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Abstract

It is often argued that without tax-exemption for the production sector environmental tax reforms substantially reduce profits. We challenge this question and investigate the consequences of different potential tax reform proposals for a monopoly. It turns out that, apart from a tax-revenue-maximizing reform, there is little reason to believe that environmental tax reforms are likely to depress profits. Rather the contrary, for a small, revenue-neutral tax reform profit increases, provided that the government faces the increasing branch of the Laffer curve; however, contrary to what one might expect, this particular tax reform may well lead to a reduction of environmental quality.

Keywords: environmental tax reform, pollutant emissions, monopoly taxation, optimal taxation, double dividend

(JEL: D42, D62, H21, H23, H32)

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1 Introduction

Within the last years a substantial part of the political debate has been dedicated to the establishment of ecological tax systems so as to correct for environmental diseconomies. Since it is not the only task of the government to redress externalities but also to provide public services, the tax system is required to raise public funds as well. In order to reach this twofold target the advocates of green tax reforms argue that environmental taxes represent, within the group of distortionary taxes, the most efficient instrument.¹ Yet, although environmental taxes may mitigate the omnipresent scarcity of public funds, they play a minor role in practice, which is due to several reasons: Firstly, since environmental taxes did historically not play any role, lawyers argue that the introduction of green taxes may cause legal, *i. e.*, tax-dogmatic problems. Secondly, in the past, but even nowadays, simply an ignorance of environmental problems may explain the minor role of green taxes — although recently in some countries first steps towards an ecological tax system have been undertaken (*e. g.*, in the Scandinavian countries and The Netherlands, and most recently, though to a minor extent, in Germany). Thirdly, economic interest groups may either successfully lobby for tax exemption in favor of their clientele or may even hinder the introduction of environmental taxes at all. Fourthly, with an already large public sector and thus with high tax duties in most OECD countries private agents, fearing a further increase of their total tax bill, are reluctant to approve the establishment of new taxes. These reasons, among others, may explain why the establishment of green taxes is still in its infancy; and it may even remain there, since at least the last two reasons could also endanger future environmental tax reforms for reasons of political economics.

Clearly the establishment of an ecological tax system embodies, as any other substantial tax reform, political and economic uncertainties: a redistribution process is set up that is feared by many people. If some socio-economic groups suspect that they will or just might endure extra costs through the establishment of green taxes (while the expected benefits are vague), they probably will offer resistance against the proposed tax reform — and possibly they are able to hamper, or even to block, the transition towards an ecological tax system, even though this step

¹See, for example, TERKLA (1984) and NORDHAUS (1993), p. 316 f.

were to yield a significant social welfare gain.²

Among those who possibly fear environmental tax reforms most are pollution- or energy-intensive firms capturing substantial double rents — rents from the divergence between the private and social costs of their factors of production and rents from imperfect competition. Since this group likely has an influential lobby which may be tempted to overstate the true cost, it is of particular interest to investigate the welfare consequences of tax reforms on pollution-intensive firms engaging in imperfect competition (*e. g.*, cement industry, power plants, steel industry). And similar arguments also apply to those who produce pollution-generating consumer goods (automobiles etc.). In order to scrutinize the most outstanding market form where profits are presumably the highest, we start with a monopoly using, among others, environmentally harmful factors of production. For this particular market structure we investigate within the framework of a partial model³ whether and to what extent the reservations and suspicions of the industry's interest groups — shareholders, consumers, and households (those who supply the non-polluting factors of production), expecting, in the course of a green tax reform, a significantly higher tax-burden, lower profits, higher output-prices, and lower employment levels of the non-polluting factors (*e. g.*, labor and capital) — are justified.

However, since the concrete design of a tax reform is *ex ante* unclear, for governments may, and most often do, deviate from their initial plans — either because the political debate has not yet terminated or because politicians have an incentive to revise their initial announcements after elections have taken place —, households and firms have to consider a range of plausible policy scenarios. Therefore, before those groups decide about their lobbying effort/voting decision,

²This is exactly the reason why, for example, PEZZEY AND PARK (1998), emphasizing the problem of instrument choice within a political economy of interest groups, argue for using instruments which raise little or no public revenue, for otherwise a policy instrument may be politically not acceptable. This and other problems of implementing environmental taxes are also analyzed by PEARSON (1995) in detail.

³But since for each individual (socio economic group) the immediately perceived or expected welfare effects are in fact the determinants of the political support/success of a tax reform, our analysis should, from the viewpoint of a political economy, focus on these direct welfare effects. Therefore, we disregard all those indirect (income) effects, which individuals probably do not take into account, and investigate this topic within the framework of a partial model.

they want to get an idea how the worst, best, most likely *etc.* tax reform will look like and what the corresponding consequences will be. To deal with this topic, we select, among all those conceivable proposals, four different, plausible ecological tax reforms, all of which may be the final outcome of the government's final consultations and which, taken together, may outline the range of possible final scenarios:⁴

- the government might introduce a small tax on environmentally harmful factors keeping the taxes on other factors constant (*introduction of a small green tax*);
- the government might pursue a revenue-neutral, environmental tax reform where the tax on non-polluting factors is decreased so as to exactly offset the increase in public revenue resulting from the higher tax on environmentally harmful factors (*small, revenue-neutral tax reform*);
- the government might adjust both tax rates so as to pursue its own interest by maximizing public revenue (*revenue-maximizing tax rates*);
- the government might benevolently fix both tax rates so as to maximize social welfare (*second-best tax rates*).

For all of these tax reform proposals we derive the respective tax formulae, providing substantial insight into the government's tax-setting behavior under different objectives. Contrasting these formulae with that one of what we call the *initial (status quo) tax regime* — in which, for clarity of the arguments, the tax rates are determined such that social welfare is maximized, subject to a zero tax on environmental inputs⁵ —, we show who the losers and winners of each reform will

⁴We do not want to discuss which of these tax reforms will be the most likely outcome of the political debate, rather we wish to illuminate what the implications of these alternative tax-reform proposals are. If one were to analyze this question, one needs to build a model of a political economy, which is, of course, an interesting question but beyond the scope of this paper.

⁵Alternatively, the status-quo regime can be interpreted as the outcome that results when the lobby-groups succeed in blocking any environmental tax reform, *i. e.*, the introduction of a green tax. Of course, many initial tax regimes are conceivable, but the more inefficient the initial regime is, the easier it is to make everybody better off by some tax reform. So we use

be.⁶

The allocational and distributional differences among those potential reforms are substantial. In particular, while the introduction of a small green tax clearly benefits those consuming public goods including environmental quality, the firm and consumers suffer, for profits and consumer surplus unambiguously fall. If however the government ensures revenue-neutrality, implying that the firm's total tax duties are maintained constant, the employment of the non-polluting factor (*e. g.*, capital or labor) as well as profits increase, provided that the government faces the increasing branch of the Laffer curve. Yet, if the initial tax on the non-polluting factor is relatively high, we obtain the remarkable result that the realization of an revenue-neutral, ecological tax reform leads to an increase of the employment of environmentally harmful factors of production, and thus environmental quality deteriorates. Interpreting this within the framework of the discussion about a possible double dividend,⁷ we must conclude from our analysis that, in this case, the double-dividend hypothesis fails.

Finally, since it is difficult to assess the consequences of non-marginal tax reforms — among which the establishment of the revenue-maximizing tax rates (Leviathan government) and of the second-best tax rates (benevolent government) may serve as the polar scenarios of a wide spectrum of conceivable tax reforms —, we apply numerical analysis in order to illustrate the likely induced effects and their size. Starting from the initial tax system, an implementation of the revenue-maximizing taxes is, apart from environmentalists, unfavorable to all groups, for employment, profit, and consumer surplus fall. An implementation of the second-best tax rates, however, seems to have little effect on profits and public revenue, whereas it clearly improves the employment of the non-polluting factor and environmental quality. In sum, we find little support (apart from revenue-maximizing tax rates) for the often expressed fear that environmental tax reforms lead to a substantial decay of profits and simultaneously endanger the employment

this restrictedly optimal tax system as a starting point, for this limits the potential gain from tax reforms.

