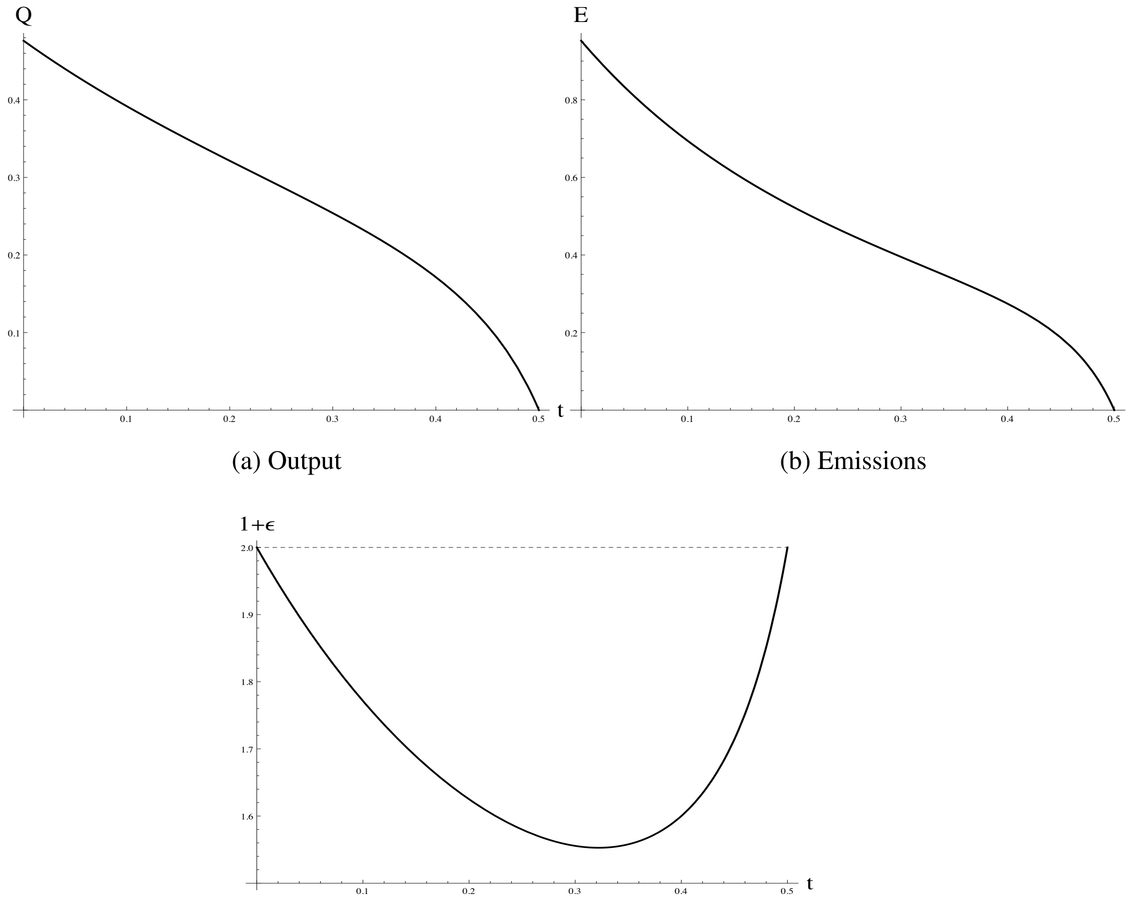
Substituting (42) in (38) obtains

$$q(t) = \frac{\gamma}{3}\left[\frac{a - t(1+\alpha)}{\gamma - \frac{4}{9}t^2}\right]. \tag{43}$$

The denominator in (42) and (43) is positive by (41). Note that, in equilibrium, $q > 0$ and $\varepsilon < \alpha$ only if $a - t(1+\alpha) > 0$. However, if $a - t(1+\alpha) \leq 0$, then we have a corner solution with $q = 0$ and $\varepsilon = \alpha$. In other words, positive production ceases to be profitable and, hence, firms do not invest in abatement.

Finally, substituting (42) and (43) into (2), we obtain

$$e(t) = \frac{\gamma[(1+\alpha)\gamma - \frac{4}{9}at][a - t(1+\alpha)]}{3[\gamma - \frac{4}{9}t^2]^2}. \tag{44}$$



(a) Output

(b) Emissions

(c) Emission Intensity

Figure 2: Total output Q, industry emissions E, and emission intensity $1{+}\varepsilon$ as functions of the tax rate t ($a = 1$, $c = 0$, $\alpha = 1$, $\gamma = 4/25$).

