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Green tax reforms: Understanding the double dividend hypothesis

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**Wirtschaftswissenschaftliche Fakultät
der Eberhard-Karls-Universität Tübingen**

Green Tax Reforms

Understanding the Double Dividend Hypothesis

by

ANNA RUOCCO
WOLFGANG WIEGARD



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Discussion Paper

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1 Introduction

Green tax reforms rank highly in both the scientific community and the political arena. According to environmentalists, green taxes come close to a miracle by earning a double (or even triple) dividend. They not only improve the environment – which is considered to be the first dividend – they also contribute to a reduction of the overall excess burden of the tax system – the second dividend – and, finally, may help to alleviate the unemployment problem – the third dividend. The latter two effects are attributed to the fact that revenue-neutral green tax reforms allow for a reduction of payroll taxes or other distorting taxes.

Economists, on the other hand, are trained to become sceptical if something like a free lunch is promised. Accordingly, a large number of theoretical and applied papers have been produced recently to study the double dividend hypothesis more closely. In a recent survey, Goulder (1995, p. 176) concludes that “although the evidence is mixed, numerical results tend to militate against the strong double dividend claim”. As to the theoretical literature, a recent seminal contribution is by Bovenberg and de Mooij (1994). Their main results are that green tax reforms lower employment and “typically exacerbate, rather than alleviate, pre-existing tax distortions”(p. 1085). Furthermore, green tax rates should typically be lower than the marginal social damage from pollution. Hence, prospects for a green tax reform are considered to be gloomy.

In our opinion, the scepticism implied by the Goulder and the Bovenberg/de Mooij results is not really appropriate. As to the theoretical model considered by Bovenberg and de Mooij, their model structure is far too special and restrictive to allow for any generalised conclusions. On the other hand, in most applied or numerical simulation models dealing with environmental problems the taxation part is modelled rather weakly¹. Taxation problems, however, are at the heart of the double dividend hypothesis.

Even if the literature on ecological tax reform in general and on the double dividend hypothesis in particular is booming, we feel some need to clarify the prospects for a double dividend. This can best be done in a small scale numerical simulation model. We start, however, by graphically illustrating the double dividend hypothesis in a partial equilibrium context in the next chapter. We then describe a simple environmental model for a full employment closed economy as well as a small open economy with taxes. The fourth chapter analyses a number of different tax reform packages. We numerically illustrate and economically explain the possibilities for a double dividend of green taxes. The paper concludes with some summarising remarks.

In what follows, by green (or: environmental) taxes we understand taxes which refer to environmentally damaging activities.

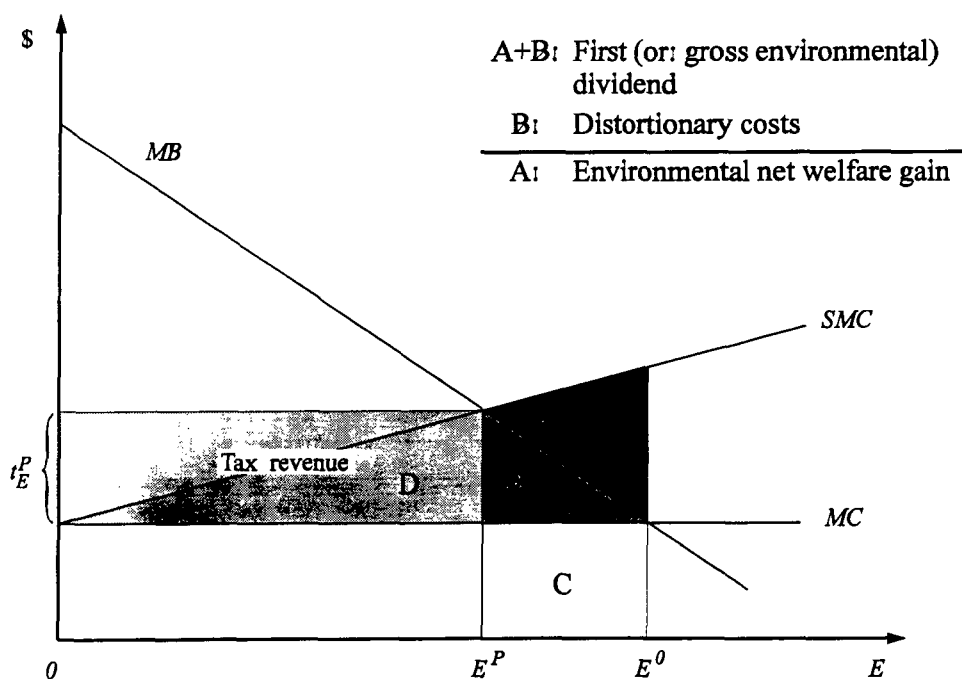
¹There are, of course, some exceptions, most notably some recent papers by Goulder (1995) and Bovenberg and Goulder (1994, 1995).

2 A partial equilibrium illustration of the double dividend hypothesis

The welfare effects of a Pigouvian tax in a first-best setting are well-known from the literature. In Figure 1, the horizontal axis depicts some environmentally damaging activity, E , which is associated with marginal benefits, MB , and private marginal costs, MC . In addition, it imposes some external costs to other parties. Adding private marginal costs and marginal external costs yields social marginal costs, SMC . For simplicity, all three curves are assumed to be linear. In the absence of any regulations or taxes, private agents will realise activity level E^0 , where private marginal benefits and costs coincide.

The welfare maximising emission level, E^P , however, is determined by the intersection of the marginal benefit curve with the social marginal cost curve.

Figure 1: Welfare effects of Pigouvian taxes in a first-best framework



Levying a Pigouvian tax at tax rate t_E^P , equal to external marginal cost at the welfare-maximising emission level E^P , guarantees that private optimising behaviour will realise the socially optimal solution. The Pigouvian tax yields a permanent revenue corresponding to the shaded rectangle D , improves the environment by area $(A + B)$, but reduces consumer surplus by area $(B + D)$. Assuming that the tax revenue is transferred costlessly back to the private sector, the triangle B represents the distortionary effects of the Pigouvian

tax². Defining the monetary equivalent of the environmental improvement as the first dividend of a green tax, and subtracting its distortionary costs yields the net welfare gain of environmental taxes, corresponding to triangle *A* in Figure 1. All this is standard textbook analysis.

The option of a second dividend can only arise if the initial situation before introducing the environmental tax is characterised by some prior distortions. Let us therefore start from a benchmark equilibrium with a distortionary income tax, as represented in Figure 2. The initial tax rate on labour income is t_w^o , the associated tax revenue is given by $(t_w^o w^o L^o)^3$ or area $(a + f + d)$ and the initial excess burden corresponds to the Harberger triangle $(c + e + b + g)$. Assume now that an environmental tax at rate t_E^P is introduced (as represented in Figure 1) and its revenue is used to reduce the tax rate on labour income. For simplicity's sake the labour market and emission activities are assumed to be completely unrelated. Figure 2 illustrates what happens on the labour market, if the tax rate is reduced from t_w^o to t_w^1 . There are welfare as well as tax revenue effects. Whereas the revenue from labour income taxation decreases by $(t_w^1 w^1 L^1 - t_w^o w^o L^o)$, corresponding to area $(d + f - b)$, consumer and producer surplus increase by areas $(d + e)$ and $(f + g)$ respectively.

Table 1 summarises the revenue and welfare effects of revenue-neutral substitution of environmental taxes for labour income taxes.