⁶PEARSON (1995) also stresses the importance to identify losers and winners of introducing an environmental tax in order to reduce political opposition/obtain political support.

⁷See, for example, BOVENBERG AND DE MOOIJ (1994a, b), BOVENBERG AND VAN DER PLOEG (1996), GOULDER (1995), DE MOOIJ AND BOVENBERG (1998), OATÉS (1995), and others.

of non-polluting factors. Quite the contrary, the employment of non-polluting factors most likely increases and, at least for countries with high initial taxes levied on non-polluting factors, this may also be true for environmentally harmful factors. In this sense, it may occur that an environmental tax reform is ‘too successful’ from an ecological point of view, but there is little reason to argue that it depresses profits.

The paper is structured as follows. In Section 2 we present the basic framework of our model, and in Section 3 we characterize the government’s optimal policy when environmental taxes are not yet introduced (initial regime). The potential tax reform proposals are discussed in the subsequent sections. In particular, Section 4 illustrates the consequences of a small, green tax reform, while Section 5 investigates the effects of a small, revenue-neutral tax reform. Moreover, the policy of a revenue-maximizing government (Leviathan) is presented in Section 6; that of a benevolent government, in Section 7 (second-best tax rates). In order to complete the analysis, we numerically assess the consequences of those different tax reform proposals discussed so far in Section 8. Finally, Section 9 summarizes the paper.

2 The Model

2.1 The Firm

Consider a monopolistic firm which produces its output by the use of a non-polluting factor, say capital⁸ (K), and an environmentally harmful factor such as energy or more broadly pollutant emissions (E); its technology can be characterized by a strictly concave, twice continuously differentiable production function $F(K, E)$ with positive marginal products. Let p_K and p_E denote the after-tax prices of capital and environmental inputs, respectively. The monopoly faces a downward sloping inverse demand curve, P , which is ‘not too convex’ in the sense that

$$P''(Q) < -\frac{2P'(Q)}{Q} \quad \forall Q \in \mathbb{R}_+. \quad (1)$$

⁸Alternatively, we may interpret this factor as labor, which would allow for a better comparison of the results presented here with those of the double-dividend literature.

Condition (1) ensures that the firm's revenue $\tilde{R}(Q) := P(Q)Q$ is a (strictly) concave function of Q which, together with the concavity of F , implies that revenue $R(K, E) := \tilde{R}(F(K, E))$ is also (strictly) concave in K and E . Therefore, profit, defined by

$$\pi(K, E; p_K, p_E) := P(Q)Q - p_K K - p_E E,$$

with $Q = F(K, E)$, is (strictly) concave in K and E . Then, the profit-maximizing behavior of the firm is characterized by⁹

$$R_K = (P + P'Q)F_K = p_K, \quad (2)$$

$$R_E = (P + P'Q)F_E = p_E. \quad (3)$$

Equations (2) and (3), in conjunction with $Q = F(K, E)$, implicitly define the (unconditional) factor demands, $K(p_K, p_E)$ and $E(p_K, p_E)$, and the firm's supply. Substituting the factor demand into the profit function gives the maximal profit as a function of factor prices (reduced profit function):¹⁰

$$\Pi(p_K, p_E) = P(F(K(\cdot), E(\cdot))) F(K(\cdot), E(\cdot)) - p_K K(\cdot) - p_E E(\cdot). \quad (4)$$

For the purpose of the subsequent analysis, we need the derivatives of the factor demands with respect to prices. Differentiation of (2) and (3) yields

$$\begin{bmatrix} dK \\ dE \end{bmatrix} = \frac{1}{|H(R)|} \begin{bmatrix} R_{EE} & -R_{KE} \\ -R_{KE} & R_{KK} \end{bmatrix} \begin{bmatrix} d\tau_K \\ d\tau_E \end{bmatrix}, \quad (5)$$

where $|H(R)|$ denotes the determinant of the Hessian matrix of $R(K, E)$. By strict concavity of R , we know that $H(R)$ is negative definite and hence

$$R_{KK} < 0, \quad R_{EE} < 0, \quad |H(R)| = R_{KK}R_{EE} - R_{KE}^2 > 0.$$

The sign of the cross-derivative R_{KE} , however, hinges on F_{KE} and the curvature of P . One plausibly may assume that R_{KE} is negative; but since the opposite can not be ruled out in general and we do not need such a limiting assumption here, we leave the question of the sign of this cross-derivative open. Solving equation (5) for the desired derivatives yields

$$K_{p_K} = \frac{R_{EE}}{|H(R)|} < 0, \quad K_{p_E} = -\frac{R_{KE}}{|H(R)|} = E_{p_K}, \quad E_{p_E} = \frac{R_{KK}}{|H(R)|} < 0. \quad (6)$$

⁹Subindices of functions denote partial derivatives as long as not stated otherwise.

¹⁰A dot as an argument of a function stands for the omitted arguments.

When R_{KE} is negative and thus the cross derivatives K_{pE} and E_{pK} are positive, capital and emissions are gross-substitutes in production; otherwise they are gross-complements.

2.2 Consumers

Consumers derive utility from consumption of the good produced by the monopolistic firm but suffer from pollutant emissions. The social damage caused by industrial pollutant emissions, $D(E)$, is assumed to be monotonously increasing, continuously differentiable, and strictly convex. In addition, residents benefit from the provision of (additional) public services, to the funding of which the tax revenue collected from the monopoly, T , contributes. Assuming strict separability, *i. e.*, abstracting from income effects, residents' welfare consists of net-consumer surplus, plus the social value of public revenue, minus the social damage stemming from industrial pollutant emissions, plus dividend income. Provided that residents hold all stocks of the firm and therefore receive its full profit as dividend income, we can write welfare as¹¹

$$\mathcal{W} = \int_0^Q P(q) dq - P(Q)Q + \lambda T - \alpha D(E) + \Pi(\cdot). \quad (7)$$

The parameter $\alpha \in [0, 1]$ represents the social weight associated with the ecological damage resulting from industrial pollutant emissions,¹² and λ denotes the marginal social value of public funds.

2.3 The Government

To finance public spending the government uses distortionary taxes, implying that the marginal social value of public funds, λ , exceeds households' marginal utility of private income, which equals unity.¹³ Some of these distortionary taxes

¹¹The concavity of \mathcal{W} in K and E is ensured by concavity of F and $-D$ in K and E and by the concavity of $\int_0^Q P(q) dq - P(Q)Q$ and $\bar{R}(Q)$ in Q .

¹²The weight α allows us to consider shifts in preferences, namely a shift towards a 'greener' welfare function, or alternatively to consider the consequences of an environmentally more ambitious policy.

¹³If an increase in public revenue increases the excess burden of the tax system, the shadow cost of public funds exceeds consumers' marginal utility of income: $\lambda > 1$. Only if public goods

are those levied on the productive factors employed by the monopoly: capital and environmental inputs (*e. g.*, energy or pollutant emissions). Let ρ_K and ρ_E denote the exogenously given before-tax prices of capital and emissions, and τ_K and τ_E the per unit taxes on capital and emissions, respectively. Then, the corresponding after-tax factor prices are given by $p_K := \rho_K + \tau_K$ and $p_E := \rho_E + \tau_E$,¹⁴ and public revenue raised from monopoly taxation, T , amounts to

$$T = \tau_K K + \tau_E E. \quad (8)$$

In our partial framework, we assume that T represents a small part of overall public funds so that their social value, λ , the Lagrangian multiplier of the overall public budget constraint, is not affected by T but can be treated as a given constant.

