Environmental tax reform and induced technological change

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Abstract

This paper examines the importance of induced technological change in considering the efficiency costs of environmental policy. In particular, in modeling an endogenous formation of energy-saving technology through a variety of intermediates, the paper studies the welfare effects of environmental tax reform in a general equilibrium model. Using this model, the paper shows that environmental tax reform induces an expansion of the variety of intermediates by increasing rents from innovating new intermediates and, thereby, brings technological change. Then, the induced variety expansion by environmental tax reform achieves positive externalities and plays an important role both to decrease the efficiency costs and to improve the environmental quality.

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1 Introduction

The trade-off between environmental quality and economic efficiency has been controversial in the design of environmental policy. To mitigate environmental problems without causing serious damage to economic efficiency, economists have considered a number of policy packages and examined the economic impacts in different situations. In this context, an environmental tax has been focused on because it has two properties: (i) it raises government revenues and (ii) it induces innovations of environmentally friendly technology.

The revenue-raising property can play an important role in the second-best economy where economic inefficiencies preexist because of distortionary taxes such as an income tax. Then, the inefficiencies may be reduced by using environmental tax revenues to cut preexisting distortionary tax rates under constant government revenues. This policy package works as both environmental regulation and fiscal reform and is known as environmental tax reform. This policy is expected to improve not only environmental quality (a first dividend) but also economic efficiency (a second dividend); i.e., there is a *double dividend*.

However, theoretical studies using general equilibrium models such as Bovenberg and de Mooij (1994), Parry (1995) and Goulder et al. (1997) show that environmental tax reform exacerbates rather than improves economic efficiencies. This result is driven by two opposite welfare effects. First, by replacing distortionary taxes, environmental tax reform can decrease preexisting distortions. This is called the *revenue-recycling effect*, which improves welfare. Second, a price rise of final goods from the environmental tax makes households substitute the final goods for leisure and, thereby, decreases labor supply. By shifting the labor supply curve to the left, this path decreases government revenues from a labor income tax and increases marginal distortions per unit of income tax revenue. This effect is known as the *tax-interaction effect*, which decreases welfare. Previous studies reveal that the tax-interaction effect is greater than the revenue-recycling effect under plausible conditions, and that the double dividend cannot be obtained.[1]

In contrast to the former general studies, some subsequent studies examines special cases to reconsider the magnitude of the tax-interaction effect (e.g., Schwartz and Repetto, 1997; Parry and Bento, 2000; Williams, 2002;

[1] Previous papers find that a strict increase in both environmental quality and economic efficiency (i.e., a strict double dividend) is not attained. Meanwhile, a weak double dividend can be obtained, that is, efficiency costs are smaller in the case where environmental tax revenues are transferred in a lump-sum fashion. For details, see Goulder (1995) and Bovenberg (1999).

Bento and Jacobsen, 2007; Yamagami, 2009). Although these studies indicate the possibility of a double dividend, there is a tendency to assume exogenous factor productivity and an independent production technology from environmental policies. In fact, an increasing number of empirical studies confirm a positive correlation between stringency of environmental regulations and total factor productivity or factor-specific productivity, especially in relation to emission abatement and energy conservation. For example, Jaffe et al. (2002), Löschel (2002) and Popp et al. (2009) provide broad surveys on the technological change induced by environmental regulations. Moreover, Goulder and Schneider (1999), Goulder and Mathai (2000) and Buonanno et al. (2001) numerically demonstrate the cost-effectiveness of the induced technological change in achieving a given goal of emission reduction. That is, the introduction of environmental policies can improve productivity by inducing the technological change and, thereby, affect the overall costs of environmental policies. This fact naturally raises the question of how the induced technological change affects the costs of environmental tax reform, that is, the tax-interaction effect. Therefore, the present paper sheds light on the other property of an environmental tax that induces innovations of environmentally friendly technology, in the framework of environmental tax reform. For this purpose, the paper models an endogenous formation of production technology related to natural resource use.[2]

Among previous papers on environmental tax reform, that by Bento and Jacobsen (2007) is closely related to our work in relation to resource use. In their paper, the resource is regarded as a fixed factor while labor is assumed to be a unique variable input. Furthermore, they suppose that pollution emissions occur as a function of output. In this model, they show that increasing emission costs as a result of an environmental tax are not fully passed on to the price of final goods because of the production function of the decreasing-returns-to-scale. Then, the tax-interaction effect that arises as a result of the price rise from the environmental tax is scaled down so that the nonenvironmental dividend is obtained. However, because pollution occurs as a function of output, a modest price rise of final goods leads to a small amount of pollution reduction instead of the small tax-interaction effect. Therefore, they find a trade-off between the two dividends.

This paper, in contrast, assumes the resource is a variable polluting factor and models an endogenous formation of resource-use productivity. A

[2]Investments in emission abatement or end-of-pipe technologies that are induced by environmental policies are considered in the literature, for example, Goulder et al. (1997) and Bovenberg et al. (2005). Although the literature finds that the emission abatement technologies help in achieving the given goals of emission reduction with low efficiency costs, these technologies cannot create a double dividend.

final good related to pollution emissions is produced with energy services and labor under the constant-returns-to-scale technology. Energy services are manufactured by using a natural resource and a composite of intermediates (or blueprints) that a research and development (R&D) sector innovates and provides in the monopolistic factor markets of Dixit and Stiglitz (1977). By adopting these intermediates, a representative firm that produces the final good constructs the technology level of processing natural resources into energy services. Then, because the composite of these intermediates enables the manufacture of a given amount of energy services with less of the natural resource, the paper refers to the composite as the energy-saving technology.

