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Environmental taxation and the double-dividend: The role of factor substitution and capital mobility

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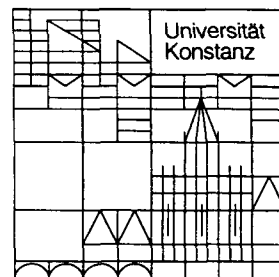
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Sonderforschungsbereich 178
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Diskussionsbeiträge



Juristische
Fakultät

Fakultät für Wirtschafts-
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Environmental Taxation and the Double-Dividend: The Role of Factor Substitution and Capital Mobility*

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ABSTRACT

This paper deals with the so-called 'double-dividend' of an environmental tax reform. We find that, in a model with only labor and a polluting input as factors of production, society faces a trade-off between internalizing environmental externalities and raising revenues in the least distortionary way. However, if either fixed or mobile capital enters the production structure, an ecological tax reform may render the tax structure more efficient from a non-environmental point of view, thereby raising not only environmental quality but also private incomes.

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1 Introduction

Recently, environmental tax reforms have received increasing attention. In particular, some economists have argued that substituting environmental taxes for pre-existing distortionary taxes on income may yield a 'double-dividend', i.e. not only a cleaner environment but also a less distortionary way of revenue-raising (see Pearce, 1991; Oates, 1991). Recent literature on the double-dividend suggests, however, that environmental taxes typically exacerbate, rather than alleviate, pre-existing tax distortions (see Bovenberg and De Mooij, 1994 and 1995; Bovenberg and Van der Ploeg, 1994a; Goulder, 1994).

This paper extends these previous analyses by exploring how inefficiencies in the initial tax system affect the potential for a double-dividend. In particular, by modelling two non-polluting production factors (i.e. labor and capital), rather than just one, we are able to allow for an inefficient distribution of the tax burden over these two factors. Within such a setting, an environmental tax reform affects private welfare through two channels. First, it expands the supply of the public consumption good of the environment, thereby raising the overall tax burden. This *tax burden effect* is responsible for the failure of the double-dividend hypothesis in previous analyses that allowed for only one clean production factor (see Bovenberg and de Mooij (1994)). With two clean production factors, however, an environmental tax reform affects private welfare through a second channel, namely the distribution of the tax burden over the two production factors. In particular, by redistributing the tax burden across the two factors, the reform affects the efficiency of the tax system as a revenue-raising device if the initial distribution of the tax burden is inefficient from a non-environmental point of view. This effect is called the *tax shifting effect*. If the reform shifts the tax burden from the overtaxed factor (i.e. the efficient factor) towards the undertaxed factor (i.e. the inefficient factor), the tax shifting effect alleviates initial inefficiencies in the tax system. However, it exacerbates these inefficiencies if the tax burden is moved onto the factor that is overtaxed already in the initial equilibrium. Hence, initial inefficiencies in the tax system provide both opportunities and dangers for environmental tax reform. In particular, a double-dividend is feasible if, by shifting the tax burden towards the undertaxed factor, the tax shifting effect makes the tax system more efficient from a non-environmental point of view and is large enough to offset the tax burden effect. In that case, the reduction in the excess burden associated with a more efficient revenue-raising system 'finances' the expansion of the supply of public consumption goods (due to a higher quality of the natural environment).

In illustrating these ideas, we allow for two extreme assumptions about the supply of capital.¹ In the first model with two production factors, capital is perfectly mobile internationally. Hence, capital supply is effectively infinitely elastic. In that case, the optimal source-based tax on capital is zero while all distortionary taxes should be levied on labor. Accordingly, capital is overtaxed if the initial source-based tax on capital is positive. Since raising polluting taxes to cut initial taxes on capital tends to reduce the tax burden in the capital-market, the tax shifting effect works in the right direction by improving the efficiency of the tax system as a revenue-raising device. Hence, a double-dividend is obtained if the tax shifting effect dominates the tax burden

¹ Labor is immobile internationally and supplied with a finite wage elasticity.

effect. This is the case if two conditions are met. First, pre-existing capital taxes should be large compared to taxes on pollution. Second, compared to pollution, capital should be a poor substitute for labor. Recycling the revenues from the pollution tax through lower labor taxes, rather than capital taxes, does not yield a double-dividend as the tax shifting effect works in the wrong way. Thus, by redistributing the tax burden towards the capital-market an ecological tax reform exacerbates rather than alleviates the initial inefficiencies in the tax system.

In the second model capital is immobile internationally. Moreover, the supply of capital is completely inelastic so that the optimal tax on capital is 100 %.² Thus, capital is under- rather than overtaxed if the capital tax is below 100 %. This production structure is similar to that of Bovenberg and Van der Ploeg (1995) who also allow for a fixed factor in production. However, in contrast to Bovenberg and van der Ploeg who consider involuntary unemployment due to rigid consumer wages, we allow flexible wages to clear the labor-market. Within this framework, we find that substituting environmental taxes for labor taxes may yield a double-dividend. Intuitively, by shifting the tax burden from labor (the overtaxed factor) towards the fixed factor (the undertaxed factor), the government may improve the efficiency of the tax system as a revenue-raising device.

The rest of this paper is structured as follows. Section 2 discusses the model. Section 3 explores the effects of a shift in the tax mix away from labor towards pollution in a simple benchmark model which contains only labor as a clean production factor. Section 4 extends the benchmark model by incorporating internationally mobile capital. That section explores the consequences of substituting environmental taxes for taxes on either labor or capital. Furthermore, we derive the optimal tax formula in a 'third-best' world where not only lump-sum taxes are absent but also one tax rate is exogenously fixed at a sub-optimal level. Section 5 discusses the model in which the supply of capital is fixed. Finally, section 6 concludes.

2 The model

2.1 The structure of the model

This section discusses the model contained in table 2.1. Notation is defined at the end of the table. The model describes a small open economy, which faces fixed world market prices for all commodities. The model distinguishes three sectors, namely firms, households and the government. These sectors are discussed below.

-- insert table 2.1 here --

Firms

Firm behavior is described by a representative firm that supplies a single commodity. The firm maximizes profits subject to a neo-classical production function (I.1), which exhibits constant returns to scale with respect to its four inputs: labor (L), an input that causes pollution when used in production (the polluting input E), clean capital (K) and a fixed factor (H). The polluting input

² If no restriction would be imposed, the optimal profit tax would exceed 100%.

and clean capital are mobile internationally so that their market prices are fixed on world markets. We normalize units so that these prices are unity. Whereas clean capital and the polluting input are in effect supplied infinitely elastic, the supply of the fixed factor is completely inelastic. The fixed factor can be interpreted as land or immobile capital. Solving the firm's maximization problem, we find the implicit demand functions for labor (I.2), clean capital (I.3) and the polluting input (I.4). Relation (I.5) defines profits.

Households

The representative household maximizes a homothetic utility function of the form (I.6) subject to its budget constraint (I.7). The household budget available for consumption consists of four components: after-tax labor income (WL), after-tax profits $((1-T_\Pi)\Pi)$ and the after-tax returns on the domestic endowments of respectively, capital (K^*) and polluting inputs (E^*). Two public goods enter household utility, namely, public consumption (G) and environmental quality (M). Environmental quality is weakly separable from private goods in utility. The individual household takes the quantities of public goods as exogenously given. Hence, in optimizing utility, it adopts leisure (V) and consumption (C) as instruments. Equations (I.8) and (I.9) represent the implicit expressions for labor supply and consumption demand, respectively. Here, λ denotes the marginal utility of private income. We normalize the time endowment to unity (see (I.10)).

Government

The government supplies public goods (G) which are financed by four taxes: a tax on labor income (T_L), a tax on capital (T_K), a profit tax (T_Π), and a tax on the polluting input (T_E). The government budget is assumed to be balanced (see (I.11)). In this paper, we examine the effects of a rise in the pollution tax under alternative options for recycling the revenues, namely, a reduction in the tax on labor income, a reduction in the tax on capital income and a reduction in the profit tax.³

Labor-market equilibrium, environment and balance of payments

Relation (I.12) represents the equilibrium condition on the labor-market, while (I.13) formalizes the inverse relationship between the demand for polluting inputs and the quality of the environment. In accordance with the law of Walras, we find the equilibrium on the balance of payments (I.14) by combining the relations for output (I.1), profits (I.5), the household budget constraint (I.7), and the government budget constraint (I.11).

2.2 Linearization

To analyse the economic consequences of an environmental tax reform, we log-linearize the model around an initial equilibrium. Table 2.2 contains the log-linearized model. Notation is defined at the end of the table. A tilde (\sim) denotes a relative change, unless indicated otherwise. The supply of public goods (G) and the domestic endowments of capital and polluting inputs are fixed exogenously (i.e. $\tilde{G} = \tilde{K}^* = \tilde{E}^* = 0$).

³ Political motives or monitoring problems may prevent changes in the profit tax (see Atkinson and Stiglitz, 1980).

-- insert table 2.2 here --

Factor demand relations

Relations (II.2), (II.3) and (II.4) represent the factor demand equations for labor, the polluting input and clean capital, respectively. The elasticities, ϵ_{ij} , ($i, j = L, K, E$) represent price elasticities of factor demand conditional on the level of the fixed factor. However, if the fixed factor is absent (i.e. $w_H = 0$), the factor demand equations in (II.2) - (II.4) do not hold and factor demand is instead expressed conditional on employment, rather than the fixed factor. These alternative factor demand equations are represented by (II.3') and (II.4').

Labor supply

Expression (II.7) reveals that a rise in the after-tax wage rate (W) boosts labor supply if the uncompensated wage elasticity (η_{LL}) is positive. Indeed, empirical evidence suggests that the value of the wage elasticity is positive, although rather small (Hausman, 1985). Hence, we will assume that this elasticity is positive. Depending on the income elasticity of labor supply (η_L), a rise in after-tax profits reduces labor supply because of a negative income effect. The quality of the environment does not directly affect private behavior because it is weakly separable from private goods in utility (see (I.6)).

2.3 Welfare

We measure the welfare effects of an environmental tax reform by the marginal excess burden, defined as the compensating variation divided by output. It corresponds to the additional transfer that must be provided to households to keep utility, after a policy shock, at its initial level. A positive excess burden thus implies a loss in welfare. The marginal excess burden, $\tilde{\beta}$, can be written as the sum of three market distortions (see appendix C)

$$\tilde{\beta} = \underbrace{-\theta_L w_L \tilde{L}}_{\text{labor-market distortion}} - \underbrace{[\theta_E - \theta_E^P] w_E \tilde{E}}_{\text{environmental distortion}} - \underbrace{\theta_K w_K \tilde{K}}_{\text{capital-market distortion}} \quad (2.1)$$

where

$$\theta_E^P \equiv \frac{1}{1 + T_E} \frac{U_M(-M_E)}{\lambda} \quad (2.2)$$

The first term at the right hand side (RHS) of (2.1) involves the impact of the reform on the labor-market distortion. Employment yields a first-order welfare gain if the pre-existing labor income tax is positive. Intuitively, the labor tax drives a wedge between the marginal social benefits of employment in terms of additional production and the marginal social opportunity costs

$$\tilde{\beta} = \underbrace{[-\theta_L w_L \tilde{L} + \theta_E w_E \tilde{E} + \theta_K w_K \tilde{K}]}_{\text{dist}} + \underbrace{\theta_E^P w_E \tilde{E}}_{\text{green}}$$

in terms of foregone leisure. Indeed, additional production due to more employment not only compensates workers for giving up their leisure, but also yields public revenues. The second term at the RHS of (2.1) denotes the environmental distortion, which is determined by the difference between two terms: On the one hand, a tax term representing the additional public revenues if polluting input demand increases and, on the other hand, a term representing the marginal social damage from pollution, defined in (2.2). If the first term exceeds the second term, a higher demand for the polluting input raises welfare as the marginal social benefits exceed the marginal social costs. The tax rate that fully internalizes the environmental distortion is the Pigovian tax, i.e. $\theta_E = \theta_E^P$. At the Pigovian level, the loss in welfare on account of more pollution is exactly offset by the welfare gain on account of the broadening of the tax base. The third term at the RHS of (2.1) stands for the distortion in the capital-market. In particular, the tax rate on capital drives a wedge between the marginal social benefits and costs of capital demand. Hence, an expansion of capital demand raises welfare.

Alternatively, the marginal excess burden can be written in terms of private incomes (see appendix C)

$$\tilde{\beta} = \underbrace{-[(1 - \theta_L)w_L \tilde{W} + w_\Pi(\tilde{\Pi} - \tilde{T}_\Pi)]}_{blue} + \underbrace{\theta_E^P w_E \tilde{E}}_{green} \quad (2.3)$$

The term in square brackets at the RHS of (2.3) indicates that an increase in after-tax private incomes raises welfare. We call this the *blue* welfare component (private or non-environmental dividend). It is associated with the efficiency of the tax system as a revenue-raising device: a more efficient tax system reduces the overall tax burden on private agents and, therefore, boosts after-tax private incomes. Welfare may improve also on account of a *green* dividend, i.e. a better quality of the environment (see the last term at the RHS of (2.3)). If both the blue and the green dividend are positive, we speak about a *double-dividend*.

3 Environmental Taxation in the Benchmark Model

In this section, we analyse the consequences of an environmental tax reform in the benchmark model in which both the fixed factor, H, and mobile capital, K, are absent. Subsequently, we extend the benchmark model by incorporating mobile capital (section 4) and fixed capital (section 5), respectively. Thus, the benchmark model is a special case of the two extended models, which are solved in appendix A and appendix B, respectively.

In the benchmark model, the blue dividend is determined by the effect on wages only because profits are zero (see (2.3)). Moreover, in the absence of capital, the capital-market distortion is zero (see (2.1)). We will discuss the effects of the ecological tax reform on blue and green welfare (see (2.3)) and on the labor-market and environmental distortions (see (2.1)). We explore also the overall welfare effects if the reform starts from specific initial equilibria, namely, equilibria without a pollution tax or where the pollution tax is at its Pigovian level. Finally, we derive the optimal tax rates on labor and the polluting input.

3.1 Tax reform

The reduced-form equations for after-tax wages, employment, the demand for the polluting input and output are given in table 3.1. The reduced-form coefficient in the third row of this table reveals that an environmental tax reform always reduces the demand for the polluting input and thus yields a green dividend. If the initial pollution tax is positive (i.e. $\theta_E > 0$), the wage rate declines so that the blue dividend is negative (see the reduced-form coefficient in the first row of table 3.1). The reason for the fall in wages is that the supply of the polluting input is effectively infinitely elastic because the market price of these inputs is fixed on the world market. Hence, the incidence of the pollution tax falls on the only immobile factor of production, labor, in the form of a lower labor productivity. An environmental tax reform thus replaces an *explicit* by an *implicit* tax on labor. The explicit labor tax is a more efficient instrument to raise public revenues than the implicit labor tax as the latter distorts not only the labor market but also reduces the demand for the polluting input, thereby eroding the tax base (if $\theta_E > 0$). Indeed, the initial tax on pollution, θ_E , measures the gap between the social benefits and the non-environmental costs of pollution. Hence, the erosion of the tax base of the pollution tax measures the non-environmental (i.e. private) costs associated with a cleaner environment. We call the costs of a cleaner environment the *tax burden effect*: it reduces real wages and, given a positive uncompensated wage elasticity of labor supply, η_{LL} , employment drops. The overall burden of taxation is thus exacerbated.

-- insert table 3.1 here --

Welfare effects if we start from a zero pollution tax

The overall welfare effect of a shift in the tax mix from labor towards the polluting input depends on the relative magnitudes of the blue and green dividends. If we start from an equilibrium without pollution taxes (i.e. $\theta_E = 0$), the introduction of a small tax leaves wages, and hence private welfare, unaffected (see the reduced-form coefficient in the first row of table 3.1 with $\theta_E = 0$). The reason is that the non-environmental costs and benefits coincide so that a zero pollution tax is optimal from a non-environmental point of view. Hence, a small movement away from this equilibrium does not yield any first-order effects on blue welfare. A marginal improvement in environmental quality thus comes free. If households care about the environment (i.e. $\theta_E^P > 0$), the zero blue dividend is accompanied by a positive green dividend. Hence, welfare improves and a positive pollution tax is optimal.

Welfare effects if we start from a Pigovian tax

If the initial tax structure fully internalizes the environmental distortion (i.e. $\theta_E = \theta_E^P$), an ecological tax reform does not produce any first-order welfare effects through the channel of the environmental distortion. Hence, welfare effects are determined solely by the effects on the labor-market distortion (see (2.1)). The reduced-form coefficient in the second row of table 3.1 reveals that, starting from a Pigovian tax (i.e. $\theta_E = \theta_E^P > 0$), an environmental tax reform reduces employment if the uncompensated wage elasticity of labor supply is positive. With a positive distortionary tax on labor, the drop in employment exacerbates the distortion on the labor-market. Hence, reducing the pollution tax below the Pigovian level raises welfare. The optimal tax on the polluting input thus lies between zero and the Pigovian level (Bovenberg and De Mooij, 1994).

3.2 Optimal taxes

To find the optimal pollution tax, we substitute the reduced-form equations for wages and pollution from table 3.1 into the marginal excess burden (2.3) and set it equal to zero. This yields for the optimal pollution tax

$$\frac{T_E}{T_E^P} = 1 - \eta_{LL} T_L \quad (3.1)$$

where $T_E^P \equiv (1 + T_E)\theta_E^P$. Accordingly, the optimal tax on the polluting input lies below the Pigovian tax if $T_L\eta_{LL} > 0$, i.e. if both the distortionary tax on labor is positive (i.e. Pigovian taxes do not suffice to finance all public goods) and the labor supply curve is upward sloping (see also Bovenberg and Van der Ploeg, 1994).