3 The Initial Tax Regime

In order to illuminate the consequences of those alternative tax-reform proposals outlined above and to show who the likely losers and winners will be, consider firstly the status quo scenario: Suppose that in the initial state environmental taxes are not yet introduced, though the established tax-rates (here the capital tax) are optimally fixed, given that $\tau_E = 0$. To obtain the initial capital tax, differentiate the welfare function (7) with respect to τ_K and evaluate terms at $\tau_E = 0$:

$$\left. \frac{\partial \mathcal{W}}{\partial \tau_K} \right|_{\tau_E=0} = \lambda(K_{p_K} \tau_K + K) - P'Q(F_K K_{p_K} + F_E E_{p_K}) - K - \alpha D' E_{p_K} = 0, \quad (9)$$

where we have substituted the public budget constraint (8). 'Solving' equation (9) for τ_K gives us the optimal (second-best)¹⁵ policy when eco-taxes are fixed at are complementary to taxed goods the excess burden may decrease with higher public spending (see AUERBACH (1985), p. 112).

¹⁴Since we want to focus on factor substitution, we consider factor taxes rather than an output tax. Yet, we can, without affecting the results, substitute one input tax by an output tax if the tax rates are adjusted appropriately. To illustrate this, Appendix A provides the first-best tax rates on capital and emissions which can be contrasted with the well-known first-best output subsidy and the Pigouvian tax.

¹⁵Or, if one likes this term: third-best.

zero:

$$\tau_K^o = \frac{1}{\lambda} \left(\frac{P'Q}{K_{pK}} \underbrace{(F_K K_{pK} + F_E E_{pK})}_{=\partial Q/\partial p_K} - (\lambda - 1) \frac{K}{K_{pK}} + \alpha D' \frac{E_{pK}}{K_{pK}} \right). \quad (10)$$

The initial tax rate on capital consists of three parts. The first one stems from the firm's non-competitive behavior: Since changing an input tax causes a factor-substitution and an output effect, production cost and the output price change. If an increase in τ_K leads to a decrease of production in which case $|F_K K_{pK}| > F_E E_{pK}$ — a condition which we shall assume to hold throughout the paper¹⁶ —, the first term is negative, indicating a decline of consumer surplus. The second term weighs the increase of public revenue against the decrease of private income, the latter resulting from lower profits. If the marginal social value of public funds exceeds the marginal utility of private income, $\lambda > 1$, a pure income transfer from residents to the government is welfare enhancing, and the relative scarcity of public revenue prompts the regulator, *ceteris paribus*, to increase the tax rate. The third term reflects the perceived environmental damage resulting from pollutant emission. When emissions and capital are gross-substitutes ($E_{pK}, K_{pE} > 0$), the capital tax is the *lower*, the higher the social value attributed to environmental damage, α , is. That is, the capital tax, serving, among others, to internalize environmental damage, is an increasing function of the extent to which the government ignores or under-estimates the environmental consequences of economic activities. If, however, capital and environmental factors are gross-complements — a condition which we find more plausible in general (and which also holds in our example presented in Sec. 8) —, greener social preferences, represented by a higher value of α , imply *ceteris paribus* a higher value of τ_K : In this case a higher tax on capital succeeds in improving environmental quality.

Let $\varepsilon_{p_j}^i$ denote the elasticity of the (derived) demand for factor i with respect to the price of factor j . Then, $\tau_K = -p_K/\varepsilon_{p_K}^K =: \theta_K$ (implicitly) defines the maximum of the capital-tax Laffer curve, $\bar{\tau}_1$, which coincides with maximum of

¹⁶Requiring $F_K F_{EE} - F_E F_{KE} < 0$ is a rather mild condition, for this is equivalent to the conditional factor demand $\hat{K}(p_K, p_E, Q)$ being an increasing function of Q which, in turn, is equivalent to marginal cost being increasing in p_K . Formally we show this in Appendix B. Similarly, we assume that $|F_E E_{pE}| > F_K K_{pE}$.

the (total) Laffer curve for $\tau_E = 0$.¹⁷ It follows that $\tau_K < \theta_K \Leftrightarrow \tau_K < \bar{\tau}_1$.¹⁸ In the subsequent analysis we primarily focus on those cases where the government faces the increasing (left) branch of the Laffer curve¹⁹, $\tau_K < \theta_K$, and only sometimes refer to the other case, for the first case seems actually to be the more relevant one. Using this notation, we can summarize our finding in the following proposition.

Proposition 1 *The initial tax rate on capital is increasing*

1. *in the social value of public funds ($\partial\tau_K/\partial\lambda > 0$), if, and only if, $\tau_K < \theta_K$,*
2. *and in the weight given to environmental damage ($\partial\tau_K/\partial\alpha < 0$), if, and only if, capital and environmental factors are gross-complements ($E_{p_K} < 0$).*

Proof: by differentiation of equation (10).

The first part gives us an intuitive ‘inverse elasticity rule’: As long as the government faces the increasing branch of the Laffer curve, more severe public financial needs (a higher value of λ) lead to an increase of the capital tax. The second part of Proposition 1 refers to the substitutionarity/complementarity between capital and environmental inputs: For any fixed output level, an increase of the price of capital induces the firm to substitute from capital to environmental inputs, *i. e.*, to emit more pollutants. If this factor substitution effect dominates the output effect, that is, if emissions and capital are gross-substitutes ($E_{p_K} > 0$), a higher tax on capital leads to a decline of the environmental quality. Therefore, the higher the value associated with a given marginal damage (α) is, the less the government finds it desirable to subsidize pollutant emissions indirectly through a more severe taxation of capital. And the reverse is true if capital and environmental inputs are gross-complements. In sum, the initial capital tax rate consists of three components reflecting the government’s endeavor, when constrained to apply a single tax rate, to pursue a threefold purpose: to regulate the output market, to raise public funds, and to improve the environmental quality.²⁰

¹⁷More precisely, for any given value of τ_E , $\bar{\tau}_1$ represents the maximum of the Laffer curve if it satisfies $\tau_K = -(K + \tau_E E_{p_K})/K_{p_K}$ (fixed point property).

¹⁸Provided, of course, that $\varepsilon_{p_K}^K$ does not fall too quickly in p_K : $(\partial\varepsilon_{p_K}^K/\partial p_K)(p_K/\varepsilon_{p_K}^K) < 1 - \varepsilon_{p_K}^K$.

¹⁹As long as it is clear that terms are evaluated at $\tau_E = 0$, we simply speak of θ_K as the maximum of the Laffer curve.

²⁰It has well been recognized that a government may well seek to pursue multiple targets by

4 The Introduction of a Small Green Tax

The most apparent tax reform proposal might be the introduction of a small tax on environmental inputs, leaving the tax on capital unaltered. The welfare effect of such a reform is given by

$$\left. \frac{\partial \mathcal{W}}{\partial \tau_E} \right|_{\tau_E=0} = \lambda(K_{pE}\tau_K + E) - P'Q(F_K K_{pE} + F_E E_{pE}) - E - \alpha D' E_{pE}. \quad (11)$$

The first bracket term equals $\partial T / \partial \tau_E |_{\tau_E=0}$ which we plausibly assume to be positive.²¹ That is, we postulate that the elasticity of energy demand with respect to the price of capital, ε_{pK}^E , should not be too large: $-\varepsilon_{pK}^E \tau_K / p_K < 1$, which is trivially fulfilled when capital and environmental inputs are gross substitutes ($R_{KE} < 0$), but imposes an upper bound on τ_K when they are gross complements ($R_{KE} > 0$): $\tau_K < -p_K / \varepsilon_{pK}^E =: \theta_E$. Thus, the condition $\tau_K = \theta_E$ implicitly defines that capital tax, $\bar{\tau}_2$, above which the introduction of a small positive tax on environmental inputs collects a negative public revenue.

