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Incentives for Innovation in Pollution Control: Emission Standards Revisited

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Abstract. Conventional analysis of the economics of environmental policy usually claims that emission taxes induce a stronger incentive for an improvement in pollution abatement technologies compared to emission standards. In contrast, recent empirical studies reveal that there is no systematic relationship between improvements in pollution abatement technologies and the policy instrument chosen. The present paper tries to clarify this contradiction. In the first step the paper shows that the conventional model of innovation in pollution control under different policy regimes is deficient in at least two ways: It neglects policy impacts on the firms' output level and it assumes a rather unrealistic type of emission standard. In the second step the paper presents a more elaborated model which tries to overcome these shortcomings. Using this model it is shown that the impact on innovation in pollution control caused by taxes and standards strongly depends on the scale of technical progress as well as on the cost structure of the firm under consideration such that there is no unique ranking of the two policies. Finally, the paper discusses the policy implications of these findings.

Keywords: Emission Standards, Emission Taxes, Incentives to Innovate.

JEL Classification: H23, Q55.

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1 Introduction

Conventional analysis of the economics of environmental policy instruments usually claims that emission taxes induce a higher incentive for improvements in pollution abatement technologies relative to emission standards.[1] This claim is justified by the fact that under a tax policy there is a positive price for every unit of pollutants whereas emission standards imply a price of zero in the case of compliance. Besides the well known static efficiency properties this advantage in terms of promoting technological change leads most economists to prefer market based instruments like emission taxes rather than direct controls like emission standards. In contrast, recent empirical studies within the field of environmental policy and technological progress[2] come to the result that there is no systematic relationship between improvements in pollution abatement technologies and the policy instrument chosen (see, e.g., Hemmelskamp 2000).

In the following we try to shed some light on this puzzling issue. In Section 2 we argue that the conventional approach of innovation in pollution control suffers from two deficiencies which lead to a systematic bias in favour of emission taxes: It neglects environmental policy impacts on the firms' output level and it employs a rather unrealistic description of emission standards. In Section 3 we lay out an extended approach which overcomes these deficiencies by explicitly accounting for output reactions and employing a more realistic description of emission standards. Using this approach we show in Section 4 that the impact on innovation in pollution control caused by taxes and standards depends crucially on the scale of technological progress as well as on the cost structure of the firm under consideration such that there is no unique ranking between the different instruments. In Section 5 we discuss the policy conclusions to be drawn from our results.

2 The conventional approach

The conventional approach of innovation in pollution control under different policy regimes can be traced back to the early seventies (see Zerbe, 1970; Wenders, 1975). In the following period this approach has been taken up and partially refined by various authors without changing its basic assumptions (e.g., Downing/White, 1986; Milliman/Prince, 1989). Starting point is a competitive industry which consists of a large number of firms that emit a homogenous pollutant into the environment. Emissions caused by a representative firm within this industry are denoted by E. Prior to innovation marginal abatement cost associated with incremental reductions in E are given by $MC_1(E)$. Without environmental regulation the firm under consideration would emit E_0 pollution units. The pollution control authority levies an emission tax of t_1 per unit of emitted pollutants or imposes an emission standard that allows only

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[1] For the conventional approach see, e.g., Zerbe (1970), Wenders (1975), Downing/White (1986) and Milliman/ Prince (1989). A more sophisticated analysis is offered by Requate (1998) who, however, concentrates on dynamic welfare aspects of taxes and tradeable emission permits.

[2] For the purpose of the following analysis it is not necessary to distinguish between technical/technological progress and innovation; we therefore use these expressions synonymously.

E_1 units to be emitted per firm and time period.[3] As shown in figure 1, this induces abatement cost of E_1E_0A. However, in the case of the emission tax the firm has additionally to bear the tax burden amounting to $0E_1At_1$, such that total cost are given by $0E_0At_1$. Now let the firm under consideration develop an innovation in pollution control which shifts its marginal cost curve from $MC_1(E)$ to $MC_2(E)$. The resulting cost savings are CE_0A under the emission standard and BE_0A under the emission tax, where the latter induces the firm to reduce emissions after innovation from E_1 to E_2. Due to $BE_0A>CE_0A$ it can be concluded from this simple graphical analysis that an emission tax provides a higher incentive to innovate relative to an emission standard.[4]

