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From regressive pollution taxes to progressive environmental tax reforms

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ABSTRACT

European countries have increased their use of environmental tax instruments by designing new tax bases. But many countries face opposition from public opinion, for fear of the distributive consequences of these environmental tax reforms. This paper sheds light on the distributive consequences of environmental tax policies when households are heterogeneous. The objective is to assess whether an environmental tax reform could be Pareto improving, when the revenue of the pollution tax is recycled by a change in labor tax properties. We show that, whatever the degree of regressivity of the environmental tax alone, it is possible to design a recycling mechanism that renders the tax reform more Pareto efficient, by simultaneously decreasing the wage tax and increasing its progressivity.

1. Introduction

European countries have increased their use of environmental tax instruments by designing new tax bases, like taxes on sulfur dioxide, plastic bags, solid waste and batteries. Even in the United States there are now advocates who strongly support taxation as apposed to the cap and trade approach. They include James Hansen, an American scientist,[1] who claims that raising the price on carbon emissions is the essential underlying support needed to make all other climate policies work: “A rising carbon price is essential to decarbonize the economy, i.e. to move the nation toward the era beyond fossil fuels. The most effective way to achieve this is a carbon tax (on oil, gas, and coal) at the well-head or port of entry. […] The public will support the tax if it is returned to them […]”. This quite surprising attitude corresponds to a larger movement in favor of the price mechanism. France, following Sweden and other Scandinavian countries, considered implementing a carbon tax in 2010, at a rate equal to €17/ton CO_2. Faced with opposition from public opinion as well as practical and legal difficulties, the government decided to postpone the project until a European policy was put in place. The Swedish presidency of the European Union (second semester of 2009) encouraged the other member countries to implement carbon taxes, bearing on all sectors of activity which are not regulated by the emission quotas system. The newly elected French government in 2012 set up a Commission of Ecological Taxation to put forward new proposals. Despite these changes, many countries have to face opposition from public opinion, for fear of the distributive consequences of these environmental tax reforms.

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[1] An eminent climatologist, he is a former director of the NASA Goddard Institute of Space Studies. After the election of U.S. President Barak Obama in November 2008, J. Hansen sent him a letter to urge him to support a carbon tax.

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So what would be the consequences on inequality of a European Carbon Tax Project or of the carbon tax currently under discussion in France? As Hansen suggests, an environmental tax can hardly be considered without adequate revenue recycling in order to enhance the acceptance of the environmental policy. But the aim of such a recycling can therefore be twofold: to reduce, or even annihilate the gross cost of the policy, as measured by the global welfare loss, or to compensate the inequities generated. The objective of this paper is to contribute to this debate by designing an environmental tax reform that could be unanimously accepted.

As with the cap and trade mechanism, the tax allows environmental objectives to be achieved while minimizing the overall cost. One of the advantages of an environmental tax is that it provides public revenues which can be recycled. This is a reason why it may be preferred to subsidies or emission quotas. It has been argued that, as governments use these revenues to decrease other distortionary taxes, an environmental tax may simultaneously improve environmental quality and achieve a less distortionary tax system, i.e. it may lead to a double dividend, according to Goulder (1995). This could be a strong argument in favor of an increasingly green tax system. Following Bovenberg and de Mooij (1994), who initially provided a refutation of the double dividend hypothesis, a large body of literature has analyzed this issue extensively. The double dividend hypothesis is rejected when the economy is made up of one productive sector, using only one productive factor (labor), and one representative consumer (Bosello et al., 2006). But, when there are several productive factors and/or several consumer groups, the double dividend can be obtained (Bovenberg and van der Ploeg, 1996; Proost and Van Regemorter, 1995). In particular, Goulder (1995) and Ligthart (1998) have shown that the existence of the double dividend essentially depends on the possibility of transferring the overall tax burden from the wage earners to some fixed production factors or to other consumers, thus emphasizing the role of heterogeneity. For instance, Proost and Van Regemorter (1995) show that the tax burden has to be supported by the pension system, therefore penalizing the retired agents. Heterogeneity of agents is above all a necessary (but not sufficient) condition for the existence of a double dividend.

But one of the disadvantages of environmental taxes is that, like any consumption tax, they often appear to be regressive, i.e. they affect more heavily the welfare of the poorest households than of the richest ones. Johnstone and Alavalapati (1998) argue that in many cases the distributional consequences of environmental tax reform may be distinctly regressive, at least in terms of relative tax burdens. In particular, in the French case, a tax on energy or transport consumption hurts the lowest wage households three times more than the highest wage households (Ruiz and Trannoy, 2008). Bureau (2011) also shows that the distributional effects of a carbon tax on car fuels in France are likely to be regressive before revenue recycling (see also Wier et al., 2005, for the Danish case).[2] Moreover, the usual recycling of the environmental tax revenues through a decrease in the labor tax rate could also be regressive (Metcalf, 1999). Somewhat surprisingly, the analyses of the double dividend issue have until recently neglected the distribution issue of the welfare gain, although it is usually obtained at the expense of some groups of agents.

