Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Economics and Management 53 (2007) 17–31
JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT
www.elsevier.com/locate/jeem

Ricardian rents, environmental policy and the 'double-dividend' hypothesis

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Received 7 October 2005
Available online 16 November 2006

Abstract

Recent studies on the so-called double dividend hypothesis find that environmental tax swaps exacerbate the costs of the tax system and therefore do not produce a double dividend. We extend these models by incorporating a fixed-factor in the production of the polluting good and, therefore, allowing Ricardian rents to be generated in the economy. In this setting, an environmental tax reform with revenues used to cut pre-existing labor taxes can produce a double dividend. Moreover, the overall costs of environmental tax swaps are negative up to 11 percent of emissions reductions, suggesting the potential for a strong double dividend and confirming that environmental taxes should be part of the optimal tax system.

JEL Classification: D62; H21; H23

Keywords: Ricardian rents; Environmental taxation; Double-dividend hypothesis

1. Introduction

A growing number of analytical and numerical studies have cast doubt on the validity of the double dividend hypothesis that is the claim that environmental taxes could simultaneously improve environmental quality and increase the efficiency of the tax system, e.g. [1,2,6,8].[1] Two welfare effects underlie these results. First, by driving up the price of (polluting) goods relative to leisure, environmental policies tend to compound the factor-market distortions created by pre-existing labor taxes, thereby producing a negative welfare impact termed *the tax-interaction effect*. Second, environmental taxes whose revenues are recycled through cuts in marginal tax rates reduce the distortions caused by the pre-existing taxes, which contributes to a positive welfare impact. Because this *revenue-recycling effect* is not strong enough to compensate for the *tax-interaction effect*, environmental tax swaps typically exacerbate rather than decrease the gross efficiency costs of the tax

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[1]For an excellent survey of the double dividend literature, see [3].

0095-0696/$ - see front matter
doi:10.1016/j.jeem.2006.03.006

system. As a consequence, there is no double dividend from an environmental tax reform. A related point is that the second best environmental tax should typically be set below the (first best) Pigouvian tax.[2]

These models typically assume that the production of all goods exhibits constant returns to scale, with labor being in most cases the unique input in production.[3] However, certain types of environmental taxes are imposed on goods whose production is intensive in exhaustible resources, with owners of these factors earning rents. In this case, unless rents are fully exhausted, the tax system is not optimal to begin with, even from a non-environmental perspective.[4]

This naturally raises the question of whether the presence of fixed factors in production and the potential existence of untaxable Ricardian rents makes it possible for a double dividend to occur. This paper extends previous literature by asking the following two questions: First, what are the implications of fixed factors in production of dirty goods for the magnitude and sign of the first and second dividends? By first dividend we mean the welfare gain from improving environmental quality; by second dividend we mean the reduction in the costs of the tax system, when environmental tax revenues are recycled to reduce the rate of a pre-existing labor tax. Second, in the presence of fixed factors in the production of dirty goods, how does the second best optimal environmental tax compare to the Pigouvian (first-best) tax? To answer these questions, we model a static economy where households allocate their time between leisure and labor supply. Labor, along with an exhaustible natural resource (i.e. coal), is used to produce a dirty good.[5] Our work is closely related to and complements recent studies by Perrori and Whaley [12] and Williams [13]. Perrori and Whaley [12] investigate the significance of rents for both the welfare costs and the optimal design of commodity taxes. Williams [13] examines the costs of trade policies in a two sector model with sector-specific factors.

We find that a revenue-neutral shift towards an environmental tax produces a double dividend. However, and interestingly, we find that there is a substantial tradeoff between the magnitude of the first and the second dividend. In particular, in the presence of a fixed factor in the production of the dirty good an environmental tax is not fully passed to the final price of the dirty good, and hence we find that fixed factors in production can substantially compromise the magnitude of the first dividend. However, and to the extent that the environmental tax is not fully passed to the final price of the polluting good, we also find that the tax interaction effect is not as strong as predicted by previous literature. In our benchmark simulations, ignoring any environmental benefits, the net impact of an environmental tax swap is to reduce the economic costs of the tax system for pollution reductions up to at least 50%. In other words the general equilibrium gross costs of the policy are less than the partial equilibrium costs, and by a substantial amount. Indeed the overall costs of pollution reduction are negative for taxes that reduce pollution by 11 percent, suggesting that even if there is uncertainty about the benefits from the environmental policy, the environmental tax should be part of the tax system. A related point is that, in contrast to typical results from earlier studies, we find the optimal environmental tax may easily exceed the Pigouvian tax.

We also explore the implications of fixed factors and Ricardian rents for the costs of other policy instruments. We find that the costs of non-auctioned pollution emissions permits relative to emissions taxes can be significantly greater. This is due to the larger effect from using revenues from environmental policies to reduce labor taxes in the presence of fixed factors in the production of polluting goods.

The rest of the paper is organized as follows. Section 2 introduces the analytical model and decomposes the general equilibrium welfare effects of an environmental tax into its different components. Section 3 describes the simulation model and Section 4 presents the simulation results. Section 5 offers conclusions.

[2]Parry and Bento [9], Parry and Bento [10], Williams [14] and Williams [15] examine special cases under which the double dividend may occur.

[3]An exception is the study by Bovenberg and Goulder [2]. In this study the authors consider several intermediate inputs including fossil fuels, but do not model the effects of Ricardian rents explicitly.

[4]It is well established in the public finance literature that, in the presence of fixed factors in production, a uniform commodity tax (or equivalently a labor tax) is not optimal. By not taxing more heavily the good whose production has a fixed factor, a uniform commodity tax system fails to fully capture the rents from this factor of production.

[5]Coal is just used as an example of an exhaustible natural resource used in the production of a dirty good. Other examples include resources like metals and cement. Further, there are likely additional costs associated with rents including rents accruing to quasi-fixed capital investments, such as depreciated coal generating facilities.