The second bracket term, however, is supposed to be negative (cf. footnote 16). Thus the benefit from higher public revenue (first term) and a higher environmental quality ($-\alpha D' E_{pE}$) has to be weighted against the fall in consumer surplus (second term) and the reduction in profit ($-E$). While shareholders and consumers can be expected to be the losers of this type of tax reform, environmental quality as well as public consumption, and therefore the welfare of those receiving public transfers or benefiting from the provision of public goods, increases. The overall welfare effect, however, is most likely to be positive. For, the social value of increased public revenue should dominate the loss in profit, $\lambda(K_{pE}\tau_K + E) - E > 0$ (a condition which is guaranteed for gross substitutes and for gross-complements when capital taxes are sufficiently low, $\tau_K \ll \theta_E$), and the reduction in consumer surplus should be dominated by the environmental benefit,

a single tax rate under imperfect competition. While in the classical Ramsey-Boiteux pricing problem the optimal (second-best) tax rate accounts for the scarcity of public funds and for non-competitive behavior of the firm(s), it accounts for monopolistic behavior and the marginal social damage stemming from pollutant emission in the regulation problems discussed by BARNETT (1980), BAUMOL AND OATES (1988) (ch. 6), and others.

²¹Otherwise even the introduction of an infinitesimal tax on environmental inputs would collect a negative public revenue, which would require this tax to erode the tax basis of the capital tax more quickly than it can collect a positive revenue from its own tax basis.

$-\alpha D'E_{p_E} > P'Q(\partial Q/\partial \tau_E)$. The latter condition simply means that consumers' marginal willingness to pay for a better environmental quality is sufficiently high, or that ecological problems are in fact substantial enough.

5 A Small, Revenue-Neutral Tax Reform

As the second possible tax-reform scenario consider the case of a small, revenue-neutral, ecological tax reform. The restriction of revenue-neutrality may either result from legal rules, prohibiting a further increase in total tax duties, or from successful lobbying for not increasing the firm's duties. In order to guarantee revenue-neutrality, the capital tax must be adjusted so as to fulfill

$$dT = \frac{\partial T}{\partial \tau_K} d\tau_K + \frac{\partial T}{\partial \tau_E} d\tau_E = 0.$$

Evaluating terms at $\tau_E = 0$ and using $K_{p_E} = E_{p_K}$ this implies

$$\left. \frac{d\tau_K}{d\tau_E} \right|_{\tau_E=0} = -\frac{\partial T/\partial \tau_E}{\partial T/\partial \tau_K} = -\frac{E}{K} \frac{1 + \frac{\tau_K}{p_K} \varepsilon_{p_K}^E}{1 + \frac{\tau_K}{p_K} \varepsilon_{p_K}^K} = -\frac{p_K}{p_E} \frac{\varepsilon_{p_E}^K}{\varepsilon_{p_K}^K} \frac{\tau_K - \theta_E}{\tau_K - \theta_K}. \quad (12)$$

For a marginal, revenue-neutral tax reform to make sense from a public finance perspective, one hopes to use the tax revenue from green taxes in order to be able to reduce other distortionary taxes. Therefore, in the following we shall assume both, that the government faces the increasing (left) branch of the Laffer curve, $\tau_K < \theta_K$, and that (at least) the introduction of a small tax on energy yields some positive tax revenue, which then can be recycled through an adjustment of the tax on capital, $\tau_K < \theta_E$ if factors are gross complements. Both properties together imply that $d\tau_K/d\tau_E$ is negative.

Moreover, let us define $\psi_K := (EE_{p_K} - KE_{p_E})|H(R)|$ and $\psi_E := (KK_{p_E} - EK_{p_K})|H(R)|$. (The economic meaning of which becomes clear soon.) Although we can not rule out in general that these terms are negative, it seems to more plausible — as we argue in Appendix B — that ψ_K and ψ_E are both positive, an assumption which we will assume throughout the subsequent analysis (and which is also supported by our example in Sec. 8). Then, we arrive at the following result:

Lemma 1

$$0 < \psi_K < \theta_K < \theta_E \quad \text{if } R_{KE} > 0,$$

$$\text{and } \theta_E < 0 < \theta_K < \psi_K \quad \text{if } R_{KE} < 0.$$

Proof: The proof is relegated to Appendix B.

Primarily we assume in the ensuing analysis that R_{KE} is positive and thus capital and environmental factors are gross-complements. (We only briefly refer to the opposite case from time to time.) As Lemma 1 shows the Laffer curve can be divided into four subintervals, the properties of which we now discuss.

Using equation (12) we obtain the total changes of factor demand resulting from a revenue-neutral introduction of an energy tax:

$$\left. \frac{dK}{d\tau_E} \right|_{\tau_E=0} = \frac{1}{|H|} \frac{\psi_E}{K + \tau_K K_{pK}} = \frac{1}{|H|} \frac{\psi_E}{K_{pK}(\tau_K - \theta_K)}, \quad (13)$$

$$\left. \frac{dE}{d\tau_E} \right|_{\tau_E=0} = \frac{1}{|H|} \frac{\tau_K - \psi_K}{K + \tau_K K_{pK}} = \frac{1}{|H|} \frac{\tau_K - \psi_K}{K_{pK}(\tau_K - \theta_K)}. \quad (14)$$

where we have used the fact that $(K_{pK} E_{pE} - K_{pE} E_{pK}) = 1/|H(R)| > 0$, which follows from the concavity of R and from (6). As long as the government faces the increasing branch of the Laffer curve, $0 < \tau_K < \theta_K$, capital demand increases in the course of a small, revenue-neutral, ecological tax reform, but else decreases. Moreover, provided that capital and energy are gross-complements, energy demand decreases — as one may hope for — only if τ_K falls short of ψ_K (or, alternatively, if $\tau_K > \theta_K$).²² If however the capital tax is relatively high — though still on the increasing branch of the Laffer curve —, $\psi_K < \tau_K < \theta_K$, the use of energy increases, implying that in the course of a small, revenue-neutral, ecological tax reform environmental quality deteriorates(!). In this sense, a small, revenue-neutral, ecological tax reform fails from an ecological point of view if initial taxes on non-polluting factors are too high. In addition, although little can be said about the sign of the composed effect of K and E on the change of output, $dQ/d\tau_E$, the impact of this tax reform on the firm's profit is unambiguous:

$$\left. \frac{d\pi}{d\tau_E} \right|_{\tau_E=0} = -K \frac{d\tau_K}{d\tau_E} - E = \tau_K \frac{dK}{d\tau_E}.$$

²²The condition $\tau_K = \psi_K$ implicitly defines the level of the capital tax $\bar{\tau}_0$ at which a revenue-neutral tax reform does not change environmental quality.

This yields the remarkable result that profit increases whenever capital demand does so, which in turn occurs for all scenarios on the increasing branch of the Laffer curve, $\tau_K < \theta_K$ (cf. eq. (13)).

Proposition 2 *Let the tax rate on capital be positive. A revenue-neutral introduction of a small environmental tax leads*

- *to an increase of profits and the use of capital if, and only if, $\tau_K < \theta_K$ and*
- *to an increase of the use of environmental inputs if, and only if, $\psi_K < \tau_K < \theta_K$ (if $R_{KE} > 0$) respectively $\theta_K < \tau_K < \psi_K$ (if $R_{KE} < 0$).*

As a consequence, if we focus on scenarios on the increasing branch of the Laffer curve, the firm's lobbyists should not seek to block a small, revenue-neutral, environmental tax reform, rather the contrary: they should support it, for the firm's profit can be expected to increase.

The consequences of Proposition 2 can also be linked to the so-called double-dividend literature. If we identify K with labor instead of capital, then we obtain:²³

Remark 1 *For high-tax countries ($\tau_K > \min\{\theta_K, \psi_K\}$) a double dividend — in the sense that environmental quality and employment may be increased simultaneously — can not be obtained.*

This is a rather negative result, which also includes the decreasing branch of the Laffer curve, for then the employment of the non-polluting factor falls implying that a double dividend can neither be obtained in this case.²⁴

6 Revenue-Maximizing Tax Rates

What firms and consumers are possibly most afraid of is a revenue-maximizing behavior by the government. They might suspect that the government exploits the

²³However, since we deal with a partial model here, this interpretation may exceed the actual framework. It remains to show that the same effects prevail within a general-equilibrium model.