Previous articles considered the distribution issues between generations by linking the standard double dividend literature with a parallel stream of papers on environmental taxes in an overlapping generations framework. In a seminal paper, John and Pecchenino (1994) examine the effects of an environmental tax whose revenue finances a public pollution abatement activity. Fisher and van Marrewijk (1998), using an endogenous growth model with pollution, derive the conditions under which a pollution tax does not slow economic growth. Bovenberg and Heijdra (1998) examine the effects of a green tax on polluting capital when the tax revenue is redistributed by lump-sum intergenerational transfers. All these papers conclude that environmental taxation implies such a welfare loss for older generations that its implementation is not desirable: it is indeed one of the generations which decides to reform the tax system that will also bear the highest burden of the reform. We have also studied the conditions for the existence of a long term double dividend, taking into account the distinction between wage earners and retired consumers within a Diamond framework (Chiroleu-Assouline and Fodha, 2005, 2006).[3] The same framework is used by Nakabayashi (2010) to examine optimal tax rules and public sector efficiency, or by Ono (2007) who introduces endogenous growth.

In this paper, as in a previous one (Chiroleu-Assouline and Fodha, 2011), we intend to analyze the distributional effects of environmental tax reforms between different categories of households. To our knowledge, these papers are the first ones to take into account the intra-generational heterogeneity of agents, which has never been considered in depth in the double dividend literature. The overlapping-generations framework is well suited to introduce different sources of households′ heterogeneities, which are necessary (but not sufficient) conditions to deal with inequities but also to obtain a successful double dividend. In our works, we take into account different skills for workers, implying different levels for wage rates among households, but also other sources for revenues, as retired agents (when old) do not work.

Besides the heterogeneity of agents, we introduce several features in our model in order to show that, even in very unfavorable circumstances, an adequately designed environmental tax reform can simultaneously lead to a decrease of pollution, an increase of the global welfare and a non-decreasing welfare for each class of households.

Like Bovenberg and Heijdra (1998) or Heijdra et al. (2006), our paper is also linked to the literature on capital taxation since pollution is generated as a by-product of capital used in production (instead of being emitted by the consumption of a brown good or by the output, like in Bovenberg and de Mooij, 1994). It implies that the tax on capital amounts to an

[2] Recent literature shows that they can be less regressive than usually argued, if measured using lifetime income or annual consumption rather than annual income (Grainger and Kolstad, 2010; Hassett et al., 2012 or Sterner, 2012).

[3] Because they focus on transitional effects, Heijdra et al. (2006) study both the efficiency and intergenerational distribution effects of environmental taxes in a Yaari-Blanchard model of a small open economy.

environmental tax. Compared to the standard literature on capital taxation (see Chamley, 1985 or Judd, 1985 for instance), which usually considers a small open economy or a representative and infinitely-lived agent framework, we assume a closed economy with heterogenous short-lived agents. The interest rate is endogenous, so capital supports the long-run burden of capital taxes because the steady-state after-tax returns is endogenous, and not fixed by the world interest rate or by the social discount rate. We depart from Bovenberg and Heijdra (1998) and Heijdra et al. (2006) contributions, by assuming intra-generational heterogeneity of agents, allowing skilled and non-skilled workers to be distinguished. This means that in any period of time poor and rich households coexist. We also add a non-linear tax rate on wages composed of a constant tax rate together with a progressive one. We assume an exogenous labor supply which means that the wage tax does not distort the labor market, and acts as a lump-sum tax. Our global tax reform consists of an increase of the pollution tax compensated by a decrease of the constant tax rate on wages, together with an increase of the progressivity of the non-linear wage tax. Conditions for a successful and fair double dividend achievement rely on the final impacts of the reform on tax distortions (which may increase because of capital taxation),[4] relative to the impacts on the externality induced by the pollution stock (which have to decrease). Taking account of distortionary taxes on labor (by assuming an endogenous labor supply for instance) would probably soften or even facilitate the conditions that have to be reached to obtain the fair double dividend. Indeed, in this case, the environmental tax reform would imply a decrease of the labor taxation, therefore reducing the total distortions of the tax structure.

Even though the standard double dividend literature assumes that the environmental externality directly affects individuals′ welfare under separability assumptions about the utility function, we follow Williams (2002, 2003), Bovenberg and de Mooij (1997) or Schwartz and Repetto (2000) by relaxing this non-separability assumption. Contrary to Schwartz and Repetto (2000) who consider that a change in environmental quality directly affects labor supply, we assume that each household supplies inelastically one unit of labor (like Bovenberg and Heijdra, 1998), but that the feedback of pollution on growth comes through the effects on health that deteriorate the workers' productivity. Aloi and Tournemaine (2013) explicitly consider an adverse public health effect of pollution that affects disproportionately the low income groups that are assumed to be more exposed to pollution because of their geographical location. Health affects workers′ labor supply and their productivity, which causes pollution to induce asymmetries among workers, that can influence income inequality. Nevertheless, since we focus on the distribution of the costs of the environmental regulation, we do not introduce differentiated health or productivity effects on the different classes of workers.