2. The analytical model

2.1. Model assumptions

We develop a static model in which a representative household enjoys utility from a polluting good (X), a non-polluting consumption good (Y)and non-market time or leisure. Leisure is equal to the household time endowment ($\bar{L}$) less labor supply (L). Emissions (E) from producing X cause environmental damages in the form of reduced consumer utility. The household utility function is given by

$$U = u(X, Y, \bar{L} - L) - \phi(E). \tag{2.1}$$

$u(.)$ is utility from non-environmental goods and is quasi-concave. $\phi(.)$ is disutility from waste emissions and is weakly convex. In our model, we have abstracted from abatement technologies, and therefore treat emissions as proportional to X. The separability restriction in (2.1) implies that the demands for X, Y and labor supply do not vary with changes in E.

X and Y are produced by competitive firms. Labor is the only input in production of Y. We assume the marginal product of labor is constant in this industry, and normalize output to imply a marginal product (and wage rate) of unity. This normalization implies that the unit cost of producing Y is unity:

$$Y = Y(L_Y). \tag{2.2}$$

In contrast, two inputs are used in the production of X, labor and a fixed factor (Z):

$$X = X(L_X, Z), \tag{2.3}$$

where L_X denotes the amount of labor used in the production of X. X exhibits decreasing returns to scale with respect to L_X. As a consequence, positive *Ricardian rents* are earned by the owners of the fixed factor (Z). In the absence of an environmental policy, rents are given by

$$I = p_X X - vL, \tag{2.4}$$

where p_X and v denote producer price of good X and gross wage, respectively.

The government levies a proportional tax of t_L on labor earnings, regulates emissions with an environmental tax (t_E), and provides a fixed lump-sum transfer G to households. We assume that the government budget balances; any revenue consequences of environmental policies are offset by adjusting t_L. We also assume that all rents (I) generated from the production of X are earned by the representative consumer. For expositional reasons, in the analytical model we have abstracted from the possibility that government can tax rents directly. We relax this assumption in the numerical model. The household budget constraint is

$$p_X X + Y = (v - t_L)L + I + G \tag{2.5}$$

where p_X is the demand price of X. Households choose X, Y and L to maximize utility (2.2) subject to the budget constraint (2.5), taking environmental damages as given. From the resulting first-order conditions and (2.5) we obtain the uncompensated demand and labor supply functions:

$$X(p_X, t_L, I); \quad Y(p_X, t_L, I); \quad L(p_X, t_L, I). \tag{2.6}$$

Substituting these equations into (2.2) gives the indirect utility function:

$$V = v(p_X, w, I) - \phi(E), \tag{2.7}$$

where w denotes the net wage rate.

With this framework we can now analyze the efficiency effects of a revenue-neutral environmental tax reform.

2.2. The welfare effects of an environmental tax reform

Consider a revenue-neutral tax of t_E imposed on X, with revenues from this tax employed to finance cuts in the distortionary tax, t_L. The government holds the level of G fixed and solves the budget constraint by adjusting t_L:

$$t_E E + t_L L = G. \tag{2.8}$$

The welfare effect of an incremental increase in the environmental tax with revenues used to reduce the labor tax can be expressed as[6]:

$$\frac{1}{\lambda}\frac{dV}{dt_E} = \underbrace{\left(\frac{\phi'}{\lambda} - \frac{dp_X}{dt_E}\right)\left(-\frac{dX}{dt_E}\right)}_{W^P} + \underbrace{\frac{dI}{dt_E}}_{W^R} + \underbrace{t_L \frac{dL}{dt_E}}_{W^L} \tag{2.9}$$

where ϕ'/λ is the marginal external cost of pollution. The first term on the right-hand side of Eq. (2.9), denoted by W^P, comprises the *Pigouvian welfare effect* of this policy. This is the efficiency gain associated with household's responding to the higher price of X induced by the emissions tax by substituting away from X to other goods and leisure. This effect equals the reduction in consumption of X multiplied by the wedge between the marginal external cost and the increase in the price of the polluting good (due to the marginal increase in the environmental tax), net of the *primary economic costs* of the policy.[7] W^R is the *rent effect*. It represents a loss in real income to the household due to a reduction in the *Ricardian rents*. This effect occurs because part of the burden of the environmental tax falls on the fixed factor in the production of X. Finally, the term W^L represents the impact of a marginal increase in the environmental tax in the labor market. This effect is given by the change in labor supply multiplied by the tax wedge between the gross and net wage created by the pre-existing labor tax. There is a welfare gain (or loss) in the labor market if the general equilibrium impact of the policy is to increase (or decrease) labor supply. By differentiating (2.5) when G is constant, we can further decompose this effect into the following three components:

$$\frac{dL}{dt_E} = \underbrace{\frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E}}_{dW^{TI}} + \underbrace{\frac{\partial L}{\partial t_L}\frac{dt_L}{dt_E}}_{dW^{RR}} + \underbrace{\frac{\partial L}{\partial I}\frac{dI}{dt_E}}_{dW^{Rent}}. \tag{2.10}$$

The term labeled dW^{TI} represents the efficiency loss from *the tax interaction effect*. The environmental tax increases the price of X, implying an increase in the cost of consumption and thus a reduction in real wage. The term labeled dW^{RR} is the efficiency gain from the (marginal) *revenue-recycling effect*. It represents the efficiency gain associated with using the revenues from the environmental tax to finance cuts in distortionary taxes. Finally, the term labeled dW^{Rent} denotes the welfare effect from using the environmental tax as a 'surrogate' tax on Ricardian rents. Effectively, it is the case that the environmental tax produces a tax shift away from labor towards fixed factors in the production of polluting goods. To the extent that a marginal increase in the environmental tax reduces rents, and in turn overall household income, households increase labor supply at the margin. This effect produces an additional welfare gain in the labor market that weakens the tax interaction effect and goes in the same direction of the revenue-recycling effect. Note that even if the reduction of rents has no effect on labor supply, the revenue recycling and rent effects (dW^{RR} in Eq. (2.10) and W^R in 2.09, respectively) will still be present and continue to drive our main result.[8] All three of the effects act in the same direction, increasing the optimal tax above the Pigouvian level.

2.3. Relation to previous literature

In many previous studies, e.g. [1,6,8,14], all goods are (ultimately) produced by labor, and therefore these models do not account for the possibility that certain polluting goods use fixed factors in their production generating Ricardian rents in the economy. The general equilibrium welfare effects of a revenue neutral

[6]We have arrived at (2.9) by totally differentiating the indirect utility function in (2.7) and the government budget constraint in (2.8), while making use of Roy's identity. A detailed derivation is available from the authors upon request.