With the benefit of having closed-form solutions for ε, q, and e, we can now study how firms respond to increases in the tax rate t more precisely. Differentiating (42) and (43) with respect to t yields

$$\frac{d\varepsilon}{dt} = -\frac{4\left[\frac{4}{9}at^2 - 2(1+\alpha)\gamma t + a\gamma\right]}{9\left[\gamma - \frac{4}{9}t^2\right]^2} \tag{45}$$

$$\frac{dq}{dt} = -\frac{\gamma\left\{(1+\alpha)\gamma + \frac{4}{9}t\left[(1+\alpha)t - 2a\right]\right\}}{3\left[\gamma - \frac{4}{9}t^2\right]^2}. \tag{46}$$

As is shown in the Appendix, the derivative of q with respect to t is unambiguously negative. In other words, a higher tax rate always leads to a subsequent decrease in output. When t is small, output is relatively large and, hence, so is the extra revenue from abatement. Firms therefore find it profitable to reduce emission intensity in response to a tax hike in this case. Since output is monotonically decreasing in the tax rate, the extra revenue from abatement is eventually so small that firms actually begin to adopt more pollution-intensive technologies. Thus, as can bee seen in the Appendix, emission intensity displays a perfectly U-shaped behavior. Although the emissions-to-output ratio is increasing for sufficiently large taxes, it can be shown that total emissions E are monotonically decreasing in t. Figure 2 illustrates these results, which we now summarize in Proposition 3.

Proposition 3. In the symmetric equilibrium,

i Output q is monotonically decreasing in the emissions tax rate t.

ii Emission intensity $1+\varepsilon$ is a U-shaped function of t.

iii Industry emissions E are monotonically decreasing in t.

As mentioned above, these results differ from Dijkstra and Gil-Molto (2011)'s two-stage linear model with quadratic installation costs in one important aspect: production and emission intensity are, respectively, always decreasing and U-shaped functions of t in our example. In contrast, it is possible for the emissions-to-output ratio to be monotonically decreasing in t with production exhibiting a U-shaped behavior in their model. This difference is, of course, due to our more realistic emission abatement specification.

5 Conclusion

This paper has examined the response of a duopoly to a higher emission tax rate in terms of its output, abatement technology, and total emissions. The model presented in Section 2 showed that the relationship between the emission intensity of production and the stringency of environmental policy is non-monotonic. For low values of the tax rate, firms find it profitable to adopt a cleaner production process since output is large; however, if the tax rate is high, it is no longer worthwhile to invest in cleaner production methods, as output is low. In fact, similar to Perino and Requate (2012), this relationship is U-shaped for the case of linear demand and quadratic installation costs. Therefore, a stricter environmental policy may have negative effects on the environment, as it may induce the adoption of dirtier technologies.

Furthermore, the paper highlights the importance of the information transmission mechanism in influencing firm behavior. In contrast with the open-loop case in which firms choose output and emission intensity simultaneously, total emissions do not necessarily decrease with higher taxes and, contrary to what one might expect, may actually increase. The explanation behind this somewhat counterintuitive result is that, by investing in a cleaner technology, a firm can credibly commit itself to a higher activity level in the future that may very well offset the reduction in pollution intensity. Therefore, a tax hike can lead to technological improvements that are pollution-increasing.

These findings show that emission taxes are significantly limited in their ability to provide incentives that spur both technology adoption and pollution reduction, proving that one must refrain from claiming that stricter environmental policy is always beneficial for the environment. However, it remains to determine whether other policy tools, such as command-and-control instruments, also lead to non-monotonic behavior in oligopolistic markets. This analysis is left for future research.

6 Appendix

Lemma 1 The denominator of (19) and (20) is positive.

Proof of Lemma 1 First note that

$$0 \geq \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i} > \frac{\partial^2 \pi_i^o}{\partial q_i^2},$$

where the first inequality follows from assumption (1) and the second from the downward sloping demand function $P(Q)$ and the convexity of $C(q)$. Thus,

$$\left| \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i} \right| < \left| \frac{\partial^2 \pi_i^o}{\partial q_i^2} \right|. \tag{47}$$