With this model, the paper shows that an environmental tax endogenously induces the technological change via an expansion of a variety of intermediates. As the environmental tax raises rents for R&D firms from innovating new intermediates by increasing demand for the energy-saving technology, an expansion of the variety of intermediates is induced. Then, the representative firm producing the final good can substitute not only existing nonpolluting inputs but also newly innovated intermediates for the polluting natural resource. Substitutions to newly innovated intermediates cause positive externalities on the resource-use productivity of the representative firm and control a price rise of the final good such as in Bento and Jacobsen (2007). The tax-interaction effect is then narrowed and, thereby, the nonenvironmental dividend is obtained. However, in contrast to Bento and Jacobsen (2007), this paper supposes that pollution occurs in relation to the amount of the resource used. The environmental dividend is then higher relative to that shown in the previous papers because of the induced expansion of the variety of intermediates for energy saving. Furthermore, this paper finds that even if the double dividend is obtained because of the positive externalities, the second-best optimal environmental tax rate cannot exceed the first-best level. The literature uses the optimal tax rate to examine whether the double dividend occurs, whereas this paper shows that it cannot be an indicator of the double dividend.

The organization of this paper is as follows. Section 2 presents a model with endogenous energy-saving technology formation and shows that a variety of intermediates used for energy saving affects the energy-saving technology level. Section 3 considers environmental tax reform and its welfare effects by examining how environmental tax reform affects the endogenously determined variety of intermediates. Section 4 provides further discussions on the contributions of the induced variety expansion of intermediates. Finally, Section 5 concludes the paper.

2 The model

The present model refers to traditional general equilibrium models of environmental tax reform (e.g., Bovenberg and de Mooij, 1994; Parry, 1995; and Goulder et al., 1997) and incorporates an endogenous productivity formation via a variety of horizontally differentiated intermediates à la Romer (1990).

2.1 Pollution emission

Pollution emission (E) occurs by using Z units of the natural resource. The emission function is assumed to be linear as follows: $E = \epsilon Z$, where $\epsilon > 0$ is an emission coefficient per unit of resource use. [3]

2.2 Final goods

Following the literature, we suppose two types of final consumption goods (X and Y). On the one hand, good X requires labor and energy services as inputs and, therefore, pollution emissions occur in this sector. Good Y, on the other hand, is environmentally neutral in its production processes because it requires only labor inputs.

2.2.1 Good Y

A representative firm competitively provides good Y by using L_Y units of labor as a unique input. In particular, it is assumed that one unit of labor produces one unit of good Y, i.e., $Y = L_Y$. Therefore, the price of good Y corresponds to the wage rate, $p_Y = w$.

2.2.2 Good X

A representative firm produces good X by using R units of energy services and L_X units of labor under CES technology:

$$X = \left(\beta_L L_X^{\frac{\sigma_x - 1}{\sigma_x}} + \beta_R R^{\frac{\sigma_x - 1}{\sigma_x}} \right)^{\frac{\sigma_x}{\sigma_x - 1}}, \tag{1}$$

where β_j ($j = \{L, R\}$) is a scale parameter for each input, and σ_x is the elasticity of substitution between factors. Similar to the numerical models in

[3]Some previous papers considers an endogenous emission parameter and, thereby, an end-of-pipe technology (e.g., Goulder et al., 1997; Bovenberg et al., 2005). However, these studies find that the end-of-pipe technology plays a role of reducing welfare cots of environmental policy while the double dividend cannot be obtained. Therefore, the present paper simplifies it and focuses on the energy-saving technology as shown below.

the previous papers, the elasticity of substitution is assumed to be strictly positive and less than one (i.e., $\sigma_x \in (0,1)$).

Energy services are manufactured from Z units of the natural resource by adopting H units of the energy-saving technology according to the Cobb–Douglas function with an exogenous parameter $\sigma_r \in (0,1)$:

$$R = Z^{\sigma_r} H^{1-\sigma_r}. \tag{2}$$

The energy-saving technology is characterized as a composite of horizontally differentiated intermediates or blueprints ($h(i)$, $i \in [0,n]$) in a CES function, where n is the variety of available intermediates:

$$H = \left(\int_0^n h(i)^{1-\sigma_r} di \right)^{\frac{1}{1-\sigma_r}}. \tag{3}$$

That is, a combination of these intermediates forms a productivity of H as the energy-saving technology used to process the natural resource and manufacture the energy services.

Alternatively, as shown in Smulders and de Nooij (2003), these production processes can be described more simply using the following expression:

$$A_H = \int_0^n \left(\frac{h(i)}{Z} \right)^{1-\sigma_r} di = \left(\frac{H}{Z} \right)^{1-\sigma_r}. \tag{4}$$

Using this expression allows us to rearrange (1) as follows:

$$X = \left\{ \beta_L L_X^{\frac{\sigma_x-1}{\sigma_x}} + \beta_R (A_H Z)^{\frac{\sigma_x-1}{\sigma_x}} \right\}^{\frac{\sigma_x}{\sigma_x-1}}.$$

The production function (1) is thus presented in a conventional form with A_H as an endogenously determined factor augmentation for resource use. Then, because the factor augmentation measures the productivity of intermediates per unit of resource use for manufacturing energy services, we simply refer to A_H as the energy-saving technology level in the following.

Factor demand

From the above, the polluting firm faces the following total cost function:

$$TC = wL_X + p_Z Z + \int_0^n p_H(i) h(i) di + t_E E, \tag{5}$$

where p_Z, $p_H(i)$ and t_E are the price of the natural resource, the price of the ith intermediate and the emission tax rate, respectively.