[7]We define primary economic costs of the policy as the marginal costs in a first-best case when we set pre-existing taxes and the level of the fixed factor to zero.

[8]This might be the case in certain heterogeneous agent models, for example, where the agents earning the rents are fully insulated from the labor market.

environmental tax in this context consist of the *Pigouvian welfare effect*, the *tax interaction effect*, and the *revenue-recycling effect*. These studies typically find that the tax-interaction effect dominates the revenue-recycling effect, and therefore the net impact of the environmental tax swap is to reduce labor supply and increase the costs of pre-existing taxes. Not surprisingly, these studies cast doubt on the "double dividend hypothesis", that is the claim that an environmental tax could both improve the environment and reduce the costs of the tax system.

The key insight from introducing sector-specific factors in the classical model of environmental tax reform is that, as a consequence, the environmental tax will not be fully passed to households in the form of higher consumer demand prices (as in the previous models). Indeed, it is the case that, in the presence of fixed factors in production:

$$\frac{\mathrm{d}p_X}{\mathrm{d}t_\mathrm{E}} < 1. \tag{2.11}$$

This suggests that the burden of the environmental tax is divided into two channels in the economy: Part of the environmental tax will be translated into higher prices of the polluting good, and second, part of the environmental tax will fall on the fixed factor extracting some of its rents.[9] This simple insight sheds light on several important points central to the double-dividend debate.

First, let us consider the implications of our model to the *first dividend* and the *primary economic costs* of the policy. We remind the reader that the "*first dividend*" is the claim that a marginal increase in the environmental tax will improve environmental quality. Before we proceed with this discussion, we also note that, perhaps surprisingly, previous literature focused *exclusively* on the direction and magnitude of the second dividend and took the first dividend for granted.[10] In fact, because the environmental tax would be fully passed to households in the form of higher polluting good prices, the first dividend would simply be the reduction in consumption of the polluting good multiplied by the wedge between the marginal external cost of pollution and the environmental tax, net of the primary cost of the policy. In contrast, our model suggests (see Eqs. (2.8) and (2.10)) that the magnitude of the first dividend can be substantially compromised in the presence of fixed factors. This is because the increase in the price of the polluting good is not given by the full amount of the tax and, as a consequence, for the same marginal increase in the environmental tax, the total reduction in the consumption of the polluting good is smaller in our model compared to previous models in the literature.

A second implication of our model is that the *primary economic costs* of the policy will be higher than previously recognized in the literature. Again, this is because in order to achieve the same level of emissions reductions, the level of the environmental tax will need to be higher in our model, since part of the environmental tax falls on the fixed factor. A related implication is that the environmental tax (at a given level) is a less effective pollution reducing instrument, which should also be taken into consideration when choosing amongst different policy instruments.

Next, let us consider the implications of our model to the *second dividend* and the design of the optimal tax system. We remind the reader that by second dividend we mean an overall reduction of the costs of the tax system when the revenues from the environmental tax are used to cut pre-existing distortionary input taxes. Eqs. (2.8) and (2.10) suggest that previous studies may have overestimated the magnitude of the *tax interaction effect*. Again, to the extent that the environmental tax will not be fully passed to households in the form of higher consumption prices, the reduction in real wage will not be as drastic as previously suggested. Second, by shifting taxes away from labor into the fixed factor and therefore reducing real income (through reductions in Ricardian rents), environmental tax reforms may even create an incentive to increase labor supply at the margin, which may have been overlooked in previous literature. This later effect will certainly weaken the tax interaction effect and makes it more likely that the second dividend be positive. We also note that, to the extent that part of the environmental tax is effectively taxing Ricardian rents, the environmental tax should be part of the optimal tax system, even from a non-environmental perspective. Therefore there are prospects for a double dividend.

[9]Since the good is produced competitively, the burden of the tax will fall on the factors of production. The portion of the tax falling on the scarce resource will be realized in the form of reduced Ricardian rents and depends on the share of resource use and elasticity of substitution.

[10]An exception is Koskela et al. [7]. In their model, firms choose clean and dirty factors of production, and there is unemployment.

We conclude this section by noting that, in a sense, there is an interesting conflict between the first and second dividend. Eqs. (2.8) and (2.10) above suggest that the first dividend is maximized in the *absence* of fixed factors while, in contrast, the second dividend would be maximized in the *presence* of fixed factors. In other words, from the perspective of reducing pollution, it is desirable that the environmental tax raises the price of the polluting good by its total amount. In contrast, if the goal is to reduce the costs of the tax system, it is desirable that the environmental tax falls as much as possible on the fixed factor, since this would get us closer to the optimal tax rule.

2.4. Optimal environmental tax

In the context of the double-dividend debate, a controversial issue that has received substantial attention in the literature is the relation between the optimal second best environmental tax and the traditional (first best) Pigouvian tax. Because previous literature typically cast doubt on the existence of a double dividend, the resulting optimal second best environmental tax lies below the Pigouvian tax. In this section, we re-examine this issue in the context of our model.

To obtain the optimal environmental tax, we set Eq. (2.10) equal to zero and solve for $\mathrm{d}p_X/\mathrm{d}t_\mathrm{E}$. The optimal environmental tax t_E^* is the tax that raises the price of the polluting good by:

$$\frac{\mathrm{d}p_X}{\mathrm{d}t_\mathrm{E}} = \frac{\phi'}{\lambda} - t_L\,\frac{\mathrm{d}L/\mathrm{d}t_\mathrm{E}}{\mathrm{d}X/\mathrm{d}t_\mathrm{E}} - \frac{\mathrm{d}I/\mathrm{d}t_\mathrm{E}}{\mathrm{d}X/\mathrm{d}t_\mathrm{E}}. \tag{2.12}$$

First, note that in the absence of pre-existing labor taxes and Ricardian rents from fixed factors in the production of the polluting good, the optimal environmental tax should be set solely based on Pigouvian considerations. From a first best (Pigouvian) perspective, the tax should be set equal to the dollar amount of the marginal external costs of pollution.