Alternatively, we can find the optimal taxes on the polluting inputs and labor by deriving the optimal tax formulas directly (see appendix A with $w_K = \theta_K = 0$)

$$T_E = \frac{1}{\eta} T_E^P \quad (3.2)$$

$$\eta = \frac{1}{1 - T_L \eta_{LL}} \quad (3.3)$$

where $\eta = \mu/\lambda$ denotes the Marginal Cost of Public Funds (MCPF) (i.e. the ratio between the marginal disutility of raising an additional unit of public funds (μ) and the marginal utility of private income (λ)). The MCPF indicates how scarce public funds are relative to private funds. If the government has access to lump-sum taxes, public funds are no scarcer than private income and the MCPF equals unity (see (3.3) with $T_L = 0$). In that case, the optimal tax on the polluting input is equal to the Pigovian tax (see (3.2) with $\eta = 1$). However, if lump-sum taxes are absent and Pigovian taxes do not yield sufficient revenues to meet revenue requirements, the government requires distortionary taxes to finance its spending. In that case, the MCPF typically lies above unity as taxation distorts economic decisions. Hence, public funds are scarcer than private funds.⁴

If the MCPF increases, relation (3.2) reveals that the optimal pollution tax falls *ceteris paribus*. Intuitively, the government adopts the tax system for a twofold task: raising revenues and internalizing environmental externalities. The higher the MCPF becomes, the more important the revenue-raising objective becomes relative to the environmental objective. Hence, the government

⁴ If labor is supplied inelastically (i.e. $\eta_{LL} = 0$), neither implicit nor explicit taxes distort the labor supply decision so that the MCPF equals unity. If the uncompensated wage elasticity of labor supply is negative, the MCPF is smaller than unity (see Ballard and Fullerton, 1992).

finds it optimal to rely more on taxes that are efficient in revenue-raising (i.e. labor taxes) and less on taxes that are relatively inefficient in revenue-raising because they are aimed at internalizing environmental externalities (i.e. environmental taxes).

4 Environmental Taxation and Mobile Capital

This section extends the benchmark model by incorporating mobile capital (K) in the production function. The government can tax the associated capital income through a source-based capital income tax. In absence of a fixed factor, the factor demand equations are expressed conditional on the level of employment (see (II.3') and (II.4')). To obtain a better understanding of what determines the own and cross price elasticities in these factor demand equations, table 4.1 presents these elasticities for three separable production functions. It reveals that both a higher price of pollution (capital) and a lower price of labor reduce the pollution/labor ratio (capital/labor ratio) (i.e. ϵ_{EE}^* and $\epsilon_{KK}^* > 0$; ϵ_{EL}^* and $\epsilon_{KL}^* < 0$). The signs of the cross elasticities, ϵ_{KE}^* and ϵ_{EK}^* are ambiguous. In particular, a higher price of pollution boosts the demand for capital relative to that of labor if, compared to labor, capital is a better substitute for pollution. Likewise, the pollution/labor ratio expands on account of a higher price of capital if capital is a better substitute for pollution than it is for labor. If inputs are equally good substitutes for each other, the cross price elasticities are zero.

-- insert table 4.1 here --

In the presence of capital, the welfare effects are determined not only by the labor-market and environmental distortions but also by the capital-market distortion (see (2.1)). In the absence of profits, blue welfare is still determined by the effect on wages only (see (2.3)). Alternatively, the private (blue) dividend can be decomposed in effects on the bases of pollution and capital taxes (see appendix C)

$$\tilde{\beta} = - \frac{1 - \theta_L}{1 - \theta_L - \theta_L \eta_{LL}} \left[\underbrace{\theta_E w_E \tilde{E}}_{blue} + \underbrace{\theta_K w_K \tilde{K}}_{green} \right] + \underbrace{\theta_E^P w_E \tilde{E}}_{green} \quad (4.1)$$

The rest of this section is organized as follows. We first discuss the optimal tax structure if the government can freely adjust taxes on capital, labor and pollution. Subsequently, we assume that two tax rates are exogenous while the third tax is adjusted endogenously to balance the government budget. In particular, in subsection 4.2 the tax rates on pollution and capital are exogenous policy instruments while the labor tax is endogenously adjusted. Subsection 4.3, in contrast, assumes that the tax on labor income is exogenous while the capital tax is endogenous. Within these settings, we explore both tax reforms and optimal taxes.

4.1 Optimal Tax Structure

Appendix A solves the optimal tax problem of the model with mobile capital. We derive the following optimal tax rates if all three taxes can be adjusted

$$T_K = 0 \quad (4.2)$$

$$T_E = \frac{1}{\eta} T_E^P \quad (4.3)$$

$$T_L = \left(1 - \frac{1}{\eta}\right) \frac{1}{\eta_{LL}} \quad (4.4)$$

The optimal tax rates on the polluting input and labor are equivalent to the optimal taxes in the benchmark model (compare (4.3) with (3.2) and (4.4) with (3.3)). The optimal tax on capital is zero. Without environmental externalities (i.e. $T_E^P = 0$), the optimal tax on the polluting input is zero as well. Intuitively, both capital and the polluting input are perfectly mobile internationally and thus supplied with infinite elasticity. Accordingly, the incidence of both taxes is borne by the only immobile factor of production, labor. Hence, the capital tax and the pollution tax are implicit taxes on labor income. Just as in case of the benchmark model, a direct, explicit tax on labor is a more efficient instrument to raise revenues than an indirect, implicit tax on labor because the latter distorts not only the labor-market but also other markets, such as the capital-market and the market for polluting inputs. Consequently, in the absence of environmental considerations, the government finds it optimal to set zero taxes on both capital and the polluting input (see (4.2) and (4.3) if $T_E^P = 0$). If environmental considerations are taken into account, a pollution tax should internalize part of the environmental externality. In accordance with the targetting principle, this tax is levied on the polluting input only (see (4.3) if $T_E^P > 0$).

4.2 Reducing labor taxes

This subsection assumes that the tax rate on labor is endogenously adjusted to keep the government budget balanced. Within this setting, we explore the consequences of a rise in environmental taxes or capital taxes.

4.2.1 Tax Reform

Appendix A derives the solutions of a rise in capital taxes and pollution taxes, recycled through lower labor taxes. The reduced-form coefficients are presented in table 4.2. The table shows that pollution taxes and capital taxes yield very similar effects (compare the first and second column of table 4.2). This is because both capital and polluting inputs are supplied with infinite elasticity. Indeed, the reduced-form coefficients for pollution taxes and capital taxes are symmetric in the initial tax rates and the price elasticities of factor demands. In view of this similarity between the

effects of pollution taxes and capital taxes, the rest of this subsection concentrates on pollution taxes only.

-- insert table 4.2 here --

Starting from zero non-labor taxes

If the initial tax rates on the polluting input and capital are zero (i.e. $\theta_E = \theta_K = 0$), the reduced-form coefficient in the first row of table 4.2 reveals that introducing a pollution tax leaves wages and thus blue welfare unaffected. Intuitively, zero taxes on the polluting input and capital are optimal from a non-environmental point of view and thus optimize blue welfare (see subsection 4.1). Hence, at the margin, all taxes are equally efficient instruments to raise revenues and a marginal change in the tax system does not yield any first-order effects on private welfare.

The effect on green welfare is determined by the own-price elasticity of the demand for polluting input, Γ_{EE} , defined below table 4.2 (see the third row of table 4.2 with $\theta_E = \theta_K = 0$). This 'general equilibrium elasticity' measures the consequences for the pollution/labor ratio due to two price changes: first, a higher price of polluting inputs (measured by ϵ_{EE}) and, second, a lower price of labor induced by the rise in the price of polluting inputs along the factor-price frontier (measured by ϵ_{EL}).⁵

Starting from a positive pollution tax: the tax burden effect

If we start from zero taxes on capital (i.e. $\theta_K = 0$) and a positive pollution tax (i.e. $\theta_E > 0$), further increases in the pollution tax amount to a shift in the tax mix away from the non-environmental optimum (in which $\theta_E = \theta_K = 0$). The resulting decline in non-environmental welfare implies a fall in private incomes and thus a negative blue dividend. Indeed, the reduced-form coefficient in the first row of table 4.2 reveals that wages (representing blue welfare) fall due to a green tax shift if the pollution tax is positive initially. The reason is that, at the margin, pollution taxes are less efficient instruments to raise revenue than taxes on labor because they not only distort the labor market but also reduce the demand for the polluting input, thereby eroding the base of the pollution tax. The associated drop in private incomes measures the costs of a cleaner environment. These costs reduce wages, thereby reducing the incentives to supply labor. The environmental benefits, in contrast, leave labor supply unaffected: these benefits are public and thus independent of labor supply. Indeed, by improving the quality of the environment, pollution taxes expand the provision of public consumption goods. As in section 3, we define the *tax burden effect* as the higher tax burden associated with the additional costs due to a higher overall provision of public goods. The erosion of the base of the pollution tax, (i.e. the first term between square brackets at the RHS of (4.1)) measures this tax burden effect.

The magnitude of the tax burden effect is determined by two elements: the initial tax rate on the polluting input and the fall in the demand for polluting inputs. The initial pollution tax measures the marginal costs of improving environmental quality. In particular, if pre-existing pollution taxes are large, a decline in the demand for the polluting input substantially reduces

⁵ The production function exhibits constant returns to scale with respect to L, K and E. Hence, the factor-price frontier expresses producer wages in terms of the other input prices (see appendix A).

public revenues by eroding the tax base.

The second element determining the tax burden effect is the elasticity of polluting input demand, Γ_{EE} . On the one hand, a large elasticity implies that the environmental tax reform is successful in cutting pollution. On the other hand, in that case a high pollution tax imposes a heavy burden on the private sector as tax revenues fall substantially due to an eroding tax base. Hence, a trade-off exists between green and blue welfare: if an environmental tax reform is successful in enhancing environmental quality, it imposes a high burden on the private sector in terms of lower wages (see also the trade-off between the first and last term at the RHS of (4.1)). To obtain a better understanding of the factors determining Γ_{EE} , table 4.3 presents this elasticity in terms of Allen elasticities of substitution for three separable production functions. This table reveals that pollution unambiguously falls due to an environmental tax reform (i.e. $\Gamma_{EE} > 0$). In particular, both the higher price of pollution and the lower price of labor induce input substitution away from pollution towards labor (see first row of table 4.3). Furthermore, because an environmental tax reform shifts the tax burden from the immobile factor (that is rather inelastic in supply) to the mobile factor (that is infinitely elastic in supply), output unambiguously falls (see second row of table 4.3). This adverse production effect reinforces the fall in pollution on account of the substitution effect.

-- insert table 4.3 --

Starting from a positive capital tax: the tax shifting effect

In the real world, tax systems are far from optimal due to political motives, monitoring problems, distributional reasons, etc. If the initial equilibrium features a zero pollution tax (i.e. $\theta_E = 0$) and a positive tax rate on clean capital (i.e. $\theta_K > 0$), the tax system is indeed sub-optimal, even from a non-environmental point of view (see section 4.1). In that case, substituting pollution taxes for labor taxes may either exacerbate or alleviate pre-existing tax distortions.

An environmental tax reform reduces wages if pre-existing capital taxes are positive and capital demand falls (see the first row in table 4.2 with $\theta_E = 0$). The effect on capital depends on the cross-price elasticity of capital demand, i.e. $\Gamma_{EK} = (w_K/w_E)\Gamma_{KE}$ (see the reduced-form for capital in the fourth row of table 4.2 with $\theta_E = 0$). This latter elasticity measures the consequences for the capital/labor ratio due to a higher price of the polluting input and the associated lower price of labor. Table 4.3 presents expressions for this elasticity for three separable production functions. It reveals that capital demand typically falls. Intuitively, the tax that is cut involves the immobile factor (which is rather inelastic in supply) while the tax that is increased directly affects the mobile factor (which is infinitely elastic in supply). Consequently, output falls -- especially if the more expensive mobile factor is a good substitute for the immobile factor. The adverse production effect typically reduces the demand for capital.⁶

⁶ Capital demand rises only if positive substitution effects, associated with the change in relative prices, dominate this adverse production effect. Substitution effects stimulate the demand for capital if, compared to the cheaper factor (i.e. labor), the more expensive factor (the polluting input) is a better substitute for capital. The adverse production effect is small if the mobile factor that is increased in price (the polluting input) is a poor substitute for the immobile factor and if the immobile factor accounts for a large production share compared to the more expensive mobile factor (i.e. $\sigma_L < w_L\sigma_{EK}$). In the rest of this subsection, we assume that this is not the case so that $\Gamma_{EK} > 0$.

The typical decline in capital demand hurts welfare by eroding the base of the tax on capital. In this way, substituting pollution taxes for labor taxes exacerbates pre-existing distortions associated with capital taxation. We call this the *tax shifting effect* because the tax burden is shifted towards capital in terms of a lower capital demand. The tax shifting effect is measured by the second term between square brackets at the RHS of (4.1).

The magnitude of the tax shifting effect is determined by the initial tax rate on capital and the cross-price elasticity of capital demand with respect to the price of the polluting input. High initial taxes on capital imply that the social benefits associated with additional capital demand are large. In particular, a fall in the demand for capital induces a large erosion of the tax base and, therefore, a substantial fall in private incomes. Second, the cross-price elasticity of capital demand, Γ_{KE} , determines how large the fall in capital demand is.

Starting from an arbitrary equilibrium

We have now uncovered three channels through which a tax shift away from labor towards pollution affects welfare. First, substitution away from polluting inputs in combination with an adverse production effect contributes to green welfare (i.e. the final term at the RHS of (4.1)). Second, pre-existing taxes on the polluting input cause a tax burden effect. In particular, the fall in pollution raises the tax burden on private incomes, thereby adversely affecting blue welfare (see the first term in square brackets at the RHS of (4.1)). Third, if the capital income tax is initially positive, an environmental tax reform induces a tax shifting effect by affecting the base of the capital income tax. Through this channel the tax distortion on the capital-market is typically exacerbated so that blue welfare falls (see the second term between square brackets at the RHS of (4.1)). Overall, starting from an arbitrary equilibrium in which both capital and pollution taxes are positive, an environmental tax reform yields a green dividend. However, blue welfare typically falls.

4.2.2 Optimal taxes

We now derive the optimal taxes if the government can use only two tax rates to optimize welfare. In particular, we solve the optimal tax problem in case T_L and T_E can be adjusted while T_K is fixed at a possibly sub-optimal rate. Furthermore, the case that T_L and T_K can be adopted as instruments is explored.

Optimal taxes from a non-environmental point of view

The non-environmental welfare effects of a shift in taxation from labor or capital towards the polluting input are determined solely by the blue welfare component (see (2.3)). By substituting the reduced-form for wages from table 4.2 into (2.3) and setting the marginal change in blue welfare equal to zero, we find the following optimal tax structures if, respectively, the capital tax and the pollution tax rate is predetermined

$$\frac{\theta_E}{\theta_K} = - \frac{\Gamma_{EK}}{\Gamma_{EE}} \quad (4.5)$$

$$\frac{\theta_K}{\theta_E} = - \frac{\Gamma_{KE}}{\Gamma_{KK}} \quad (4.6)$$

The terms at the RHS of (4.5) and (4.6) are typically negative. Consequently, from a non-environmental point of view, the polluting input should be subsidized if the capital tax is set exogenously at a positive value (see (4.5)). Intuitively, the pollution subsidy raises production, thereby expanding capital demand. In this way, the pollution subsidy acts as an indirect instrument to alleviate the distortion in the capital-market. A similar argument holds for the optimal capital tax if the tax rate on pollution is fixed (see (4.6)).

Optimal taxes in the presence of environmental externalities

Appendix A derives the following solution for the optimal tax structure if environmental considerations are taken into account (if, respectively, the capital tax and the pollution tax are fixed)

$$\frac{\theta_E - \frac{1}{\eta} \theta_E^P}{\theta_K} = \frac{\Gamma_{EK}}{\Gamma_{EE}} \quad (4.7)$$

$$\frac{\theta_K}{\theta_E - \frac{1}{\eta} \theta_E^P} = \frac{\Gamma_{KE}}{\Gamma_{KK}} \quad (4.8)$$

where $\eta = \lambda/\mu$ is the MCPF. The optimal pollution tax in (4.7) consists of two components. The first term at the RHS of (4.7) aims at internalizing pollution externalities. Whereas this term thus offsets the environmental distortion, the second term alleviates the distortion in the capital-market due to source-based tax on capital. The optimal pollution tax is smaller than the Pigovian tax (i.e. marginal environmental damages) for two reasons. First, in the presence of distortionary taxes, the marginal costs of public funds typically exceeds unity so that the environmental term is smaller than the Pigovian tax. Intuitively, if public revenues are scarce as reflected in a large value for the marginal cost of public funds, the government cannot afford to fully internalize environmental externalities and relies less on taxes that are targetted at environmental protection (i.e. the pollution tax) and more on taxes that are efficient from a revenue-raising point of view (i.e. the labor tax) (see also Bovenberg and van der Ploeg (1994a)). The second reason why the pollution tax is smaller than the Pigovian tax is that the pollution tax is used not only to internalize environmental externalities but also to alleviate the capital-market distortion. The latter task of the pollution tax calls for a subsidy rather than a tax.