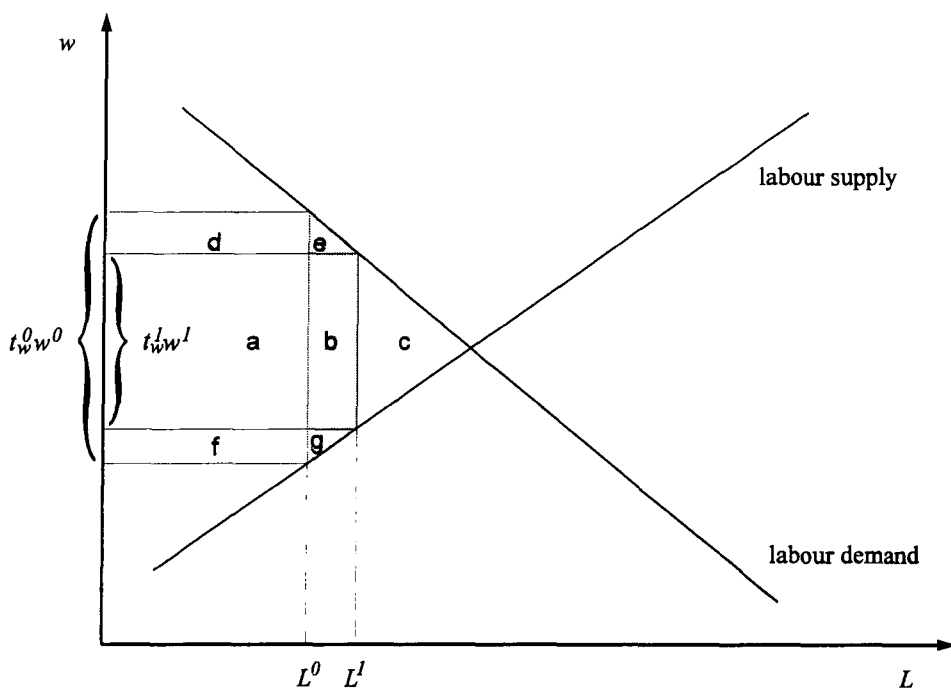
On the labour market, excess burdens are reduced by area $(e + b + g)$, whereas the introduction of environmental taxes adds distortionary costs to the tax system corresponding to triangle *B* in Figure 2. The difference is called the (strong) second dividend of green taxes (Goulder, 1995). This second dividend is positive and, hence, a double dividend occurs, whenever the welfare gain from reduced excess burdens on the labour market exceeds the distortionary costs of green taxes. Otherwise, the second dividend is negative and green taxes do not earn a double dividend. Whether or not the second dividend is positive or negative is the very heart of the double dividend discussion and will be examined more closely in a later chapter.

Separating the first from the second dividend is equivalent to separating the ecological from the public finance aspects of environmental tax swaps. Note that command and control instruments such as standards could lead to the same reduction in emissions as environmental taxes. Imposing an emission standard E^P in Figure 1 could result in exactly the same environmental net welfare gain (area *A* in Figure 1). The crucial difference is that command and control instruments do not raise any revenue and cannot contribute to a reduction of pre-existing tax distortions. Consequently, even for identical reductions in polluting activities, green taxes yield a higher total welfare gain than command and control instruments, or, to put it in other words, green taxes allow to realise a weak

²Equivalently, triangle *B* could be interpreted as abatement cost (area $B + C$) minus reduction in private costs (rectangle *C*).

³Here, w denotes the gross wage rate and L is labour demand or supply.

Figure 2: Change in excess burden on the labour market due to an environmental tax reform



second dividend when compared with ecologically equivalent but non-revenue-generating environmental instruments⁴. In our graphical illustrations this weak second dividend, which is necessarily positive, corresponds to area $(e + b + g)$ in Figure 2, the reduction in excess burdens on the labour market.

Unfortunately, matters are a little bit more complicated than our partial equilibrium illustrations suggest. The most important omission is probably the interaction between pollution activities and the labour market. Taking these interdependencies into account might even turn the total welfare gain of green tax reforms negative. On the other hand, these “tax interaction effects” are hard to grapple with in a graphical context. A simple, but complete general equilibrium model is more appropriate in order to fully understand the implications of the double dividend claim.

⁴As far as we know, the difference between the weak and strong form of a double dividend was introduced by Goulder (1995). The weak-second-dividend-claim is in sharp contrast to Zimmermann (1994, p. 35) who believes that “the revenue effect of environmental charges will more and more appear as a disadvantage”.

Table 1: Revenue and welfare effects of revenue-neutral green tax reforms

sectors → changes in ... ↓	labour market	emission sector	aggregate economy
... tax revenue	$-(d + f - b)$	D	0
... environmental quality	—	$(A + B)$	$A + B$ = first dividend
... consumer surplus	$(d + e)$	$-(D + B)$	} $(e + b + g) - B$ = (strong) second dividend
... producer surplus	$(f + g)$	—	
... net welfare	$(e + b + g)$ = weak second dividend	A = environmen- tal net wel- fare gain	$(e + b + g) + A$ = total welfare gain

3 The structure of the model

In this chapter we will extend the partial equilibrium framework to a very simple general equilibrium model. In the first section we describe a full employment closed economy model, the second section presents a small open economy model and the third one contains the numerical specifications. Our intention is to gain some insight into the double dividend hypothesis. For this, the most basic model structure seems to be more appropriate than an elaborate and empirically oriented computable general equilibrium model.

3.1 The closed economy case

Our model features five commodities: the two primary factors labour (L) and capital (K), one public good (G), one pure consumption good with X and Y as quantities consumed

and produced, and one commodity (E) which is used as a consumption good in quantity E_H as well as an intermediate factor in the production of Y (in quantity E_Y). For ease of reference we will call X (or Y) the clean commodity and E the dirty one. Sometimes, the dirty good is referred to as energy. The total production of E causes some environmental damage which is modelled as a (marginal) utility loss.

We assume a representative household with total time endowment \bar{F} and a fixed capital endowment \bar{K} . The (well-behaved) utility function is given by

$$U(X, E_H, \bar{F} - L, G, E) = u(X, E_H, \bar{F} - L, G) + v(E_H + E_Y), \quad (1)$$

with positive marginal utilities except for $\partial v/\partial E$ which is negative.

The strong separability assumption between the externality generating production of E and all other goods allows us to analytically separate the first from the second dividend of green taxes. The public good is assumed to be fixed in supply ($G = \bar{G}$) and, hence, can be omitted from the domain of the utility function.

On the production side of the economy, all three commodities are produced according to the following linear-homogenous production functions

$$E = f_E(K_E, L_E) \quad (2)$$

$$\bar{G} = f_G(K_G, L_G) \quad (3)$$

$$Y = f_Y(K_Y, L_Y, E_Y), \quad (4)$$

where the usual properties shall hold.

Adding the conditions that the use of goods or factors cannot exceed (or: are equal to) the supply:

$$Y = X \quad (5)$$

$$E = E_H + E_Y \quad (6)$$

$$\bar{K} = K_E + K_G + K_Y \quad (7)$$

$$L = L_E + L_G + L_Y, \quad (8)$$

completes the description of the production and consumption technology.

A Pareto-optimal allocation of resources is characterised by the following set of equations:

$$\frac{\partial f_E/\partial L_E}{\partial f_E/\partial K_E} = \frac{\partial f_G/\partial L_G}{\partial f_G/\partial K_G} = \frac{\partial f_Y/\partial L_Y}{\partial f_Y/\partial K_Y} \quad (9)$$

$$\frac{\partial u/\partial E_H}{\partial u/\partial X} = \frac{\partial f_Y}{\partial E_Y} \quad (10)$$

$$\frac{\partial u/\partial(\bar{F} - L)}{\partial u/\partial X} = \frac{\partial f_Y}{\partial L_Y} \quad (11)$$

$$\frac{\partial f_Y/\partial E_Y}{\partial f_Y/\partial L_Y} \left(1 + \frac{\partial v/\partial E}{\partial u/\partial E_H} \right) = \left(\frac{\partial f_E}{\partial L_E} \right)^{-1}. \quad (12)$$

These equations are self-explanatory: (9) is the necessary condition for an efficient use of labour and capital in production, (10) and (11) describe the optimal coordination of production and consumption decisions for X , $(\bar{F} - L)$ and E_H , whereas (12) is the efficiency condition for the use and production of the externality generating dirty commodity.

Let us now turn to market allocations. Commodity and factor markets are assumed to be competitive. Let w and r denote the factor prices of labor and capital net of any factor taxes; q_E, q_G, q_Y denote producer prices and p_E, p_G, p_X consumer prices of the commodities in question. The difference between producer and consumer prices is due to the following taxes:

- a uniform value added tax at tax rate t_c ,
- a labour income tax at tax rate t_w ,
- a tax on the use of capital in production at rate t_K ,
- a tax on the use of energy in the household sector at rate t_E^H ,
- a tax on the use of energy as an input at rate t_E^Y .