As discussed above, it is not possible to sign the term $\mathrm{d}L/\mathrm{d}t_\mathrm{E}$, that is, the general equilibrium impact of the environmental tax on the labor market. If it is the case that labor supply increases in response to the environmental tax then the second term in Eq. (2.12) suggests an increase in the environmental tax above and beyond its Pigouvian level. Finally, the third term in Eq. (2.12) is unambiguously positive, suggesting that the presence of fixed factors in polluting industries call for higher environmental taxes, since the environmental tax is, in this case, effectively serving as a 'surrogate' to a Ricardian rent tax. This last term suggests that, from an optimal tax rule perspective, the environmental tax should be part of the tax system.

We conclude this section by noting that it is not possible to say a priori whether the optimal environmental tax should lie below or above the (first-best) Pigouvian tax. It is certainly the case, however, that the optimal second best environmental tax should be greater than recognized in the literature, reflecting the contribution of the third term in Eq. (2.12) to the optimal level of the tax.

3. Simulation model

In this section we numerically examine the general equilibrium costs of an environmental tax reform. In addition, we also consider the costs of alternative revenue-recycling schemes and grandfathered tradable permits. The simulation model reproduces the key analytical results derived above and provides magnitudes of the effects of alternative scenarios under large policy changes. Subsections A and B present the functional forms and calibration, respectively.

3.1. Functional forms

The representative household's utility is given by the nested constant elasticity of substitution (CES) utility function:

$$U = (\alpha_{UC} C^{\sigma_U - 1/\sigma_U} + \alpha_{Ul} l^{\sigma_U - 1/\sigma_U})^{\sigma_U/\sigma_U - 1} - \phi(E), \tag{3.1}$$

$$C = (\alpha_{CX} X^{\sigma_C - 1/\sigma_C} + \alpha_{CY} Y^{\sigma_C - 1/\sigma_C})^{\sigma_C/\sigma_C - 1}, \tag{3.2}$$

where l is the household's consumption of leisure and C is the part of utility derived from consumption of goods. Y is a clean good representing the majority of consumption and X is a polluting good. σ_U and σ_C are the elasticities of substitution between goods and leisure and between the consumption of X and Y, respectively. The α parameters control the share of total income spent on leisure and each of the goods. Note that disutility from emissions, E, is separable and given by the function $\phi(E)$, where $\phi' > 0$ and $\phi'' \geqslant 0$.

There are two notable restrictions implied by the form of utility. First, the separability of environmental damage rules out any interaction between emissions and labor/leisure and consumption tradeoffs made by the household. Second, the nesting of the clean and dirty goods in C implies that they are equal substitutes for leisure.

Production of the clean good is as in a standard one factor model, while production of the dirty good, X, is given by a CES production function incorporating labor and a fixed factor F:

$$Y = L_Y, \tag{3.3}$$

$$X = \gamma_X \cdot (\alpha_{LX} L_X^{\sigma_X - 1/\sigma_X} + \alpha_{FX} F^{\sigma_X - 1/\sigma_X})^{\sigma_X/\sigma_X - 1}, \tag{3.4}$$

σ_X is the elasticity of substitution between labor and the fixed factor in the production of X. In our analysis, we will vary the scale parameter for F; note that in the limiting case when $\alpha_{FX} = 0$ the model reduces to the usual one factor case. Production of both goods is constant returns to scale and pollution is proportional to the production of the dirty good.

The final agent is government, which provides a transfer G to households. We extend the analytical model and consider the case where the government levies three taxes: a labor tax, τ_L, a tax on the fixed factor, τ_F, and a tax on emissions, τ_E. We assume the government budget is kept in balance by

$$G = \tau_L L + \tau_F P_F F + \tau_E E. \tag{3.5}$$

For our central simulations the government holds G fixed in real terms and balances the budget by adjusting τ_L. The pre-existing tax levied on the fixed factor is held constant for any given policy, but varied in a sensitivity analysis. In order to isolate the revenue recycling effect and provide a larger variety of policies, we also include alternate simulations where factor taxes are held fixed and the government returns additional revenue from the emissions tax lump sum.

The numerical model is solved by setting prices and taxes such that the government budget balances, the desired emissions level is reached, and the factor markets clear. The government budget is given above and emissions are set by adjusting the level of τ_E. The labor market equilibrium is given by

$$L = L_X + L_Y, \tag{3.6}$$

where the supply of labor and demands for the two goods are given by the solution to the household's problem which consists of maximizing (3.1) subject to the budget constraint:

$$p_X X + Y \leqslant (1 - \tau_L) L + (1 - \tau_F) p_F F + G. \tag{3.7}$$

Firms choose inputs to minimize production costs which determines the producer prices of X and Y and demands for inputs. Demand and supply of inputs and goods is equated in equilibrium.

3.2. Model calibration

The elasticity of substitution between consumption of goods and leisure (σ_U) is calibrated to be consistent with econometric evidence of labor supply elasticities. In our very aggregate model, this elasticity will represent the total supply response of labor in terms of hours worked and participation rates averaged across the labor force. In order to make the model consistent with estimates of both compensated and uncompensated elasticities, we use both the elasticity parameter σ_U and the initial ratio of total time endowment to labor supply ($\bar{L}/L$) for calibration. We use values of 0.15 and 0.40 for the uncompensated and compensated elasticities, respectively, approximating the mean values reported in Fuchs et al. [4].[11] Following

[11] Goulder et al. [6] also calibrates their model to these values for the labor supply elasticities.

Table 1
Fraction of fuel costs in electricity production

Electric utilities	Investor owned	Publicly owned	Total
Share of US electricity sales[a]	76%	15%	91%
Fuel purchases			
As % of operation and maintenance costs[b]	40.3%	28.8%	39.1%
As % of total expenses[c]	24.8%	20.2%	24.4%
Estimated fuel costs net of refining and transportation[d]			
As % of operation and maintenance costs	31.0%	22.2%	30.1%
As % of total expenses	19.1%	15.6%	18.7%

Financial Statistics of Major US Investor Owned Electric Utilities 1996, US Department of Energy DOE/EIA-0437(96)/1, December 1997.
Financial Statistics of Major US Publicly Owned Electric Utilities 1996, US Department of Energy DOE/EIA-0437(96)/2, March 1998.
[a]Remaining 9% is from cooperatives and federal utilities.
[b]Includes all electricity generation, transmission and distribution costs.
[c]Includes operation and maintenance plus depreciation, amortization, and taxes.
[d]Based on fuel share weighted ratio of wellhead (minemouth) price of gas (coal) to delivered price of 0.77.

earlier studies (e.g. [6]), we assume a benchmark distortionary labor tax rate (τ_L) of 40 percent. This is meant to include the combined effects of personal, payroll, and sales taxes.