We therefore have that

$$\begin{aligned}
\frac{\partial^2 \pi_i^o}{\partial q_i^2} \frac{\partial^2 \pi_j^o}{\partial q_j^2} - \frac{\partial^2 \pi_i^o}{\partial q_i \partial q_j} \frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j} &= \left(-\frac{\partial^2 \pi_i^o}{\partial q_i^2} \right) \left(-\frac{\partial^2 \pi_j^o}{\partial q_j^2} \right) - \left(-\frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i} \right) \left(-\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j} \right) \\
&= \left| \frac{\partial^2 \pi_i^o}{\partial q_i^2} \right| \left| \frac{\partial^2 \pi_j^o}{\partial q_j^2} \right| - \left| \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i} \right| \left| \frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j} \right| \\
&> \left| \frac{\partial^2 \pi_i^o}{\partial q_i^2} \right| \left| \frac{\partial^2 \pi_j^o}{\partial q_j^2} \right| - \left| \frac{\partial^2 \pi_i^o}{\partial q_i^2} \right| \left| \frac{\partial^2 \pi_j^o}{\partial q_j^2} \right| \\
&= 0,
\end{aligned}$$

where the inequality follows from (47). ■

Proof of Equation (27) Differentiating (25) with respect to ε_i yields

$$\frac{\partial \pi_i^o}{\partial q_i}\frac{\partial q_i}{\partial \varepsilon_i}+\frac{\partial \pi_i^o}{\partial q_j}\frac{\partial q_j}{\partial \varepsilon_i}-F'(\varepsilon_i)-tq_i-t(1+\varepsilon_i)\frac{\partial q_i}{\partial \varepsilon_i}=0.$$

Collecting terms,

$$\left[\frac{\partial \pi_i^o}{\partial q_i}-t(1+\varepsilon_i)\right]\frac{\partial q_i}{\partial \varepsilon_i}+\frac{\partial \pi_i^o}{\partial q_j}\frac{\partial q_j}{\partial \varepsilon_i}-F'(\varepsilon_i)-tq_i=0.$$

From (14) it follows that the term in square brackets is equal to zero, thus yielding first-order condition (27). ■

Proof of Proposition 1 To prove part (i), evaluate the left-hand side of (27) to obtain

$$\left.\frac{\partial \pi_i}{\partial \varepsilon_i}\right|_{\varepsilon_i=\alpha}=\left[P'(Q)\frac{\partial q_j}{\partial \varepsilon_i}-t\right]q_i\leq 0, \tag{48}$$

where the inequality follows from (20). Thus, $\varepsilon_i \leq \alpha$ when $t>0$. Since $\varepsilon_i=\alpha$ when $t=0$, emission intensity is decreasing in the tax rate when t is small.

To prove part (iii), let us define t^* as

$$t^*=\frac{\partial \pi_i^o(0,0)}{\partial q_i}. \tag{49}$$

In other words, t* is the emission tax rate at which firms no longer find it profitable to produce in the second stage of the game, regardless of their respective emission intensities. Anticipating this, firms do not invest in abatement and set $\varepsilon=\alpha$ for $t\geq t^*$. Since $\varepsilon_i \leq \alpha$ by (48), it follows that emission intensity must eventually be an increasing function of t. ■

Proof of Corollary 1 The first term in (31) is negative by (24). The term in square brackets is given by

$$\frac{\partial q_i}{\partial \varepsilon_i}+\frac{\partial q_i}{\partial \varepsilon_j}=\frac{\partial q_i}{\partial \varepsilon_i}+\frac{\partial q_j}{\partial \varepsilon_i}$$

$$=\frac{t\left(\frac{\partial^2 \pi_j^o}{\partial q_j^2}-\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\right)}{\frac{\partial^2 \pi_i^o}{\partial q_i^2}\frac{\partial^2 \pi_j^o}{\partial q_j^2}-\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}}$$

$$=\frac{t\left(\frac{\partial^2 \pi_j^o}{\partial q_j^2}-\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\right)}{\left(\frac{\partial^2 \pi_j^o}{\partial q_j^2}-\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\right)\left(\frac{\partial^2 \pi_j^o}{\partial q_j^2}+\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\right)}$$

$$=\frac{t}{\left(\frac{\partial^2 \pi_j^o}{\partial q_j^2}+\frac{\partial^2 \pi_j^o}{\partial q_i \partial q_j}\right)}\leq 0,$$

where the first and second equalities follow by imposing symmetry and the last inequality follows from (1) and (8).

If $\pi_i^o(\cdot)$ is a smooth function, it is straightforward to verify that

$$\lim_{t \to 0} \frac{dq}{dt} = \frac{(1+\alpha)}{\frac{\partial^2 \pi_i^o}{\partial q_i^2} + \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}} + (0)\left[-\frac{q_0}{F''(\alpha)}\right]$$

$$= \frac{(1+\alpha)}{\frac{\partial^2 \pi_i^o}{\partial q_i^2} + \frac{\partial^2 \pi_i^o}{\partial q_j \partial q_i}} \leq 0,$$

where q_0 denotes equilibrium output per firm when $t = 0$. Thus, industry output is decreasing in the tax rate when t is small.