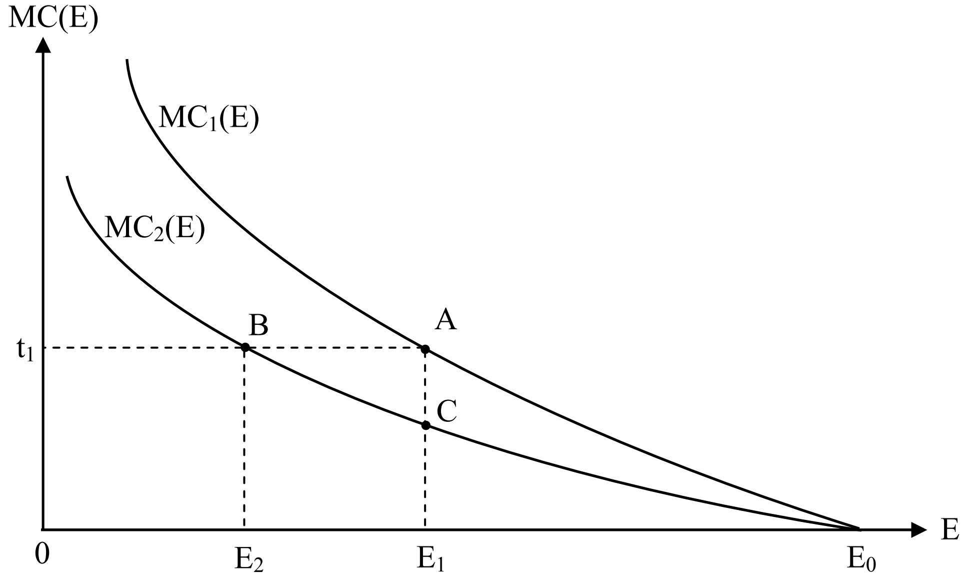

Figure 1: The conventional approach of innovation in pollution control.

Although the above analysis is compelling at first glance due to its simplicity and vividness, it suffers from two deficiencies. The first and more fundamental one is related to the fact that the conventional approach assumes a fixed output level and concentrates entirely on minimising pure abatement cost caused by so-called “end of pipe”-measures (plus transfers in the case of an emission tax).[5] However, different policy instruments like taxes and standards will induce different output levels such that the impact of innovation on profits also depends on the policy instruments chosen. As a consequence, the appropriate measure of the incentive to innovate is not given by reductions in pure abatement cost (including tax transfers), as assumed above, but by increases in profits. Obviously, this cannot be analysed by simple graphical means like figure 1 since true “abatement cost” in terms of profits forgone depend on the policy instrument chosen and for different instruments one would obtain different abatement cost curves.

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[3] Using the above model various authors have also analysed emission control subsidies and tradeable permits. These instruments are suppressed here because they are outside the scope of the following considerations.

[4] If the new technology spreads across the industry and the authority tries to stick with the initial level of emissions, it will *lower* the tax rate which even reinforces the above arguments in favour of an emission tax.

[5] This shortcoming has also been recognized be Requate (1998) who, however, concentrates on taxes and tradeable permits and uses a model somewhat different from our model developed in the next Section.

The second deficiency relates to the description of the emission standard. As customary in the pollution control literature the approach above employs an emission standard which is fixed in terms of *absolute* quantities like, e.g., tons per year. In practice, however, emission standards regularly are fixed in terms of the concentration of pollutants in waste water or waste gas, respectively. The reason is that standards in terms of concentrations can equally be applied to a wide range of different sources whereas standards in terms of absolute quantities would have to be differentiated according to the size of each single emission source. Such a differentiation, however, would hamper the process of environmental policy making by requiring a vast amount of information and possibly provoking lengthy discussions between governmental authorities and the firms or industries involved.

Summing up we conclude that the conventional model of innovation in pollution control under different policy regimes is based on doubtful assumptions about the optimization behaviour of the innovating firm as well as about the nature of the emission standard. Policy recommendations extracted from this model should therefore be handled with care. In the following section we will draw up a more elaborated model that avoids these shortcomings.[6] Using this model we will again compare the incentives for improvements in pollution abatement technologies under emission taxes and standards.[7]