Since our results will depend heavily on the relative size of the polluting sector (X) and the fraction of input coming from a fixed factor (α_{FX}), we let this vary in the sensitivity analysis. The calibration for the central case, however, is meant to roughly reflect the size and composition of the United States electricity market. We take the electricity sector to be 2.7 percent of the economy, consistent with aggregate data from the Department of Energy.[12] Values of 1 and 10 percent are considered in the sensitivity analysis.

The relative size of the fixed factor in the central case is taken to be 25 percent, based on the approximate value of the fossil fuel used in US electricity generation. Table 1 shows a decomposition of generation expenses, supporting this central case estimate. The fraction of electricity generation expenses that represent Ricardian rents to a fixed factor is one of the most important parameters in our analysis and one of the least well agreed upon. In order to make the analysis as broadly applicable as possible, we consider a large range for this parameter letting the size of the fixed factor vary between 0 and 50 percent. Preexisting rent taxes (τ_F) play an opposite but very similar role to the size of the fixed factor, effectively reducing the amount of rents remaining in the resource sector. We set these to 10 percent in the benchmark, as a rough approximation to United States resource royalties. Low and high values of zero and 40 percent are also presented.[13]

Our example of electricity production and fossil fuel is one of several cases where environmental taxes might be levied in the presence of a factor earning Ricardian rents. Another example is the cement industry, which produces substantial environmental externalities and employs large quantities of mineral resources. Similarly, taxes on the steel industry could fall partially on rent-earning iron ore resources. Finally, not all fixed factors earning Ricardian rents need be natural resources: Our analysis could also apply to quasi-fixed capital, such as a fully depreciated power plant, earning this type of rents.

The elasticity of substitution in the production of the polluting good (σ_X) is initially set to unity; a halving and doubling of this to 0.5 and 2.0 are considered in the sensitivity analysis. Similarly, the consumption elasticity of substitution between the two goods (σ_C) in the economy is set to unity in the benchmark. The assumption on these two elasticities is standard given the aggregate nature of the model.[14]

[12]1996 electricity sales of $212 billion (*Electric Power Annual 1996*, DOE/EIA-0348(96)/1, August 1997.) divided by 1996 US GDP ($7,813 billion).

[13]The situation where the government cannot extract any of the rents through taxation could represent less developed regions where competition among countries absorbs all the rents, although this issue may present further distortion that we are unable to consider.

[14]Goulder et al. [6] choose slightly lower elasticities of 0.9 for input substitution and 0.85 for substitution between the final goods. We consider values as low as 0.5 in our sensitivity analysis and find that changing these elasticities has little effect on our results.

4. Results

This section presents our simulation results illustrating how the presence of fixed factors in the production of polluting goods and Ricardian rents affects the price of the polluting good, the costs, overall welfare impacts, and optimal levels of environmental policies.

4.1. Impact of the fixed factor on the price of the polluting good

In Fig. 1 we compare the increase in the price of the polluting good (due to the environmental tax) in our model relative to models that do not incorporate a fixed factor in production.

P^{NNF} indicates the increase in the price when we set the value of the fixed factor equal to zero. This curve has a zero intercept, and is given by the 45°- line, suggesting that, in a world without a fixed factor in the production of the polluting good, the impact of the environmental tax is to raise the price of the polluting good by the full amount of the tax. Thus, for example, a 10 percent increase in the tax translates to a 10 percent increase in the price of the polluting good.

p^{FF} shows the increase in price of the polluting good in the presence of a fixed factor. This curve lies below the 45° line. The difference between $p^{\mathrm{FF}}$and p^{NFF} confirms that, in the presence of the fixed factor, part of the burden of the environmental tax will fall on the fixed factor, and hence, the overall increase in the price of the polluting good will be lower. Our model suggests that roughly 85 percent of the tax is passed to consumers in the form of higher prices while the remaining 15 percent falls on the fixed factor.

4.2. Marginal costs

In Fig. 2 we compare the marginal cost of reducing pollution under different scenarios for revenue-recycling. Marginal costs are expressed as a percent of the initial value of income in the economy.

MC^{PRIM_0} indicates marginal costs in a first-best case when we set pre-existing taxes and the level of the fixed factor to zero. This curve reflects the *primary economic costs* of the environmental tax. MC^{PRIM_0} has a zero intercept, and is upward sloping, reflecting the increasing marginal cost of substituting other goods and leisure for the polluting good.

$MC^{\mathrm{PRIM}_{\mathrm{FF}}}$ shows the marginal costs when we include the fixed factor in the model, but still set labor taxes at zero. The difference between $MC^{\mathrm{PRIM}_{\mathrm{FF}}}$ and MC^{PRIM_0}isolates the importance of the fixed factor to the

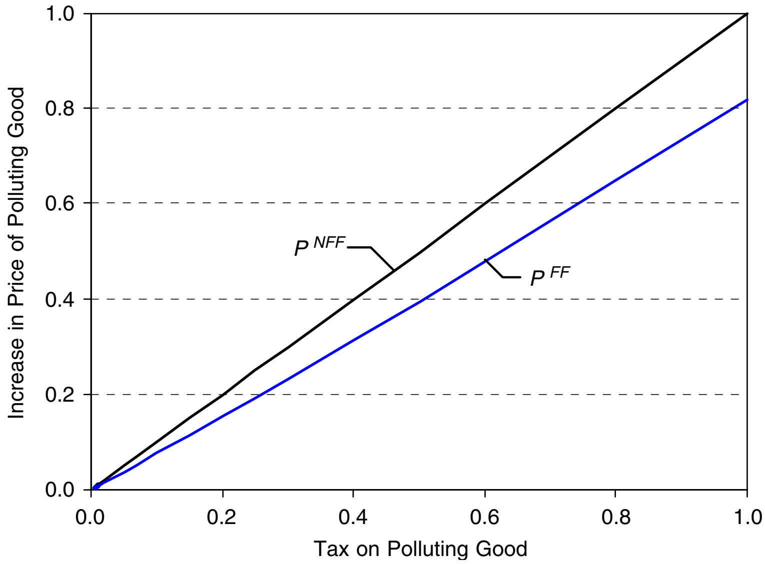

Fig. 1. Price effect of emissions tax on polluting good.