²⁴This result is consistent with that obtained by BAYINDIR-UPMANN AND RAITH (1998) in a completely different framework.

opportunity for a tax reform in order to increase, and eventually maximize, public revenue. Hence, one may ask how the tax system will look when a Leviathan government seeks to maximize tax revenue once it is entitled to pursue a tax reform. To see the consequences of such a policy, differentiate T with respect to τ_K and τ_E simultaneously:

$$\begin{aligned}\frac{\partial T}{\partial \tau_K} &= E_{p_K} \tau_E + K_{p_K} \tau_K + K = 0, \\ \frac{\partial T}{\partial \tau_E} &= E_{p_E} \tau_E + K_{p_E} \tau_K + E = 0.\end{aligned}$$

'Solving' these two equations for τ_K and τ_E we obtain

$$\tau_K^* = \psi_K \quad \text{and} \quad \tau_E^* = \psi_E. \quad (15)$$

Thus, (loosely speaking) ψ_K and ψ_E denote the revenue-maximizing tax levels, both of which are positive and where τ_K falls short of the maximum of the Laffer curve for $\tau_E = 0$. It may be added that this pair of revenue-maximizing tax rates consists of the combination of an emission-maximizing/minimizing tax on capital, all of which are characterized by $\tau_K = \psi_K$, and a capital-maximizing/minimizing tax on environmental inputs, $\tau_E = \psi_E$.²⁵

7 Second-Best Tax Rates

When a new tax rate becomes available, the initial tax rates are ex post fixed at inefficient levels, in general. Therefore, from a welfare-theoretic point of view, the initial tax rates (here, the tax on capital) should also be adjusted in the course of a tax reform. Though from the perspective of a political economy, an optimal adjustment, *i. e.*, a welfare-maximizing tax reform, is not supposed to be the most likely outcome, it nevertheless represents at least a conceivable scenario which may also serve as a point of reference.

To obtain the second-best tax rates, differentiate \mathcal{W} with respect to τ_K and τ_E , yielding

$$\frac{\partial \mathcal{W}}{\partial \tau_K} = \lambda(E_{p_K} \tau_E + K_{p_K} \tau_K + K) - P'Q(F_K K_{p_K} + F_E E_{p_K}) - K - \alpha D' E_{p_K} = 0,$$

²⁵This can be seen by maximizing K respectively E for any given amount of public revenue. Similarly, the firms output is maximized by any tax tuple satisfying $F_K(\tau_E - \psi_E) - F_E(\tau_K - \psi_K) = 0$.

$$\frac{\partial W}{\partial \tau_E} = \lambda(E_{p_E}\tau_E + K_{p_E}\tau_K + E) - P'Q(F_K K_{p_E} + F_E E_{p_E}) - E - \alpha D' E_{p_E} = 0,$$

'Solving' these equations for both tax rates gives the government's optimal policy when eco-taxes are available:

$$\begin{bmatrix} \hat{\tau}_K \\ \hat{\tau}_E \end{bmatrix} = \begin{bmatrix} \frac{1}{\lambda} P'Q F_K + \frac{\lambda-1}{\lambda} \psi_K \\ \frac{1}{\lambda} P'Q F_E + \frac{\lambda-1}{\lambda} \psi_E + \frac{1}{\lambda} \alpha D' \end{bmatrix}, \quad (16)$$

The second-best tax rates are determined by two and three terms respectively. Within each tax formula, the first term reflects the firm's monopolistic behavior, representing the marginal impact of the respective tax rate on consumer surplus. These *imperfect-competition terms* stem from the government's endeavor to correct for the distortion on the output market by enhancing the firm's output, *i. e.*, the tax system serves as an indirect device to promote production.

The second terms in equation (16) result from distortionary taxation and may be referred to as *simplified Ramsey-terms*. The factor $(\lambda - 1)/\lambda$ reflects the divergence between the private and social value of income and can be interpreted as the marginal excess burden of distortionary taxation. As long as public funds are 'relatively scarce' in the sense that $\lambda > 1$, the second parts of the right hand side of (16) are non-negative. In this sense, the introduction of an environmental tax improves the efficiency of the tax system by both taxing away the quasi-rents from environmental factors and broadening the tax base.

The third term determining τ_E results from the full marginal environmental damage of industrial pollutant emissions — *the Pigouvian term*. The higher the marginal environmental damage but the lower the marginal value of public funds, the more severely the government taxes pollutant emissions. However, due to the other two terms the optimal environmental tax differs from the Pigouvian level, in general.

With the signs of these terms at hand, we have the following result.

Proposition 3 *The second-best capital tax is increasing in the social value of public funds ($\partial \tau_K / \partial \lambda > 0$). The emission tax is increasing in the social value of public funds ($\partial \tau_E / \partial \lambda > 0$) if, and only if, $\alpha D' < \psi_E - P'Q F_E$; moreover, it is increasing in α .*

Proof: by differentiation of equation (16).

A higher social value of public funds makes the government tighten the tax screw. However, contrary to what one might expect, when ecological problems are pressing, $\alpha D' > \psi_E - P'QF_E$, the emission tax is the lower, the higher public financial needs are. This confirms the general equilibrium results of previous analyses that environmental taxes represent a less efficient instrument for raising public revenue when their primary purpose is to internalize environmental diseconomies: "Therefore, the higher the efficiency cost of the existing tax structure are, the higher the environmental benefits need to be in order to justify the additional costs of environmental taxes in terms of a less efficient mechanism for financing public spending." (cf. BOVENBERG AND DE MOOIJ (1994b), p. 677). The reason for this is that, for environmental purposes, the eco-tax aims at eroding its own tax basis (and possibly also erodes that of other taxes), an effect which is less welcome the higher the social value of public funds.

Since $\partial\tau_K/\partial\lambda > 0$ is equivalent to $\tau_K < \psi_K$, Proposition 3 also implies that the second-best tax rate *ceteris paribus* falls short of its revenue-maximizing level. Similarly, the second-best emission tax falls short of its revenue-maximizing level if, and only if, $\partial\tau_E/\partial\lambda > 0$.

Observe that if the government were free to choose any fiscal instrument, *i. e.*, it were not urged to use a distortionary tax system, the marginal cost of public funds would equal unity, public goods would be provided efficiently, and, therefore, the marginal excess burden would equal zero. In this case, the first-best solution could be established by adjusting lump sum transfers and the tax rates appropriately.²⁶

Corollary 1 *If the marginal social cost of public funds is equal to unity, $\lambda = 1$, the optimally reformed tax rates are first-best.*

Proof: by comparison of equations (16) and (A.4) of Appendix A.

²⁶This is a generalization of EBERT's (1992) result (cf. eq. (8c) therein) in the sense that we consider the taxation of two independent production factors whereas EBERT assumes that emissions are perfectly related to output; therefore, his model is confined to output taxation.

8 An Example

Since direct comparisons of allocations resulting from different tax scenarios are difficult, at least as far as *drastic* tax reforms are concerned, we provide the reader with an example. This illustrates our findings of the preceding analysis and provides further insights into and some intuition for the effects of those tax reforms.

Let the social damage resulting from industrial pollutant emissions be a quadratic function of E ,

$$D(E) = \frac{d_0}{2}E^2, \quad d_0 > 0. \quad (17)$$

Suppose that the firm's production technology can be characterized by a Cobb-Douglas production function,

$$F(K, E) = a_0 K^{a_1} E^{a_2}, \quad a_0, a_1, a_2 > 0. \quad (18)$$

Moreover, let the firm face an affine-linear inverse demand curve,

$$P(Q) = 1 - Q \quad \forall Q \in [0, 1]. \quad (19)$$

Note that P satisfies Condition (1), which, in conjunction with a decreasing returns to scale technology, guarantees an interior solution of the profit-maximization problem.