With an exogenous pollution tax, the sign of the optimal capital tax corresponds to the sign of the term between square brackets at the right-hand side of (4.8). This term measures the

net social damage due to an additional unit of pollution. Without a tax on polluting inputs, the social value of pollution is negative due to the associated adverse pollution externalities. In that case, by reducing production, a positive capital tax acts as an indirect instrument to internalize these externalities. If the pollution tax is sufficiently large, however, the net social value of an additional unit of pollution is positive as the social value of the increase in tax revenue due to the broadening of the pollution tax base offsets the environmental costs.⁷ With additional pollution raising welfare, the optimal capital tax is negative; by boosting production, the capital subsidy expands the demand for the polluting input, thereby generating a first-order welfare gain.

4.3 Reducing capital taxes

This subsection explores the consequences of shifting the tax burden away from capital towards either pollution or labor. We first explore the consequences of a tax reform, starting from equilibria that are not necessarily optimal. Subsequently, we derive the third-best taxes on capital and the polluting input in case the labor tax is fixed exogenously.

4.3.1 Tax reform

Raising either pollution or labor taxes to cut taxes on capital yields solutions presented in table 4.4 (see appendix A for a derivation). Comparing the reduced-form coefficients in table 4.4 with those in table 4.2, we confirm that an increase in labor taxes, recycled as lower capital taxes, yields exactly the opposite effects as an increase in capital taxes returned as lower labor taxes. In view of this similarity, this subsection concentrates on increases in pollution taxes only.

Starting from zero non-labor taxes

Zero taxes on polluting inputs and capital (i.e. $\theta_E = \theta_K = 0$) are optimal from a non-environmental point of view (see (4.2) and (4.3)). Consequently, a marginal change in the tax system away from this optimum does not yield any first-order effects on blue welfare. Intuitively, substituting one implicit tax on labor, i.e. the pollution tax, for another, i.e. the capital income tax, leaves the wage rate unaffected (see the reduced-form in the first row of table 4.4 with $\theta_E = \theta_K = 0$) because, at the margin, all these implicit labor taxes are equally efficient.

The effects on green welfare are determined by the difference between two elasticities, i.e. $\Gamma_{EE} - \Gamma_{KE}$ (see the third row in table 4.4 with $\theta_E = \theta_K = 0$), which can be expressed as follows

$$\Gamma_{EE} - \Gamma_{KE} = \epsilon_{EE}^* - \frac{w_E}{w_K} \epsilon_{EK}^* \quad (4.9)$$

Hence, $\Gamma_{EE} - \Gamma_{KE}$ measures how the pollution-labor ratio changes due to a higher producer price of the polluting input (i.e. the first term at the RHS of (4.9)) and the associated lower producer price of capital (i.e. the second term at the RHS of (4.9)). Table 4.5 presents this general equilibrium elasticity for three separable production functions. It reveals that the shift from capital towards

⁷The environmental damages are divided by the marginal costs of public funds in order to express these damages in terms of government revenues.

pollution taxes typically yields a green dividend. If the term in (4.9) is positive, we refer to this as the normal case.

In the exceptional case that the term in (4.9) is negative, the introduction of a pollution tax, rather paradoxically, raises pollution. Intuitively, the revenues from the pollution tax are used to introduce a capital subsidy, which raises production and thereby pollution. In that case, compared to a pollution tax, a capital tax is a better instrument to cut pollution.⁸ This exceptional case occurs if, compared to pollution, capital is a much better substitute for labor (see table 4.5 if E is separable and σ_E is small compared to σ_{LK}). The tax reform then boosts production because the mobile factor that is elastic in demand (i.e. capital which is a good substitute for labor) becomes cheaper while the mobile factor that is rather inelastic in demand (i.e. the polluting input which is a relatively poor substitute for labor) becomes more expensive. At the same time, the adverse substitution effect on the demand for the polluting input due to the higher cost of pollution is small because the polluting input is a poor substitute for the two other inputs (i.e. σ_E is relatively small). Accordingly, the positive output effect dominates the adverse substitution effect and pollution thus increases.

-- insert table 4.5 here --

Starting from a positive pollution tax: the tax burden effect

If the initial equilibrium features a positive pollution tax (i.e. $\theta_E > 0$) and zero taxes on capital (i.e. $\theta_K = 0$), further increases in the pollution tax typically shift the tax system further away from the non-environmental optimum, thereby harming blue welfare. Indeed, the reduced-form coefficient in the first row of table 4.4 reveals that wages decline if the initial pollution tax is positive and the demand for polluting inputs falls, i.e. if we are in the normal case so that (4.9) is positive. Intuitively, the reduction in pollution erodes the base of the environmental tax. Therefore, given an exogenous revenue-requirement, the government needs to raise other tax rates, thereby harming private welfare. As in subsection 4.2, we call the erosion of the pollution tax base associated with a higher environmental quality the tax burden effect (i.e. the first term between square brackets at the RHS of (4.1)). In the exceptional case when a higher pollution tax raises pollution, the tax burden effect is actually negative. In that case, the tax reform yields a positive blue dividend but at the costs of a negative green dividend. Thus, the double-dividend always fails if the initial equilibrium features a positive pollution tax and a zero capital tax: the blue and green dividends have opposite signs.

Starting from a positive capital tax: the tax shifting effect

Substituting pollution taxes for capital taxes is likely to produce a double-dividend if such a reform starts from an initial equilibrium with a zero pollution tax (i.e. $\theta_E = 0$) and a positive tax on capital (i.e. $\theta_K > 0$). With this initial equilibrium, expression (4.1) reveals that the sign of the blue dividend depends on how the reform affects capital demand. This is determined by the

⁸ Schöb (1994) finds a similar result for pollution taxes on consumption. In particular, he shows that a tax on a non-polluting consumption commodity that is complementary to the polluting consumption commodity may be a better instrument for environmental protection than a tax on the polluting commodity.

difference between two elasticities, i.e. $\Gamma_{KK} - \Gamma_{EK}$ (see the fourth row in table 4.4 with $\theta_E = 0$), which can be written by using the definitions of the Γ 's as

$$\Gamma_{KK} - \Gamma_{EK} = \epsilon_{KK}^* - \frac{w_K}{w_E} \epsilon_{KE}^* \quad (4.10)$$

The general equilibrium elasticity, $\Gamma_{KK} - \Gamma_{EK}$, measures how capital demand (scaled by the immobile input, labor) changes as a result of a higher price for the polluting input (measured by the second term at the RHS of (4.10)), and the lower price of capital (i.e. the first term at the RHS of (4.10)). Table 4.5 shows that (4.10) is typically positive so that the demand for capital expands. Intuitively, lower capital costs boost the demand for capital through positive substitution effects. In the normal case, this positive substitution effect dominates the output effect. Hence, capital demand increases and private welfare rises.

The intuition behind the expansion of private welfare is that the environmental tax reform moves the tax system closer to a non-environmental optimum. In particular, in the initial equilibrium, one of the non-polluting factors, namely capital, is overtaxed compared to the other non-polluting factor, namely, labor. Raising the pollution tax and reducing the capital tax typically reduces the tax burden on the overtaxed factor because, in contrast to the pollution tax, the capital tax directly impacts the capital-market. The reallocation of the tax burden away from the overtaxed factor resulting in an expansion of capital demand is called the tax shifting effect.⁹

Only in the exceptional case that a negative output effect is strong enough to offset the positive substitution effect does the demand for capital decline so that private welfare falls. In this case, the tax shifting effect is negative since it works in the wrong way by further raising the burden of taxation on the capital-market. This occurs if the polluting input is a much better substitute for labor than capital (see table 4.5 if K is separable and σ_K is small compared to σ_{EL}). Intuitively, output contracts because the tax burden is shifted away from the input that is inelastic in demand (i.e. capital which is a poor substitute for labor) towards the input that is in relatively elastic demand (i.e. the polluting input which is a relatively good substitute for labor). With only limited possibilities to substitute capital for other inputs, the adverse production effect dominates the substitution effect so that capital demand drops.

Starting from an arbitrary equilibrium

The welfare effects of an ecological tax reform starting from an arbitrary equilibrium can be decomposed into parts. First, in the normal case, substitution effects produce a green dividend (see final term at the RHS of (4.1)). Second, with pre-existing taxes on the polluting input, the base of the environmental taxes erodes in the normal case, implying a positive tax burden effect.

⁹ The ultimate burden of all taxes in terms of reduced real incomes is borne by labor because the supply of capital is infinitely elastic. Thus, the burden of taxation on the capital-market is reflected only in a decline of capital demand and not a drop in the after-tax return on capital. The burden in terms of reduced incomes is shifted back unto labor. In a more general model in which capital supply would be less than infinitely elastic, the burden of taxation in the capital-market would reduce not only capital demand but also the after-tax return on capital. Hence, labor and capital would share the burden of taxation in terms of lower after-tax incomes (see also section 5).

This reduces blue welfare (see first term between square brackets at the RHS of (4.1)). Third, with pre-existing taxes on capital income, a positive tax shifting effect creates the potential for an improvement in private welfare (see the second term between square brackets at the RHS of (4.1)).

In the normal case, substitution effects dominate output effects so that the demand for capital expands while the demand for the polluting input contracts. Consequently, both the tax shifting effect and the tax burden effect are positive. Blue welfare improves if the tax shifting effect is large compared to the tax burden effect so that the improvement in non-environmental efficiency of the tax system (i.e. the tax shifting effect) 'finances' the costs of enhancing environmental quality (i.e. the tax burden effect). A double-dividend requires that the initial capital tax is large compared to the initial pollution tax. Intuitively, large initial capital taxes indicate a substantial potential for non-environmental efficiency improvements while small initial pollution taxes imply that environmental improvements are relatively cheap.

A double-dividend is feasible only in the normal case, i.e. if substitution effects dominate output effects. In the exceptional case that large positive output effects cause pollution to rise, the green dividend is negative. In the other exceptional case, the blue dividend is negative as negative production effects reduce capital demand.

4.3.2 Optimal taxes

This subsection derives the optimal taxes if the government can employ only T_K and T_E to optimize welfare. The labor tax T_L is set exogenously at a level that yields insufficient revenues to meet the revenue requirement so that positive tax rates on either capital or the polluting input are required.

Optimal tax from a non-environmental point of view

By substituting the reduced-form for wages from table 4.4 into (2.3) and setting the marginal change in blue welfare equal to zero, we find the tax structure that is optimal from a non-environmental point of view

$$\frac{\theta_E}{\theta_K} = \frac{\Gamma_{KK} - \Gamma_{EK}}{\Gamma_{EE} - \Gamma_{KE}} \quad (4.11)$$

To obtain a better understanding of what determines the optimal taxes, table 4.6 presents the optimal tax structure in (4.11) for three separable production functions. It reveals that the polluting input and capital should both be taxed if these two inputs do not differ too much in the ease with which they can be substituted for labor. To illustrate, capital and the polluting input are equally good substitutes for labor if they enter the same nest of the CES production function. In that case, it is optimal to levy uniform taxes on capital and the polluting input. If capital and pollution do not enter the same nest in the CES production structure, the highest tax should be levied on the factor that is the poorest substitute for labor. Intuitively, poor substitution with the immobile factor render the demand for the factor inelastic. In accordance with the Ramsey principle of optimal taxation, inelastic demands should be taxed relatively heavy to limit tax

distortions. If substitution possibilities with labor differ substantially across the two mobile factors, the factor that is the best substitute for labor (i.e. the factor that is elastic in demand) should be subsidized. To illustrate, if, compared to capital, pollution is a much better substitute for labor, it may be optimal to subsidize, rather than tax, pollution (see table 4.6 if K is separable and σ_{EL} is much larger than σ_K).

-- insert table 4.6 here --

Optimal taxes in the presence of environmental externalities

Solving the optimal tax problem with respect to the taxes on capital and the the polluting input, we find

$$\frac{\theta_E - \frac{1}{\eta}\theta_E^p}{\theta_K} = \frac{\Gamma_{KK} - \Gamma_{EK}}{\Gamma_{EE} - \Gamma_{KE}} \quad (4.12)$$

We see that the optimal level of the pollution tax from a non-environmental point of view in (4.11) should be corrected for the social value of the external effect of pollution if environmental considerations are taken into account (see (4.12)). By using the first-order conditions in appendix A, we derive the following reduced-forms for the optimal pollution tax and the optimal capital tax

$$\theta_E = \frac{1}{\eta}\theta_E^p + \left[\left(1 - \frac{1}{\eta}\right)\frac{1}{\eta_{LL}} - T_L\right] \frac{\frac{(1 - \theta_L)w_L(\Gamma_{KK} - \Gamma_{EK})}{\Gamma_D}}{\frac{1}{\eta_{LL}} + \frac{[w_K(\Gamma_{EE} - \Gamma_{KE}) + w_E(\Gamma_{KK} - \Gamma_{EK})]}{\Gamma_D}} \quad (4.13)$$

$$\theta_K = \left[\left(1 - \frac{1}{\eta}\right)\frac{1}{\eta_{LL}} - T_L\right] \frac{\frac{(1 - \theta_L)w_L(\Gamma_{EE} - \Gamma_{KE})}{\Gamma_D}}{\frac{1}{\eta_{LL}} + \frac{[w_K(\Gamma_{EE} - \Gamma_{KE}) + w_E(\Gamma_{KK} - \Gamma_{EK})]}{\Gamma_D}} \quad (4.14)$$

where $\eta = \lambda/\mu$ is the MCPF and $\Gamma_D = \Gamma_{KK}\Gamma_{EE} - \Gamma_{EK}\Gamma_{KE}$. The optimal pollution tax in (4.13) consists of two terms: the first term at the right-hand side of (4.13) represents the role of pollution taxes in internalizing environmental externalities. Just as in (4.7), the weight that the government assigns to internalizing externalities declines with on the MCPF. If the government cannot freely use the labor tax -- which is the most efficient instrument to raise revenues -- the government may wish to employ pollution taxes as a revenue-raising device. The second term at the right-hand side of (4.13) reflects the revenue-raising task of pollution taxes. In particular, this term is zero if the labor tax is at its optimal level as is indicated by the term between square brackets at the RHS of

(4.13). Indeed, the optimal pollution tax would then correspond to its level in the optimal tax system of section 4.1 (compare (4.3) and (4.4)). However, if the initial labor tax is below its optimal level, the term between square brackets is positive. In that case, labor taxes do not raise sufficient revenues so that pollution and capital taxes are necessary to meet revenue requirements. The optimal pollution tax may thus exceed the Pigovian level. In accordance with Ramsey principles, pollution should be taxed relatively heavy if, compared to capital, pollution is inelastic in demand.¹⁰

5. Environmental taxation and fixed capital

This section extends the benchmark model by including fixed capital in the production function. Whereas section 4 discusses the extreme case in which capital is supplied with infinite elasticity, this section thus explores another extreme case, namely, in which capital is supplied inelastically. The factor demand equations for labor and polluting inputs (i.e. (II.2) and (II.3)) are expressed conditional on the fixed factor, rather than on employment. To obtain more insight into the price elasticities in these factor demand equations, table 5.1 presents them for three separable production functions. Comparing this table with the elasticities in tables 4.3 and 4.5, we find that the elasticities are equivalent. However, as the factor demand relations are expressed conditional on the fixed factor, rather than on employment, the fixed factor in table 5.1 plays the role of employment in tables 4.3 and 4.5. In view of the similarity with the demand elasticities in section 4, this section does not discuss the role of factor substitution in detail.

In the presence of a fixed factor pure profits emerge. Hence, blue welfare is no longer determined by wages only. In particular, the marginal excess burden in (2.3) reveals that the effect on blue welfare depends on both after-tax wage income and after-tax profits. Alternatively, relationship (2.1) indicates that welfare is determined by the sum of the labor-market and the environmental distortion. The capital-market distortion is absent in this section.

The rest of this section is organized as follows. First, the optimal tax structure is presented if the government is able to adjust all taxes, i.e. the labor tax, the pollution tax and the profit tax. Subsequently, in subsection 5.2 the consequences of a reform away from labor taxation are investigated. We also derive the optimal tax structure between labor and pollution taxes if the profit tax is fixed. Reforms away from profit taxation are discussed in subsection 5.3.

-- insert table 5.1 here --

5.1 Optimal tax structure

Appendix B derives the optimal tax structure if the government optimizes welfare with respect to the three tax rates, i.e. the labor tax, the pollution tax and the profit tax. If no restrictions are imposed on tax rates -- that may thus exceed 100% -- this yields the following solution

¹⁰ Expression (4.13) is similar to the optimal tax formula between in Bovenberg and Van der Ploeg (1995) if in our model $\eta_{LL} = 0$. Their model contains two inputs that are supplied with infinite elasticity (i.e. polluting resources and labor) and one fixed factor. In our model, labor plays the role of the fixed factor if it is supplied inelastically.

$$T_L = 0 \quad (5.1)$$

$$T_E = T_E^P \quad (5.2)$$

$$\eta = 1 \quad (5.3)$$

Expressions (5.1) - (5.3) reveal that the government finds it optimal from a non-environmental point of view (i.e. $T_E^P = 0$) to set both the labor tax rate and the pollution tax rate at zero. Hence, all revenues are raised by profit taxes. Intuitively, the profit tax amounts to a non-distortionary or lump-sum tax. Hence, we are in a first-best world in which the MCPF equals unity (see (5.3)). In such a first-best framework without environmental considerations it is indeed optimal to raise all revenues through lump-sum profit taxes and set distortionary taxes on labor and pollution at zero. However, in the presence of environmental externalities, the tax system not only aims at raising revenues with the least costs to private incomes but also at internalizing the external effect of pollution. In accordance with the targetting principle, this calls for a positive tax on pollution (see (5.2) with $T_E^P > 0$).¹¹

This illustrates the role of capital mobility for the optimal tax structure between labor, capital and pollution. Whereas labor taxes are the most efficient instruments from a non-environmental point of view if capital is supplied with infinite elasticity, the optimal labor tax is zero if capital is in fixed supply (compare (4.2) - (4.4) with (5.1) and (5.2)). Capital, in contrast, is typically undertaxed if it is inelastically supplied whereas it is more likely to be overtaxed in case it is mobile internationally.