Any market allocation is characterised by

- the market clearing conditions (5) - (8);
- the budget constraints of all agents in the economy, which are: the representative consumer

$$p_X X + p_E E_H = w(1 - t_w)L + r\bar{K}, \quad (13)$$

the firms (zero-profit conditions)

$$q_E E = wL_E + r(1 + t_K)K_E \quad (14)$$

$$q_G \bar{G} = wL_G + r(1 + t_K)K_G \quad (15)$$

$$q_Y Y = wL_Y + r(1 + t_K)K_Y + q_E(1 + t_E^Y)E_Y, \quad (16)$$

and the government

$$\begin{aligned} q_G \bar{G} = & t_c(q_X X + q_E(1 + t_E^H)E_H) + t_w wL + t_K r(K_E + K_G + K_Y) \\ & + t_E^H q_E E_H + t_E^Y q_E E_Y \end{aligned} \quad (17)$$

- the first-order conditions

$$\frac{w}{(1+t_K)r} = \frac{\partial f_E/\partial L_E}{\partial f_E/\partial K_E} = \frac{\partial f_G/\partial L_G}{\partial f_G/\partial K_G} = \frac{\partial f_Y/\partial L_Y}{\partial f_Y/\partial K_Y} \quad (18)$$

$$\frac{q_E}{q_Y} = \frac{\partial u/\partial E_H}{\partial u/\partial X} (1+t_E^H)^{-1} = \frac{\partial f_Y}{\partial E_Y} (1+t_E^Y)^{-1} \quad (19)$$

$$\frac{w}{q_Y} = \frac{\partial u/\partial(\bar{F}-L)}{\partial u/\partial X} \frac{(1+t_c)}{(1-t_w)} = \frac{\partial f_Y}{\partial L_Y} \quad (20)$$

$$\frac{q_E}{w} = \frac{\partial f_Y/\partial E_Y}{\partial f_Y/\partial L_Y} (1+t_E^Y)^{-1} = \left(\frac{\partial f_E}{\partial L_E}\right)^{-1}. \quad (21)$$

Fixing all the tax rates except one and relating consumer and producer prices by

$$q_E(1+t_E^H)(1+t_c) = p_E; \quad q_G = p_G; \quad q_Y(1+t_c) = p_X, \quad (22)$$

yields 21 equations in the same number of variables. Due to Walras' law one budget constraint or one market clearing condition is automatically fulfilled if all other equations hold. Therefore, we can omit one equation and fix one price, say $r = 1$.

From equations (18) to (21) we can draw the following conclusions. First, the taxation of capital does not interfere with an efficient allocation of resources. In our closed economy model, capital taxes are equivalent to lump sum taxes. This, of course, is due to our assumption that domestic capital supply is fixed and equal to domestic demand. Second, a Pareto-optimal allocation (9) to (12) will be supported by a market allocation if tax rates are set at

$$t_c = t_w = 0; \quad t_E^H = t_E^Y = -\frac{\frac{\partial v/\partial E}{\partial u/\partial X}}{1 + \frac{\partial v/\partial E}{\partial u/\partial X}} \quad (23)$$

and the difference between government expenditures, $q_G\bar{G}$, and energy taxes is balanced by capital (lump-sum) taxes. As is easily checked, equations (9) to (12) and (18) to (21) coincide, if tax rates satisfy (23). Note that energy tax rates t_E^H and t_E^Y refer to tax-exclusive producer prices. Equivalently, one could define tax rates \tilde{t}_E^H and \tilde{t}_E^Y referring to tax-inclusive user prices and instead of (23) get the more familiar condition that Pigouvian tax rates fully internalise the external marginal cost from pollution, i.e.

$$\tilde{t}_E^H = \tilde{t}_E^Y = -\frac{\partial v/\partial E}{\partial u/\partial X}. \quad (24)$$

Obviously, in a first-best setting there is no room for a double dividend of green tax reforms. A necessary condition for a double dividend to occur is that some prior (tax) distortions

exist in the benchmark equilibrium before green taxes are introduced or increased. The third observation from equations (18) to (21) is on which efficiency margins the different taxes operate. A uniform value-added tax as well as the labour income tax distort the leisure-consumption choice according to (20). Green taxes, on the other hand, if levied at differentiated rates in consumption and production, distort the choice between consumption goods - equation (19) - as well as between leisure and consumption⁵. Furthermore, environmental taxes distort the intermediate input choice according to (21). These distortions may counterbalance the distortions from taxes on labour income and on value-added on the one hand, and, on the other, might be outweighed by welfare gains from correcting market failure in environmental allocation. The easiest way to deal with these problems is by performing numerical simulations.

3.2 The small open economy case

As a second model specification we will consider the case of a small open economy. This allows us to examine how the structure of optimal environmental taxes and the double dividend hypothesis depend on the model structure chosen.

In an open economy one has to distinguish between local and global environmental problems. Under the former, only the domestic economy is subject to the externality, which is due to domestic activities. As an example, one might think of road congestion, noise disturbances or local air pollution. The climate problem is the typical example for a global externality. In a small open economy, however, it is difficult to explicitly model global externalities. This is why we will confine ourselves to local externalities in this section. The advantage is that we don't have to change the utility function (1).

Because small open economy models cannot explain which goods and factors are tradable and which are not we will make the following assumptions. Throughout we assume that capital is internationally mobile whereas labour is immobile between countries. To balance the current account we consider three different cases in which only the clean commodity, only the dirty commodity or both commodities are tradable. For local externalities, the destination principle for commodity trade is the appropriate one. As to the taxation of capital income, either the residence or the source principle may apply. In case of the residence principle, domestic capital supply will be taxed at the rate t_K^R . In equation (13), domestic capital income is given by $r(1 - t_K^R)\bar{K}$, whereas we have $t_K = 0$ in equations (14) to (16). There are also some obvious changes in the government budget constraint (17). In our static model, taxing capital income according to the residence principle is

⁵This follows from

$$\frac{w}{q_E} = \frac{\partial u / \partial (\bar{F} - L)}{\partial u / \partial E_H} \frac{(1 + t_E^H)(1 + t_c)}{(1 - t_w)} = \frac{\partial f_E}{\partial L_E},$$

which is implied by equations (19) - (21).

again equivalent to a lump-sum tax. Let t_K^S be the capital tax rate under the source principle. In this case equations (14) to (16) remain valid if t_K is replaced by t_K^S , the capital tax rate under the source principle. The important point to note is that capital taxation according to the source principle drives a wedge between the world interest rate and domestic marginal product of capital or, equivalently, between foreign and domestic marginal products of capital (provided source taxes are not internationally harmonised) and, hence, distorts international capital allocation.

Finally, the reader should be aware that (some of) the market clearing conditions (5) to (7) have to be replaced by the balance of payments. For example, if both the clean and the dirty good are tradable, instead of (5) to (7) we will have the equation

$$q_Y(Y - X) + q_E(E - E_H - E_Y) + r(\bar{K} - K_Y - K_G - K_E) = 0,$$

where the notation is as before. In our static context, there is no capital account and the balance of payments is equivalent to the current account. In the absence of international transfers, a possible deficit (surplus) in the trade account has to be matched by an inflow (outflow) of capital income from abroad.

3.3 Numerical specifications

In order to numerically solve the theoretical models described above, one has to specify functional forms as well as parameter values. We assume that functional forms and parameter values are the same in the closed and the small open economy case.