Recall that ε is increasing in the tax rate for large values of t. This implies that the second-term in (31) is negative and, hence, that total output is decreasing in the tax rate when t is high. ■

Proof of Corollary 2 We have already shown that total emissions E are decreasing in the tax rate t when t is small. It remains to prove that E is also decreasing in t when t is large. To do so, note that $q \to 0$ as $t \to t^*$, where t^* is as defined in (49). This implies that the first term in (32) approaches zero while the second term in (32) becomes negative as $t \to t^*$. ■

Proof of Proposition 3 To prove part (i), first note that the denominator in (46) is positive by (41). Thus, the sign of (46) is completely determined by the expression in curly braces, which we will denote by ϕ. The first and second derivatives of ϕ with respect to t are

$$\frac{\partial \phi}{\partial t} = \frac{8}{9}[(1+\alpha)t - a] \tag{50}$$

and

$$\frac{\partial^2 \phi}{\partial t^2} = \frac{8}{9}(1+\alpha) > 0. \tag{51}$$

Hence ϕ is a convex function of t and has a global minimum at

$$t_o = \frac{a}{(1+\alpha)}. \tag{52}$$

Evaluating ϕ at t_o yields

$$(1+\alpha)[\gamma - \frac{4}{9}t_o^2] > 0,$$

where the inequality follows from (41). We thus conclude that q is monotonically decreasing in t.

To prove part (ii), we focus on the expression in curly braces in (45), which we will denote by θ. The first and second derivatives of θ with respect to t are given by

$$\frac{\partial \theta}{\partial t} = \frac{8}{9}at - 2(1+\alpha)\gamma$$

and

$$\frac{\partial^2 \theta}{\partial t^2} = \frac{8}{9}a > 0.$$

Hence θ is also a convex function of t and reaches a global minimum at

$$t' = \frac{9\gamma}{4a}(1+\alpha).$$

Note that $t' \geq t_o$ if and only if $\gamma - \frac{4}{9}t_o^2 \geq 0$, which is true by (41). As mentioned above, however, we have a corner solution for $t > t_o$.[4] Thus, assuming an interior solution, the relevant global minimum is found at t_o.

Evaluating ϕ at $t = 0$ and $t = t_o$, we have that

$$\theta\Big|_{t=0} = a\gamma \geq 0 \tag{53}$$

and

$$\theta\Big|_{t=t_o} = -a[\gamma - \frac{4}{9}t_o^2] \leq 0, \tag{54}$$

where the second inequality follows from (41).

Since θ is a convex function with a global minimum at $t = t_o$, it behaves monotonically in $[0, t_o]$. This, in combination with inequalities (53) and (54), implies that there exists a tax rate t^* such that θ is positive for all $t \in [0, t^*]$ and negative for all $t \in [t^*, t_o]$. Thus, ε is a U-shaped function of t.

To prove part (iii), let us begin by differentiating (44) with respect to t. It is straightforward to verify that

$$\frac{de}{dt} = -\frac{\gamma}{3\left[\gamma - \frac{4}{9}t^2\right]^3}\left\{\frac{4\gamma}{9}[a - t(1+\alpha)]^2 + \left[\gamma(1+\alpha) - \frac{4at}{9}\right]^2 + \frac{8t}{9}\left[a - t(1+\alpha)\right]\left[\frac{4t}{9}a - \gamma(1+\alpha)\right]\right\}.$$

The sign of $\frac{de}{dt}$ is thus determined by the expression in curly braces, which we

[4]In this case, $\varepsilon = \alpha$ and $\frac{d\varepsilon}{dt} = 0$

now denote by η. Differentiating η with respect to t yields

$$\frac{\partial \eta}{\partial t} = -\frac{24}{9}(1+\alpha)\left[a - t(1+\alpha)\right]\left[\gamma - \frac{4}{9}t_o t\right],$$

where t_o is as defined in (52).

Notice that $\gamma - \frac{4}{9}t_o t \geq 0$ if $t \leq t_o$, since

$$\gamma - \frac{4}{9}t_o t \geq \gamma - \frac{4}{9}t_o^2 \geq 0,$$

where the last inequality follows from (41). Hence η is a decreasing function of t in $[0, t_o]$.

Evaluating η at $t = t_o$ obtains

$$\eta\Big|_{t=to} = \left[\gamma(1+\alpha) - \frac{4t}{9}a\right]^2 \geq 0. \tag{55}$$

Since η is monotonically decreasing in $[0, t_o]$ and positive at t_o, it follows that η is positive for all $t \in [0, t_o]$. This implies that total emissions are decreasing in the tax rate.[5] ■

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[5] If $t > t_o$, then $e = 0$ and $\frac{de}{dt} = 0$.

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