By taking H as given, factor demand for the ith intermediate is given as follows (see Appendix A.1 for the derivation):

$$h(i) \;=\; \frac{p_H(i)^{-\frac{1}{\sigma_r}}\;H}{\left(\int_0^n p_H(j)^{-\frac{1-\sigma_r}{\sigma_r}}dj\right)^{\frac{1}{1-\sigma_r}}}. \tag{6}$$

That is, the demand for each intermediate is decreasing in its own price, while increasing in the prices of rival intermediates. Regarding the variety, when all intermediates are assumed to be identical in pricing (i.e., $p_H(i) = p_H(j)$, $\forall i \neq j \in [0, n]$), the demand for a certain intermediate (6) is rewritten as $h = n^{-1/(1-\sigma_r)}H$. This expression indicates that an expansion of the variety leads to a smaller demand for each existing intermediate because, taking H as given, demand is equally spread among all intermediates including the newly innovated ones.

Subsequently, taking R as given, the factor demands for the natural resource and energy-saving technology are derived as follows:

$$Z \;=\; \left(\frac{\sigma_r}{1-\sigma_r}\,\frac{c_H}{c_Z}\right)^{1-\sigma_r} R, \tag{7}$$

$$H \;=\; \left(\frac{1-\sigma_r}{\sigma_r}\,\frac{c_Z}{c_H}\right)^{\sigma_r} R, \tag{8}$$

where c_Z and c_H are the unit costs of resource use and energy-saving technology, defined as follows:

$$c_Z \;\equiv\; p_Z + \epsilon t_E \tag{9}$$

$$c_H \;\equiv\; \left(\int_0^n p_H(i)^{-(1-\sigma_r)/\sigma_r} di\right)^{-\sigma_r/(1-\sigma_r)}. \tag{10}$$

As shown in (7) and (8), these factors are substitutes for each other under a given amount of energy services. Therefore, (9) shows that the emission tax causes a lower demand for the natural resource and a greater demand for the energy-saving technology. Moreover, in the symmetric equilibrium of $p_H(i) = p_H(j)$ $\forall i \neq j \in [0, n]$, (10) is rewritten in reduced form, $c_H = n^{-\sigma_r/(1-\sigma_r)}p_H$, and the unit cost of energy-saving technology (10) is lowered when the variety of intermediates is expanded.

Facing a given amount of supply for good X, the polluting firm demands labor and energy services as follows:

$$L_X \;=\; \left(\frac{\beta_L}{w}\right)^{\sigma_x} \frac{X}{\left(\beta_L^{\sigma_x} w^{1-\sigma_x} + \beta_R^{\sigma_x} c_R^{1-\sigma_x}\right)^{\frac{\sigma_x}{\sigma_x - 1}}}, \tag{11}$$

$$R \;=\; \left(\frac{\beta_R}{c_R}\right)^{\sigma_x} \frac{X}{\left(\beta_L^{\sigma_x} w^{1-\sigma_x} + \beta_R^{\sigma_x} c_R^{1-\sigma_x}\right)^{\frac{\sigma_x}{\sigma_x - 1}}}, \tag{12}$$

where c_R is the unit cost of the energy service, defined as:

$$c_R \equiv \left(\frac{c_H}{1-\sigma_r}\right)^{1-\sigma_r}\left(\frac{c_Z}{\sigma_r}\right)^{\sigma_r}. \tag{13}$$

Finally, by using (6) to (13), the total cost (5) is rearranged as follows:

$$TC = c_X \cdot X, \tag{14}$$

where c_X is a unit cost to supply good X:

$$c_X \equiv \left(\beta_L^{\sigma_x} w^{1-\sigma_x} + \beta_R^{\sigma_x} c_R^{1-\sigma_x}\right)^{\frac{1}{1-\sigma_x}}. \tag{15}$$

Consequently, as the representative firm is assumed to be competitive, c_X corresponds to the marginal cost of producing good X. Then, the supply curve of good X is horizontal at $p_X = c_X$.

2.3 Natural resource

A representative firm Z is assumed to competitively supply natural resources by employing L_Z units of labor as a unique input. The production function in this sector is described as a simple form, $Z = L_Z$, that is, one unit of labor input produces one unit of natural resource. As its supply curve is then horizontal the price of natural resource is set at a marginal cost, $p_Z = w$.

2.4 Intermediates for energy saving

The R&D sector in which intermediates for energy saving are innovated is assumed to require F_H units of labor input to develop a new intermediate and one unit of labor input to produce one unit of intermediate (i.e., $h(i) = L_H(i)$). Moreover, these intermediates are priced under monopolistic competition (cf. Dixit and Stiglitz, 1977). Then, the profit function of firm i is given as $\pi_H(i) = \{p_H(i) - w\}h(i) - wF_H$.

By using (6), a monopolistic price is set at:[4]

$$p_H(i) = \frac{w}{1-\sigma_r}. \tag{16}$$

Thus, the price of the ith intermediate is greater than the marginal cost because of the markup rate, $(1-\sigma_r)^{-1} > 1$.

[4]It is supposed that each firm in the R&D sector is so small on a continuous space that it cannot recognize an integral part of demand for its supplying intermediate. That is, H and $\int_0^n p_H(i)^{1-\sigma_r} di$ in (6) are taken as given in monopolistic pricing. The demand elasticity is then $-\frac{p_H(i)}{h(i)}\frac{\partial h(i)}{\partial p_H(i)} = \frac{1}{\sigma_r}$ by each firm.