5.2 Reducing labor taxes

This subsection starts from non-optimal tax systems by exploring the welfare consequences of tax reforms. In particular, we explore the consequences of a rise in pollution taxes and profit taxes if the revenues are used to reduce the labor tax, starting from several initial equilibria. Furthermore, the optimal levels of labor and pollution taxes are derived if the profit tax is fixed exogenously. Hence, a similar reform as in section 4.2 is investigated albeit that capital is supplied inelastically, rather than with infinite elasticity.

5.2.1 Tax reform

The reduced forms for employment, pollution, wages, profits and total private income (i.e. blue welfare) in case of an endogenous labor tax are given in table 5.2 (see appendix B for a derivation)

-- insert table 5.2 here --

¹¹ The optimal tax structure between labor, pollution and profit taxes can also be derived from the marginal excess burden in (2.1). In particular, the marginal excess burden is zero if (5.1) and (5.2) hold.

A rise in the profit tax

The first column of table 5.2 presents the consequences of higher profit taxes, recycled through lower labor taxes. In particular, the reduced-form coefficient in the fifth row of table 5.2 reveals that such a shift improves blue welfare. Intuitively, substituting profit taxes for labor taxes amounts to a shift from the overtaxed factor (labor) towards the undertaxed (fixed) factor (see section 5.1). Hence, the tax system moves towards the non-environmental optimum and, therefore, private welfare improves. The magnitude of the blue dividend depends on four elements. First, the profit share in output (w_Π) determines the importance of profits in total household income. If this share is large a substantial part of the tax burden can be shifted from labor unto the return on the fixed factor. Second, the initial distortionary tax rates on labor and polluting inputs (i.e. θ_L and θ_E , respectively) measure the social benefits associated with an increase in employment and pollution. Third, the sensitivity of labor demand (ϵ_{LL}) and pollution demand ($\epsilon_{LE} = (w_E/w_L)\epsilon_{EL}$) with respect to the producer price of labor determines how much labor and pollution demand actually expand due to a lower producer price of labor. Table 5.1 reveals that both employment and pollution typically increase due to a lower price of labor, especially if these inputs are good substitutes for the fixed factor.¹² Finally, the compensated wage elasticity of labor supply is important for the blue dividend. This elasticity measures the distortionary effect of labor taxes, relative to profit taxes. In particular, if labor is supplied inelastically (i.e. $\eta_{LL}^* = \eta_{LL} = \eta_L = 0$), labor taxes are non-distortionary at the margin so that a shift from labor towards profit taxation involves no efficiency improvement. However, if η_{LL}^* is large, blue welfare rises substantially as the tax that is cut (i.e. the labor tax) imposes large distortions compared to the tax that is raised (i.e. the profit tax).

A rise in the pollution tax

The consequences of higher taxes on the polluting input, recycled through lower taxes on labor, are determined by the coefficients in the second column of table 5.2. We discuss the reduced-form coefficients in this column by considering different initial equilibria.

Starting from a 100% profit tax and a zero pollution tax

If the initial pollution tax is zero ($\theta_E = 0$) while profits are fully taxed away (i.e. $T_\Pi = 1$), the fifth row of table 5.2 reveals that a shift from labor towards pollution taxes leaves private income unchanged. The reason is that the owners of the fixed factor receive zero profit income and thus cannot bear the burden of taxation. In fact, the government receives the return on the fixed factor by imposing a 100% profit tax and, therefore, bears the full burden of lower profit incomes. As a result, labor is the only source of private income that can bear the burden of taxes. This brings us to the benchmark model. In particular, the swap of pollution taxes for labor taxes boils down to substituting implicit for explicit taxes on labor income. In absence of initial pollution taxes, employment and wages do not change due to such a shift and the blue dividend is zero (see also section 3). A green dividend, however, is obtained as producers reduce their demand for polluting inputs.

¹² Pollution may fall due to a lower producer price of labor (i.e. $\epsilon_{EL} < 0$) if fixed capital is separable in production while it is a much better substitute for labor than pollution is (see table 5.1 if $\sigma_H > w_H\sigma_{LE}$).

Starting from a positive pollution tax: the tax burden effect on labor

If the initial pollution tax is positive ($\theta_E > 0$) but profits are fully taxed away (i.e. $T_\Pi = 1$), the results from the benchmark model still hold. In particular, an environmental tax reform from labor towards pollution reduces employment and wages and thus produces a negative blue dividend. Intuitively, by inducing substitution away from pollution, environmental taxes erode the pollution tax base thereby producing a tax burden effect. The magnitude of the tax burden effect depends on the the initial pollution tax (θ_E) and on the substitution possibilities between pollution and the two other inputs, determined by ϵ_D .¹³ Similar to the benchmark model, the tax burden effect is fully borne by wage incomes.

Starting from a less than 100% profit tax: the tax shifting effect

If profits are not fully taxed away by the government (i.e. $T_\Pi < 1$), blue welfare may improve due an environmental tax reform if the term Z is positive (see the reduced-form for private incomes in table 5.2). Intuitively, if $T_\Pi < 1$, labor taxes and pollution taxes are not only borne by workers but also by the owners of the fixed factor. Compared to explicit profit taxes, implicit profit taxes are less efficient instruments to tax away the rents from the fixed factor as the latter also distort the markets for polluting inputs and labor. A reshuffling between labor and pollution taxes will change the magnitudes of these latter two distortions. Hence, a tax reform may, on balance, render the tax system more efficient in its role to tax away the rents from the fixed factor. Whether this occurs depends on the term Z which contains two terms. On the one hand, the higher producer price for pollution reduces the demand for polluting inputs if $\epsilon_{EE} - \epsilon_{LE} > 0$, which is typically true.¹⁴ Accordingly, the base of the pollution tax erodes which causes a fall in private incomes if $\theta_E > 0$. We call this the tax burden effect on profits. On the other hand, a fall in the labor tax boosts labor demand if $\epsilon_{LL} - \epsilon_{EL} > 0$, i.e. if the own price effect on labor demand dominates the cross price effect.¹⁵ The rise in labor demand, however, not directly induces an actual increase in employment. Indeed, in order to clear the labor-market, the market wage rate needs to rise thereby stimulating labor supply (if $\eta_{LL}^* > 0$). An environmental tax reform thus changes the distribution of incomes in favor of workers and at the expense of capital owners (see the reduced-form coefficient for wages and profits in table 5.2 with $\theta_E = 0$).¹⁶ Accordingly, we

¹³ This elasticity is large if the fixed factor is unimportant. In particular, if w_H approaches zero (so that fixed capital is absent) ϵ_D goes to infinity (see table 5.1).

¹⁴ This term may be negative if polluting inputs are separable in production and, compared to labor, polluting inputs are a much better substitute for fixed capital (see table 5.2). We, however, rule out this possibility and assume that own price effects dominate cross price effects.

¹⁵ Table 5.1 reveals that $\epsilon_{LL} - \epsilon_{EL}$ is always positive if pollution or the fixed factor are separable. However, this term may be negative if labor is separable. In particular, it is negative if producers find it much easier to substitute pollution than labor for the fixed factor. In this section, we rule out this possibility and assume that $\epsilon_{LL} - \epsilon_{EL} > 0$.

¹⁶ The compensated, rather than the uncompensated, elasticity of labor supply is relevant for the consequences of the tax shifting effect for employment (see the first element in the reduced-form for employment in table 5.1). The reason is that the negative income effect on labor supply is offset by the fall in profits. Hence, only substitution effects matter. In case of the tax burden effect, however, the uncompensated elasticity of labor supply is relevant for employment. This is because the reduction in after-tax wages associated with the tax burden effect leaves profits unchanged (see the second element in the reduced-form for employment in table 5.1).

call this the tax shifting effect. The expansion of employment due to the tax shifting effect broadens the base of the labor tax so that public revenues increase endogenously. This allows for a further reduction in the tax rate on labor and, consequently, a rise in private incomes.

If the rise in private incomes due to the tax shifting effect dominates the fall in private incomes due to the tax burden effect on profits, an environmental tax reform succeeds in improving the efficiency in which the rents on the fixed factor are taxed away. This requires that initial labor taxes are large compared to pollution taxes and that labor demand is elastic relative to pollution.

Overall, the incidence of taxation may bear on both labor incomes and profit incomes if we start from an arbitrary equilibrium. As far as the incidence of taxes bears on labor, we find that it is more efficient from a non-environmental point of view to tax labor through explicit taxes, rather than an implicit taxes. Indeed, pollution taxes cause a tax burden effect on labor thereby reducing private incomes from work. As far as the tax incidence bears on profits, however, it is efficient to distribute the tax burden across labor and pollution. Hence, an environmental tax reform offers an opportunity to improve the efficiency of taxation if labor is overtaxed compared to pollution. In that case, private incomes increase due to a more efficient taxation of profits. If this second effect is positive and large enough to dominate the tax burden effect on workers, an environmental tax reform renders the tax systems more efficient from a non-environmental point of view. This holds if four conditions are met. First, the fixed factor should be able to bear a large part of the tax burden. Hence, this requires a small profit tax and a large share of the fixed factor in production (implying that ϵ_D is small). Second, labor taxes should be large compared to pollution taxes. Third, labor demand should be elastic relative to the pollution tax base. Finally, it is important how elastic labor supply is with respect to wages and profits, i.e. how labor-market distortions are affected by changes in incomes. In particular, if labor is supplied with infinite wage elasticity (i.e.

$\eta_{LL} \rightarrow \infty$), after-tax wages are fixed (i.e. $\tilde{W} = 0$). Hence, wage incomes cannot bear the burden of taxation and the tax burden effect on labor is zero. Blue welfare is thus solely determined by the difference between the tax shifting effect and the tax burden effect on profits (Bovenberg and Van der Ploeg, 1995, find a similar result). In contrast, if labor is supplied inelastically (i.e. $\eta_{LL} = \eta_{LL}^* = \eta_L = 0$) employment amounts to a fixed factor (i.e. $\tilde{L} = 0$).

Hence, shifting the burden of taxation from workers towards the owners of the fixed factor leaves employment unchanged so that the tax shifting effect is zero. The tax burden effect on labor due to an eroding base of the pollution tax, however, exerts a negative impact on wage incomes, thereby reducing blue welfare. Empirical evidence suggests that labor is supplied with a finite positive (compensated and uncompensated) wage elasticity and a positive income elasticity. Hence, the tax burden effect on labor incomes, the tax burden effect on profits and the tax shifting effect are all relevant for the welfare effects of an environmental tax reform. Whether a blue dividend is obtained is thus ambiguous.

These results again demonstrate the importance of capital mobility for the double-dividend hypothesis. In particular, if capital is perfectly mobile internationally an environmental tax reform

from labor towards pollution amounts to a shift away from the non-environmental optimum. Indeed, labor taxes are the more efficient instrument to raise revenues than taxes on capital or pollution. Hence, labor is typically undertaxed compared to capital and pollution. In contrast, if capital is fixed in supply it amounts to the inefficient factor rather than the efficient factor. Hence, taxing the return on fixed capital is more efficient as a revenue-raising device than taxing labor or pollution. Consequently, labor may be overtaxed, rather than undertaxed, so that a shift away from labor taxation may improve non-environmental welfare. Indeed, this section has shown that a shift from labor towards pollution taxes improves the efficiency of the tax system from a non-environmental point of view if it succeeds in shifting the tax burden from labor towards the fixed factor. This result is contrary to the previous section in which capital was perfectly mobile internationally.

5.2.2 Optimal taxes

If the government can only adjust pollution taxes and labor taxes while the profit tax is fixed exogenously, the optimal tax rates look as follows (see appendix B for a derivation)

$$\theta_L = \frac{(1 - \frac{1}{\eta}) \frac{1}{\eta_{LL}}}{1 + (1 - \frac{1}{\eta}) \frac{1}{\eta_{LL}}} \left[1 + \eta_{LL}^* \frac{(1 - T_{\Pi})(\epsilon_{EE} - \epsilon_{LE})}{\epsilon_D} \right] \quad (5.4)$$

$$\theta_E = \frac{1}{\eta} \theta_E^p + (1 - \frac{1}{\eta}) \frac{1}{\eta_{LL}} \eta_{LL}^* \frac{(1 - T_{\Pi})(\epsilon_{LL} - \epsilon_{EL})}{\epsilon_D} \quad (5.5)$$

Relation (5.5) reveals that pollution taxes are adopted for two reasons. First, to internalize environmental externalities (i.e. the first term at the RHS of (5.5)). Similar to sections 3 and 4, this term declines with the MCPF. The second reason to adopt pollution taxes is to raise revenues with the least cost to private incomes (i.e. the second term at the RHS of (5.4)). The optimal tax formulas in (5.4) and (5.5) reveal that the revenue-raising elements of labor and pollution taxes depend on the elasticities of pollution and labor demand and the elasticity of labor supply. In order to obtain some more intuition behind the optimal tax formula's we first explore two special cases, namely the case in which profits cannot bear the burden of taxation and the case in which labor is supplied with infinite elasticity.

Optimal taxes if profits cannot bear the burden of taxation

If profits would be fully taxed away through a 100% profit tax (i.e. $T_{\Pi} = 1$), the owners of the fixed factor cannot bear the burden of other taxes. This is also true if the share of the fixed factor, w_H , becomes infinitely small so that $\epsilon_D \rightarrow \infty$. Under such circumstances, the optimal tax structure would look as follows

$$T_E = \frac{1}{\eta} T_E^P \quad (5.6)$$

$$T_L = \left(1 - \frac{1}{\eta}\right) \frac{1}{\eta_{LL}} \quad (5.7)$$

Relations (5.6) and (5.7) are similar to the optimal tax formulas in the benchmark model in which the fixed factor is absent (i.e. $w_H = 0$). In particular, pollution taxes should be adopted only to internalize part of the environmental externality and not as a revenue-raising instrument (see section 3).

Optimal taxes if labor is supplied with infinite elasticity

If $\eta_{LL} \rightarrow \infty$, the optimal taxes look as follows

$$\theta_L = \left(1 - \frac{1}{\eta}\right) \frac{(1 - T_{\Pi})(\epsilon_{EE} - \epsilon_{LE})}{\epsilon_D} \quad (5.8)$$

$$\theta_E - \frac{1}{\eta} \theta_E^P = \left(1 - \frac{1}{\eta}\right) \frac{(1 - T_{\Pi})(\epsilon_{LL} - \epsilon_{EL})}{\epsilon_D} \quad (5.9)$$

In this case, the model contains two inputs which are supplied with infinite elasticity (i.e. labor and pollution) and one input that is supplied inelastically (the fixed factor). Relations (5.8) and (5.9) reveal that, for a given profit tax, the two elastic inputs should be taxed according to their demand elasticities. This result is more pronounced if we derive the optimal tax ratio from (5.8) and (5.9)¹⁷

$$\frac{\theta_E - \frac{1}{\eta} \theta_E^P}{\theta_L} = \frac{\epsilon_{LL} - \epsilon_{EL}}{\epsilon_{EE} - \epsilon_{LE}} \quad (5.10)$$

Hence, the optimal tax structure between pollution taxes and labor taxes from a non-environmental point of view (i.e. $\theta_E^P = 0$) depends on the respective demand elasticities. In particular, in

¹⁷ The optimal taxes on the two elastic factors (i.e. labor and pollution) are similar to the optimal tax structure between the two elastic factors in section 4 (i.e. capital and polluting inputs) if, in that model, labor would be supplied inelastically, i.e. $\eta_{LL} = 0$ (i.e. if labor would play the role of the fixed factor). Indeed, the optimal tax structure in (5.9) is similar to (4.12) (see also Bovenberg and Van der Ploeg, 1995).

accordance with the Ramsey principle for taxation, the government should impose the largest tax on the relatively inelastic input (compare (5.10) with (4.11)).¹⁸ In the presence of environmental externalities, the optimal pollution tax should be corrected for the social value of pollution from an environmental point of view.