3 The model

3.1 Basic assumptions

Consider again a firm within a competitive industry which consists of a large number of firms emitting a homogenous pollutant into the environment. Denote the output of the firm under consideration by y and the market price by p. Assume that production cost are given by a continuous cost function $c_1[y]$ that satisfies the usual assumption of increasing marginal cost, i.e. $c_1'[y]>0$ and $c_1''[y]>0$. Let $\varepsilon>0$ indicate the amount of pollutants emitted per unit of output before any abatement by “end of pipe”-measures. Denote the amount of pollutants abated by v and the amount of pollutants finally emitted to the environment by e, i.e.: $e=\varepsilon y-v$. Finally, assume that the cost of abatement by “end of pipe”-measures are given by a continuous cost function $c_2[v]$ that also exhibits increasing marginal cost: $c_2'[v]>0$ and $c_2''[v]>0$. Without any environmental regulation the firm would choose v=0 and emissions would amount to e^{max}.

The pollution control authority levies an emission tax of t per unit of emitted pollutant or imposes an emission standard. In contrast to the conventional approach described in Section 2, the latter is fixed in terms of the concentration of pollutants in waste water or waste gas, respectively. Assuming a linear relationship between output y and the amount of waste water or waste gas, this translates into an emission standard that allows a maximum of $\bar{\varepsilon}<\varepsilon$ units of pollutants per unit of output. Hence, the amount of pollutants to be abated is given by $v=y(\varepsilon-\bar{\varepsilon})$. In order to ensure comparability of the two policy instruments we assume that both instruments initially (i.e. prior to innovation) are adjusted in such a way that profit

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[6] The following model is a generalized version of a more simple precursor presented by Michaelis (2004).

[7] We do not explicitly consider tradeable emission permits because within the framework of the following model the incentives to innovate are the same under taxes and tradeable permits.

maximization by the firm leads to the same amount of pollutants finally emitted to the environment, denoted by e_n. Obviously, under this assumption a comparison of instruments only makes sense if the regulation under consideration actually has an impact on emissions (i.e., $\bar{\varepsilon} < \varepsilon$ or t>0, respectively, such that $e_n < e^{max}$) and if at least one marginal unit of pollutants is left over after complying with it (i.e., $e_n > 0$). We therefore restrict the following analysis to cases satisfying $0 < e_n < e^{max}$ prior to innovation.

3.2 Profit maximization

In contrast to the conventional approach presented in Section 2 which assumes a fixed output level, in our model the firm under consideration is endowed with two possible measures for reducing emissions. Emissions can be reduced by reducing output and/or by means of "end of pipe" treatment. In the case of the emission standard the firm seeks to maximize the profit function $\pi_s = py - c_1[y] - c_2[v]$ subject to the constraint $v = y(\varepsilon - \bar{\varepsilon})$. This leads to the following optimality condition where y_s^* indicates the optimal output under the emission standard:

(1) $p = c_1'[y_s^*] + (\varepsilon - \bar{\varepsilon})c_2'[y_s^*(\varepsilon - \bar{\varepsilon})]$.

This condition requires to equalize price and marginal cost. The latter are composed of two parts: marginal cost of production plus marginal cost caused by the abatement of $(\varepsilon - \bar{\varepsilon})$ additional units of the pollutant under consideration. Substituting $y_s^*(\varepsilon - \bar{\varepsilon})$ by $\varepsilon y_s^* - e_n$ yields:[8]

(2) $p = c_1'[y_s^*] + (\varepsilon - \bar{\varepsilon})c_2'[\varepsilon y_s^* - e_n]$.

In the case of the tax the firm aims at maximizing $\pi_t = py - c_1[y] - c_2[v] - t(\varepsilon y - e_n)$. This leads to the following optimality conditions where y_t^* and v_t^* indicate the optimal output and the optimal amount of abatement, respectively:

(3) $p = c_1'[y_t^*] + \varepsilon t$.

(4) $c_2'[v_t^*] = t$.

Condition (3) requires to equalize price and marginal production cost plus marginal tax burden; condition (4) requires to equalize marginal abatement cost and the tax rate. Combining together and substituting v_t^* by $\varepsilon y_t^* - e_n$ yields:[9]

(5) $p = c_1'[y_t^*] + \varepsilon c_2'[\varepsilon y_t^* - e_n]$.

Since marginal cost of production as well as marginal cost of pollution abatement are monotonic increasing functions of y, there exist unique solutions for y_s^* and y_t^*, respectively. Moreover, comparing (2) and (5) reveals that due to increasing marginal cost the output level under the standard is always higher than the output level under the tax regime: $y_s^* > y_t^*$. Since both instruments are adjusted as to lead to the same emission level e_n, this implies also $v_s^* > v_t^*$ and $\pi_s^* > \pi_t^*$.