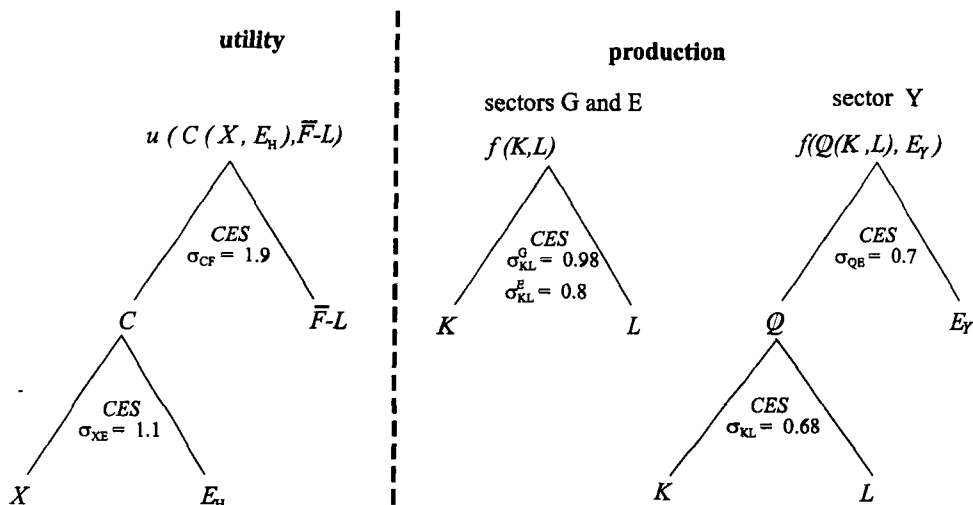
As to functional forms, we use nested constant-elasticity-of-substitution (CES) utility and production functions. The details are given in Figure 3. By σ_{ij} we denote the elasticity of substitution between the variables i and j . C is an aggregate consumption commodity and Q stands for a composite labour-capital input.

In addition, we have to specify a functional form for the environmental damage function $v(E)$. For our purposes, any function with the required properties will do and we simply assume

$$v(E) = A - \frac{\gamma}{2}E^2. \tag{25}$$

In Table A1 in the appendix we list all the parameter values which define our base case parameter set. At a later stage we will perform some sensitivity analysis to check how robust our conclusions are. Note that the only tax which is levied in the benchmark equilibrium is a labour income tax. Whereas all prices except one are endogenously determined in the closed economy model, the prices of all tradable goods are fixed (at the world market price level) in the small open economy.

Figure 3: Nested utility and production functions



In the next chapter we will consider a number of equal yield green tax reform packages by replacing or supplementing the labour income tax by environmental taxes. We characterise each tax reform package by a number $j = 1, 2, \dots$ and add a superscript to the variables in the corresponding equilibrium. The benchmark equilibrium is characterised by number 0. We use the Hicksian equivalent variation, HEV^j , to measure the welfare change from a tax program j compared with the labour income tax in the benchmark equilibrium. For nested CES utility functions the equivalent variation can be calculated as

$$\begin{aligned}
 HEV^j &= \frac{U^j - U^o}{U^o} Y^o \\
 &= \left(\frac{u^j - u^o}{u^o} Y^o \right) \frac{u^o}{U^o} + \left(\frac{v^j - v^o}{v^o} Y^o \right) \frac{v^o}{U^o},
 \end{aligned} \tag{26}$$

where Y is full disposable income, defined as $Y := w(1 - t_w)\bar{F} + r\bar{K}$.

The strong separability property of the utility function allows us to decompose the total welfare change due to a specific tax program j into a change in excess burdens and a change in environmental damage. It seems plausible to define

$$D_1^j := \left(\frac{v^j - v^o}{v^o} Y^o \right) \frac{v^o}{U^o} \quad \text{und} \quad D_2^j := \left(\frac{u^j - u^o}{u^o} Y^o \right) \frac{u^o}{U^o} \tag{27}$$

as the first and the second dividend of a green tax reform.

4 Green tax reforms: Balancing the ecological and the public finance view

In this chapter we will investigate whether or not the introduction of green taxes will increase economic welfare. Environmental taxes influence welfare through two different channels. On the one hand, they contribute to an improvement in environmental quality which is considered the first dividend. This is the ecological aspect of green tax reforms. On the other hand, green taxes will change the overall excess burdens of the tax system. This is the public finance aspect, which is summarised in the sign and level of the second dividend.

At a first glance, green tax reforms which allow for a double dividend seem to be particularly attractive policy options because they will find support from both the ecological as well as the public finance view. On second thought, however, matters are less clear. A double dividend is only a sufficient but not a necessary condition for a welfare-improving environmental tax reform. Our intention, therefore, is to clarify under which conditions a double dividend can or will occur. The answer essentially depends on the efficiency properties of the initial tax system, on the tax instruments which are available for tax reform, and, finally, on the purposes of taxation.

As a general rule, a double dividend is excluded from the outset whenever the initial tax system is first-best or second-best from a public finance point of view. In these cases, green taxes definitely introduce additional distortions and the second dividend will clearly be negative. A necessary (but not sufficient) condition for reaping a double dividend is hence that the benchmark equilibrium's tax system is third-best only or even worse. Under these conditions prospects for the second dividend becoming positive are more favourable the more tax instruments are available for reform.

In the first section of this chapter we will deal with the closed economy case and in the second one with the small open economy.

4.1 Green taxes in closed economies

Starting from an initial situation with only labour income taxes, we consider the following tax reform programs. Under the first, labour income tax may be supplemented by green taxes in consumption as well as in production (no. 1a) or in consumption only (no. 1b). The second tax reform option includes green taxes as well as a value-added tax as a supplement to or a substitute for labour income taxes. Finally, the last tax reform package includes in addition capital taxes which, in the static closed economy model, are equivalent to lump-sum taxes. These tax reform programs are listed in the head column of Table 2.

Prospects for a double dividend also depend on the purposes of taxation. To illustrate this

point we make different assumptions with respect to the information available about the environmental damage function $v(E)$. Under full information, i.e. if the environmental damage is known with certainty, the purpose of taxation is twofold. Taxes have to finance the supply of public goods and they have to correct for the externality from pollution. We assume that ecologists and taxation experts cooperate and ask what a welfare-maximising green tax reform should look like.

Full information about environmental damage is a rather heroic assumption. Generally such information is not available. For example, with respect to the global climate problem, there is not only considerable uncertainty about the link between gaseous emissions and global mean temperature, but also great uncertainty about the economic impacts of a climate change (Nordhaus, 1993). As an opposite extreme to full information we will assume that there is no information at all about environmental damage, i.e. the precise form of the $v(E)$ -function is completely unknown. The question then is what are the guidelines for tax policy under these informational constraints? What are the prospects for a green tax reform and for a double dividend? We consider three different scenarios. Under the first, only the public finance view determines tax policy; environmental considerations are completely neglected. Policy makers try to minimise excess burdens or maximise the second dividend, without caring about the first one. Even in this case, green taxes may become part of the tax system, depending on the availability of other tax instruments. If they do, a double dividend should occur. Under the next two scenarios, both, the public finance as well as the ecological view count – albeit with different weights. In one case, the public finance view dominates policy but is subject to the ecological constraint that tax reforms should not increase the environmentally damaging activity. Let us call this a “sustainable” tax reform, because the state of the environment is sustained by tax reforms. This scenario corresponds to maximising the second dividend under the condition that the first dividend is non-negative. The alternative assumption is that ecologists dominate policy but public finance people define the tax policy constraints. To make this scenario operational we assume that the policy objective is to minimise the level of environmentally damaging activities subject to the constraint that welfare does not decrease⁶ when compared with the benchmark equilibrium. This is equivalent to maximising the first dividend – whatever the precise form of the environmentally damage function $v(E)$ is – under the constraint that the second dividend is non-negative. Green tax reforms could be considered as some kind of a “no-regrets-policy”. Even if it should turn out one day that the environmental damage from emissions is negligible, green tax reforms must not be regretted (too much), because they sustained the initial welfare level.⁷ In all three scenarios optimal tax policies depend on the admissible tax instruments.

In Table 2 we combine information constraints and constraints on tax instruments and

⁶Here welfare refers to the $u(X, E_H, \bar{F} - L)$ part of the utility function only.

⁷Our definition of no-regrets policies slightly differs from the more common characterisation according to which policy makers should “do those things which reduce greenhouse gas emissions, and which are also costless ...” (Manne, 1991, p. 31).

designate a number to each tax reform program considered. For each tax reform we compute the optimal tax rates, with the objective function and the constraints being described above. Tabel A2 in the appendix contains all the necessary information. For each equilibrium we present the optimal tax rates, the first and the second dividend, as well as percentage changes of quantities as compared with the benchmark equilibrium⁸. In the following subsections we will comment on these numerical results.