2.5 Household

Following the literature (cf. Bovenberg and de Mooij, 1994; Parry, 1995), a representative household supplies L units of labor and consumes final consumption goods X and Y. In our model, the household receives additive separable benefits from G units of public services, and suffers environmental damages from pollution emissions. Then, her/his utility function is given as: $U = u_0(G) + u_1(X, Y, \bar{L} - L) - D(E)$, where $\bar{L}$ is the total time endowment. Normalizing the wage rate to unity (i.e., $w = 1$ and therefore $p_Y = 1$) and taking the price of consumption goods, environmental externalities and policy instruments as given, the household maximizes its utility under the budget constraint $p_X X + Y = (1 - t_L)L$, where t_L is the income tax rate.

The demand functions for consumption goods and a labor supply function are then derived as $X(p_X, t_L)$, $Y(p_X, t_L)$, $L(p_X, t_L)$. By using these demand and supply functions, the indirect utility from consuming private goods and leisure is rewritten as $v_1(p_X, t_L)$.

2.6 Government

The government balanced-budget constraint is written as:

$$TR = t_L L + t_E E, \tag{17}$$

where TR is the total government revenue requirement. The public services are provided by spending this revenue. For simplicity, it is assumed that one unit of labor input is employed to provide one unit of public service ($G = L_G$). As the wage rate is normalized to one, government revenue is transformed to $G = TR$ units of public services.

2.7 Equilibrium

As the wage rate is normalized to unity, the equilibrium in the final goods and labor markets is characterized by $p_X = c_X$ and $X(c_X, t_L)$ for good X, $p_Y = w$ and $Y(c_X, t_L)$ for good Y and $w = 1$ and $L(c_X, t_L) = L_X + L_Y + L_Z + nF_H + \int_0^n L_H(i)di + L_G$ for labor. The equilibrium price of the natural resource market equals to the wage $p_Z = w$ so that the equilibrium quantity of Z is determined by (7). Moreover, the monopolistic price of all intermediate for energy saving is all identical as shown in (16) i.e., $p_H(i) = p_H(j)$ $\forall i \neq j \in [0, n]$. This implies that the equilibrium quantity of intermediates is also identical (i.e., $h(i) = h(j)$ $\forall i \neq j \in [0, n]$).

Symmetric equilibrium with free entry in intermediate markets

By unifying the prices of intermediates to p_H, demand for each intermediate (6) is rewritten as follows:

$$h = n^{-\frac{1}{1-\sigma_r}} H. \tag{18}$$

From (18), it is clearly seen that, taking demand for energy-saving technology as given, the demand for each intermediate decreases with respect to the variety of intermediates as a result of spreading demand between existing and new intermediates.

In contrast, by substituting (16) and (18) and setting $w = 1$, the profit function is rewritten as:

$$\pi_H = \frac{\sigma_r}{1-\sigma_r} n^{-\frac{1}{1-\sigma_r}} H - F_H.$$

That is, the demand for energy-saving technology, H, takes the form of rents for each R&D firm from increasing sales and, thereby, profits. The assumption of free entry implies that new entrants appear as long as the profit is strictly positive. However, as (18) shows a decreasing demand for existing intermediates in variety, new entry stops when the rents of each firm in the R&D sector reach zero. Consequently, because the zero profit condition holds at equilibrium, the variety of intermediates is finally determined as:

$$n = \left(\frac{\sigma_r}{1-\sigma_r} \frac{H}{F_H} \right)^{1-\sigma_r}. \tag{19}$$

Thus, the market equilibrium of all intermediates is identically characterized by the free entry assumption and, as a result, leads to the endogenously determined variety of intermediates (19). Then, the rents of the demand for energy-saving technology, H, encourages potential R&D firms to develop new intermediates while the fixed costs discourage them.

Moreover, as the price of all intermediates is identical, as shown in (16), the unit cost of energy-saving technology, c_H, in (10) is rewritten as follows:

$$c_H = \frac{n^{-\sigma_r/(1-\sigma_r)}}{1-\sigma_r}. \tag{20}$$

The unit cost for energy-saving technology decreases with respect to the variety of intermediates. That is, when a new intermediate appears, firm X spreads the demand for each existing intermediate to satisfy a given amount of demand for energy-saving technology.

Then, by substituting (7), (8), (9) and (20) into (4), the endogenous energy-saving technology level, A_H, can be rearranged as a function of the number of available intermediates: $A_H = \left\{ \frac{(1-\sigma_r)^2}{\sigma_r}(p_Z + \epsilon t_E) \right\}^{1-\sigma_r} n^{\sigma_r}$. This expression indicates that the energy-saving technology level can be affected by the emission tax, that is, that the induced technological change in energy saving occurs as a result of the emission tax. To show this, differentiating it with respect to the emission tax rate gives:

$$\frac{dA_H/dt_E}{A_H} = (1-\sigma_r)\frac{\epsilon}{p_Z + \epsilon t_E} + \sigma_r \frac{dn/dt_E}{n}. \tag{21}$$

This represents an induced rate of change in the energy-saving technology level. Thus, by increasing the costs of resource use, the emission tax affects the energy-saving technology level via two paths. First, the emission tax makes the firm substitute the natural resource for existing nonpolluting inputs. Additionally, there is an indirect effect from an induced variety expansion of intermediates. The emission tax stimulates rents from innovations of intermediates by increasing the demand for energy-saving technology. Thus, as the variety of intermediates expands, firm can raise the energy-saving technology level by adopting not only existing intermediates but also newly developed ones. As shown below, this second effect on the induced technological change via the variety expansion of intermediates has an important effect on the welfare effects of environmental tax reform.

3 Revenue-neutral environmental tax reform

3.1 Welfare effects

We consider here the welfare effects of environmental tax reform by which increasing emission tax revenue is used to reduce the labor income tax rate under constant government spending.