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[8] Remember that both instruments are adjusted in such a way that they lead to emissions of e_n units of the pollutant under consideration. Consequently, we obtain $e_n = \varepsilon y_s^* - v_s^*$. Together with $v_s^* = (\varepsilon - \bar{\varepsilon})y_s^*$ this implies $y_s^*(\varepsilon - \bar{\varepsilon}) = \varepsilon y_s^* - e_n$

[9] In the Appendix it is shown, that e_n is a continuously changing function in t. Hence, the control authority can achieve any non-negative level of e_n by choosing the appropriate level of t.

4 Incentives to innovate

In principle, the above model allows to analyse two different types of technological progress in pollution control: cost saving progress in "end of pipe"-treatment which shifts down the cost function $c_2[v]$ and pollution saving progress in the production process itself which shifts down the emission coefficient ε. The following analysis concentrates on the latter case since there is ample evidence to assume that "end of pipe"-technologies are almost fully developed,[10] whereas changes in the production process itself still offer a wide range of opportunities to reduce emissions (see, e.g., German Council of Environmental Advisors 1994, pp.134). Moreover, "end of pipe"-measures usually lead only to a shift of pollutants between the different environmental media whereas by changes in the production process itself it is possible to reduce the generated amount of pollutants at its origin.

In the following we assume that the firm under consideration has developed or discovered an innovation which reduces the amount of pollution generated per unit of output without changing production cost. We then ask how the firm's profit level would be affected by adopting this new technology under the different policy regimes.[11] In doing so, we differentiate between a marginal and a non-marginal decrease in ε. However, particularly with respect to the latter case an important caveat associated with the possibility of diffusion should be noted (see, e.g., Milliman/Prince, 1989): Although the firm under consideration is small in terms of its contribution to total emissions, it cannot be ruled out that the innovation once adopted will spread across the industry thereby altering total emissions. If this happens, the pollution control authority might recognise the change in total emissions and adjust the standard or the tax rate, respectively. In principle, the firm under consideration should try to anticipate this effect when deciding whether or not to adopt the innovation. In practice, however, such a degree of "clairvoyance" seems extremely unrealistic since it implies complete information and a process of political decision making which follows well understandable patterns. Both assumptions are violated in reality. No innovating firm possess sufficient information in order to completely anticipate the speed and degree of diffusion and even highly sophisticated scholars in political economy are far from understanding the whole complexity of the process of political decision making. Therefore, the following analysis supposes that the innovating firm calculates the private value of innovation under the assumption that the standard or the tax rate, respectively, will remain unchanged.

4.1 Marginal technological progress

In this section we assume an innovation which leads only to a marginal decrease in ε. The incentive to innovate is then represented by the first derivate of the profit function. A reduction

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[10] An important exception are recent attempts to develop "end of pipe"-measures for removing CO_2-emissions from power plants and similar facilities (see, e.g., Grimston et al., 2001).

[11] It should be noted that the following analysis is not concerned with optimal investments in R&D from the social point of view. Instead, we follow Milliman/Prince (1989) and look only at the private value of an innovation once it has been found. In comparing environmental policy instruments this approach is sufficient, since R&D expenditures for a given project do not depend on the instrument employed by the control authority (see, e.g., Downing/White, 1986, p.21).

of ε induces three effects on profits. First, two indirect effects through changing the optimal level of production and abatement and second a direct effect on profits. However, due to the envelope theorem the two indirect effects of a marginal change in ε can be disregarded such that only the direct effect on profits remains (e.g. Sydsaeter et al. 2000, p. 94). Consequently, in the case of an emission standard differentiating the corresponding Lagrangian function $L_s = py_s^* - c_1[y_s^*] - c_2[v_s^*] + \lambda(e_n - \varepsilon y_s^* + v_s^*)$ with respect to ε yields:

$$(6) \quad \frac{\partial L_s}{\partial \varepsilon} = -\lambda y_s^* .$$

Moreover, the Lagrangian multiplier λ satisfies the following first order condition of profit maximization: $\lambda = c_2'[v_s^*]$. Inserting into (6) yields the change in profits and thereby the incentive to innovate in the case of an emission standard:

$$(7) \quad \frac{\partial L_s}{\partial \varepsilon} = -c_2'[v_s^*]y_s^* > 0 .^{12}$$