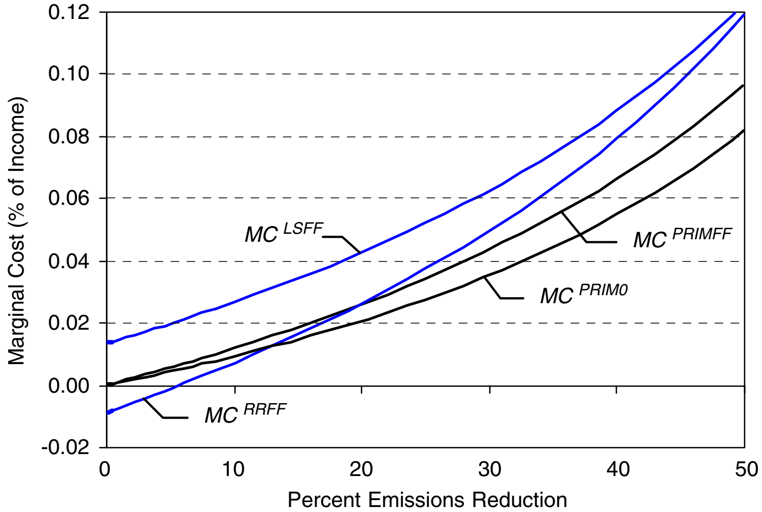

Fig. 2. Marginal cost of emissions reductions.

magnitude of the *primary costs* of the policy. This difference suggests that the presence of fixed factor in the production of the polluting good indeed increases the primary costs of the environmental tax. For example at 30 percent emissions reduction, the difference in cost is about 20 percent, and reflects the fact that, in the presence of a fixed factor, in order to achieve the same emissions reductions, the level of the environmental tax needs to be higher.

$MC^{\mathrm{LS_{FF}}}$ shows the marginal costs of the environmental tax with a pre-existing labor tax but no revenue-recycling effect; in this case, the revenues generated by the environmental tax are neutralized by adjusting the lump-sum transfer. The difference between this curve and $MC^{\mathrm{PRIM_{FF}}}$ isolates the importance of the *tax-interaction effect* for the costs of the policy. This effect causes a substantial upward shift of the marginal cost curve (see [6] for more discussion). For example, at 30 percent emissions reduction, the difference in cost is about 40 percent.

$MC^{\mathrm{RR_{FF}}}$ shows the marginal cost under the pollution tax with revenues used to reduce the labor tax. It equals $MC^{\mathrm{LS_{FF}}}$ net of the benefit from the *revenue-recycling effect*. A novel aspect of this curve is its negative intercept. In fact, it is the case that marginal costs are negative up to about 6 percent. The environmental tax essentially allows the burden of the tax system to shift away from labor towards the fixed factor in the economy. Therefore, up to a point, the environmental tax reform reduces the overall costs of the tax system, not counting environmental benefits. Also, note that $MC^{\mathrm{RR_{FF}}}$ crosses $MC^{\mathrm{PRIM_0}}$ at 12 percent emissions reductions reflecting the fact that interactions with the tax system lower the costs of environmental taxes up to 12 percent. However, $MC^{\mathrm{RR_{FF}}}$ eventually converges to $MC^{\mathrm{LS_{FF}}}$ suggesting an erosion of the tax base and an increase in distortions as emissions reduction levels increase.

4.3. Total costs

We now consider the total costs of emissions reductions. Like in the previous figure, we compare how the costs are sensitive to the introduction of the fixed factor in the model and the mechanism of revenue-recycling. In addition, we also provide a comparison between (partially) grand-fathered tradable permits and environmental taxes. Total costs are expressed relative to total primary cost. When a curve lies above (below) unity, the net impact of interactions with the tax system is to raise (lower) the overall cost of the policy above (below) its primary costs.

The most novel feature of Fig. 3 is the total cost curve for the environmental tax in the presence of a fixed factor, with revenues used to reduce the labor tax. This curved, denoted by $TC^{\mathrm{RR_{FF}}}$, lies below the horizontal axis for emission reductions up to 12 percent. When total costs are negative the welfare gain from reducing the costs of the tax system is more than offsetting the primary cost of the policy. In his reader's guide Goulder [5]

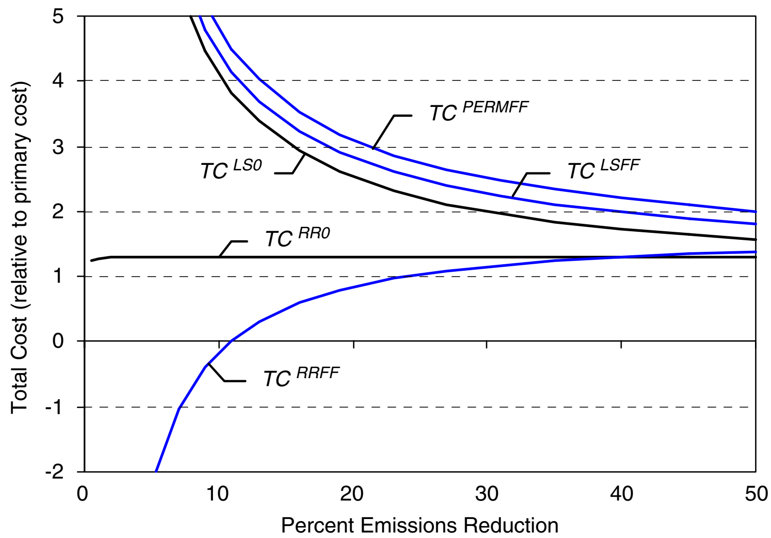

Fig. 3. Total cost of emissions reduction.

refers to this as a "*strong*" form of a double dividend from environmental tax reform; even without accounting for the environmental gain, the policy increases overall welfare. When total costs are positive but less than primary cost (indicated at unity on our figure), there is still a net welfare gain from interactions with the tax system. In our central parameter case, we find that this intermediate form of the double dividend occurs up to 23 percent of emissions reductions. For emission reductions greater than 23 percent, the costs of the policy are higher than the primary costs, suggesting that the rents from the fixed factor are exhausted. At this point, the exacerbation of the distortion in the labor market begins to dominate.