Optimal taxes in a general model

In the general case, not only demand elasticities but also the elasticity of labor supply matters for optimal tax rates. This is illustrated by expressions (5.4) and (5.5). We derive for the optimal tax ratio

$$\frac{\theta_E - \frac{1}{\eta} \theta_E^p}{\theta_L} = \left[1 + \left(1 - \frac{1}{\eta}\right) \frac{1}{\eta_{LL}} \right] \frac{\frac{(1 - T_{\Pi})(\epsilon_{LL} - \epsilon_{EL})}{\epsilon_D}}{\frac{(1 - T_{\Pi})(\epsilon_{EE} - \epsilon_{LE})}{\epsilon_D} + \frac{1}{\eta_{LL}^*}} \quad (5.11)$$

Relation (5.11) indicates that the optimal tax ratio between pollution taxes (corrected for the environmental externality) and labor taxes amounts to a weighted average of supply and demand elasticities for labor and polluting inputs. In particular, the nominator of the term at the RHS of (5.11) contains the direct and indirect elasticities of pollution demand and the reciprocal of the elasticity of labor supply. The denominator contains the direct and indirect elasticities of labor demand. The reciprocal of the elasticity of pollution supply is zero because pollution is supplied infinitely elastic. Hence, this term does not enter the denominator of (5.11). The optimal tax ratio in (5.11) reveals that pollution should be taxed heavily compared to labor if labor demand and supply are elastic, relative to pollution demand and supply.

5.3 Reducing Profit Taxes

This subsection explores the consequences of a rise in labor taxes and pollution taxes if the revenues are used to cut the profit tax rate. First, we do tax reform analysis. Subsequently, we derive the optimal taxes if either labor or pollution taxes are predetermined.

5.3.1 Tax Reform

The reduced-forms for employment, pollution, wages and profits in case of an endogenous profit tax are given in table 5.3 (see appendix B for a derivation)

-- insert table 5.3 here --

If we compare the reduced-form coefficients in the second column of table 5.3 with those in first column of table 5.2, we see that a shift from labor towards profit taxes yields opposite effects as a

¹⁸ In the exceptional case that pollution increases due to an environmental tax reform (see table 5.1 if E is separable and $\sigma_E < w_E \sigma_{LH}$), it would be optimal to subsidize rather than to tax labor.

shift from profit to labor taxes. In particular, by shifting the tax burden from the undertaxed to the overtaxed factor (labor), private incomes fall. Furthermore, table 5.3 reveals that substituting pollution taxes for profit taxes also harms blue welfare. Indeed, such a tax reform also amounts to a shift from the overtaxed factor (pollution) towards the undertaxed (fixed) factor, thereby reducing both labor incomes and before-tax profit incomes.

These findings also illustrate the importance of capital mobility for the welfare consequences of environmental tax reforms from capital towards pollution. In particular, if capital would be supplied with infinite elasticity, capital taxes are distortionary. Indeed, capital may be overtaxed as the optimal tax on capital is zero (see (4.2)). Hence, a shift from capital towards pollution taxes may improve non-environmental welfare (see section 4). However, if capital is supplied inelastically it amounts to a fixed factor so that capital taxes are non-distortionary. In particular, if the tax rate is below 100%, fixed capital is undertaxed, rather than overtaxed. Hence, a shift from capital towards pollution taxes unambiguously harms blue welfare.

5.3.2 Optimal taxes

We now derive the optimal tax rates if either labor or pollution taxes are fixed. Hence, the government can only optimize welfare with respect to two tax rates.

Optimal labor tax if pollution taxes are fixed

If pollution taxes are fixed, the government may optimize the tax system with respect to labor and profit taxes. This yields for the optimal labor tax

$$T_L = - \frac{1}{\epsilon_{LL} + \epsilon_{LE}(\theta_E - \frac{1}{\eta} \theta_E^P)} \left[(\theta_E - \frac{1}{\eta} \theta_E^P) + (1 - \frac{1}{\eta}) \frac{\eta_{LL}^* + \epsilon_{LL}}{\eta_{LL}^* - \eta_{LL}} \right] \quad (5.12)$$

The optimal labor tax consists of two terms. The first term indicates the net social value of additional pollution. In particular, if the environmental tax is below the value of the external effect (i.e. $\theta_E < (1/\eta)\theta_E^P$), it is optimal to adopt labor taxes as an instrument to reduce pollution and thus to internalize the environmental externality. However, if the pollution tax is larger than the value of the environmental externality (i.e. $\theta_E > (1/\eta)\theta_E^P$), an additional unit of pollution yields a net benefit to society. Accordingly, this asks for subsidies rather than taxes on labor in order to raise pollution. The second term between square brackets at the RHS of (5.12) denotes the non-environmental distortions associated with labor taxes. In particular, if pollution taxes cause the MCPF to lie above unity (i.e. $\eta > 1$), the government should raise additional profit taxes in order to subsidize labor. The reason is that labor subsidies boost employment and pollution, thereby alleviating the non-environmental distortions associated with non-optimal pollution taxes.

Optimal taxes if the labor tax is fixed

If the labor tax would be fixed exogenously, optimizing the tax system with respect to pollution and profit taxes yields the following solution for pollution taxes

$$\theta_E = \frac{1}{\eta} \theta_E^P - \frac{1}{1+T_L} [T_L \epsilon_{LL} + (1 - \frac{1}{\eta}) \frac{\eta_{LL}^* + \epsilon_{LL}}{\eta_{LL}^* - \eta_{LL}}] \quad (5.13)$$

The first term at the RHS of (5.13) indicates that pollution taxes aim at environmental protection. In particular, if people care more about the environment (i.e. θ_E^P increases), the optimal pollution tax rises. The second term at the RHS of (5.13) indicates the role of pollution taxes as a revenue-raising instrument. It reveals that initial distortions in the tax system due to distortionary labor taxes (i.e. $T_L > 0$ and thus $\eta > 1$) call for negative pollution taxes. The reason is that pollution subsidies alleviate the labor-market distortions associated with labor taxes by reducing wages and stimulating labor supply. Whether pollution should be taxed or subsidized on balance depends on the magnitude of initial distortions. In particular, if labor-market distortions are large (i.e. T_L and η are large), the government aims less at internalizing environmental externalities so that it is likely that the optimal pollution tax is negative.

6 Conclusions

This paper shows that initial distortions in the tax system may set the scope for a double-dividend of environmental tax reforms. In particular, if the initial distribution of the tax burden is inefficient from a non-environmental point of view, redistributing the tax burden across factors may improve the efficiency of the tax system as a revenue-raising device. This is illustrated by two models in which three inputs enter the production function: labor, pollution and capital. In the first model, capital is supplied with infinite elasticity as it is mobile internationally. We find that a shift from capital towards pollution taxes may enhance non-environmental welfare if two conditions are met: initial capital taxes are large compared to pollution taxes (i.e. capital is overtaxed initially) and capital is elastic in demand relative to pollution. This latter condition requires that compared to pollution, capital is a better substitute for labor. If capital is mobile, a shift away from labor towards pollution taxes typically harms non-environmental welfare. Hence, a double-dividend can only be obtained if the revenues from pollution taxes are used to cut initial capital taxes, rather than labor taxes.

In the second model, ~~capital is supplied inelastically~~. In that case, capital is undertaxed if the tax rate is below 100%. Labor, however, may be overtaxed compared to pollution if the initial labor tax is large compared to the pollution tax and labor supply and demand elasticities are not too large. Indeed, substituting pollution taxes for labor taxes may shift the burden of taxation from labor towards the return on fixed capital, thereby enhancing non-environmental welfare. Accordingly, raising pollution taxes and recycling the revenues through reductions in the labor tax rate, rather than the capital tax, may yield a double-dividend.

These findings illustrate the importance of capital mobility for the optimal tax structure between capital, labor and pollution. Indeed, whereas the optimal tax on mobile capital is zero, fixed capital should ideally bear the full burden of taxation, possibly requiring a tax rate above 100%. Furthermore, labor taxes are efficient relative to capital taxes if capital is perfectly mobile, but inefficient if capital is fixed in supply. In reality, different types of capital are supplied with

different elasticities, most of them being between the two extreme cases of this paper. Besides, capital is likely to be supplied with a different elasticity in the long run than in the short run. Furthermore, developments such as the completion of the single European market affect the degree of capital mobility in countries of the EC. Hence, the consequences of environmental tax reforms are ambiguous and depend on the type of capital being taxed, whether the consequences in the short run or in the long run are considered, which country is investigated and how easy it is to substitute pollution and capital for labor.

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Table 2.1: The model***Firms***

Production Function

$$Y = f[H, L, E, K] \quad (I.1)$$

First-Order Conditions

$$\frac{df}{dL} = (1 + T_L) W \quad (I.2)$$

$$\frac{df}{dE} = 1 + T_E \quad (I.3)$$

$$\frac{df}{dK} = 1 + T_K \quad (I.4)$$

Profits

$$\Pi = Y - (1 + T_L)WL - (1 + T_E)E - (1 + T_K)K \quad (I.5)$$

Households

Utility Function

$$U = u[M, Q(V, C, G)] \quad (I.6)$$

Household Budget Constraint

$$WL + (1 - T_\Pi)\Pi + E^* + K^* = C \quad (I.7)$$

First-Order Conditions

$$\frac{\partial u}{\partial V} = \lambda W \quad (I.8)$$

$$\frac{\partial u}{\partial C} = \lambda \quad (I.9)$$

Labor Supply

$$L_S = 1 - V \quad (I.10)$$

Government

Government Budget Constraint

$$G = T_L WL + T_K K + T_E E + T_\Pi \Pi \quad (I.11)$$

Labor-Market Equilibrium

$$L = L_s \quad (I.12)$$

Environmental Quality

$$M = g(E) \quad (\text{I.13})$$

Walras Law: Balance of Payments

$$Y = C + G + (E - E^*) + (K - K^*) \quad (\text{I.14})$$

Endogenous: $Y, L, E, K, \Pi, V, C, L_s, W, M$, and T_L, T_K or T_Π

Exogenous: T_E, G, H, E^*, K^* and T_L, T_K or T_Π

Notation

Y = domestic output

H = fixed capital

E = polluting input demand

L = labor demand

K = demand for mobile capital

K^* = stock of domestically owned capital

E^* = domestic endowment of polluting inputs

T_L = ad-valorem tax on labor income

T_E = specific tax on pollution

T_K = ad-valorem tax on capital income

T_π = tax on pure profits

W = market wage rate

V = leisure

M = environmental quality

G = public consumption

Π = pure profits (= return on the fixed factor)

L_s = labor supply

C = private consumption

λ = marginal utility of income

Table 2.2: Linearized model

Firms

Domestic Output

$$\tilde{Y} = w_H \tilde{H} + w_E \tilde{E} + w_L \tilde{L} + w_K \tilde{K} \quad (\text{II.1})$$

Labor Demand (with a fixed factor)

$$\tilde{L} = \tilde{H} - \epsilon_{LL} (\tilde{W} + \tilde{T}_L) - \epsilon_{LE} \tilde{T}_E - \epsilon_{LK} \tilde{T}_K \quad (\text{II.2})$$

Polluting Input Demand (with a fixed factor)

$$\tilde{E} = \tilde{H} - \epsilon_{EL} (\tilde{W} + \tilde{T}_L) - \epsilon_{EE} \tilde{T}_E - \epsilon_{EK} \tilde{T}_K \quad (\text{II.3})$$

Polluting Input Demand (without a fixed factor)

$$\tilde{E} = \tilde{L} - \epsilon_{EL}^* (\tilde{W} + \tilde{T}_L) - \epsilon_{EE}^* \tilde{T}_E - \epsilon_{EK}^* \tilde{T}_K \quad (\text{II.3}')$$

Capital Demand (with a fixed factor)

$$\tilde{K} = \tilde{H} - \epsilon_{KL} (\tilde{W} + \tilde{T}_L) - \epsilon_{KE} \tilde{T}_E - \epsilon_{KK} \tilde{T}_K \quad (\text{II.4})$$

Capital Demand (without a fixed factor)

$$\tilde{K} = \tilde{L} - \epsilon_{KL}^* (\tilde{W} + \tilde{T}_L) - \epsilon_{KE}^* \tilde{T}_E - \epsilon_{KK}^* \tilde{T}_K \quad (\text{II.4}')$$

Profits

$$(1 + \theta_\Pi) w_\Pi \tilde{\Pi} = w_H \tilde{H} - w_L (\tilde{W} + \tilde{T}_L) - w_E \tilde{T}_E - w_K \tilde{T}_K \quad (\text{II.5})$$

Households

Household Budget Constraint

$$w_L (1 - \theta_L) (\tilde{L} + \tilde{W}) + w_\Pi (\tilde{\Pi} - \tilde{T}_\Pi) = w_C \tilde{C} \quad (\text{II.6})$$

Labor Supply

$$\tilde{L}_S = \eta_{LL} \tilde{W} - \eta_L \frac{w_\Pi}{w_C} (\tilde{\Pi} - \tilde{T}_\Pi) \quad (\text{II.7})$$

Government

Government Budget Constraint

$$\begin{aligned} w_G \tilde{G} &= w_L \tilde{T}_L + w_K \tilde{T}_K + w_E \tilde{T}_E + w_\Pi \tilde{T}_\Pi \\ &+ \theta_\Pi w_\Pi \tilde{\Pi} + \theta_L w_L (\tilde{W} + \tilde{L}) + \theta_K w_K \tilde{K} + \theta_E w_E \tilde{E} \end{aligned} \quad (\text{II.8})$$

Labor-Market Equilibrium

$$\tilde{L}_S = \tilde{L} \quad (\text{II.9})$$

$$\tilde{M} = -\gamma \tilde{E} \quad (\text{II.10})$$

Walras Law: Balance of Payments

$$\tilde{Y} = w_C \tilde{C} + w_G \tilde{G} + w_E (1 - \theta_E) \tilde{E} + w_K (1 - \theta_K) \tilde{K} \quad (\text{II.11})$$

Endogenous:

$$\tilde{Y}, \tilde{L}, \tilde{E}, \tilde{K}, \tilde{\Pi}, \tilde{L}_S, \tilde{C}, \tilde{W}, \tilde{M} \text{ and } \tilde{T}_L, \tilde{T}_K \text{ or } \tilde{T}_{\Pi}$$

Exogenous:

$$\tilde{H}, \tilde{G}, \tilde{T}_E \text{ and } \tilde{T}_L, \tilde{T}_K \text{ or } \tilde{T}_{\Pi} \text{ and } \tilde{K}^* = \tilde{E}^* = 0$$

Parameters

ϵ_{ij} = uncompensated direct or indirect price elasticity of factor i with respect to price j ($i, j = L, E, K$) in the model with a fixed factor

ϵ_{ij}^* = uncompensated direct or indirect price elasticity of factor i with respect to price j ($i, j = L, E, K$) in the model without a fixed factor

η_{LL} = uncompensated labor supply elasticity

η_L = income elasticity of labor supply

$\eta_{LL}^* = \eta_{LL} + (1 - \theta_L)(w_L/w_C)\eta_L$ compensated labor supply elasticity

γ = elasticity that measures the effect of more polluting inputs on environmental quality

Taxes

$$\tilde{T}_E = \frac{dT_E}{1 + T_E} \quad ; \quad \tilde{T}_L = \frac{dT_L}{1 + T_L} \quad ; \quad \tilde{T}_K = \frac{dT_K}{1 + T_K} \quad ; \quad \tilde{T}_{\Pi} = \frac{dT_{\Pi}}{1 - T_{\Pi}}$$

$$\theta_L = \frac{T_L}{1 + T_L} \quad ; \quad \theta_E = \frac{T_E}{1 + T_E} \quad ; \quad \theta_K = \frac{T_K}{1 + T_K} \quad ; \quad \theta_{\Pi} = \frac{T_{\Pi}}{1 - T_{\Pi}}$$

Shares

$$w_{\Pi} = (1 - T_{\Pi})\Pi/Y$$

$$w_E = (1 + T_E)E/Y$$

$$w_C = C/Y$$

$$w_H = (1 + \theta_{\Pi})\Pi/Y$$

$$w_K = (1 + T_K)K/Y$$

$$w_L = (1 + T_L)WL/Y$$

$$w_G = G/Y$$

Relations between shares

$$w_H + w_E + w_L + w_K = 1 \quad (\text{S1})$$

$$w_H = (1 + \theta_{\Pi})w_{\Pi} = 1 - w_L - w_E - w_K \quad (\text{S2})$$

$$(1 - \theta_L)w_L + w_{\Pi} = w_C \quad (\text{S3})$$

$$w_G = \theta_L w_L + \theta_E w_E + \theta_K w_K + \theta_{\Pi} w_{\Pi} \quad (\text{S4})$$

$$1 = w_C + w_G + w_E(1 - \theta_E) + w_K(1 - \theta_K) \quad (\text{S5})$$

Table 3.1: Reduced-form coefficients for the pollution tax in the benchmark model

	\tilde{T}_E
$\Delta \tilde{W}$	$-w_E \theta_E \frac{\sigma_L}{w_L}$
$\Delta \tilde{L}$	$-\theta_E w_E \eta_{LL} \frac{\sigma_L}{w_L}$
$\Delta \tilde{E}$	$-[\Delta + \theta_E w_E \eta_{LL}] \frac{\sigma_L}{w_L}$
$\Delta \tilde{Y}$	$-[\Delta + \theta_E \eta_{LL}] w_E \frac{\sigma_L}{w_L} \varpi$

$$\Delta \equiv (1 - \theta_L) w_L - \eta_{LL} [\theta_L w_L + \theta_E w_E] > 0$$

Table 4.1: Price elasticities of factor demands (conditional on employment) in the model with mobile capital

	$Y = F[q(L,K),E]$	$Y = F[q(E,K),L]$	$Y = F[q(L,E),K]$
ϵ_{EL}^*	$-\frac{w_K \sigma_{LK} + w_L \sigma_E}{1 - w_E}$	$-\sigma_L$	$-\sigma_{EL}$
ϵ_{EE}^*	$(1 - w_E) \sigma_E$	$\frac{w_K \sigma_{EK} + w_E \sigma_L}{1 - w_L}$	σ_{EL}
ϵ_{EK}^*	$\frac{w_K (\sigma_{LK} - \sigma_E)}{1 - w_E}$	$\frac{w_K (\sigma_L - \sigma_{EK})}{1 - w_L}$	0
ϵ_{KL}^*	$-\sigma_{LK}$	$-\sigma_L$	$-\frac{w_E \sigma_{EL} + w_L \sigma_K}{1 - w_K}$
ϵ_{KE}^*	0	$\frac{w_E (\sigma_L - \sigma_{EK})}{1 - w_L}$	$\frac{w_E (\sigma_{EL} - \sigma_K)}{1 - w_K}$
ϵ_{KK}^*	σ_{LK}	$\frac{w_E \sigma_{EK} + w_K \sigma_L}{1 - w_L}$	σ_K

Table 4.2: Reduced-form coefficients for the pollution tax and the capital tax in the model with mobile capital and an endogenous labor tax.