Under taxation the profit function is given by $\pi_t = py_t^* - c_1[y_t^*] - c_2[v_t^*] + t(\varepsilon y_t^* - v_t^*)$. Again using the envelope theorem yields:

$$(8) \quad \frac{\partial \Pi_t}{\partial \varepsilon} = -ty_t^*$$

where t satisfies the following first order condition of profit maximization: $t = c_2'[v_t^*]$.[13] Inserting into (8) yields the incentive to innovate in the case of taxation:

$$(9) \quad \frac{\partial \Pi_t}{\partial \varepsilon} = -c_2'[v_t^*]y_t^* > 0$$

Comparing (7) and (9) in view of $y_s^* > y_t^*$ and $v_s^* > v_t^*$ as derived in Section 3.2 reveals that for a marginal decrease in ε an emission standard always provides a higher incentive to innovate relative to an emission tax:

$$(10) \quad \frac{\partial L_s}{\partial \varepsilon} > \frac{\partial \Pi_t}{\partial \varepsilon} .$$

4.2 Non-marginal technological progress

For analysing non-marginal technological progress we introduce a parameter $\alpha \in]0,1]$ measuring the degree of technological progress. I.e., the level of the emission coefficient *after innovation* is given by $(1-\alpha)\varepsilon$ where ε still indicates the initial level prior to innovation. As a consequence, in the case of an emission standard which remains unchanged the profit function after innovation is given by:

$$(11) \quad \Pi_s[\alpha] = \begin{cases} py_s^* - c_1[y_s^*] - c_2[v_s^*] + \lambda(e_n - (1-\alpha)\varepsilon y_s^* + v_s^*) & \text{if} \quad \alpha < \dfrac{\varepsilon - \bar{\varepsilon}}{\varepsilon} \\ py_s^* - c_1[y_s^*] & \text{if} \quad \alpha \geq \dfrac{\varepsilon - \bar{\varepsilon}}{\varepsilon} \end{cases} .$$

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[12] Note, that the incentive to innovate is always positive, since technological progress implies a *decrease* in ε.

[13] It should be noted, that this condition always holds prior to innovation since we have assumed $0<e_n<e^{max}$.

With respect to the interpretation of (11) it should be noted that no further pollution control is necessary if $\alpha \geq (\varepsilon - \bar{\varepsilon})/\varepsilon$ such that the emission coefficient decreases to a level $(1-\alpha)\varepsilon \leq \bar{\varepsilon}$. Under these circumstances profits reach the upper bound indicated by the unregulated case such that further technological progress beyond this level would add nothing more to profits.

Regarding the profit function after innovation in the case of an unchanged emission tax t>0 we again have to differentiate between two cases according to the degree of innovation:

$$(12)\quad \Pi_t[\alpha] = \begin{cases} py_t^* - c_1[y_t^*] - c_2[v_t^*] + t((1-\alpha)\varepsilon y_t^* - v_t^*) & \text{if} \quad \alpha < \bar{\alpha} \\ py_s^* - c_1[y_s^*] - c_2[(1-\alpha)\varepsilon y_t^*] & \text{if} \quad \alpha \geq \bar{\alpha} \end{cases}.$$

For $\alpha < \bar{\alpha}$ a strictly positive amount of emissions remains after abatement such that the condition $t = c_2'[v_t^*]$ holds. In contrast, for $\alpha \geq \bar{\alpha}$ the decrease in the emission coefficient ε is so strong that for the given tax rate it is profitable to abate *all* emissions and no more tax is paid. The latter situation occurs if marginal abatement costs for the last unit of emission caused by production are smaller than the tax rate: $t > c_2'[v_t^*]$.