Let us begin by differentiating the utility function with $dTR = dG = 0$: $\frac{dV}{dt_E} = \frac{\partial v_1}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial v_1}{\partial t_L}\frac{dt_L}{dt_E} - D'(E)\frac{dE}{dt_E}$. By using Roy's identity (λ represents the marginal utility of income): $\frac{\partial v_1}{\partial p_X} = -\lambda X$, $\frac{\partial v_1}{\partial t_L} = -\lambda L$, the welfare change is rearranged as follows:

$$\frac{1}{\lambda}\frac{dV}{dt_E} = -X\frac{dp_X}{dt_E} - L\frac{dt_L}{dt_E} - \frac{D'(E)}{\lambda}\frac{dE}{dt_E}. \tag{22}$$

Totally differentiating the government budget constraint (17) gives a policy rule whereby the income tax rate is reduced with constant government spending ($dG = dTR = 0$):

$$\frac{dt_L}{dt_E} = -\frac{\left(E + t_E \frac{dE}{dt_E}\right) + t_L \frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E}}{L + t_L \frac{\partial L}{\partial t_L}}. \tag{23}$$

When the economy initially satisfies the conditions that the emission tax rate is low and the labor market size is large, the income tax rate is successfully reduced as a result of the revenue-neutral environmental tax reform. This paper considers this case and assumes that dt_L/dt_E is strictly negative.

By substituting this policy rule into (22), the welfare change is rewritten as follows:

$$\begin{aligned} \frac{1}{\lambda}\frac{dV}{dt_E} &= \underbrace{\left\{-\frac{D'(E)}{\lambda}\frac{dE}{dt_E} + \left(E + t_E\frac{dE}{dt_E}\right) - X\frac{dp_X}{dt_E}\right\}}_{dW_P} \\ &\quad + \underbrace{M\left(E + t_E\frac{dE}{dt_E}\right)}_{dW_R} + \underbrace{(1+M)t_L\frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E}}_{dW_I}, \end{aligned} \tag{24}$$

where M is the *marginal welfare cost of income taxation*, representing a partial equilibrium marginal welfare loss via income taxation, weighted by its marginal revenue. It is defined by $M = \frac{-t_L\frac{\partial L}{\partial t_L}}{L+t_L\frac{\partial L}{\partial t_L}}$.

dW_P is the *primary welfare effect*, describing the welfare gains that arise when the emission tax rate is increased and its revenue is transferred to households in a lump-sum fashion, in the absence of preexisting distortionary taxes. That is, this is the first-best welfare effect of an emission tax. In particular, the first term in dW_P is known as the *Pigouvian effect*, which represents an improvement in environmental quality measured in monetary terms. The second is a primary direct effect if emission tax revenues are transferred as a lump sum. The third is, however, the marginal loss of consumer surplus in the market for good X, which is called the *primary welfare cost*, because it involves an increase in the price of good X as a result of an emission tax. In the first-best economy, the optimal emission tax rate is then derived such that the primary welfare effect becomes zero.

Moreover, the welfare is also influenced by how the emission tax revenues are used. The tax reform cuts the income tax rates such that an increase in the total government revenues from an emission tax is offset. The preexisting distortions in the labor market thus can be reduced and, thereby, there appears a nonenvironmental welfare gain. This effect is known as the *revenue-recycling effect* and is written by dW_R in (24). That is, this effect equals zero in the case where the emission tax revenue is transferred as a lump sum. In contrast, there is another nonenvironmental welfare effect from the *tax-interaction effect*. This effect occurs because the increasing emission tax rate raises the market price of good X, which leads to a relative increase in price of good X. Then, household behavior that substitutes good X for leisure results in a decrease in the preexisting labor tax revenue and, thereby, prevents tax swapping. At the same time, as decision making on labor–leisure choice is distorted (the labor supply curve shifts), preexisting distortions per unit of income tax revenue in the labor market are magnified by $1 + M$.

The literature reports that the tax-interaction effect is greater than the revenue-recycling effect and, therefore, environmental tax reform decreases market efficiencies. This conclusion is brought about by restricted functional forms for production and emissions. In contrast, by introducing R&D firms, the present model shows that the magnitude of the tax-interaction effect depends on the price change of good X in (24), i.e., dp_X/dt_E. Therefore, to clarify its magnitude, how the price of good X is affected has to be resolved.

3.2 Induced technological change and price change

As $p_X = c_X$, by differentiating (15) and using emission function ($E = \epsilon Z$), (7), (9), (12), (13) and (20), the effect of the environmental tax reform on the price of good X is described as follows:[5]

$$\frac{dc_X}{dt_E} = \frac{E}{X}\left(1 - \frac{c_Z}{\epsilon n}\frac{dn}{dt_E}\right). \tag{25}$$

The effects on price of the emission tax are shown in two parts. The first term is the *primary price effect*, which represents a direct price rise from the emission tax. Then, taking the variety of intermediates for energy-saving technology as given, this term includes only a marginal increase in the production cost as a result of the increasing emission tax rate and the substitution of Z for labor and the existing variety of intermediates. In addition, the second term is the *indirect price effect from an induced variety expansion*. This term represents a price change via a substitution of Z for newly developed intermediates for energy saving and its magnitude depends on the expansion level of the variety, n. Therefore, at the same time as improving the technology level for energy saving as shown in (21), the new innovations of intermediates will increase the opportunity of controlling an increase in the marginal production cost of good X.

[5]Note that $E/X = (\frac{\beta_R c_X}{c_R})^{\sigma_x} \cdot \frac{\epsilon \sigma_R c_R}{c_Z}$ from the emission function, (7), (12) and (13).