Inserting equations (18) and (19) into the firm's revenue function, R , yields

$$\begin{aligned} R_K &= \frac{a_1}{K} Q(1 - 2Q), \\ R_E &= \frac{a_2}{E} Q(1 - 2Q), \\ R_{KK} &= \frac{a_1}{K^2} Q(-1 + a_1 + 2Q - 4a_1 Q), \\ R_{EE} &= \frac{a_2}{E^2} Q(-1 + a_2 + 2Q - 4a_2 Q), \\ R_{KE} &= \frac{a_1 a_2}{K E} Q(1 - 4Q), \\ |H(R)| &= \frac{a_1 a_2}{K^2 E^2} Q^2 (2Q - 1)(a_1 + a_2 - 1 + 2[1 - 2(a_1 + a_2)]Q), \end{aligned}$$

with $Q = F(K, E)$.

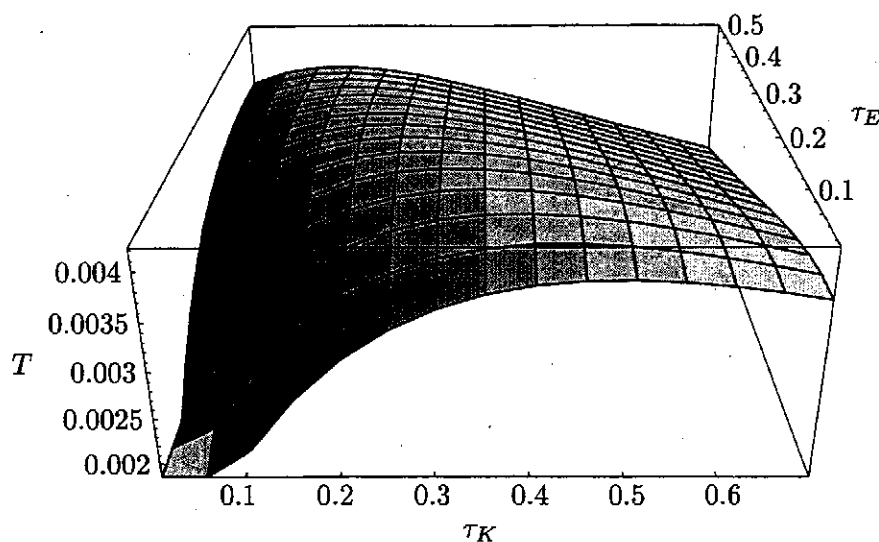


Figure 1: Laffer curve

We apply the following parameter specification: $a_0 = 1$, $a_1 = 0.5$, $a_2 = 0.3$, $d_0 = 10$, $\alpha = 1$, $\rho_K = 1$, $\rho_E = 0.5$, and $\lambda = 1.5$.²⁷ This specification implies that capital and environmental inputs are gross-complements, a feature which holds for a wide range of values but which may eventually change if we increase some of the a_i -values sufficiently. Substituting the demand functions into the public budget constraint, public revenue depends on τ_K and τ_E exclusively; this gives us the Laffer curve which is shown in Figure 1.

The initial and the second-best tax scenario are summarized in Table 1. Yet, we can illustrate the consequences of all tax-reform scenarios discussed thus far very neatly by means of two figures. First, project the iso-revenue lines of the Laffer curve into the τ_K - τ_E plane, yielding those loop-shaped curves displayed in Figure 2. Then suppose we wish to maximize public revenue for any given level of the tax on capital. This gives us the locus of points where the slopes of the iso-revenue curve are infinite, given by the $f_E(\tau_K)$ -curve in Figure 2. Similarly the $f_K(\tau_E)$ -curve gives us those capital taxes which maximize, for any given tax on environmental inputs, tax public revenue. Moreover, the dashed lines represent

²⁷As stated by FREEBAIRN (1995), p. 127, "Estimates of the marginal cost of taxation [...] are very sensitive to the estimation model and to the parameter assumptions." However using an interval of 10 to 50 percent covers the range of the estimates of most analyses. (See BROWNING (1987), FREEBAIRN (1995), and the references therein.)

Variable	Initial	2nd-best	Variable	Initial	2nd-best
τ_K	0.231	0.0656	$R(Q)$	0.0349	0.0345
τ_E	0.0	0.1428	$C(Q)$	0.0269	0.0265
p_K	1.231	1.0656	$\Pi(Q)$	0.008	0.0079
p_E	0.5	0.6428	T	0.0031	0.0032
K	0.0136	0.0156	\mathcal{W}	0.0114	0.0122
E	0.0201	0.0155	ψ_K	0.323	0.2787
Q	0.0362	0.0357	ψ_E	0.1312	0.1682
K_{pK}	-0.0305	-0.0404	θ_K	0.4465	0.3855
K_{pE}	-0.0287	-0.0256	θ_E	0.7007	0.604
E_{pE}	-0.0827	-0.0496	$\bar{\tau}_0$	0.3378	
τ_K^*	0.3131		$\bar{\tau}_1$	0.5070	
τ_E^*	0.1565		$\bar{\tau}_2$	0.8685	

Table 1: Example

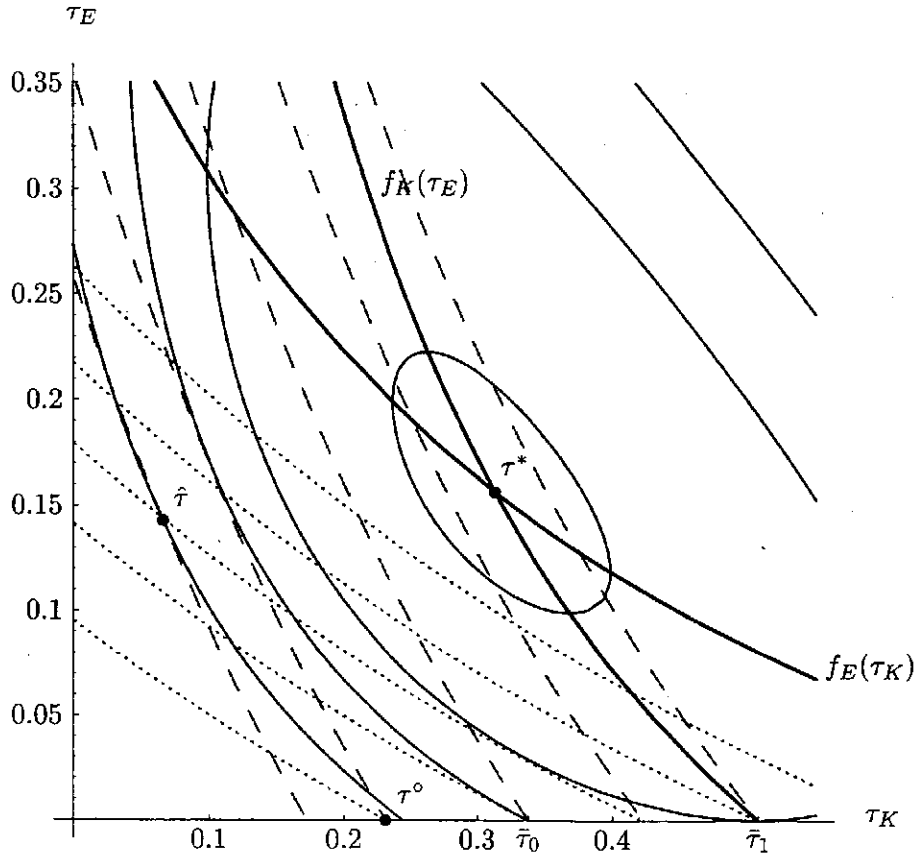


Figure 2: The Laffer curve and factor demand in the τ_K - τ_E plane

curves of constant employment of capital, while the dotted lines represent curves of constant use of environmental inputs. Among those, the more we move to the South-West the higher the respective employment levels become. That is, the more we move towards the lower right corner of Figure 2, the higher are the employment levels of both factors, and, therefore, the more the environmental quality deteriorates. Lastly, Figure 2 shows the overall maximum of the Laffer curve at τ^* ; the initial and the second-best tax rates represented by τ° and $\hat{\tau}$ respectively; as well as $\bar{\tau}_0$ and $\bar{\tau}_1$ — those values of the capital tax for which, evaluated at $\tau_E = 0$, a revenue-neutral tax reform does not affect E respectively public tax revenue is maximal. The welfare consequences of those tax reforms considered above are now obvious: Starting from τ° , and introducing a small green tax we directly move to the North, implying that public revenue increases and the employment of both factors decreases. On the other hand, a marginal, revenue-neutral tax reform means that we move slightly from τ° to the North-West along the iso-revenue curve passing through this point (not shown). We see that in the course of a small, revenue-neutral tax reform the use of environmentally harmful factors decreases for lower values of the initial capital tax, $\tau_K < \bar{\tau}_0 = 0.3378$, but for higher initial values the reverse is true: the employment levels of both environmental friendly and harmful factors increase, for the slope of the iso-revenue curves, along the horizontal axis, decreases and eventually the iso-revenue curves become flatter than the iso-employment curves.