Using (11) and (12) the incentive to innovate can be calculated as the difference in profits after (α>0) and before (α=0) innovation. Differentiating (11) and (12) with respect to α and employing the envelope theorem, these differences in profits can also be expressed as integrals between zero and say α'. Consequently, we obtain for the case of an emission standard and an emission tax, respectively:

$$(13)\quad \Delta\Pi_s[\alpha] = \begin{cases} \Pi_s[\frac{\varepsilon - \bar{\varepsilon}}{\varepsilon} > \alpha' > 0] - \Pi_s[\alpha = 0] = \int_0^{\alpha'} c_2'[v_s^*]\varepsilon y_s^* d\alpha & \text{if} \quad \alpha' \leq \frac{\varepsilon - \bar{\varepsilon}}{\varepsilon} \\ \Pi_s[\alpha' = \frac{\varepsilon - \bar{\varepsilon}}{\varepsilon}] - \Pi_s[\alpha = 0] = \int_0^{\frac{\varepsilon - \bar{\varepsilon}}{\varepsilon}} c_2'[v_s^*]\varepsilon y_s^* d\alpha & \text{if} \quad \alpha' \geq \frac{\varepsilon - \bar{\varepsilon}}{\varepsilon} \end{cases}.$$

$$(14)\quad \Delta\Pi_t[\alpha] = \begin{cases} \Pi_t[\bar{\alpha} > \alpha' > 0] - \Pi_t[\alpha = 0] = \int_0^{\alpha'} t\varepsilon y_t^* d\alpha & \text{if} \quad \alpha < \bar{\alpha} \\ \Pi_t[\alpha' > \bar{\alpha}] - \Pi_t[\alpha = 0] = \int_0^{\bar{\alpha}} t\varepsilon y_t^* d\alpha + \int_{\bar{\alpha}}^{\alpha'} c_2[(1-\alpha)]\varepsilon y_t^* d\alpha & \text{if} \quad \alpha \geq \bar{\alpha} \end{cases}.$$

The second addend in the second part of (14) shows the increase in profits when y_t^* is still raised and all additional emissions are fully abated. Note, that this expression is independent of the tax rate, since no taxes are paid. Consequently the output level depends only on marginal production and marginal abatement costs. (13) and (14) are continuous as well as monotonously increasing functions in α, except for innovations with $\alpha \geq (\varepsilon - \bar{\varepsilon})/\varepsilon$ in the case of an emission standard, where the incentive to innovate is constant.

Now suppose a ”total” innovation with $\alpha = 1$. For this case, (11) and (12) show that both instruments lead to the same level of profits *after* innovation. Clearly, taxes and standards are equal, if emissions can be abated without any costs. Moreover, in Section 3.2 it has been shown, that *before* innovation profits under an emission standard always exceed profits under taxation if both instruments lead to the same emission level e_n. As a consequence, for the case of a "total" innovation with $\alpha=1$ an emission tax always provides a higher incentive to innovate relative to an emission standard: $\Delta\pi_t(\alpha=1) > \Delta\pi_s(\alpha=1)$.[14] Contrary, in the case of a marginal innovation with $\alpha\rightarrow 0$ in Section 4.1 for the incentive to innovate the reverse order has been observed: $\Delta\pi_s(\alpha\rightarrow 0) > \Delta\pi_t(\alpha\rightarrow 0)$. Together with the continuity of $\Delta\pi_s$ and $\Delta\pi_t$ these two results imply the existence of at least one α^* satisfying $\Delta\pi_a(\alpha^*)=\Delta\pi_t(\alpha^*)$ in the range of $0<\alpha<1$ (see Figure 2). As a consequence, the incentive to innovate under emission standards and taxes crucially depends on the extent to which technological progress decreases the emission coefficient ε. For a relative small decrease ($\alpha<\alpha^*$) an emission standard provides a higher incentive to innovate compared to an emission tax, whereas for a relatively large decrease ($\alpha>\alpha^*$) the reverse is true. Moreover, the magnitude of α^* depends not only on the strength of environmental policy ($\bar{\varepsilon}$ or t, respectively) but also on the individual costs of production and abatement of the firm under consideration. Therefore, generalized conclusions across different firms can not be drawn.