If we remove the fixed factor from the model, the total cost of an environmental tax, when revenues are used to cut labor taxes, will now be above unity. TC^{RR_0} illustrates this situation. In this case there is no potential for a double dividend; the general equilibrium costs of this policy exceed primary costs by around 30 percent. Fig. 3 clearly shows that—by neglecting the potential existence of fixed factors in the production of polluting goods and the possibility of environmental taxes to serve as rent taxes—the magnitude of costs of environmental tax reforms may be substantially overstated, and possibly of the opposite sign. For example, for a reduction in emissions of about 15 percent, models not considering a fixed factor might estimate costs equal to 133 percent of primary costs; in contrast our analysis predicts a welfare gain equal to 50 percent of primary costs. The magnitude of this effect will depend directly on how important the rent-earning fixed factor is in production. Because of this important relationship, we later let the size of the fixed factor vary smoothly between 0 and 50 percent of the cost of production in our sensitivity analysis.[15]

When the revenues from the environmental tax are neutralized by lump-sum transfers, total costs are given by TC^{LS_0} for a model without a fixed factor and by $TC^{\mathrm{LS}_{\mathrm{FF}}}$ for a model with a fixed factor. By comparing these two curves, one can conclude that the costs of the environmental tax are higher in the presence of the fixed factor because the need for a higher tax creates some additional distortions in the economy.

4.4. *Optimal policies*

To calculate optimal second best emissions reductions, we postulate different values for the marginal environmental benefit from reducing pollution. In Fig. 4, along the horizontal axis we measure Pigouvian emissions reduction and on the vertical axis the optimal second best pollution reduction (relative to Pigouvian reductions).

[15]Notice that a case where only partial rents are earned would be modeled in our framework as one where the size of the fixed-factor in production is proportionately smaller. Labor costs (of extraction, for example) are netted out when determining how large the fixed factor is.

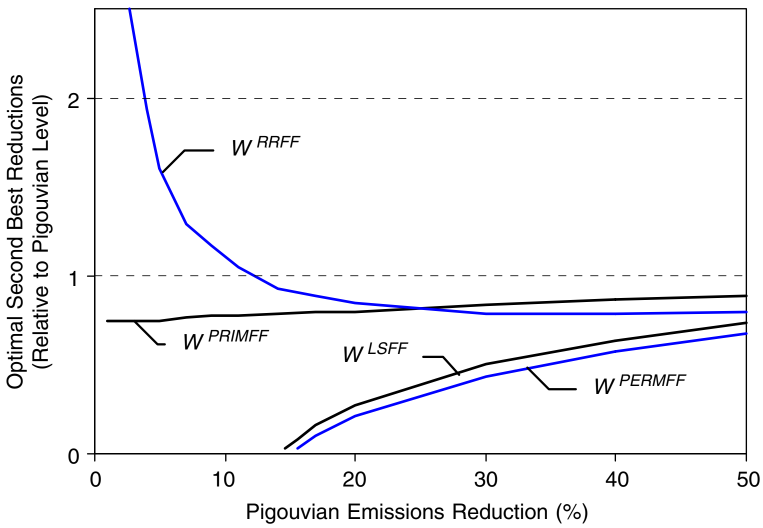

Fig. 4. Optimal policy relative to Pigouvian level.

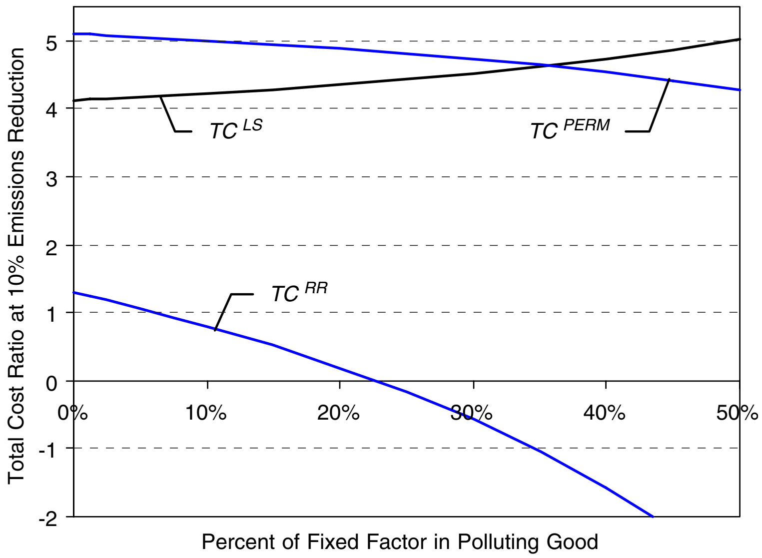

Fig. 5. Total cost at 10% abatement, varying size of fixed factor.

Again, the novel feature of this figure is the curve for the pollution tax in the presence of a fixed factor, $W^{\mathrm{RR}_{\mathrm{FF}}}$. Over an initial range, this curve lies above unity, while the curves for all other policies lie below unity. This suggest that, up to 11 percent emissions reduction, the optimal second best environmental tax should be higher that the Pigouvian tax. This result re-enforces the importance of the rent effect in Eq. (2.9) in the analytical model. In fact, up to 11 percent, the rent effect fully dominates the tax interaction effect.

4.5. Varying the size of the fixed factor

As mentioned, the importance of a fixed factor (perhaps measured as the share of remaining Ricardian rents in electricity cost) is difficult to estimate and subject to debate. In order to address this, we now vary the share of the fixed factor in the production of the polluting good over the range zero to 50 percent. We then measure the total costs of policies for a fixed reduction in emissions of 10% and present the results in Fig. 5.