Consider the case where the variety of intermediates is fixed. Then, the indirect price effect does not exist and the price change is given simply as $dc_X/dt_E = E/X$. This expression is used commonly in the literature, implying that the double dividend cannot be obtained under plausible conditions. The present model, on the other hand, shows that the free entry assumption characterizes an endogenous variety of intermediates. As shown in (19), the variety is affected by a change in the demand for energy-saving technology, H. Differentiating (19) gives:

$$\frac{dn}{dt_E} = (1-\sigma_r)\frac{n}{H}\frac{dH}{dt_E}. \tag{26}$$

That is, when the emission tax increases the demand for energy-saving technology, rents from innovating new intermediates are increased. This leads to an expansion of the variety of available intermediates.

By using (8), (12) and (20), and considering the feedback effect, a total change in H by the emission tax is derived as follows:

$$\begin{aligned}\frac{dH}{dt_E} \;=\; \frac{H}{1-\sigma_r}\Bigg[&\frac{\epsilon}{c_Z}\cdot\frac{\sigma_r(1-\sigma_x)\beta_L^{\sigma_x}+\sigma_r(1-\eta_x)\beta_R^{\sigma_x}c_R^{1-\sigma_x}}{\{1+\sigma_r(1-\sigma_x)\}\beta_L^{\sigma_x}+\{1+\sigma_r(1-\eta_x)\}\beta_R^{\sigma_x}c_R^{1-\sigma_x}}\\ &+\frac{(\beta_L^{\sigma_x}+\beta_R^{\sigma_x}c_R^{1-\sigma_x})\frac{\partial X/\partial t_L}{X}\frac{dt_L}{dt_E}}{\{1+\sigma_r(1-\sigma_x)\}\beta_L^{\sigma_x}+\{1+\sigma_r(1-\eta_x)\}\beta_R^{\sigma_x}c_R^{1-\sigma_x}}\Bigg],\end{aligned} \tag{27}$$

where η_x is the price elasticity of demand for good X and is assumed to be strictly less than one: $\eta_x = -\frac{p_X}{X}\frac{\partial X}{\partial p_X}$ and $\eta_x \in (0,1)$. This expression implies that there are two paths to stimulate rents for providing intermediates for energy saving. As the emission tax raises the cost of using natural resources, the first term in square brackets represents a substitution of the natural resources for nonpolluting inputs including the energy-saving technology. The second term exhibits an increase in production inputs including the energy-saving technology as a result of environmental tax reform. A partial derivative consisting this second term, $\frac{\partial X}{\partial t_L}$, is rewritten as $\frac{\partial X}{\partial t_L} = -w\bar{L}\frac{\partial X}{\partial I}$ where $I = (1-t_L)w\bar{L}$ is an exogenous after-tax income for household. As long as the income leads to an increase in demand for good X, a decrease in the income tax rate leads to more of good X in equilibrium and, thereby, more of production inputs including the energy-saving technology are required.[6]

[6]Considering the second term as a feedback effect for environmental tax reform, we can rearrange the tax-swapping rule of (23), again. However, the analytical results earned by doing so are identical to those found by simply using (27), which will be shown below. To avoid confusing expressions, we use (27) to reveal the welfare effects in the following.

Consequently, both of the two paths, by increasing the demand for energy-saving technology, raises the rents of innovating new intermediates for R&D firms (i.e., $dH/dt_E > 0$).

As $dH/dt_E > 0$, (26) shows that the variety of intermediates is expanded (i.e., $dn/t_E > 0$). From (21) and (25), the induced variety expansion of intermediates for energy saving thus results in not only the induced technological change in energy-saving technology level but also the controlled the price rise of good X. Therefore, the price change is strictly less than the primary price effect, E/X.

3.3 Positive externalities from the induced variety expansion of intermediates for energy saving

Consider a case where the labor income tax rate is zero, $t_L = 0$, and the emission tax revenue is transferred to the household as a lump sum. That is, the whole welfare effect in this case corresponds to the primary welfare effect, dW^P, in (24). Then, by using (25), the welfare effects are manipulated as:

$$\frac{1}{\lambda}\frac{dV}{dt_E}\bigg|_{t_L=0} = \underbrace{\left(-\frac{D'(E)}{\lambda} + t_E\right)\frac{dE}{dt_E}}_{dW^E} + c_Z Z \cdot \frac{dn/dt_E}{n}. \tag{28}$$

dW^E is the primary environmental effect that corresponds to the first-best welfare effects from environmental protection when the induced technological change is not considered. This term is then referred to as the first dividend if its sign is positive. Moreover, the present model brings an additional effect as shown in the last term on the right-hand side of (28). This effect comes from a controlled price rise whose origin is the induced variety expansion of intermediates for energy saving. This effect thus creates positive externalities on welfare in the nonenvironmental part of the economy. Consequently, the first-best optimal emission tax rate is strictly greater than the marginal environmental damage in monetary terms:

$$t_E^{1st} = \frac{D'(E)}{\lambda} + \frac{c_Z}{\epsilon}\left(-\frac{E}{n}\frac{\frac{dn}{dt_E}}{\frac{dE}{dt_E}}\right). \tag{29}$$

3.4 Double dividends in the presence of induced technological change

As in the literature, let us suppose that the consumption goods are equal substitutes for leisure. By substituting (25) into (24), the welfare effect of environmental tax reform can be rearranged as follows (see Appendix A.2 for the derivation of (30)):

$$\frac{1}{\lambda}\frac{dV}{dt_E} = \underbrace{\left(-\frac{D'(E)}{\lambda} + t_E\right)\frac{dE}{dt_E}}_{dW^E} + \underbrace{Mt_E\frac{dE}{dt_E}}_{dW_1^{NE}} + \underbrace{(1+M)c_Z Z\frac{dn/dt_E}{n}}_{dW_2^{NE}}. \tag{30}$$

The welfare effect can be decomposed into the following three effects: primary environmental effect, dW^E, and two nonenvironmental effects, dW_1^{NE} and dW_2^{NE}. The primary environmental effect equals the one shown in the first-best economy. In addition, the first nonenvirnomental effect (dW_1^{NE}) occurring in the second-best setting is a summation of the revenue-recycling effect and a primary part of the tax-interaction effect. The sign of dW_1^{NE} is negative unless $t_E = 0$ because of the sufficiently large tax-interaction effect. The sum of these two effects (i.e., $dW^E + dW_1^{NE}$) corresponds to that in the literature which explains that the double dividend cannot be obtained (e.g., Goulder et al., 1997).