	\tilde{T}_E	\tilde{T}_K
$\Delta_L \tilde{W}$	$- [\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}] w_E$	$- [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_K$
$\Delta_L \tilde{L}$	$- [\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}] w_E \eta_{LL}$	$- [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_K \eta_{LL}$
$\Delta_L \tilde{E}$	$- [\Gamma_{EE} \Delta_L + (\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}) w_E \eta_{LL}]$	$- [\Delta_L \Gamma_{EK} + (\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}) w_K \eta_{LL}]$
$\Delta_L \tilde{K}$	$- [\Gamma_{KE} \Delta_L + (\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}) w_E \eta_{LL}]$	$- [\Delta_L \Gamma_{KK} + (\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}) w_K \eta_{LL}]$
$\Delta_L \tilde{Y}$	$- [(\Delta_L + \theta_E \eta_{LL}) \Gamma_{EE} + (\Delta_L + \theta_K \eta_{LL}) \Gamma_{EK}]$	$- [(\Delta_L + \theta_E \eta_{LL}) \Gamma_{KE} + (\Delta_L + \theta_K \eta_{LL}) \Gamma_{KK}]$

$$\Delta_L \equiv (1 - \theta_L)w_L - \eta_{LL} [\theta_L w_L + \theta_E w_E + \theta_K w_K] > 0$$

$$\tilde{\Gamma}_{EE} = \epsilon_{EE}^* - \frac{w_E}{w_L} \epsilon_{EL}^* \quad ; \quad \Gamma_{KE} = \epsilon_{KE}^* - \frac{w_E}{w_L} \epsilon_{KL}^*$$

$$\Gamma_{EK} = \epsilon_{EK}^* - \frac{w_K}{w_L} \epsilon_{EL}^* \quad ; \quad \Gamma_{KK} = \epsilon_{KK}^* - \frac{w_K}{w_L} \epsilon_{KL}^*$$

$$where \quad w_E \Gamma_{EK} = w_K \Gamma_{KE}$$

Table 4.3: General Equilibrium Price Elasticities of factor demands (conditional on employment) of a higher price of the polluting input (or capital) and a lower price of labor

		$Y=F[q(L,K),E]$	$Y=F[q(E,K),L]$	$Y=F[q(L,E),K]$
Γ_{EE}	substitution effect	σ_E	$\frac{w_E\sigma_L + w_K\sigma_{EK}}{1 - w_L}$	σ_{EL}
	output effect	$\frac{w_E}{w_L} \frac{w_K\sigma_{LK} + w_L\sigma_E}{1 - w_E}$	$\frac{w_E}{w_L} \sigma_L$	$\frac{w_E}{w_L} \sigma_{EL}$
	overall effect	$\frac{w_L \sigma_E + w_E w_K \sigma_{LK}}{w_L (1 - w_E)}$	$\frac{w_E \sigma_L + w_L w_K \sigma_{EK}}{w_L (1 - w_L)}$	$\frac{(1 - w_K) \sigma_{EL}}{w_L}$
Γ_{KE}	substitution effect	$-\frac{w_E(\sigma_E - \sigma_{LK})}{1 - w_E}$	$-\frac{w_E(\sigma_{EK} - \sigma_L)}{1 - w_L}$	0
	output effect	$\frac{w_E}{w_L} \frac{w_K\sigma_{LK} + w_L\sigma_E}{1 - w_E}$	$\frac{w_E}{w_L} \sigma_L$	$\frac{w_E}{w_L} \sigma_{EL}$
	overall effect	$\frac{w_E}{w_L} \sigma_{LK}$	$\frac{w_E}{w_L} \frac{\sigma_L - w_L \sigma_{EK}}{1 - w_L}$	$\frac{w_E}{w_L} \sigma_{EL}$
overall effects				
Γ_{EK}	σ	$\frac{w_K}{w_L} \sigma_{LK}$	$\frac{w_K}{w_L} \frac{\sigma_L - w_L \sigma_{EK}}{1 - w_L}$	$\frac{w_K}{w_L} \sigma_{EL}$
Γ_{KK}		$\frac{(1 - w_E) \sigma_{LK}}{w_L}$	$\frac{w_K \sigma_L + w_L w_E \sigma_{EK}}{w_L (1 - w_L)}$	$\frac{w_L \sigma_K + w_K w_E \sigma_{EL}}{w_L (1 - w_K)}$

Table 4.4: Reduced-form coefficients for the pollution tax and the labor tax in the model with mobile capital and an endogenous capital tax.

	\tilde{T}_E	\tilde{T}_L
$\Delta_K \tilde{W}$	$- [\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E$	$+ [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L$
$\Delta_K \tilde{L}$	$- [\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E \eta_{LL}$	$+ [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \eta_{LL}$
$\Delta_K \tilde{E}$	$-(\Gamma_{EE} - \Gamma_{KE}) \Delta_K$ $- [\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E \eta_{LL}$	$+ [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \eta_{LL}$
$\Delta_K \tilde{K}$	$\frac{w_E}{w_K} (\Gamma_{KK} - \Gamma_{EK}) \Delta_K$ $- [\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E \eta_{LL}$	$+ [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \eta_{LL}$
$\Delta_K \tilde{Y}$	$-(\Delta_K + \theta_E \eta_{LL})(\Gamma_{EE} - \Gamma_{KE}) w_E$ $+ (\Delta_K + \theta_K \eta_{LL})(\Gamma_{KK} - \Gamma_{EK}) w_E$	$+(\Delta_K + \theta_E \eta_{LL}) w_L \Gamma_{KE}$ $+(\Delta_K + \theta_K \eta_{LL}) w_L \Gamma_{KK}$

↳

$$\Delta_K \equiv [(1 - \theta_L)w_L - \theta_E w_L \Gamma_{KE} - \theta_K w_L \Gamma_{KK}] - \eta_{LL} [\theta_L w_L + \theta_E w_E + \theta_K w_K]$$

Table 4.5: General Equilibrium Price Elasticities of factor demands (conditional on employment) of a higher price of the polluting input and a lower price of capital

		$Y=F[q(L,K),E]$	$Y=F[q(E,K),L]$	$Y=F[q(L,E),K]$
$\Gamma_{EE} - \Gamma_{KE}$	substitution effect	σ_E	σ_{EK}	$\frac{w_L \sigma_{EL} + w_E \sigma_K}{1 - w_K}$
	output effect	$-\frac{w_E(\sigma_{LK} - \sigma_E)}{1 - w_E}$	0	$-\frac{w_E(\sigma_K - \sigma_{EL})}{1 - w_K}$
	overall effect	$\frac{\sigma_E - w_E \sigma_{LK}}{1 - w_E}$	σ_{EK}	σ_{EL}
$\Gamma_{KK} - \Gamma_{EK}$	substitution effect	$\frac{w_E w_L \sigma_{LK} + w_K \sigma_E}{w_K (1 - w_E)}$	$\frac{w_E}{w_K} \sigma_{EK}$	$\frac{w_E}{w_K} \sigma_K$
	output effect	$\frac{w_E(\sigma_{LK} - \sigma_E)}{1 - w_E}$	0	$\frac{w_E(\sigma_K - \sigma_{EL})}{1 - w_K}$
	overall effect	$\frac{w_E}{w_K} \sigma_{LK}$	$\frac{w_E}{w_K} \sigma_{EK}$	$\frac{w_E}{w_K} \frac{\sigma_K - w_K \sigma_{EL}}{1 - w_K}$

Table 4.6: Optimal tax structure between pollution taxes and capital taxes (with a fixed labor tax) from a non-environmental point of view in the model with mobile capital.

$Y = F[q(L,K),E]$	$Y = F[q(E,K),L]$	$Y = F[q(L,E),K]$
$\frac{\theta_K}{\theta_E} = 1 - \frac{\sigma_{LK} - \sigma_E}{(1 - w_E) \sigma_{LK}}$	$\theta_E = \theta_K$	$\frac{\theta_E}{\theta_K} = 1 - \frac{\sigma_{EL} - \sigma_K}{\sigma_{EL}(1 - w_K)}$

Table 5.1: Price Elasticities of factor demands in the model with fixed capital under different separability assumptions.

	$Y = F[q(L,H),E]$	$Y = F[q(E,H),L]$	$Y = F[q(L,E),H]$
ϵ_{LL}	$\frac{\sigma_{LH}(1 - w_E)}{w_H}$	$\frac{\sigma_L + \sigma_{EH}w_Lw_E/w_H}{1 - w_L}$	$\frac{w_L\sigma_H/w_H + w_E\sigma_{LE}}{1 - w_H}$
ϵ_{LE}	$\frac{w_E\sigma_{LH}}{w_H}$	$\frac{w_E\sigma_{EH}}{w_H}$	$\frac{w_E(\sigma_H/w_H - \sigma_{LE})}{1 - w_H}$
ϵ_{EE}	$\frac{\sigma_E + \sigma_{LH}w_Lw_E/w_H}{1 - w_E}$	$\frac{(1 - w_L)\sigma_{EH}}{w_H}$	$\frac{w_E\sigma_H/w_H + w_L\sigma_{LE}}{1 - w_H}$
ϵ_{EL}	$\frac{w_L\sigma_{LH}}{w_H}$	$\frac{w_L\sigma_{EH}}{w_H}$	$\frac{w_L(\sigma_H/w_H - \sigma_{LE})}{1 - w_H}$
$\epsilon_{LL} - \epsilon_{EL}$	σ_{LH}	$\frac{\sigma_L - w_L\sigma_{EH}}{1 - w_L}$	σ_{LE}
$\epsilon_{EE} - \epsilon_{LE}$	$\frac{\sigma_E - w_E\sigma_{LH}}{1 - w_E}$	σ_{EH}	σ_{LE}
ϵ_D	$\frac{\sigma_{LH}\sigma_E}{w_H}$	$\frac{\sigma_L\sigma_{EH}}{w_H}$	$\frac{\sigma_H\sigma_{LE}}{w_H}$

$$\epsilon_D = \epsilon_{LL}\epsilon_{EE} - \epsilon_{LE}\epsilon_{EL}$$

Table 5.2: Reduced-form coefficients for the profit tax and the pollution tax in the model with a fixed factor in which the labor tax is endogenous.

	\tilde{T}_Π	\tilde{T}_E
$\Delta_F \tilde{L}$	$w_\Pi \epsilon_{LL} \eta_{LL}^*$	$\eta_{LL}^* (1 - T_\Pi) (\epsilon_{LL} - \epsilon_{EL}) w_E$ $- \eta_{LL} \theta_E w_E \epsilon_D$
$\Delta_F \tilde{E}$	$w_\Pi \epsilon_{EL} \eta_{LL}^*$	$- \eta_{LL}^* (1 - T_\Pi) (\epsilon_{EE} - \epsilon_{LE}) w_L$ $- [1 - \theta_L - \eta_{LL} \theta_L] w_L \epsilon_D$
$\Delta_F \tilde{W}$	$+ w_\Pi \epsilon_{LL}$ $+ w_\Pi \frac{w_L}{w_C} \eta_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}]$	$+ [(1 - T_\Pi) (\epsilon_{LL} - \epsilon_{EL}) - \theta_E \epsilon_D] w_E$ $+ (1 - T_\Pi) \frac{w_L}{w_C} \eta_L Z w_E$
$\Delta_F \tilde{\Pi}$	$(1 - T_\Pi) w_L \eta_{LL}^*$	$+ \eta_{LL} (1 - T_\Pi) Z w_E w_L$ $- (1 - \theta_L) w_L (1 - T_\Pi) (\epsilon_{LL} - \epsilon_{EL}) w_E$
$\Delta_F [(1 - \theta_L) w_L \tilde{W} + w_\Pi (\tilde{\Pi} - \tilde{T}_\Pi)]$ Total Private Income = <i>blue welfare</i>	$+ \eta_{LL}^* w_L (\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}) w_\Pi$	$- (1 - \theta_L) w_L \theta_E w_E \epsilon_D$ $+ \eta_{LL}^* (1 - T_\Pi) Z w_E w_L$

$$\Delta_F = \eta_{LL}^* (1 - T_\Pi) w_L - \eta_{LL} w_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}] + (1 - \theta_L) w_L \epsilon_{LL}$$

$$\epsilon_D = \epsilon_{LL} \epsilon_{EE} - \epsilon_{LE} \epsilon_{EL}$$

$$\eta_{LL}^* = \eta_{LL} + \eta_L (1 - \theta_L) \frac{w_L}{w_C}$$

$$Z = \theta_L (\epsilon_{LL} - \epsilon_{EL}) - \theta_E (\epsilon_{EE} - \epsilon_{LE})$$

Table 5.3: Reduced-form coefficients for the profit tax and the pollution tax in the model with a fixed factor in which the profit tax is endogenous.

	\tilde{T}_E	\tilde{T}_L
$\Delta_H \tilde{L}$	$-[\eta_{LL}^* \epsilon_{LE} - \frac{w_E}{w_C} \eta_L \theta_E \epsilon_D]$	$-\epsilon_{LL} \eta_{LL}^*$
$\Delta_H \tilde{E}$	$-[\eta_{LL}^* \epsilon_{EE} + (1 - \frac{w_L}{w_C} \eta_L \theta_E) \epsilon_D]$	$-\epsilon_{EL} \eta_{LL}^*$
$\Delta_H \tilde{W}$	$-[\epsilon_{LE} + \frac{w_E}{w_C} \eta_L (\theta_L \epsilon_{EL} + \theta_E \epsilon_{EE})]$	$-\left[\epsilon_{LL} + \frac{w_L}{w_C} \eta_L (\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE})\right]$
$\Delta_H w_\Pi \tilde{\Pi}$	$-\frac{w_L}{w_C} \eta_L (1 - T_\Pi) Z$ $-w_E (1 - T_\Pi) [\eta_{LL}^* + \epsilon_{LL} - \epsilon_{LE}]$	$-(1 - T_\Pi) w_L \eta_{LL}^*$

$$\Delta_H = \eta_{LL}^* + \epsilon_{LL} + \frac{w_L}{w_C} \eta_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}]$$

Appendix A: Tax Reform and Optimal Taxes in the Model with Mobile Capital

In this appendix, we solve the model from table 2.2 if fixed capital is absent. Besides, we solve the optimal tax problem. We assume that government spending and the endowments of domestic capital and polluting inputs remain fixed, i.e. $\tilde{G} = \tilde{K}^* = \tilde{E}^* = 0$.

Tax Reform

To solve the model, we substitute equation (II.1), into (II.11) to eliminate \tilde{Y}

$$w_L \tilde{L} = w_C \tilde{C} - w_E \theta_E \tilde{E} - w_K \theta_K \tilde{K} \quad (\text{A1})$$

We will express the endogenous variables at the RHS of (A1) in terms of \tilde{L} and \tilde{W} . To find \tilde{C} , we derive from (II.6) with $\tilde{T}_H = \tilde{\Pi} = 0$

$$w_C \tilde{C} = w_L (1 - \theta_L) (\tilde{W} + \tilde{L}) \quad (\text{A2})$$

To find \tilde{E} and \tilde{K} in terms of \tilde{L} and \tilde{W} , we use the factor demand relations for polluting inputs and capital from table 2.2 in case the fixed factor is absent (i.e. (II.3') and (II.4'), respectively).