The curve TC^{RR} shows the total costs of reducing emissions under the environmental tax, when revenues are recycled to cut pre-existing labor taxes. We note that, as the percent of fixed factor in the polluting good rises, the total cost of the policy falls relatively sharply. The costs of the policy actually become negative when the share of fixed factor is higher than 22 percent. If, on the other hand, we totally eliminate the fixed factor from the model, the costs of the policy are about 133 percent of the primary costs, a result which is consistent with previous studies (see e.g., [6]).

The curve TC^{LS} shows the total cost of the emissions tax, when the revenues are returned in a lump sum fashion. The increasing availability of the Ricardian rents no longer reduces the cost of policy, but in fact causes a slight *increase* in cost as the tax rate required to achieve a 10% emissions reduction increases.

In the case where some of the emissions permits are grandfathered (TC^{PERM}) we see that costs are initially higher than in the lump sum case but then begin to fall. This reflects the growing amount of emissions tax revenue coming from Ricardian rents while the fraction of total revenue grandfathered remains constant. As the Ricardian rents become very important they begin to offset the losses from grandfathering, although of course at a slower rate than the TC^{RR} case where no permits are grandfathered.

5. Further sensitivity analysis

We end this section by exploring the sensitivity of the above results to some additional parameter variation. We focus on the cases where a change in the parameters would likely affect the magnitude of the efficiency channels embedded under the different policies and we include the benchmark as the reference case. In particular we vary the size of the polluting industry, the fraction of the fixed factor in the polluting industry, the pre-existing tax on the fixed factor and the elasticity of substitution in production between labor and the fixed factor. Table 2 summarizes the results of the sensitivity analysis.

(i) *Varying the size of the polluting industry*: In the third row in Table 2, we vary the size of the polluting industry between 1 percent (low) and 10 percent (high). We remind the reader that in the central case, we have assumed that the size of the polluting industry was 2.7 percent. Varying the size of the polluting industry scales total costs but the ratio of second best to primary costs remains roughly constant. For a 10 percent emissions reductions this ratio is −0.17 in the central case and it varies between −0.18 and −0.13 in the low and high scenarios. Similarly, for 50 percent emissions reductions, in the central case the ratio of second best costs to primary cost is 1.37 while in the low and high scenarios is 1.37 and 1.39, respectively.

(ii) *Varying the fraction of fixed factor in the polluting industry*: In the forth row in Table 2, we vary the fraction of the fixed factor in the polluting industry between 12.5 percent (low case) and 50 percent

Table 2
Ratio of "second best" total cost to primary cost

Pollution reduction	10%	25%	50%
Central Case	−0.17	1.03	1.37
Size of polluting industry			
Low	−0.18	1.02	1.37
High	−0.13	1.07	1.39
Fraction fixed factor in polluting industry			
Low	0.66	1.18	1.33
High	−2.89	0.62	1.54
Preexisting tax on fixed factor			
Low	−0.37	0.96	1.35
High	0.45	1.24	1.45
Elasticity of subs. in production			
Low	−1.36	0.91	1.45
High	0.51	1.13	1.33

(high case). The central value was 25 percent. Not surprisingly, our results are very sensitive to the share of fixed factor in the production of the polluting good, reflecting the fact that the amount of rent available in the economy varies with this parameter.

(iii) *Varying the pre-existing tax on rents from fixed factor*: In the fifth row in Table 2, we vary the pre-existing tax on the fixed factor between 0 and 40 percent. Increasing the pre-existing tax on the rents from the fixed factor, increases dramatically the ratio of second best costs to primary cost. An increase in the pre-existing tax essentially uses up some of the resource rents and eliminates the possibility for the environmental tax to swap burden away from the labor market towards the Ricardian rent.

(iv) *Varying the elasticity of substitution in the production of the polluting good*: In the last row in Table 2, we vary the elasticity of substitution in the production of the polluting good between 0.5 and 2. Varying this parameter highlights two interesting results. First, at 10 percent emissions reductions, increasing the elasticity of substitution reduces the rents from the fixed factor and, in turn, increases the ratio of second best cost to primary cost. Second, increasing the elasticity of substitution also decreases the costs of substitution for higher levels of emissions reductions. Therefore the ratio of second best total cost to primary cost at 50 percent is actually lower in the high elasticity case.

We conclude this section by noting the following two additional points. At 10 percent emissions reductions, the cost ratio is quite sensitive to the choice of parameter values. However, as the level of emissions reductions increases, the ratios converge to the results presented in Goulder et al. [6], a reflection of the dominance of the traditional tax interaction effect. Second, for moderate levels of emissions reduction, the second best cost with a fixed factor and revenue-recycling is always cheaper than primary costs, suggesting a potential for a double-dividend to occur.

6. Conclusions

This paper uses simple analytical and numerical simulation models to demonstrate the potential importance of fixed-factors and Ricardian rents in the production of polluting goods for the general equilibrium welfare effects of environmental policies. In the presence of fixed factors in the production of polluting goods and (partially) untaxable Ricardian rents, a tax system consisting of a labor tax is not optimal to begin with, even from a non-environmental perspective. In this setting the welfare gain from introducing an environmental tax with revenues used to cut pre-existing labor taxes can be significantly higher than implied by earlier models. In fact, under certain conditions, the overall costs of an environmental tax swap can be negative and produce a strong double dividend. In our simulations, this was the case up to 11 percent of emissions reductions. This result has clear implications for policy analysis and suggests that even in the absence of clear evidence about the benefits from emissions reductions, the environmental tax should be part of the tax system. Our results also suggest that the cost savings from using revenue-neutral environmental taxes over non-auctioned pollution permits can be dramatically higher than suggested in previous literature.

In some sense our results highlight the tradeoffs between primary costs, first, and second dividends of environmental policies. From an environmental perspective, the presence of fixed factors in the production of polluting goods can compromise the magnitude of the first dividend, simply because part of the tax falls on the fixed factor and the price of the polluting good does not increase by the full amount of the environmental tax. However, and for the exact same reason, the environmental tax swap reduces the overall cost of the tax system because it shifts the burden away from labor towards the fixed factor, producing a positive second dividend.

Acknowledgments

We thank Lawrence Goulder, Rob Williams, the two referees and the editor for very helpful comments.

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