Lastly, the establishment of the second-best tax system leads to an increase of the employment of capital but at the same time significantly reduces the use of environmental inputs implying a substantial improvement of environmental quality. The private sector's fear that such a drastic tax reform might lead to a significant increase in total tax duties is not justified. (Only a small increase in public revenue occurs.) Yet, the picture drastically changes for a Leviathan government seeking to increase public revenue: Any movement towards τ^* reduces the employment of both factors, and — as a side effect — significantly enhances environmental quality.

In order to illustrate the consequences of these tax reforms for the firm, we have drawn the iso-profit curves in the τ_K - τ_E plane in Figure 3. Since profit increases as we move to the South-West, the introduction of a small green tax lowers profit, whereas a revenue-neutral tax reform — even a non-marginal one

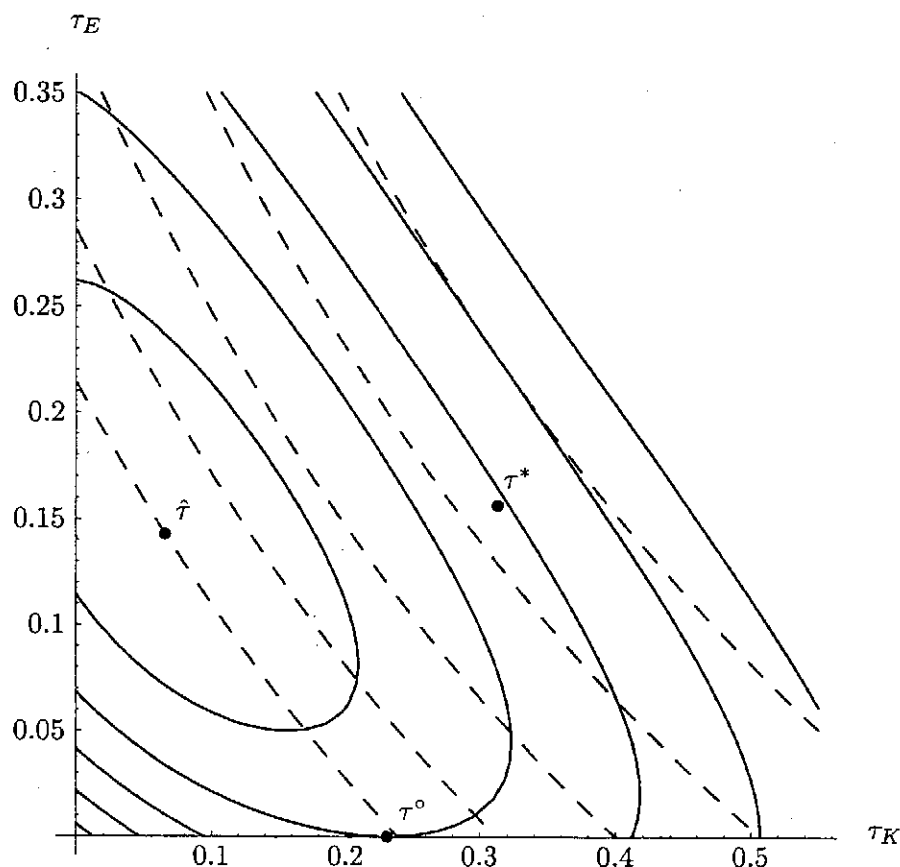


Figure 3: Welfare and profit in the τ_K - τ_E plane

— leads to a higher profit. A drastic tax reform which implements the second-best tax rates leads to (slightly) lower profits if we start from the tax regime τ^o . However, as we see this result crucially hinges on the initial situation: For an initial capital tax slightly exceeding τ_K^o , establishing the second-best tax rates leads to higher profits. Lastly, while the fear for revenue-neutral tax reforms is not justified, the fear for a Leviathan's policy is: Any tax reform in the direction towards the the overall Laffer-curve maximum, τ^* , is diametrical to the interest of the firm, though over some range this movement is welfare improving.

9 Conclusions

Often those industries earning substantial profits particularly fear environmental tax reforms. Suspecting a fall in profits and a reduction of employment (of capital,

labor, or any other factor), the affected interest groups (including employers' associations, labor unions, and shareholders' associations) may well argue for dismissing the idea of pursuing an environmental tax reform. Whether these fears are in fact justified depends, of course, on the nature of any particular tax reform proposal. From the viewpoint of a political economy, however, the concrete tax scheme which eventually will be the outcome of political debates is vague *ex ante*, *i. e.*, at the moment when the political discussion about a possible tax reform is initiated. Therefore voters and interest groups have to take into account different tax reform scenarios trying to figure out from which of them they may benefit or suffer. As a consequence, those proposals will be most approved/least hindered from which a majority of the directly affected parties benefits.

Focusing on the case where the potential profits, which may possibly be endangered by a tax reform, are presumably the largest, we consider the case of a monopoly. Starting from an initial tax system where tax rates are, apart from taxes on environmental factors, optimally set, we scrutinize the effects of different tax reform scenarios: the introduction of a small green tax, a marginal, revenue-neutral tax reform, revenue-maximizing tax rates (Leviathan government), and finally welfare-maximizing tax rates (benevolent government). For all of those cases, the corresponding tax formulae are derived and the resulting effects are characterized with respect to profits, environmental quality, employment, and public revenue.

The most remarkable results are the following. Even though we assume that the initial tax system is optimized to some extent, a marginal, revenue-neutral tax reform increases the firm's profit and the employment of the non-polluting factor, provided that the government faces the increasing branch of the Laffer curve. This raises substantial doubts on lobbyists' often expressed view that environmental tax reforms will depress profits and endanger employment — rather the reverse is true. And, also contrary to what one might expect, such a tax reform may well lead to an increased use of environmentally harmful factors, a conclusion which holds for all tax intervals except for the lowest. Relating this result to the so-called double-dividend literature, we conclude that for high-tax countries a double dividend can not be obtained by means of a small, revenue-neutral tax reform — even though employment of non-polluting factors increase —, for the environmental dividend is lost.

Since assessing the effects of drastic tax reforms is a delicate task, we apply numerical analysis to illustrate the likely consequences of a switch from the initial tax regime towards the second-best and towards the revenue-maximizing tax rates. Establishing the second-best tax rates most likely leads to higher employment of non-polluting factors and to an improvement of environmental quality, but it seems to have little impact on public revenue and profits. Again, it appears — but this conclusion is less firm here — that industry's fear for an ecological tax reform is hardly justified. However, the picture changes drastically when the government seeks to maximize public revenue. Only environmentalists and the beneficiaries of public spending would applaud such a tax reform — if at all —; for employment and profits drastically fall (and possibly even welfare). In sum, the suspected reductions in profits and employment of non-polluting factors often expressed in political debates seem well be exaggerated or even be flawed. This holds in particular for small, revenue-neutral tax reforms which clearly increase profits and the employment of clean factors of production (*e. g.*, capital and labor).