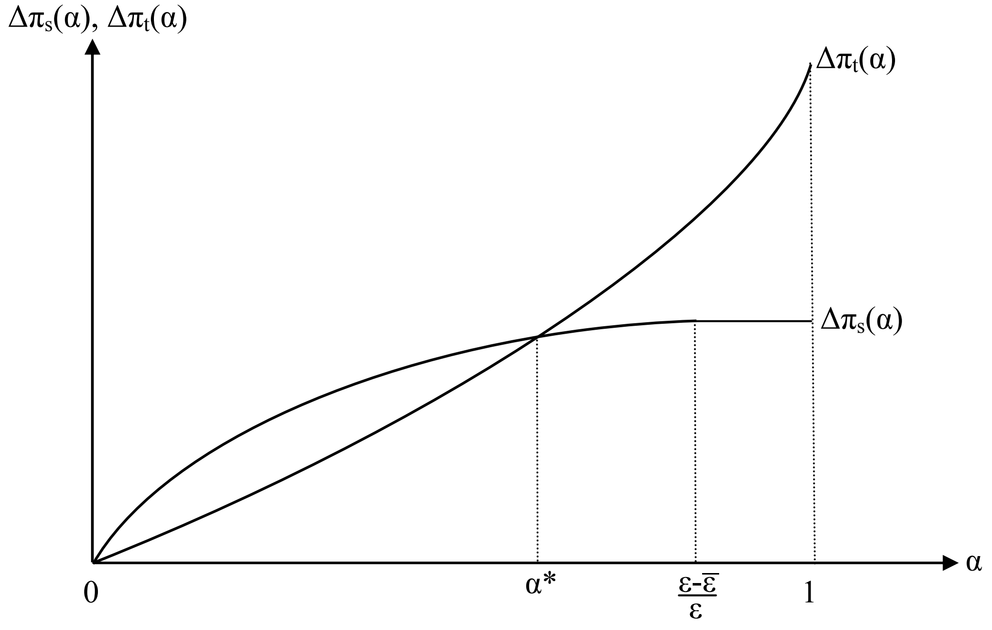

Figure 2: Incentives to innovate in the case of non-marginal technical progress.

5. Summary and conclusions

Conventional analysis of the economics of environmental policy instruments usually claims that emission taxes induce a higher incentive for improvements in pollution abatement technologies relative to emission standards. This result, however, crucially depends on some rather unrealistic assumptions. Using a more realistic model, which explicitly accounts for output markets and employs a more elaborated description of emission standards, the above

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[14] The reason for this result are the additional tax payments which can be economized unlike if an emission standard is applied.

analysis has shown that there is no unique ranking between taxes and standards with respect to the induced incentive to innovate. Which instrument provides a higher incentive to innovate depends on the specific circumstances of the case under consideration and in particular on the specific patterns of technological progress: If technological progress is expected to come as a “big bang” (implying a large α in our model), then the conventional view holds and emission taxes induce a higher incentive to innovate compared to emission standards. However, the reverse is true if technological progress is expected to come as a sequence of comparatively small steps independent of each other (implying a small α in our model). As a consequence, no general political advice can be given in favour of taxes or standards and there might emerge a dilemma concerning the choice of the appropriate instrument: Whereas emission taxes - even if one explicitely considers output reactions - exhibit strong advantages concerning economic efficiency (see, e.g., Katsoulacos/Xepapadeas, 1996, p.6), it cannot be ruled out that under certain circumstances emission standards might induce a higher incentive to innovate. In practice, this might lead to a conflict between short-term goals concerning economic efficiency and long-term goals concerning technological progress. In weighting up these goals it should be recognized that, on the one hand, inefficiencies caused by an unique emission standard are the smaller the more homogenous are the firms within the regulated industry. On the other hand, the weight applied to the issue of technological progress should be the higher, the larger are the remaining potentials for improvements by innovation (“technological opportunities” in the sense of Klevorick et al., 1995). As a consequence, in cases where firms are sufficiently homogenous, technological opportunities are large and improvements are expected to come in a continuous “step-by-step” process, it could be quite sensible from an economic point of view to use emission standards instead of emission taxes.

Appendix

We assumed that $c_1'[y]$ and $c_2'[v]$ are monotonously increasing differentiable functions. This implies that the reverse functions exist and are also monotonously increasing differentiable functions. From (3) and (4), respectively, we obtain:

$$\frac{\partial t}{\partial y_t^*} = -\frac{c_1''[y_t^*]}{\varepsilon} \qquad \Rightarrow \qquad \frac{\partial y_t^*}{\partial t} = -\frac{\varepsilon}{c_1''[y_t^*]} < 0$$

$$\frac{\partial t}{\partial v_t^*} = c_2''[v_t^*] \qquad \Rightarrow \qquad \frac{\partial v_t^*}{\partial t} = \frac{1}{c_2''[v_t^*]} > 0$$

Due to $e_n = \varepsilon y_t^* - v_t^*$ this implies that

$$\frac{\partial e_n}{\partial t} = -\frac{\varepsilon^2}{c_1''[y_t^*]} - \frac{1}{c_2''[v_t^*]}$$

is also a continuously decreasing function in t.

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