Two different versions of the model will be solved in this appendix. First, we derive the reduced forms for the case that the revenues from higher pollution taxes are used to reduce \tilde{T}_L endogenously. Subsequently, we do the same for the case that the revenues are used to cut \tilde{T}_K . To eliminate the endogenous taxes from (II.3') and (II.4'), we use (II.5) from table 2.2. In absence of a fixed factor, firms earn no pure profits. Hence, the expression for profits (II.5) becomes a non-profit condition

$$0 = w_L (\tilde{W} + \tilde{T}_L) + w_E \tilde{T}_E + w_K \tilde{T}_K \quad (\text{A3})$$

Endogenous Labor Tax

If the revenues from environmental taxes are used to cut the labor tax, we substitute (A3) into (II.3') and (II.4') in order to eliminate the wage costs, $\tilde{W} + \tilde{T}_L$. This yields for polluting input demand and capital demand

$$\tilde{E} = \tilde{L} - \Gamma_{EE} \tilde{T}_E - \Gamma_{EK} \tilde{T}_K \quad (\text{A4})$$

$$\tilde{K} = \tilde{L} - \Gamma_{KE} \tilde{T}_E - \Gamma_{KK} \tilde{T}_K \quad (\text{A5})$$

where

$$\begin{aligned} \Gamma_{EE} &= \epsilon_{EE}^* - \frac{w_E}{w_L} \epsilon_{EL}^* & ; & & \Gamma_{EK} &= \epsilon_{EK}^* - \frac{w_K}{w_L} \epsilon_{EL}^* \\ \Gamma_{KE} &= \epsilon_{KE}^* - \frac{w_E}{w_L} \epsilon_{KL}^* & ; & & \Gamma_{KK} &= \epsilon_{KK}^* - \frac{w_K}{w_L} \epsilon_{KL}^* \end{aligned} \quad (\text{A6})$$

Substituting (A2), (A4) and (A5) into (A1), we find a relation between \tilde{L} , \tilde{W} , and \tilde{T}_E

$$[\theta_L w_L + \theta_E w_E + \theta_K w_K] \tilde{L} - (1 - \theta_L) w_L \tilde{W} = [\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}] w_E \tilde{T}_E + [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_K \tilde{T}_K \quad (\text{A7})$$

where we used $w_K \Gamma_{KE} = w_E \Gamma_{EK}$. The relation for labor supply in (II.7) (with $\tilde{T}_\Pi = \tilde{\Pi} = 0$) and (A7) form a set of two equations and two endogenous variables \tilde{L} and \tilde{W} . In matrix notation, we write them as

$$\begin{pmatrix} \theta_L w_L + \theta_E w_E + \theta_K w_K & -(1 - \theta_L) w_L \\ 1 & -\eta_{LL} \end{pmatrix} \begin{pmatrix} \tilde{L} \\ \tilde{W} \end{pmatrix} = \begin{pmatrix} (\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}) w_E & (\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}) w_K \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \tilde{T}_E \\ \tilde{T}_K \end{pmatrix} \quad (A8)$$

By inverting the matrix at the LHS of (A8), we derive

$$\Delta_L \begin{pmatrix} \tilde{L} \\ \tilde{W} \end{pmatrix} = \begin{pmatrix} -\eta_{LL} & (1 - \theta_L) w_L \\ -1 & \theta_L w_L + \theta_E w_E + \theta_K w_K \end{pmatrix} \begin{pmatrix} (\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}) w_E & (\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}) w_K \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \tilde{T}_E \\ \tilde{T}_K \end{pmatrix} \quad (A9)$$

where

$$\Delta_L = (1 - \theta_L) w_L - \eta_{LL} [\theta_L w_L + \theta_E w_E + \theta_K w_K] > 0 \quad (A10)$$

From (A9), we derive the reduced forms for employment and wages

$$\Delta_L \tilde{L} = -\eta_{LL} [\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}] w_E \tilde{T}_E - \eta_{LL} [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_K \tilde{T}_K \quad (A11)$$

$$\Delta_L \tilde{W} = -[\theta_E \Gamma_{EE} + \theta_K \Gamma_{EK}] w_E \tilde{T}_E - [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_K \tilde{T}_K \quad (A12)$$

By substitution of (A11) into (A4) and (A5), we derive the reduced forms for polluting input demand and capital demand. The reduced form for output is found by substituting (A11) and the reduced forms for polluting input and capital into (II.1).

Endogenous Capital Income Tax

If the revenues from environmental taxes are used to cut the capital income tax, rather than the labor income tax, we substitute (A3) into (II.3') and (II.4') to eliminate the capital income tax. Thus, we find for polluting input and capital demand

$$\tilde{E} = \tilde{L} - (\Gamma_{EE} - \Gamma_{KE}) \tilde{T}_E + \frac{w_L}{w_K} \Gamma_{EK} (\tilde{W} + \tilde{T}_L) \quad (A13)$$

$$\tilde{K} = \tilde{L} + \frac{w_E}{w_K} (\Gamma_{KK} - \Gamma_{EK}) \tilde{T}_E + \frac{w_L}{w_K} \Gamma_{KK} (\tilde{W} + \tilde{T}_L) \quad (A14)$$

Substituting (A13) and (A14) as well as (A2) into (A1), we find a relation between \tilde{L} , \tilde{W} , \tilde{T}_E and \tilde{T}_L

$$\begin{aligned} & [\theta_L w_L + \theta_E w_E + \theta_K w_K] \tilde{L} - [(1 - \theta_L) w_L - w_L (\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK})] \tilde{W} \\ & = [\theta_E (\Gamma_{EE} - \Gamma_{KE}) - \theta_K (\Gamma_{KK} - \Gamma_{EK})] w_E \tilde{T}_E - [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \tilde{T}_L \end{aligned} \quad (A15)$$

Combining (A15) and (II.7) and applying the method of matrix inversion, we find the following reduced forms for employment and wages

$$\Delta_K \tilde{L} = -\eta_{LL} [\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E \tilde{T}_E + \eta_{LL} [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \tilde{T}_L \quad (A16)$$

$$\Delta_K \tilde{W} = -[\theta_E(\Gamma_{EE} - \Gamma_{KE}) - \theta_K(\Gamma_{KK} - \Gamma_{EK})] w_E \tilde{T}_E + [\theta_E \Gamma_{KE} + \theta_K \Gamma_{KK}] w_L \tilde{T}_L \quad (A17)$$

where

$$\Delta_K = (1 - \theta_L) w_L - \theta_E w_L \Gamma_{KE} - \theta_K w_L \Gamma_{KK} - \eta_{LL} [\theta_L w_L + \theta_E w_E + \theta_K w_K] \quad (A18)$$

By substituting (A16) into (A13) and (A14), we arrive at the reduced forms for polluting input demand and capital demand. The solution for output is found by substituting the reduced forms for employment, polluting inputs and capital into (II.1).

Optimal Taxes

We now solve the optimal tax problem in absence of fixed capital. As we assume that the production function, $F(L, K, E)$ features CRS, we can derive from (I.3) and (I.4) the factor demand equations conditional on the level of employment (compare its linearized equivalents (A3) and (A4))

$$E = L e[1 + T_K, 1 + T_E] \quad ; \quad K = L k[1 + T_K, 1 + T_E] \quad (A19)$$

By substituting (A19) into (I.2), we can express the producer wage rate, $W^P = (1 + T_L)W$, as an implicit function of the producer prices of polluting inputs and capital

$$W^P = w[1 + T_E, 1 + T_K] \quad (A20)$$

where we derive from the non-profit condition (I.5)

$$\frac{\partial w}{\partial (1 + T_E)} = -\frac{E}{L} \quad ; \quad \frac{\partial w}{\partial (1 + T_K)} = -\frac{K}{L} \quad (A21)$$

The optimal tax problem amounts to optimizing household utility with respect to the tax rates on labor (T_L), capital (T_K) and polluting inputs (T_E), given the optimizing behavior of private firms and households and the government budget constraint (I.11). We do not optimize with respect to the amount of public goods provision, so that the government's revenue requirement is constant, $dG = 0$. Accordingly, we have the following optimization problem

$$\begin{aligned} \text{MAX}_{T_L, T_K, T_E} \quad \mathcal{L} = & V(1, W, G, M) + \mu [T_L WL + T_K K + T_E E] \end{aligned} \quad (A22)$$

where μ denotes the shadow price of public funds and V is the indirect utility function

$$\begin{aligned} V(1, W, G, M) = & \max u(C, V, G, M) \\ \text{s.t.} \quad & WL + E^* + K^* = C \end{aligned} \quad (A23)$$

where the endowments of domestic capital and polluting inputs are constant. The first-order conditions of this optimization problem are

$$\frac{\partial \mathcal{L}}{\partial T_L} = \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_L} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_L} + \mu [WL + T_L L \frac{\partial W}{\partial T_L} + T_L W \frac{\partial L}{\partial T_L} + T_K \frac{\partial K}{\partial T_L} + T_E \frac{\partial E}{\partial T_L}] = 0 \quad (A24)$$

$$\frac{\partial \mathcal{L}}{\partial T_K} = \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_K} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_K} + \mu [T_L L \frac{\partial W}{\partial T_K} + T_L W \frac{\partial L}{\partial T_K} + K + T_K \frac{\partial K}{\partial T_K} + T_E \frac{\partial E}{\partial T_K}] = 0 \quad (\text{A25})$$

$$\frac{\partial \mathcal{L}}{\partial T_E} = \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_E} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_E} + \mu [T_L L \frac{\partial W}{\partial T_E} + T_L W \frac{\partial L}{\partial T_E} + T_K \frac{\partial K}{\partial T_E} + E + T_E \frac{\partial E}{\partial T_E}] = 0 \quad (\text{A26})$$

We rewrite these equations in different notation. First, using the fact that $W = W^p/(1+T_L)$, we derive

$$\frac{\partial W}{\partial T_L} = -\frac{W}{1+T_L} \quad ; \quad \frac{\partial W}{\partial T_K} = -\frac{K}{(1+T_L)L} \quad ; \quad \frac{\partial W}{\partial T_E} = -\frac{E}{(1+T_L)L} \quad (\text{A27})$$

From Roy's identity, we know

$$\frac{\partial V}{\partial W} = \lambda L \quad (\text{A28})$$

Define the following elasticities

$$\begin{aligned} \frac{\partial k}{\partial T_K} \frac{1+T_K}{k} &= -\Gamma_{KK} \quad ; \quad \frac{\partial k}{\partial T_E} \frac{1+T_E}{k} = -\Gamma_{KE} \\ \frac{\partial e}{\partial T_E} \frac{1+T_E}{e} &= -\Gamma_{EE} \quad ; \quad \frac{\partial e}{\partial T_K} \frac{1+T_K}{e} = -\Gamma_{EK} \end{aligned} \quad (\text{A29})$$

The elasticities in (A29) represent changes in the polluting input/labor ratio (E/L) and the capital/labor ratio (K/L) as a result of price changes. Hence, they are equivalent to the elasticities in (A6). By using (A19) and (A29), substituting (A27) and (A28) and dividing through by $\frac{\partial W}{\partial T_i}$ for $i = L, K, E$, respectively, we rewrite (A24) - (A26) as follows

$$[\theta_L + \theta_K \frac{w_K}{w_L} + (\theta_E - \frac{1}{\eta} \theta_E^p) \frac{w_E}{w_L}] \eta_{LL} = (1 - \theta_L)(1 - \frac{1}{\eta}) \quad (\text{A30})$$

$$[\theta_L + \theta_K \frac{w_K}{w_L} + (\theta_E - \frac{1}{\eta} \theta_E^p) \frac{w_E}{w_L}] \eta_{LL} + \theta_K \Gamma_{KK} + (\theta_E - \frac{1}{\eta} \theta_E^p) \Gamma_{KE} = (1 - \theta_L)(1 - \frac{1}{\eta}) \quad (\text{A31})$$

$$[\theta_L + \theta_K \frac{w_K}{w_L} + (\theta_E - \frac{1}{\eta} \theta_E^p) \frac{w_E}{w_L}] \eta_{LL} + \theta_K \Gamma_{EK} + (\theta_E - \frac{1}{\eta} \theta_E^p) \Gamma_{EE} = (1 - \theta_L)(1 - \frac{1}{\eta}) \quad (\text{A32})$$

where $\eta = \mu/\lambda$ denotes the marginal cost of public funds, the Pigovian tax level is defined in (C4) in appendix C and we used the fact that $w_E \Gamma_{EK} = w_K \Gamma_{KE}$. From the first-order conditions in (A30) - (A32) we can derive the optimal taxes presented in section 4. In particular, if the government cannot optimize with respect to either of the three taxes, the corresponding first-order condition does not necessarily hold so that the remaining two conditions determine the optimal taxes.

Appendix B: Tax Reform and Optimal Tax in the Model with Fixed Capital

This appendix solves the model from table 2.2 if mobile capital is absent (i.e. $w_K = 0$). Again, we assume that government spending and the endowments of domestic polluting inputs remain fixed (i.e. $dG = dE^* = 0$). First, we solve the model if the labor tax is endogenously adjusted to balance the government budget. Second, we do the same if the profit tax is endogenous. Furthermore, we solve the optimal tax problem.

Tax Reform

Endogenous Labor Tax

To solve the model, we derive three equations in terms of the three endogenous variables \tilde{L} , \tilde{W} and \tilde{T}_L and the exogenous taxes, \tilde{T}_E and \tilde{T}_Π . First, we subtract (II.11) from (II.1) to eliminate \tilde{Y}

$$w_L \tilde{L} = w_C \tilde{C} - w_E \theta_E \tilde{E} \quad (B1)$$

By substituting (II.3) and (II.6) into (B1) to eliminate \tilde{E} and \tilde{C} , respectively, we find

$$\theta_L w_L \tilde{L} = w_L (1 - \theta_L) \tilde{W} + w_\Pi (\tilde{\Pi} - \tilde{T}_\Pi) + w_E \theta_E [\epsilon_{EL} (\tilde{W} + \tilde{T}_L) + \epsilon_{EE} \tilde{T}_E] \quad (B2)$$

Profits can be eliminated by substituting (II.5) into (B2)

$$\theta_L w_L \tilde{L} = w_L (1 - \theta_L) \tilde{W} - w_\Pi \tilde{T}_\Pi - (1 - T_\Pi) [w_L (\tilde{W} + \tilde{T}_L) + w_E \tilde{T}_E] + w_E \theta_E [\epsilon_{EL} (\tilde{W} + \tilde{T}_L) + \epsilon_{EE} \tilde{T}_E] \quad (B3)$$

Second, by substituting (II.5) into (II.7), we find for labor supply

$$\tilde{L}_S = \eta_{LL} \tilde{W} + \frac{\eta_L}{w_C} (1 - T_\Pi) [w_L (\tilde{W} + \tilde{T}_L) + w_E \tilde{T}_E + (1 + \theta_\Pi) w_\Pi \tilde{T}_\Pi] \quad (B4)$$

Relations (II.3), (B3) and (B4) from three equations in terms of \tilde{L} , \tilde{W} , \tilde{T}_L , \tilde{T}_E and \tilde{T}_Π . They can be written in matrix notation as

$$\begin{pmatrix} 1 & \epsilon_{LL} & \epsilon_{LL} \\ 1 & -[\eta_{LL} + \eta_L (1 - T_\Pi) \frac{w_L}{w_C}] & -\eta_L (1 - T_\Pi) \frac{w_L}{w_C} \\ \theta_L w_L & -w_L [(1 - \theta_L) - (1 - T_\Pi) + \theta_E \epsilon_{LE}] & w_L [(1 - T_\Pi) - \theta_E \epsilon_{LE}] \end{pmatrix} \begin{pmatrix} \tilde{L} \\ \tilde{W} \\ \tilde{T}_L \end{pmatrix} = \begin{pmatrix} -\epsilon_{LE} & 0 \\ \eta_L (1 - T_\Pi) \frac{w_E}{w_C} & \eta_L \frac{w_\Pi}{w_C} \\ -(1 - T_\Pi) w_E + \theta_E w_E \epsilon_{EE} & -w_\Pi \end{pmatrix} \begin{pmatrix} \tilde{T}_E \\ \tilde{T}_\Pi \end{pmatrix} \quad (B5)$$

Applying Cramer's Rule to (B5), we find the following solutions for employment, the wage rate and the labor tax

$$\Delta_F \tilde{L} = \eta_{LL}^* (1 - T_\Pi) (\epsilon_{LL} - \epsilon_{EL}) w_E \tilde{T}_E - \eta_{LL} \theta_E w_E \epsilon_D \tilde{T}_E + w_\Pi \epsilon_{LL} \eta_{LL}^* \tilde{T}_\Pi \quad (B6)$$

$$\begin{aligned}\Delta_F \bar{W} = & [(1 - T_\Pi)(\epsilon_{LL} - \epsilon_{EL}) - \theta_E \epsilon_D] w_E \bar{T}_E + (1 - T_\Pi) \frac{w_L}{w_C} \eta_L [\theta_L(\epsilon_{LL} - \epsilon_{EL}) - \theta_E(\epsilon_{EE} - \epsilon_{LE})] w_E \bar{T}_E \\ & + w_\Pi \epsilon_{LL} \bar{T}_\Pi + w_\Pi \frac{w_L}{w_C} \eta_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}] \bar{T}_\Pi\end{aligned}\quad (B7)$$

$$\begin{aligned}\Delta_F \bar{T}_L = & -\eta_{LL} [(1 - T_\Pi) w_E - \theta_L w_L \epsilon_{LE} - \theta_E w_E \epsilon_{EE}] \bar{T}_E - [(1 - T_\Pi)(\epsilon_{LL} - \epsilon_{EL}) - \theta_E \epsilon_D] w_E \bar{T}_E \\ & - (1 - T_\Pi) \frac{w_L}{w_C} \eta_L w_E [\theta_L(\epsilon_{LL} - \epsilon_{EL}) - \theta_E(\epsilon_{EE} - \epsilon_{LE})] \bar{T}_E - (1 - \theta_L) w_L [\epsilon_{LE} + (1 - T_\Pi) \eta_L \frac{w_E}{w_C}] \bar{T}_E \\ & - w_\Pi [\eta_{LL} + \epsilon_{LL}] \bar{T}_\Pi - w_\Pi \frac{w_L}{w_C} \eta_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}] \bar{T}_\Pi\end{aligned}\quad (B8)$$

where

$$\Delta_F = \eta_{LL} [(1 - T_\Pi) w_L - \theta_L w_L \epsilon_{LL} - \theta_E w_E \epsilon_{EL}] + (1 - \theta_L) w_L [\epsilon_{LL} + (1 - T_\Pi) \eta_L \frac{w_L}{w_C}] > 0 \quad (B9)$$

$\epsilon_D = \epsilon_{LL} \epsilon_{EE} - \epsilon_{LE} \epsilon_{EL}$ and $\eta_{LL}^* = \eta_{LL} + \eta_L \frac{(1 - \theta_L) w_L}{w_Q}$ is the compensated elasticity of labor supply. The determinant in (B9) should be positive for the equilibrium to be stable. The reduced forms for pollution and profits are found by substituting (B7) and (B8) into (II.3) and (II.5), respectively.