⁸Our computer program, which is written in GAMS, is available upon request.

Table 2: Gallery of tax reform programs for the closed economy model

Environmental damage function Admissible tax instruments	full information	no information		
		pure public finance view ("optimal taxation")	public finance view dominates ("sustainable tax reforms")	ecological view dominates ("no-regrets tax reforms")
t_w, t_E^H, t_E^Y	1a	4a	7a	10 a
t_w, t_E^H	1b	4b	7b	10b
t_c, t_w, t_E^H, t_E^Y	2a	5a	8a	11a
t_c, t_w, t_E^H	2b	5b	8b	11b
$t_K, t_c, t_w, t_E^H, t_E^Y$	3	6	9	12

4.1.1 Optimal environmental taxes under full information

Under full information about environmental damage, the government maximises utility $u(X, E_H, \bar{F} - L) + v(E)$ when determining the optimal environmental policy. The first question to be answered is about the structure of the optimal tax system. The second one concerns the double dividend hypothesis. The answers to both questions depends on the efficiency properties of the initial tax system, on the tax instruments available for tax reform and on the purposes of taxation.

Let us start our exercise by considering tax reform program 1a, where the benchmark equilibrium's labour income tax can be supplemented by green taxes on the use of the dirty commodity in consumption as well as in production. The initial labour income tax is clearly suboptimal from an ecological point of view. Even from the public finance viewpoint, taxes on labour income are third-best only because they are dominated by lump-sum taxes as the first-best choice, and a uniform VAT as the second-best one. The (second-best) optimality of a uniform VAT follows from the weak separability and the homotheticity properties of the utility function. Hence, there is considerable room for welfare improvement and even for a double dividend.

Turning to the optimal tax structure under our first reform program, one has to be aware of the double role to be played by green taxes. Besides correcting for the externality from pollution, green taxes could also be used to partially compensate for the unnecessarily high distortions of the labour income tax. While hitting the environmental target requires a uniform tax on both uses of the dirty commodity in consumption and production, the public finance view may call for a rate differentiation. As to the latter, two opposing forces are at work. On the one hand, according to the Diamond/Mirrlees (1971) production efficiency theorem, input taxes should be zero in a second-best framework. On the other hand, if tax instruments are limited, an optimal taxation argument may call for a rate differentiation, depending on the price elasticities of demand in consumption and production. As a rule of thumb, the use of the dirty commodity which is more inelastic in demand should be taxed at a higher rate. The main determinant of the price elasticity of demand is the elasticity of substitution, a lower substitution elasticity implying a lower price elasticity. In our base case parameter set we have a rather low elasticity of substitution in production but a rather high one in consumption. This suggests that the use of the environmentally damaging commodity in production should be taxed higher than its use in consumption. This intuition is confirmed by the optimal tax rates given in the first line of Table A2. As a further check we performed some sensitivity analysis with respect to substitution elasticities in production and consumption. And indeed, if the substitution elasticity in production is higher than in consumption, the use of the dirty commodity in consumption should be taxed more heavily.

In addition to optimal tax rates, Table A2 also informs us about quantity and welfare changes of the different tax reform programs. Quantities are given as a percentage change

from their benchmark equilibrium values. Welfare changes are decomposed into the first and second dividend and are expressed as a percentage of the benchmark equilibrium's tax revenue. The total monetary welfare gain of switching from labour income taxes in the initial situation to tax reform program 1a amounts to almost 10 per cent of tax revenue. Note that both the first and the second dividend are positive and, hence, a double dividend occurs. Whereas the first dividend being positive is self-explanatory, the sign of the second dividend is less clear. It basically depends on the level of distortions caused by the labour income tax in the benchmark equilibrium. The higher the wage income tax rate, the higher the distortion and the more favourable are the prospects for a double dividend. For the base case parameter set, the initial tax rate on wage income is about 40 percent. When switching to the green tax reform program 1a, the additional distortions on commodity markets due to the introduction of green taxes are quantitatively less important than the reduction in labour market distortions from lowering the tax rate on labour income. This is why the second dividend is positive. But this result should be reversed if we start from a sufficiently low labour market distortion in the benchmark equilibrium. This is illustrated in the first line of Table A3, which contains some sensitivity analysis. We simply changed the share parameter in public good production from its initial value of 0.32 to 0.13 and 0.4, respectively. This changes the benchmark equilibrium's labour income tax rate to about 34 and 43 per cent, respectively⁹. In the first case, the initial labour market distortions are lower than in our base case which should reduce the second dividend from green tax reforms. Actually, the second dividend even becomes negative. On the other hand, when increasing the initial tax distortion in the second sensitivity run, the second dividend increases further when compared with the base case. All of this corresponds with our intuition.

In tax reform program 1b we exempt from taxation the use of the dirty commodity in production. This clearly lowers the first dividend as compared with program 1a, but it also lowers the second one. The reason is that some tax instruments which is valuable from an ecological as well as from a public finance point of view, is excluded from the Treasury's tool box. The more or less obvious lesson is that there is no need for tax exemptions in production if externalities occur within boundaries and if plant relocations are excluded. One would not, however, expect this result to remain valid in an open economy context.

In tax program numbers 2a and 2b in addition to labour income taxes, we allow for a uniform VAT as well as green taxes on the different uses of the dirty commodity. Negative tax rates, i.e. subsidies, have to be excluded. Otherwise, combining a positive VAT rate with a negative one on labour income would be equivalent to taxing capital income and,

⁹The economic explanation runs as follows. Decreasing the share parameter implies a lower capital and a higher labour demand in public good production. Because the other two industries produce more labour-intensively, there will be an excess supply on the capital market and an excess demand on the labour market. As a consequence, the gross wage rate will rise relative to the interest rate. If the uncompensated labour supply elasticity is positive, this in turn implies that the representative household will supply more labour. This extends the labour income tax base and in order to raise a given tax revenue, the labour income tax rate can be reduced.

By analogous reasoning it follows that increasing the share parameter will increase the labour tax rate.

hence, to a lump-sum tax. Remembering that a uniform VAT is second-best from a public finance view, suggests the following results. First, the second dividend and probably the total welfare gain from green tax reforms should be higher when optimal green taxes supplement uniform consumption tax rates rather than less efficient labour taxes. Second, because a uniform VAT is second-best from a public finance viewpoint, green taxes can only be justified by environmental goals, but cannot compensate for VAT distortions. Because the environmental damage depends on the aggregate consumption of the dirty commodity, the externality correcting tax rate should be the same, independent of whether it is used in final consumption or as an intermediate input in production. Third, the tax rate on labour income should be zero in the presence of a uniform VAT and if there are no restrictions on environmental tax rates. The reason is that a uniform VAT is equivalent to levying a uniform tax rate on labour income and on fixed capital income or on wealth endowment. Hence, if there are no other distortions, consumption taxation is superior to income taxation.

Tax reform program 2b once again exempts from taxation the use of the dirty commodity in production. Compared with the previous tax reform variant, the first dividend, as well as total welfare gains should decrease. The second dividend, on the other hand, should increase. From a pure public finance point of view, there is no place for input taxation in a second-best tax system. Hence, abolishing input taxes should lower overall excess burdens, or increase the second dividend. Note that if there are artificial restrictions on the use of environmental taxes, it might make sense to supplement a uniform VAT with a labour income tax. This result shows up in our sensitivity analysis in Table 3A in case of a low share parameter in public good production. In our view, however this result is too special and unimportant to deserve too much of attention.

Our final tax reform program in addition to all other taxes includes capital or lump-sum taxes as well. This allows us to realise a first-best allocation, yielding the highest total welfare gain which is possible. This, however, does not, imply that the second dividend of green tax reforms is higher under this tax reform option than under the alternative ones, nor does it imply that it will be positive. As Table 3A illustrates, the second dividend will again be negative if tax distortions on the labour market are low in the benchmark equilibrium.