Appendix A: First-best allocation

Within a command and control economy the regulator could establish the first-best allocation by choosing the real variables K and E directly and by undertaking any income transfer sufficient to equate the marginal cost of public funds and the private marginal utility of income. Maximizing welfare, (7), w. r. t. capital, emissions, and the transfer payment yields

$$PF_k = \rho_k, \quad (\text{A.1})$$

$$PF_e = \rho_e + D', \quad (\text{A.2})$$

$$\lambda = 1. \quad (\text{A.3})$$

Equation (A.1) states that capital should be used up to that point where its marginal product equals its (net) factor price. Similarly, the environmental factor should be used to that extent where its marginal product equals its social cost, which consists of its (net) market price plus the marginal social damage caused by the use of environmental inputs (eq. (A.2)). In addition, overall resources should be used to provide public services efficiently: the marginal rate of substitution between the private and the public good equals its marginal rate of transformation which is equal to unity (eq. (A.3)).

Next, the question arises how can the first-best outcome be sustained in a decentralized market economy? If the appropriate fiscal instruments, namely a capital tax, an emission tax, and poll taxes, are available, the efficient solution can be supported by adjusting τ_k and τ_e according to

$$\begin{bmatrix} \tau_k \\ \tau_e \end{bmatrix} = \begin{bmatrix} P'QF_k \\ P'QF_e + D' \end{bmatrix}, \quad (\text{A.4})$$

and by levying head taxes sufficient to provide public services efficiently.²⁸

When poll taxes can be imposed such that public goods are provided efficiently, the government does not face any fiscal incentive to raise additional public funds through distortionary taxation. Rather it exclusively seeks to correct for the firm's non-competitive behavior by subsidizing the use of capital,

²⁸A similar formula for the emission tax was found by BARNETT (1980). Yet, due to the lack of a second complementary tax rate, the optimal emission tax given therein (eq. (9)) is second-best.

$\tau_k < 0$ thereby encouraging production. The sign of the emission tax, however, remains ambiguous. Whether the emission tax is positive or negative depends on the steepness of the inverse demand curve and on the social damage function. Yet, in any case, the emission tax falls short of the social marginal damage. This reflects the fact that, evaluated at $\tau_k = \tau_e = 0$, output is too low, such that, though the firm ignores its negative production externality, the regulator taxes emissions below the Pigouvian level. Note, however, that the tax system (A.4) is nevertheless first-best: Classically, first-best is established by subsidizing output and taxing emissions without imposing any tax (or subsidy) on capital. In this case, the output tax would be equal to $P'Q < 0$; and the emissions tax, equal to $D' > 0$. It can be easily shown that (A.4) is perfectly equivalent to such a tax system, implying that an additional output tax is redundant here.

Appendix B: Proofs

Claim 1 *The firm's supply is decreasing in factor prices, $\partial Q/\partial p_K = F_K K_{p_K} + F_E E_{p_K} < 0$ and $\partial Q/\partial p_E = F_K K_{p_E} + F_E E_{p_E} < 0$, if, and only if, capital and environmental inputs are normal factors, i. e., marginal cost are increasing in p_K and p_E , respectively.*

First using $\tilde{R}(Q) := P(Q)Q$, we obtain

$$\begin{aligned} F_K K_{p_K} + F_E E_{p_K} &= \frac{1}{|H|} (F_K R_{EE} - F_E R_{KE}) \\ &= \frac{1}{|H|} (F_K (F_{EE} \tilde{R}' + F_E^2 \tilde{R}'') - F_E (F_{KE} \tilde{R}' + F_K F_E \tilde{R}'')) \\ &= \frac{\tilde{R}'}{|H|} (F_K F_{EE} - F_E F_{KE}). \end{aligned}$$

Since we know from the firm's cost-minimization problem that for conditional factor demand, we have $\partial \hat{K}/\partial Q = (F_E F_{KE} - F_K F_{EE})/|F^*|$, where $|F^*|$ denotes the determinant of the bordered Hessian matrix of F . Let MC denote the firm's marginal cost. By Shepard's Lemma $\partial \hat{K}/\partial Q = \partial MC/\partial p_K$ holds. And thus we have $\partial Q/\partial p_K < 0 \Leftrightarrow \partial \hat{K}/\partial Q = \partial MC/\partial p_K > 0$. (Symmetric arguments hold for $\partial Q/\partial p_E$.) \square

Claim 2 *ψ_K and ψ_E are positive under 'reasonable' assumptions.*

We proceed by providing plausible, sufficient conditions under which ψ_K and ψ_E are both positive. Recall the definitions: $\psi_K := (E E_{p_K} - K E_{p_E})|H(R)|$ and $\psi_E := (K K_{p_E} - E K_{p_K})|H(R)|$. Since $|H(R)|$ is positive, it remains to show that

$$\begin{aligned} E E_{p_K} - K E_{p_E} &= -\frac{1}{|H|} (K R_{KK} + E R_{KE}), \\ K K_{p_E} - E K_{p_K} &= -\frac{1}{|H|} (K R_{KE} + E R_{EE}), \end{aligned}$$

are under 'reasonable' assumptions positive. Suppose that $R(K, E)$ is homogenous of degree μ , implying that $R_K K + R_E E = \mu R$. Differentiating this equation with respect to K and E , we obtain

$$K R_{KK} + E R_{KE} = (\mu - 1) R_K, \quad (\text{B.1})$$

$$K R_{KE} + E R_{EE} = (\mu - 1) R_E, \quad (\text{B.2})$$

respectively. Both expressions are negative, if, and only if, $\mu < 1$, that is, if R exhibits decreasing returns-to-scale. But this is a rather mild condition, for $\mu < 1$ only requires that F does not exhibit ‘too large’ increasing returns-to-scale (marginal cost may not decrease too quickly). To see this, recall that

$$KR_{KK} + ER_{KE} = \tilde{R}'' F_K (KF_K + EF_E) + \tilde{R}' (KF_{KK} + EF_{KE}).$$

Since \tilde{R} is concave, the right-hand side is negative unless $KF_{KK} + EF_{KE}$ is sufficiently positive to dominate the first term. However, for a homogenous production function of degree ν , implying that $KF_{KK} + EF_{KE} = (\nu - 1)F(K, E)$, this would require a degree of homogeneity significantly exceeding unity:

$$\frac{\nu - 1}{\nu} > -\sigma \frac{F_K}{Q} > 0,$$

where $\sigma := Q\tilde{R}''/R' < 0$ denotes the elasticity of revenue. But a quickly falling marginal cost function is not what one typically assumes. Therefore, we conclude that ψ_K and ψ_E are ‘most plausibly’ positive.

Claim 3 (Proof of Lemma 1) $0 < \psi_K < \theta_K < \theta_E$ if $R_{KE} > 0$, and $\theta_E < 0 < \theta_K < \psi_K$ if $R_{KE} < 0$.

(i) Note that $\psi_K < \theta_K \Leftrightarrow R_{KE} > 0$. For, $\psi_K < \theta_K \Leftrightarrow K_{p_K}(EE_{p_K} - KE_{p_E}) > -K/|H|$ and using $|H|^{-1} = K_{p_K}E_{p_E} - K_{p_E}E_{p_K}$ this is equivalent to $-E_{p_K}\psi_E/|H| = R_{KE}\psi_E/|H|^2 > 0$.

(ii) Next, $\theta_K < \theta_E \Leftrightarrow R_{KE} > 0$. This follows because $\theta_K < \theta_E \Leftrightarrow K/R_{EE} > -E/R_{KE}$. The latter holds whenever $R_{KE} > 0$, for then this inequality is equivalent to $\psi_E/|H| > 0$. For $R_{KE} < 0$, however, the opposite condition is never satisfied, because this would require $\psi_E/|H| < 0$.

(iii) From steps (i) and (ii) it follows that for $R_{KE} > 0$ we have $0 < \psi_K < \theta_K < \theta_E$; and for $R_{KE} < 0$ we have $\theta_E < 0 < \theta_K < \psi_K$. \square

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