Endogenous Profit Tax

If the profit tax would be endogenous while the labor tax is an exogenous policy variable, relations (II.3), (B3) and (B4) form three equations in the three endogenous variables \bar{L} , \bar{W} and \bar{T}_Π . Hence, they can be written in matrix notation as

$$\begin{aligned}& \begin{pmatrix} 1 & \epsilon_{LL} & 0 \\ 1 & -[\eta_{LL} + \eta_L(1 - T_\Pi) \frac{w_L}{w_C}] & -\eta_L \frac{w_\Pi}{w_C} \\ \theta_L w_L & -w_L[(1 - \theta_L) - (1 - T_\Pi) + \theta_E \epsilon_{LE}] & w_\Pi \end{pmatrix} \begin{pmatrix} \bar{L} \\ \bar{W} \\ \bar{T}_\Pi \end{pmatrix} \\ & = \begin{pmatrix} -\epsilon_{LE} & -\epsilon_{LL} \\ \eta_L(1 - T_\Pi) \frac{w_E}{w_C} & \eta_L(1 - T_\Pi) \frac{w_L}{w_C} \\ -(1 - T_\Pi) w_E + \theta_E w_E \epsilon_{EE} & -w_L[(1 - T_\Pi) - \theta_E \epsilon_{LE}] \end{pmatrix} \begin{pmatrix} \bar{T}_E \\ \bar{T}_L \end{pmatrix}\end{aligned}\quad (B10)$$

Applying Cramer's Rule to (B10), we find the following solutions for employment, wages and the profit tax rate

$$\Delta_H \bar{L} = -\epsilon_{LL} \eta_{LL}^* \bar{T}_L - [\eta_{LL}^* \epsilon_{LE} - \frac{w_E}{w_C} \eta_L \theta_E \epsilon_D] \bar{T}_E \quad (B11)$$

$$\begin{aligned}\Delta_H \bar{W} = & -[\epsilon_{LL} + \frac{w_L}{w_C} \eta_L (\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE})] \bar{T}_L \\ & - [\epsilon_{LE} + \frac{w_E}{w_C} \eta_L (\theta_L \epsilon_{EL} + \theta_E \epsilon_{EE})] \bar{T}_E\end{aligned}\quad (B12)$$

$$\begin{aligned}
\Delta_H \tilde{T}_\Pi = & -\eta_{LL} [(1 - T_\Pi)w_E - \theta_L w_L \epsilon_{LE} - \theta_E w_E \epsilon_{EE}] \tilde{T}_E - [(1 - T_\Pi)(\epsilon_{LL} - \epsilon_{EL}) - \theta_E \epsilon_D] w_E \tilde{T}_E \\
& - (1 - T_\Pi) \frac{w_L}{w_C} \eta_L w_E [\theta_L (\epsilon_{LL} - \epsilon_{EL}) - \theta_E (\epsilon_{EE} - \epsilon_{LE})] \tilde{T}_E - (1 - \theta_L) w_L [\epsilon_{LE} + (1 - T_\Pi) \eta_L \frac{w_E}{w_C}] \tilde{T}_E \\
& - \eta_{LL} [(1 - T_\Pi)w_L - \theta_L w_L \epsilon_{LL} - \theta_E w_E \epsilon_{EL}] \tilde{T}_L - (1 - \theta_L) w_L [\epsilon_{LE} + (1 - T_\Pi) \eta_L \frac{w_E}{w_C}] \tilde{T}_L
\end{aligned} \tag{B13}$$

where

$$\Delta_H = \eta_{LL} + \epsilon_{LL} + \frac{w_L}{w_C} \eta_L [\theta_L \epsilon_{LL} + \theta_E \epsilon_{LE}] > 0 \tag{B14}$$

The reduced forms for pollution and profits are found by substituting (B12) and (B13) into (II.3) and (II.5), respectively.

Optimal Tax

We now solve the optimal tax problem of the model with a fixed factor. The factor demand equations in (I.2) and (I.3) can be derived conditional on the fixed factor (compare its linearized equivalents in (II.2) - (II.3))

$$L = Hl[(1 + T_L)W, 1 + T_E] \quad ; \quad E = He[(1 + T_L)W, 1 + T_E] \tag{B15}$$

By substituting (I.1) into (I.5), we can express profits as an implicit function of the producer prices of polluting inputs and labor

$$\Pi = \pi[(1 + T_L)W, 1 + T_E] \tag{B16}$$

where we derive from the profit equation (I.5)

$$\frac{\partial \pi}{\partial (1 + T_E)} = -E \quad ; \quad \frac{\partial \pi}{\partial (1 + T_L)W} = -L \tag{B17}$$

Similar to appendix A, the optimal tax problem boils down to optimizing household utility with respect to the tax rates on labor (T_L), polluting inputs (T_E) and profits (T_Π). Hence, the government faces the following optimization problem

$$\begin{aligned} \text{MAX}_{T_L, T_E, T_\Pi} \quad \mathcal{L} = & V(1, W, G, M) + \mu [T_L WL + T_E E + T_\Pi \Pi] \end{aligned} \tag{B18}$$

where μ denotes the shadow price of public funds and V is the indirect utility function (see (A23)). The household budget constraint is given by (I.7). The first order conditions of the optimal tax problem are

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial T_L} = & \frac{\partial V}{\partial (1 - T_\Pi) \Pi} (1 - T_\Pi) \frac{\partial \Pi}{\partial T_L} + \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_L} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_L} \\
& + \mu [WL + T_L L \frac{\partial W}{\partial T_L} + T_L W \frac{\partial L}{\partial T_L} + T_E \frac{\partial E}{\partial T_L} + T_\Pi \frac{\partial \Pi}{\partial T_L}] = 0
\end{aligned} \tag{B19}$$

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial T_E} = & \frac{\partial V}{\partial (1 - T_\Pi) \Pi} (1 - T_\Pi) \frac{\partial \Pi}{\partial T_E} + \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_E} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_E} \\
& + \mu [T_L L \frac{\partial W}{\partial T_E} + T_L W \frac{\partial L}{\partial T_E} + T_E \frac{\partial E}{\partial T_E} + E + T_\Pi \frac{\partial \Pi}{\partial T_E}] = 0
\end{aligned} \tag{B20}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial T_E} &= \frac{\partial V}{\partial (1-T_\Pi)\Pi} (1-T_\Pi) \frac{\partial \Pi}{\partial T_\Pi} + \frac{\partial V}{\partial W} \frac{\partial W}{\partial T_\Pi} + \frac{\partial V}{\partial M} \frac{\partial M}{\partial E} \frac{\partial E}{\partial T_\Pi} \\ &+ \mu [T_L L \frac{\partial W}{\partial T_\Pi} + T_L W \frac{\partial L}{\partial T_\Pi} + T_E \frac{\partial E}{\partial T_\Pi} + T_\Pi \frac{\partial \Pi}{\partial T_\Pi} + \Pi] = 0 \end{aligned} \quad (B21)$$

Define the following elasticities (compare the factor demand equations in (II.3) and (II.4) and the expression for labor supply in (II.7))

$$\begin{aligned} \frac{\partial e}{\partial (1+T_E)} \frac{1+T_E}{e} &= -\epsilon_{EE} \quad ; \quad \frac{\partial e}{\partial (1+T_L)W} \frac{(1+T_L)W}{e} = -\epsilon_{EL} \\ \frac{\partial l}{\partial (1+T_E)} \frac{1+T_E}{l} &= -\epsilon_{LE} \quad ; \quad \frac{\partial l}{\partial (1+T_L)W} \frac{(1+T_E)W}{l} = -\epsilon_{LL} \\ \frac{\partial L_S}{\partial W} \frac{W}{L_S} &= \eta_{LL} \quad ; \quad \frac{\partial L_S}{\partial (1-T_\Pi)\Pi} \frac{C}{L_S} = -\eta_L \end{aligned} \quad (B22)$$

Labor demand is implicitly determined by (B15) while labor supply can be derived from (I.8) as a function of the relative prices of leisure and consumption and the after-tax profits (compare its linearized equivalent in (II.7))

$$L_S = l_s[W, (1-T_\Pi)\Pi] \quad (B23)$$

A change in either tax rate has an equivalent effect on both labor supply and labor demand as wages equilibrate the labor market (i.e. $\frac{dL_S}{dT_i} = \frac{dL_D}{dT_i}$). Accordingly, we derive the effect of various tax changes on the wage rate

$$\frac{\partial W}{\partial T_L} \frac{1+T_L}{W} = - \frac{\epsilon_{LL} + (1-T_\Pi) \frac{w_L}{w_C} \eta_L}{\epsilon_{LL} + \eta_{LL} + (1-T_\Pi) \frac{w_L}{w_C} \eta_L} \quad (B24)$$

$$\frac{\partial W}{\partial T_E} \frac{1+T_E}{W} = - \frac{\epsilon_{LE} + (1-T_\Pi) \frac{w_E}{w_C} \eta_L}{\epsilon_{LL} + \eta_{LL} + (1-T_\Pi) \frac{w_L}{w_C} \eta_L} \quad (B25)$$

$$\frac{\partial W}{\partial T_\Pi} \frac{1+T_\Pi}{W} = - \frac{(1-T_\Pi) \frac{w_\Pi}{w_C} \eta_L}{\epsilon_{LL} + \eta_{LL} + (1-T_\Pi) \frac{w_L}{w_C} \eta_L} \quad (B26)$$

By using the definitions in (B22), Roy's identity from (A28), and relations (B24) - (B26), we rewrite the first-order conditions in (B19) - (B21) as follows

$$\theta_L \epsilon_{LL} + (\theta_E - \frac{1}{\eta} \theta_E^p) \epsilon_{LE} = (1 - \frac{1}{\eta}) \frac{1}{\eta_{LL}} [(1-T_\Pi) \eta_{LL} + \frac{\epsilon_{LL}}{1+T_L}] \quad (B27)$$

$$\begin{aligned}
& \theta_L \epsilon_{EL} + (\theta_E - \frac{1}{\eta} \theta_E^P) [\epsilon_{EE} + \frac{\epsilon_D}{\eta_{LL}}] \\
& - (1 + T_L)(1 - T_\Pi) \frac{\eta_{LL}^* - \eta_{LL}}{\eta_{LL}} [\theta_L (\epsilon_{LL} - \epsilon_{EL}) - (\theta_E - \frac{1}{\eta} \theta_E^P) (\epsilon_{EE} - \epsilon_{LE})] \\
& = (1 - \frac{1}{\eta}) \frac{1}{\eta_{LL}} [(1 - T_\Pi)(\eta_{LL}^* + \epsilon_{LL} - \epsilon_{EL}) + \frac{\epsilon_{EL}}{1 + T_L}]
\end{aligned} \tag{B28}$$

$$\theta_L \epsilon_{LL} + (\theta_E + \frac{1}{\eta} \theta_E^P) \epsilon_{LE} = - (1 - \frac{1}{\eta}) \frac{\eta_{LL}^* + \epsilon_{LL}}{\eta_{LL} - \eta_{LL}} \frac{1}{1 + T_L} \tag{B29}$$

From (B27) - (B29), the solutions for the optimal tax rates, presented in section 5, can be derived.

Appendix C: The Marginal Excess Burden

In this appendix, we derive the marginal excess burden which is defined as the compensating variation ($d\beta$) relative to national income (Y). The compensating variation amounts to the transfer that needs to be provided to the household to keep its utility, after a policy shock, at its initial level

$$0 = - \frac{\partial u}{\partial V} dL + \frac{\partial u}{\partial M} dM + \frac{\partial u}{\partial C} dC + \frac{\partial u}{\partial G} dG \tag{C1}$$

We assume that $dG = 0$. Substituting (I.8) and (I.9) into (C1) and adding the compensating variation, we arrive at

$$0 = d\beta - W dL + (u_M / \lambda) dM + dC \tag{C2}$$

Dividing (C2) by Y and substituting the household budget constraint (II.6 to eliminate \tilde{L} and \tilde{C} , we find

$$\tilde{\beta} = - w_L (1 - \theta_L) \tilde{W} - w_\Pi (\tilde{\Pi} - \tilde{T}_\Pi) + \theta_E^P w_E \tilde{E} \tag{C3}$$

where

$$\theta_E^P = \frac{1}{1 + T_E} \frac{u_M (-M_E)}{\lambda} \tag{C4}$$

By subtracting (II.8) from (II.5) we derive:

$$w_L (1 - \theta_L) \tilde{W} + w_\Pi (\tilde{\Pi} - \tilde{T}_\Pi) = \theta_L w_L \tilde{L} + \theta_E w_E \tilde{E} + \theta_K w_K \tilde{K} \tag{C5}$$

Substituting (C5) into (C3), we arrive at the following alternative expression for the marginal excess burden

$$\tilde{\beta} = - \theta_L w_L \tilde{L} - \theta_K w_K \tilde{K} - (\theta_E - \theta_E^P) w_E \tilde{E} \tag{C6}$$

To derive expression (4.1), we substitute labor supply (II.7) into (C5) to eliminate the wage rate and use the fact that profits are zero. This yields

$$w_L(1 - \theta_L)\tilde{L} = \eta_{LL}[\theta_L w_L \tilde{L} + \theta_E w_E \tilde{E} + \theta_K w_K \tilde{K}] \quad (C7)$$

Using (C7), we can eliminate employment from the marginal excess burden in (C6). Thus, we arrive at a third expression for the marginal excess burden

$$\bar{\beta} = - \frac{1 - \theta_L}{1 - \theta_L - \theta_L \eta_{LL}} [\theta_K w_K \tilde{K} - \theta_E w_E \tilde{E}] + \theta_E^p w_E \tilde{E} \quad (C8)$$

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Workshop 1995

Environmental Policy in Open Economies

June 5-7, 1995
Waldhaus Jakob, Eichhornstrasse 84, D-78464 Konstanz

Monday, June 5, 1995

19.00 - 21.00 Welcome Reception.

Tuesday, June 6, 1995

- 9.00 - 10.00 *Opening Address:* Hans-Jürgen Vosgerau (Speaker of the SFB 178, Konstanz).
 Introduction: Bernd Genser (SFB 178, Konstanz).
- 10.00 - 10.30 Coffee Break.
- 10.30 - 12.00 James R. Markusen (University of Colorado, Boulder):
 Costly Pollution Abatement, Competitiveness, and Plant Location Decisions.
 Discussant: Klaus Conrad (University of Mannheim).
 Gunter Stephan (University of Bern):
 Laissez-Faire, International Cooperation or National Greenhouse Policy:
 A CGE Study.
 Discussant: Andreas Haufler (University of Konstanz).
- 12.00 - 14.00 Lunch Break.
- 14.00 - 15.30 Roger D. Congleton (George Mason University):
 Return to Rio, on the Politics of Environmental Treaties.
 Discussant: Hans Peter Grüner (University of Konstanz).
 Rolf Bommer (SFB 178, Konstanz):
 Endogenous Environmental Policy and Trade Liberalization - A Signaling
 Approach.
 Discussant: Ronald Jones (University of Rochester).
- 15.30 - 16.00 Coffee Break.

- 16.00 - 17.30 Michael Rauscher (University of Kiel):
Protectionists, Environmentalists, and the Formation of Environmental Policy in an Open Economy.
 Discussant: John S. Chipman (University of Minnesota).
 Achim Körber (SFB 178, Konstanz):
Raising Rivals' Costs with Environmental Policy - A Lobbying Approach.
 Discussant: Hans Gersbach (University of Basel).

Wednesday, June 7, 1995

- 9.00 - 10.30 Ernst Mohr (University of Kiel, Hochschule St. Gallen):
Sustainable Development and International Distribution: Theory and Application to Rainforests as Carbon Sinks.
 Discussant: Carsten Schmidt (University of Konstanz).
 Sebastian Killinger (SFB 178, Konstanz):
Decentralized Internalization of International Externalities.
 Discussant: Sven Arndt (McKenna College).
- 10.30 - 11.00 Coffee Break.
- 11.00 - 12.30 Ronnie Schöb (University of München) and
 Eirik S. Amundsen (University of Bergen):
Environmental Taxes on Exhaustible Resources.
 Discussant: Günther Schulze (SFB 178, Konstanz).
 Frank Hettich (SFB 178, Konstanz):
Environmental Care and Economic Growth.
 Discussant: Lucas Bretschger (University of Zürich).
- 12.30 - 14.30 Lunch Break.
- 14.30 - 16.00 Albert Schweinberger (SFB 178, Konstanz):
Environmental and Commercial Policies in More or Less Populous Open Economies.
 Discussant: Christian Gliesmann (University of Tübingen).
 Ruud de Mooij (Ministry of Economic Affairs, The Hague) and
 Lans A. Bovenberg (University of Tilburg):
Environmental Taxation and the Double Dividend: The Role of Factor Substitution and Capital Mobility.
 Discussant: Gebhard Kirchgässner (University of St. Gallen).
- 16.00 Closing Address: Heinrich Ursprung (SFB 178, Konstanz).

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