4.1.2 Optimal green taxes with no information about environmental damage

In this section we will assume that environmental welfare gains from reducing emissions are highly uncertain. Policy makers are aware that polluting activities can be harmful to the environment but they do not have any reliable estimates about the welfare consequences of an improved environment. The most extreme assumption is that there is no information at all about the environmental damage function $v(E)$. What are possible guidelines for tax reform in this no-information-case? And what are the prospects for green taxes in general

and a positive second dividend in particular?

The answers depend on the relative weight on the policy process of the public finance view on the one hand and the ecological view on the other. As explained in the introduction to this chapter, the three scenarios considered are first, that only the public finance view counts, second that it dominates tax policy but is subject to ecological constraints, and, third, that the ecological view dominates tax policy.

Under the first two scenarios the policy objective function is to maximise $u(X, E_H, \bar{F} - L)$, disregarding the utility component $v(E)$. Whereas there is no additional¹⁰ constraint in the first scenario, the ecological constraint in the second scenario requires that total emissions should not exceed those in the benchmark equilibrium, i.e. $E \leq E^o$. If this constraint is binding, environmental quality will be unchanged and the first dividend is zero. The objective function under the third scenario is to minimise total emissions E , subject to the constraint that overall excess burdens of the tax system do not increase. This is equivalent to the constraint $u(X, E_H, \bar{F} - L) \leq u(X^o, E_H^o, \bar{F} - L^o)$.

In Tables A2 and A3, tax reform programs 4 to 6 describe our numerical simulation results for the first scenario under different parameter constellations. These results are readily explained. From a pure public finance view, it is clearly optimal to only employ lump-sum taxes whenever possible. If lump-sum taxes are not available, a uniform VAT is the second-best choice from an efficiency point of view, provided the utility function is weakly separable and homothetic. Green taxes should be avoided in both cases. Lines 6 and 5 in the second part of Table A2 (as well as Table A3) contain the optimal tax rates and quantity and welfare changes. Under both tax reform programs the use of the dirty commodity increases substantially from its benchmark level. The deterioration of the environment could entail considerable welfare losses, if the “true” damage function $v(E)$ were known. The corresponding numbers are included in brackets. This is a reminder that ecological considerations did not count when determining the optimal tax structure. Under tax reform programs 4a and 4b, lump-sum taxes as well as VAT are excluded, but the benchmark equilibrium’s labour income tax may be supplemented by green taxes. Because a labour income tax is third-best only, the introduction of green taxes is potentially welfare-increasing even from a pure public finance view, i.e. when environmental concerns are completely neglected. This case is referred to by Goulder (1995) as the strong double dividend claim. Policy makers do not have to worry about the exact magnitude of environmental welfare gains; green taxes should become part of an optimal tax system quite independent of environmental goals. Our numerical results illustrate that green tax rates should be differentiated. The line of reasoning is the same as above. But the rate differentiation should now be stronger simply because environmental arguments, calling for uniform rates, are no longer relevant. Comparing the relevant parts of Tables A2 and A3 makes clear that although the level of tax rates depends on parameter values, the structure

¹⁰“Additional” means additional to the usual constraints as, for example, the government budget constraint, behavioural functions etc.

of optimal taxation does not. This is hardly surprising.

In our second scenario we take into account that ecologists will oppose any tax reform that reduces environmental quality. Preserving nature or the environment is the green guiding principle which imposes a constraint on tax policy. Tax reform programs 7 to 9 describe “sustainable” tax reforms, characterised by the requirement that the aggregate use of dirty goods and, hence, pollutant emissions do not increase above its benchmark equilibrium level. Whereas tax reforms 4a and 4b are sustainable, reforms 5 and 6 are not. As a consequence, VAT or even lump-sum taxes have to be supplemented by green taxes to fulfill ecological minimum requirements. If possible, both uses of the dirty commodity, in consumption as well in production, should be subject to the same tax rates. The reason is simply that green taxes cannot contribute to improving the tax system from a public finance point of view but should be targeted to hit the environmental goal. Tables A2 and A3 illustrate that there is considerable room for tax reforms which do not harm the environment but reduce the overall excess burdens of the tax system compared with the benchmark equilibrium. The welfare gains from sustainable tax reforms are still remarkable. The D_1 -welfare differences between tax reform options 5 and 8 or 6 and 9 implicitly define the “price” for preserving the environment. At least for the parameter values underlying Tables A2 and A3, this price does not seem too high when compared with the D_1 -welfare losses which might occur under pure public finance tax reforms.

Finally, our third scenario assumes that green policies are decisive but restricted by the public finance requirement that overall excess burdens should not increase over those from the pre-reform situation. The last parts of Tables A2 and A3 contain the numerical results. A cursory glance at these tables suffices to realise that green tax rates should, of course, be higher than before, but the optimal tax structure can be explained by the previously presented arguments.

We performed a lot of sensitivity analysis with respect to single parameter values or combinations of it. Whereas the level of optimal tax rates change, the structure of optimal green tax systems basically remains unchanged. Also, all of our arguments concerning the sign of the second dividend remain valid, so that there is no need to elaborate more extensively on sensitivity analysis.

In the last chapter we will summarise the general lessons which can be drawn from all of our simulation experiments.

4.2 Green taxes in a small open economy

In a small open economy, too, optimal tax rates depend on which taxes are available for reforming the tax system and they depend on the purposes of taxation. But additionally, they also depend on which goods or factors are tradables and which are the non-tradables. In order to save space as well as the reader’s time we will elaborate on optimal (green) taxes

under the two extreme assumptions of full and of no information about the environmental damage function, but skip the sustainability and no regrets scenarios. And we will comment in greater detail only on those cases where qualitative results in the small open economy case differ from those in a closed economy. Table A4 summarises the more interesting numerical results for the three trade scenarios considered¹¹.

Let us start with the case that capital and the clean commodity are tradable. If all taxes are available, including a realised based capital tax, a first best allocation can be realised. The structure of optimal tax rates will be the same as in lines 3 and 6 of Table A2. If residence taxation of capital is excluded, but all other taxes are allowed, the optimal tax structure in the small open economy coincides with that of lines 2a and 5a in Table A2 for the closed economy, with the additional result that no source-based capital taxes should be levied. This, too, is a standard result from optimal taxation theory, being an application of Diamond/Mirrrees' (1971) production efficiency theorem. Now consider the case that not only residence-based capital taxes but also VAT are excluded, for whatever reasons. The first line in Table A4 contains the optimal tax rates. The following results seem to be noteworthy. First, even in a third-best framework, source-based capital income taxes should be avoided in the full as well as in the no information case. Second, in the no information case, the labour income tax should be supplemented by taxing the use of the dirty commodity in consumption. Its use as an intermediate input, however, should not be taxed. This is in contrast to the closed economy case (line 4a of Table A2). The reason is that taxing inputs of an internationally traded commodity worsens its competitiveness on the world markets. In a small open economy, where product prices are given, input taxation could even imply that it is more advantageous to shut down domestic production and to serve domestic needs from imports only. Hence, zero input taxes are optimal from a public finance point of view. In our first trade scenario, however, domestic production of the clean commodity is necessary, because it is – by assumption – the only way to balance the current account. This restrictive assumption will be relaxed in a later trade scenario. The third observation is that from an environmental point of view some modest taxation of polluting inputs into internationally traded commodities might be desirable. Even if this would reverse the sign of the second dividend from positive to negative, it could be over-compensated by the welfare gain from the first dividend. Let us emphasise again that all these results heavily depend on the assumed trade scenario.

Assumed now that the dirty commodity E is traded in exchange for capital imports or exports. If, in addition to green taxes, residence based capital taxes or VAT are available to replace the benchmark equilibrium's labour income tax, our previous results remain qualitatively unchanged. The only case that deserves some comment is when first-best and second-best taxes are excluded. The second line in Table A4 presents the numerical results. As to green taxes in the full as well as in the no information case, the optimal tax

¹¹In Table A4 the balance of payment equations indicate the three different trade scenarios. The head column specifies the taxes which are available. The numbers before (after) the slashes are the optimal tax rates and welfare changes for the full (no) information case.

structure is the same as for similar tax reforms in the closed economy. The use of the dirty commodity which is more inelastic in demand should be taxed more heavily. Taxation of the tradable dirty commodity is optimal because the destination principle is applied and trade in the clean good – to which the dirty commodity is an input – is excluded. What is remarkable, however, is that now some very modest source-based capital taxation forms part of the optimal tax system. The explanation is that taxation of the use of capital partially compensates for the distortion caused by other input taxes. Note that the inclusion of source-based capital taxation in optimal tax systems can occur in third-best (or worse) situations only.