However, in the presence of the induced technological change, the second nonenvironmental effect (dW_2^{NE}) arises via the controlled price rise by the induced variety expansion of intermediates, and its sign is positive regardless of the initial emission tax rate. The two nonenvironmental effects, $dW_1^{NE} + dW_2^{NE}$, are referred to as the second dividend if the sum of these effects is strictly positive. Then, note that when the initial emission tax rate is zero, dW_1^{NE} equals zero, whereas dW_2^{NE} remains positive. That is, the sum of these two nonenvironmental effects is positive, at least, in a range of sufficiently low emission tax rates. Then, as both dW^E and $dW_1^{NE} + dW_2^{NE}$ are strictly positive at the same time, the double dividend can be obtained.

4 Further discussions

4.1 Magnitude of the first dividend

Bento and Jacobsen (2007) derive the trade-off between the first and second dividends by showing that emission tax burdens are not fully transferred to the price of polluting goods as well as in the present model. The trade-off arises in their model because of an assumption that pollution emissions increase with respect to the total output of good X. Then, the modest price rise of polluting goods relative to an increase in the emission tax rate implies a modest decrease in the quantity of traded polluting goods in size. Thus, instead of decreasing the tax-interaction effect, the pollution reduction (the first dividend) also becomes small.

In contrast, this result does not hold in the present model because pollution emissions arise from resource use as an input and the positive externalities from the induced variety expansion. To show this, the emission function, $E = \epsilon Z$, is differentiated with respect to the emission tax rate and rearranged by using (7):

$$\frac{dE}{dt_E} = \left.\frac{dE}{dt_E}\right|_{\frac{dn}{dt_E}=0} - \frac{\sigma_r(1-\sigma_x)\beta_L^{\sigma_x} + \sigma_r(1-\eta_x)\beta_R^{\sigma_x} c_R^{1-\sigma_x}}{\beta_L^{\sigma_x} + \beta_R^{\sigma_x} c_R^{1-\sigma_x}} \cdot E \cdot \frac{dn/dt_E}{n}.$$

The first term is the amount of reduced emissions in the case where the variety of intermediates is fixed.[7] The second term exhibits a further effect that reduces emissions through the induced variety expansion of intermediates because the polluting firm can substitute not only existing nonpolluting inputs but also newly developed intermediates for polluting inputs. The variety expansion enforces the first dividend and, consequently, breaks the trade-off between the first and second dividends.

4.2 Comparison of the optimal emission tax rates

Here, the optimal emission tax rates in the first- and the second-best settings are compared. By setting the left-hand side of (30) to be zero and using (29), the second-best optimal emission tax rate is given as:

$$t_E^{2nd} = t_E^{1st} - \frac{M}{1+M}\frac{D'(E)}{\lambda}.$$

That is, the second-best emission tax rate is strictly less than the first-best level even if environmental tax reform brings about the double dividend. This result arises because the positive externalities are not included in the first environmental dividend whereas it is taken into account when setting the optimal emission tax rate.

The literature uses the optimal emission tax rates in the first- and the second-best settings to distinguish whether the double dividend is obtained. However, the present paper indicates that this approach is not available.

[7] This term is given as:

$$\left.\frac{dE}{dt_E}\right|_{\frac{dn}{dt_E}=0} = E\left[-\frac{\epsilon}{c_Z}\frac{\{1-\sigma_r(1-\sigma_x)\}\beta_L^{\sigma_x} + \{1-\sigma_r(1-\eta_x)\}\beta_R^{\sigma_x} c_R^{1-\sigma_x}}{\beta_L^{\sigma_x} + \beta_R^{\sigma_x} c_R^{1-\sigma_x}} + \frac{\partial X/\partial t_L}{X}\frac{dt_L}{dt_E}\right].$$

The second term in square brackets implies that environmental tax reform increases pollution emissions by cutting income tax rates and increasing demand for good X. However, this term is sufficiently small so that previous numerical simulations as in Goulder et al. (1997) show a change in the pollution emission to be negative under plausible parameter sets.

5 Conclusion

This paper studied the welfare effects of environmental tax reform in the presence of an induced technological change in energy saving. The energy-saving technology is described as a composite of intermediates that helps in producing a given amount of energy services with a small amount of a natural resource. These intermediates are innovated by R&D firms and supplied under monopolistic competition. Then, the paper shows that a combination of these intermediates endogenously constructs the energy-saving technology.

Using this model, the paper found two paths where the technological change is induced by an emission tax. The first path is a substitution of the polluting natural resource for existing nonpolluting inputs including the intermediates for energy saving. The second is an induced variety expansion of intermediates that occurs because the emission tax increases demand for energy-saving technology and raises rents from innovating new intermediates. Then, the polluting firm can also adopt the newly developed intermediates to substitute for resource use. Therefore, these two paths construct a cleaner production process when the emission tax is raised.