The most interesting trade scenario is the last one, where both the clean and the dirty commodity are tradables. The lower part of Tabel A4 illustrates that now the intermediate use of the dirty commodity should not be taxed under any circumstances. For the no information case when only the public finance view counts, this result is already known from our first trade scenario. There is however one important difference. Taxing inputs to internationally traded commodities under our third trade scenario would result in a complete crowding out of domestic production and full substitution by imports. This could only be prevented if it would be possible to apply border tax adjustments to the full carbon content of imported commodities¹² or to so-called “grey energy” imports. Because this is impossible from a practical point of view, green taxes on inputs to internationally traded commodities should be banned from the tax system. Turning to the full information case it is optimal to shut down domestic production of the clean commodity even if its dirty inputs are not taxed. The reason is that from an environmental point of view it is better to import clean goods. In our model, environmental damage depends on the use of dirty commodities in domestic production and consumption. Dirty inputs which are used in foreign production do no harm to domestic externalities. Closing polluting industries is not a major problem in timeless full employment models. Needless to say, results differ when unemployment and structural adjustment costs are taken into account.

Results would also differ, if global instead of local externalities were at stake. In this case, shifting from domestic production to imports could not improve environmental quality. On the other hand, it would still be optimal for a single country not to tax the intermediate use of dirty commodities. Otherwise, domestic consumers would switch to cheaper imports without reducing global emission levels. This is known as the “leakage” effect (e.g. OECD, 1996, chapter 3).

¹²For this problem and for a discussion of international taxation principles applied to green taxes see Goulder (1992).

5 Conclusions

Time has come to summarise the basic insights from our computable general equilibrium treatise on the double dividend claim of green tax reforms. The hypothesis is that green taxes do not only improve the environment but also reduce overall excess burdens of the tax system; both the first and the second dividend from environmental tax reforms are considered to be positive.

Let us start our evaluation by assuming full information about environmental damage. A natural policy goal then is to maximise the sum of the first and the second dividend for a given set of tax instruments. It immediately follows that any green tax optimum is characterised by the marginal first and marginal second dividend being equal but opposite in sign. Hence, from a marginal point of view, a necessary feature of successful green tax policies is that further reforms cannot bring about a double dividend. Therefore, a necessary (but not sufficient) condition for a double dividend to occur is that the initial tax system is sub-optimal from the environmental as well as the public finance point of view. An obvious question then is how it can be that possible efficiency gains could remain unexploited. Within the narrow bounds of our model there is no convincing answer to this question; one has to resort to model-extraneous arguments. On the other hand, it seems to be a matter of fact that existing tax systems hardly satisfy efficiency requirements and embody a considerable potential for efficiency-oriented tax reform strategies. And there is some reason to assume that, due to an increased awareness of environmental problems, tax reforms are easier to implement when green taxes are included. If one accepts this view, the methodology chosen in this paper seems to be the appropriate one.

Looking again at the full information parts of Tables A2, A3 and A4 one could gain the impression that a double dividend, even if not self-evident, is quite typical for green tax reforms. This, indeed, is true if, as in our case, the benchmark equilibrium's tax system does not include any environmental policies and, furthermore, is only third-best or even worse from a public finance point of view. Even if a double dividend can occur under full information, it is not necessarily an attractive policy goal. Any increase in overall excess burdens of the tax system due to green taxes, i.e. a negative second dividend, is acceptable, if it is overcompensated by an increase in environmental gains, i.e. in the first dividend. Hence, under full information, the double dividend claim is not really an interesting issue. Accordingly, in the literature, the double dividend discussion is closely related to what we have called the no-information case.

Rigorously, only the second but not the double dividend is at stake in the no-information case because environmental concerns are completely neglected. It is, however, taken for granted that the introduction of green taxes will reap a positive first dividend in any case, even if the magnitude of this dividend is highly uncertain. Hence, environmental tax reforms guaranteeing a non-negative second dividend are considered to be costless (Goulder, 1995, p. 158). Both assertions are not necessarily correct or are at least imprecise. Even

if green taxes allow for reaping a second dividend, environmental tax reform may involve opportunity costs. Instead of green taxes one could have implemented some other tax reforms which are possibly superior from a pure public finance view. Consider our model economy with a labour income tax in the benchmark equilibrium. Additionally introducing environmental taxes is welfare-increasing from a public finance view because green taxes partially shift the tax burden from labour to income from fixed endowments such as land rents or, in our context, capital income. But from a purely public finance point of view, there clearly are better alternatives to green taxes. Switching from wage taxation to a uniform VAT or, in our static model, to residence-based capital income taxation, would involve a more complete shift of tax burdens from labour to fixed factors and, hence, yield a higher second dividend than green tax reforms. The corresponding welfare differences may be considered as the public finance opportunity costs of green taxes. The problem with a uniform VAT or even a first-best lump-sum tax is that both increase consumption of the clean as well as the dirty commodity and, in consequence, harm the environment. The deterioration of environmental quality could be prevented if second-best or, whenever possible, first-best taxes from a public finance point of view would be supplemented by green taxes in order to not increase the initial emission level. We have called this scenario an environmentally sustainable tax reform. There is no guarantee that a revenue-neutral switch from labour income taxes to a combination of VAT and green taxes can sustain the environmental quality. But if it can, this is our favourite green tax reform, whenever the magnitude of environmental improvements is highly uncertain or unknown. Instead of heading for a double dividend, implement those tax reforms that maximise the second dividend (or minimise excess burdens) under the constraint that current emission levels do not increase. Our numerical simulations for the small open economy case suggest that green taxes should only be levied on the household sector but should be avoided in the production sector.

The green tax reforms implemented in some Nordic countries (OECD, 1995) come very close to our suggestions.

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Table A 1: Base case parameter values and benchmark equilibrium quantities

Exogenous parameter values	
time endowment \bar{F}	24
capital endowment \bar{K}	6
public expenditure \bar{G}	4.6
substitution elasticities in consumption σ_{XE}/σ_{CF}	1.1 / 1.9
share parameters in consumption for $E_H/(\bar{F} - L)$	0.3 / 0.25
substitution elasticities in production $\sigma_{KL}^G, \sigma_{KL}^E, \sigma_{KL}^Y, \sigma_{QE}$	0.98 / 0.8 / 0.68 / 0.7
share parameters in production for K_G, K_E, K_Y, Q	0.32 / 0.3 / 0.4 / 0.8
environmental damage function A/γ	2 / 0.1
(some) Benchmark equilibrium values	
labour income tax rate t_w (in %)	39.39
labour supply elasticity implied by base case parameter values	0.12
quantities produced $K E/G/Y$	5.88 / 4.6 / 9.31
labour inputs $L_E/L_G/L_Y$	4.14 / 3.20 / 4.55
capital inputs $K_E/K_G/K_Y$	1.70 / 1.40 / 2.89
energy input E_Y	1.87
quantities consumed X/E_H	4.02 / 9.31
labour supply L	11.94

Table A2: Numerical simulation results for the closed economy (base case)

No. of tax reform	Optimal tax rates (in %)					Real net wage rate	Percentage changes in quantities				Welfare changes in % of tax revenue		
	t_K	t_c	t_w	t_E^H	t_E^Y		\hat{L}	\hat{X}	\hat{E}_H	\hat{E}	\hat{D}_1	\hat{D}_2	$H\hat{E}V$
	full information												
1a	-	-	12.30	60.79	67.40	0.6455	10.32	18.96	- 19.16	- 16.11	9.03	1.02	10.05
1b	-	-	26.34	47.38	-	0.6182	5.42	16.57	- 23.23	- 10.38	5.99	0.18	6.18
2a	-	9.26	0.00	56.17	56.17	0.6748	14.62	22.60	-15.04	- 11.19	6.44	4.55	10.98
2b	-	18.13	0.00	46.27	-	0.6815	15.29	25.08	- 15.99	- 2.43	1.46	6.63	8.09
3	21.34	0.00	0.00	61.26	61.26	0.7097	19.83	27.60	- 13.45	- 9.28	5.39	5.95	11.35
	no information / optimal taxes												
4a	-	-	24.64	24.68	41.19	0.6291	6.73	9.97	- 5.71	- 6.63	3.91	3.68	7.59
4b	-	-	32.50	21.12	-	0.6092	3.27	8.90	- 11.34	- 4.80	2.85	1.80	4.66
5a = 5b	-	29.88	0.00	0.00	0.00	0.6972	16.76	13.45	15.62	15.37	- 10.09	11.91	1.83
6	127.16	0.00	0.00	0.00	0.00	0.8423	34.87	26.81	31.71	31.14	- 21.94	16.32	- 5.61

Table A2: Numerical simulation results for the closed economy (continued)

No. of tax reform	Optimal tax rates (in %)					Real net wage rate	Percentage changes in quantities				Welfare changes in % of tax revenue		
	t_K	t_c	t_w	t_E^H	t_E^Y		\hat{L}	\hat{X}	\hat{E}_H	\hat{E}	\hat{D}_1	\hat{D}_2	$H\hat{E}V$
	no information / sustainability												
7a = 4a													
7b = 4b													
8a	-	17.13	0.00	28.84	28.84	0.6875	15.72	19.42	- 2.36	0.00	0.00	9.32	9.32
8b	-	19.53	0.00	38.32	-	0.6849	15.57	23.60	- 11.73	0.00	0.00	7.97	7.97
9	36.54	0.00	0.00	42.94	42.94	0.7411	23.51	28.15	- 3.31	0.00	0.00	10.38	10.38
	no information / no regret												
10a	-	-	10.01	68.42	73.67	0.6471	10.82	20.28	- 21.53	- 17.96	9.96	0.00	9.96
10b	-	-	26.03	48.98	-	0.6185	5.51	16.94	- 23.88	- 10.69	6.17	0.00	6.17
11a	-	4.59	0.00	78.21	78.21	0.6638	13.71	24.07	- 23.17	- 18.52	10.24	0.00	10.24
11b	-	6.11	13.45	68.31	-	0.6429	10.06	24.42	- 28.76	- 11.48	6.60	0.00	6.60
12	8.77	0.00	0.00	83.83	83.83	0.6772	15.93	26.48	- 23.51	- 18.63	10.30	0.00	10.30

$\hat{\cdot}$ indicates percentage change of a variable; - means that the tax instrument has been excluded; in contrast, 0.0 means that the tax instrument is available but the optimal tax rate is zero.

Table A3: Sensitivity analysis¹

No. of tax reform	Optimal tax rates (in %)					Welfare changes in % of tax revenue		
	t_K	t_c	t_w	t_E^H	t_E^Y	\hat{D}_1	\hat{D}_2	$H\hat{E}V$
1a	-/-	-/-	8.69/14.54	62.00/61.25	65.07/71.01	14.54/6.80	- 3.20 / 3.59	11.34/10.39
1b	-/-	-/-	21.79/29.29	47.90/48.54	-/-	9.68/4.54	- 2.53/1.78	7.15/6.33
2a	-/-	6.36/11.32	0.0/0.0	60.33/53.88	60.33/53.88	12.96/3.5	- 1.23/8.37	11.73/11.87
2b	-/-	15.46/20.03	0.18/0.0	44.66/44.38	-/-	6.44/- 0.87	1.42/10.23	7.86/9.36
3	16.21/25.16	0.0/0.0	0.0/0.0	63.88/60.02	63.88/60.02	12.14/2.30	- 0.22/10.08	11.92/12.38
4a	-/-	-/-	24.65/24.90	16.45/29.82	26.63/50.94	[4.74/3.23]	1.69/5.47	[6.43/8.69]
4b	-/-	-/-	29.94/34.29	12.95/26.81	-/-	3.07/2.55	0.74/2.83	[3.81/5.38]
5a = 5b	-/-	27.79/31.57	0.0/0.0	0.0/0.0	0.0/0.0	- 8.76/- 11.01	8.28/14.92	- 0.48/3.9
6	143.79/125.50	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0	[- 21.79/- 22.59]	12.58/19.56	[- 9.21/3.03]

Table A3: Sensitivity analysis (continued)

No. of tax reform	Optimal tax rates (in %)					Welfare changes in % of tax revenue		
	t_K	t_c	t_w	t_E^H	t_E^Y	\hat{D}_1	\hat{D}_2	$H\hat{E}V$
7a = 4a 7b = 4b								
8a	-/-	18.94/16.10	0.0/0.0	18.61/36.72	18.61/36.72	0.0/0.0	6.83/11.29	6.83/11.29
8b	-/-	20.53/19.11	0.0/0.0	24.02/49.97	-/-	0.0/0.0	6.13/9.30	6.13/9.30
9	48.54/31.93	0.0/0.0	0.0/0.0	32.35/51.02	32.35/51.02	0.0/0.0	8.27/12.18	8.27/12.18
10a	-/-	-/-	15.42/6.62	41.03/89.39	46.71/93.44	10.47/9.49	0.0/0.0	10.47/9.49
10b	-/-	-/-	25.95/26.23	28.08/55.47	-/-	6.22/5.91	0.0/0.0	6.22/5.91
11a	-/-	7.61/2.95	0.0/0.0	55.01/96.18	55.01/96.18	11.67/9.57	0.0/0.0	11.67/9.57
11b	-/-	11.81/2.61	4.47/20.49	53.77/76.21	-/-	7.80/6.04	0.0/0.0	7.80/6.04
12	16.73/5.32	0.0/0.0	0.0/0.0	63.15/110.14	63.15/110.14	11.92/9.59	0.0/0.0	11.92/9.59

¹ The share parameter in public good production was changed from a value of 0.32 to 0.13 or 0.4. In each entry, the first number refers to 0.13, the second one to 0.4.

Table A4: Optimal taxes and welfare changes for a small open economy under full / no information (base case parameter set)

Tax instruments available	Optimal tax rates (in %)						Welfare changes in % of tax revenue		
	t_K^R	t_K^S	t_c	t_w	t_E^H	t_E^Y	\hat{D}_1	\hat{D}_2	$H\hat{E}V$
	$q_Y[Y - X] + r[\bar{K} - K_Y - K_G - K_E] = 0$								
t_w, t_K^S, t_E^H, t_E^Y	-/-	0.0/0.0	-/-	10.94/26.68	63.14/24.38	53.12/0.0	13.70/(1.76)	- 2.28/3.73	11.42/(5.49)
	$q_E[E - E_H - E_Y] + r[\bar{K} - K_Y - K_G - K_E] = 0$								
t_w, t_K^S, t_E^H, t_E^Y	-/-	0.90/3.60	-/-	6.66/18.14	65.12/25.38	68.46/39.10	10.93/(3.39)	2.08/6.13	13.02/(9.52)
	$q_Y[Y - X] + q_E[E - E_H - E_Y] + r[\bar{K} - K_Y - K_G - K_E] = 0$								
$t_K^R, t_K^S, t_c, t_w, t_E^H, t_E^Y$	47.18/76.67	0.0/0.0	0.0/0.0	0.0/0.0	43.77/0.0	0.0/0.0	25.14/(- 19.40)	13.25/19.24	38.39/(- 0.16)
$t_K^S, t_c, t_w, t_E^H, t_E^Y$	-/-	0.0/0.0	17.62/27.72	0.0/0.0	37.45/0.0	0.0/0.0	26.72/(- 12.42)	9.44/13.50	36.16/(1.0)
t_K^S, t_w, t_E^H, t_E^Y	-/-	-/-	-/-	21.66/26.7	45.75/24.37	0.0/0.0	29.69/(- 1.25)	2.30/3.73	32.00/2.48