The induced variety expansion of intermediates then prevents a full transfer of marginal emission costs from increased emission tax rates to the price of a final good so that it derives positive externalities on welfare. It reduces the efficiency costs of environmental tax reform which arise via a price rise of final goods. Therefore, the second (nonenvironmental) dividend can be obtained, at least, in a range of sufficiently low emission tax rates. Furthermore, considering the magnitude of the first (environmental) dividend, the paper reveals that the induced variety expansion also accelerates a reduction of pollution emissions and, thereby, enforces the first dividend. However, even if the double dividend is obtained, the second-best optimal emission tax rate cannot be greater than first-best tax rate.

Appendix

A.1 Derivation of factor demand functions

The polluting firm faces the following minimization problem for total cost:

$$\min_{L_X, Z, h(i)\ \forall i\in[0,n]} (5), \quad \text{s.t. } E = \epsilon Z, \text{ (1), (2) and (3).}$$

To derive demand functions for the respective factor inputs, we solve this problem in three steps: (i)$h(\cdot)$; (ii) H and Z; and (iii) R and L_X.

At the first step, the polluting firm determines the optimal combination of intermediates related to energy saving, taking H as given:

$$\min_{h(i)\ \forall i\in[0,n]} \int_0^n p_H(i)h(i)di \qquad \text{s.t.}(3) \tag{A.1}$$

Solving this problem results in the factor demand for intermediates of (6). By substituting (6) into (A.1), we obtain the following minimized cost of a variety of intermediates for energy saving and emission abatement: (A.1)': $c_H H$. Therefore, c_H can be considered to be a minimized marginal cost to satisfy a given amount of energy-saving technology, given as (10).

By using (A.1)', at the second step and taking R as given, the polluting firm considers an optimal combination of natural resource and energy-saving technology input by solving the following problem:

$$\begin{aligned} \min_{Z,H} \quad & p_Z Z + c_H H + t_E E, \\ \text{s.t.} \quad & E = \epsilon Z \text{ and } (2). \end{aligned} \tag{A.2}$$

Thus, the factor demand functions for Z and H are written as in (7) and (8), and we define the unit cost of the natural resource use in manipulation, shown in (9). Furthermore, substituting (7), (8) and (9) into (A.2) gives: (A.2)': $c_R R$, where c_R is a minimized marginal cost of providing a given amount of energy services, shown in (13).

Finally, at the third step, the polluting firm should decide on an optimal combination of labor and energy services, given X, by minimizing the rearranged cost function (5), as follows:

$$\min_{R,L_X} wL_X + c_R R, \qquad \text{s.t.}(1). \tag{A.3}$$

Therefore, the respective factor demand functions are given as shown in (11) and (12). As well as the above, the substitution of (11) and (12) determines (14).

A.2 Derivation of (30)

Using (25), we rearrange (24) as follows:

$$\begin{aligned} \frac{1}{\lambda}\frac{dV}{dt_E} \;=\; & \left(-\frac{D'(E)}{\lambda}\frac{dE}{dt_E} + t_E\frac{dE}{dt_E} + c_Z Z\frac{dn/dt_E}{n}\right) \\ & + Mt_E\frac{dE}{dt_E} - (1+M)\frac{t_L}{X}\frac{\partial L}{\partial p_X} c_Z Z\frac{dn/t_E}{n}. \end{aligned} \tag{A.4}$$

The portion of the tax-interaction effect, $\frac{t_L}{X}\frac{\partial L}{\partial p_X}$, is rewritten as: $-\frac{M}{1+M}\ \frac{L}{X}\ \frac{\partial L/\partial p_X}{\partial L/\partial t_L}$. Slutsky equations and Slutsky's symmetry property are used to rearrange this expression as:

$$\frac{t_L}{X}\frac{\partial L}{\partial p_X} = -\frac{M}{1+M}\ \frac{L}{X}\ \frac{\frac{X}{1-t_L}\left(\frac{1-t_L}{X}\frac{\partial X^c}{\partial 1-t_L} + \frac{\partial L}{\partial I}(1-t_L)\right)}{\frac{L}{1-t_L}\left(\frac{1-t_L}{L}\frac{\partial L^c}{\partial t_L} + \frac{\partial L}{\partial I}(1-t_L)\right)}, \tag{A.5}$$

where the superscript c stands for the compensated demand functions, and I is disposable income.

By taking the total derivative of household utility and assuming that the utility level is unchanged, the compensated demand function has the following relation, from its definition: $(1-t_L)\frac{\partial L^c}{\partial 1-t_L} = p_X\frac{\partial X^c}{\partial 1-t_L} + p_Y\frac{\partial Y^c}{\partial 1-t_L}$. Substituting this relation into (A.5) gives:

$$\frac{t_L}{X}\frac{\partial L}{\partial p_X} = -\frac{M}{1+M}\ \frac{\eta^c_{XL} + \eta_{LI}}{\left(\frac{p_X X}{(1-t_L)L}\eta^c_{XL} + \frac{p_Y Y}{(1-t_L)L}\eta^c_{YL} + \eta_{LI}\right)},$$

where $\eta^c_{XL} = \frac{1-t_L}{X}\frac{\partial X^c}{\partial 1-t_L}$, $\eta^c_{YL} = \frac{1-t_L}{Y}\frac{\partial Y^c}{\partial 1-t_L}$, $\eta_{LI} = -(1-t_L)\frac{\partial L}{\partial I}$. Therefore, by assuming that goods X and Y are equal substitutes for leisure, that is, $\eta^c_{XL} = \eta^c_{YL}$, because all income is spent on consumption goods, (A.5) is written in reduced form as $-M/(1+M)$. By substituting this into (A.4), (30) is obtained.

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