Our analysis of the distributional effects of environmental tax reforms leads us to put forward an appropriate policy mix to ensure a non-decreasing welfare for each class of workers. We show that whatever the degree of regressivity of the environmental tax alone, it is possible to re-design a recycling mechanism that renders the tax reform Pareto-improving,[5] by modifying the progressivity characteristics of the tax system, instead of lump-sum transfers or any other form of homogeneous compensation.

We assume that the production technology is a function of capital and heterogeneous labor. Heterogeneous households live two periods (young and old) and earn wages corresponding to their skills. The tax system is composed of a labor tax (tax on wages) and a capital tax. To keep the model general, the labor tax is assumed to be either progressive or proportional. Our framework allows us to take into account both intra-generational and intergenerational heterogeneities; indeed, we consider: (i) the heterogeneity characteristics of the labor market and (ii) the heterogeneity of the individual income sources. As in Heijdra et al. (2006), pollution is generated as a by-product of capital used in production. The environmental policy consists therefore of increasing the tax on polluting capital, in a second-best framework. We then characterize the necessary conditions for obtaining a long term double dividend,[6] i.e. an improvement of the environmental quality and an improvement of welfare on the steady state equilibrium when the revenue of the pollution tax is recycled by a change in the labor tax rates. Previous studies show that the double dividend requires economic conditions so that the double dividend hypothesis seems unrealistic, unless it is obtained through the worsening of inequalities. Conversely, we show that the distributive properties of the labor taxes work as an effective tool for obtaining a double dividend. The results depend on the initial tax system. In a more general framework than our paper in 2011 (Chiroleu-Assouline and Fodha, 2011),[7] we show that such a Pareto-improving policy can be obtained even in the worst cases of regressivity of the environmental tax alone.

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[4] Actually, we show that a tax reform using capital taxation may enhance economic efficiency. This result may be in opposition with the general literature on capital taxation in an overlapping generations context. Uhlig and Yanagawa (1996) have already shown that under some mild conditions, capital income taxes may lead to higher economic growth in an OLG – endogenous growth context.

[5] In line with the double dividend literature, we are not seeking the optimal tax system, which would require using several instruments in order to internalize the externalities. Nevertheless, according to our Pareto-improving criterion, our results provide conditions so that the economy moves closer to its Pareto optimal equilibrium.

[6] Our paper focuses on the comparison of long term steady state equilibria because a necessary condition to obtain an intertemporal double dividend is that the generations on the new steady state equilibrium are made better off with respect of both environmental and non-environmental welfare. Our objectives are in fact to study the necessary conditions for environmental policy to be beneficial in the long term. It is indeed clear that the policy might not be Pareto-improving for all generations during the transition (Bovenberg and Heijdra, 1998), but the relative weights of generations' welfare depend upon the social discount factor. When some generations are made worse off along the transition path, this negative impact must be compensated with the increase of the welfare of the infinite number of generations alive in the final steady-state equilibrium. Evaluating the occurrence probability of an intertemporal double dividend needs to reopen the debate on social discounting or on intergenerational transfers, like debt or pensions system.

[7] In Chiroleu-Assouline and Fodha (2011), we assume weak heterogeneity among households, who only differ via their labor skill. Moreover, the environmental tax bears on savings. The model is fully solved analytically as we have specified, in the simplest way, preferences and technologies.

The paper is organized as follows. Section 2 presents first the basic model and some extensions to account for abatement activities. Section 3 outlines the specification of the budget-neutral tax reform and Section 4 gives the welfare analysis of a tax policy. In Section 5 we present the environmental effects of the tax reform and Section 6 examines the welfare effects of such a combined reform. The last section concludes.

2. The model

2.1. The basic model

We consider an overlapping-generations economy with heterogeneous households. We assume that population remains constant, so we normalize it to unity. Agents live two periods (young and old) and earn wages corresponding to their skills. Each class of households is characterized by its skills i. There are I classes of agents, and the size of each class i is q_i (with $\sum_{i=1}^{I} q_i = 1$). q_i and I are supposed to be exogenous. Each agent supplies inelastically one unit of labor[8] when young, and earns a wage w_t^i, the labor tax rate is $\tau^i \in [0,1[$. He/she divides his/her net labor income between consumption and savings s_t^i. In the second period, the household consumes its savings and the interest earned. The welfare of an individual born at t is measured with the intertemporal separable utility function[9]

$$U(c_t^{iy}, c_{t+1}^{io}) = u(c_t^{iy}) + \beta^i v(c_{t+1}^{io}) \tag{1}$$

with c_t^y denoting the first-period consumption of the agent born at t, c_{t+1}^o his/her second-period consumption.

The different labor classes are conventionally ranked with respect to their wages (skills) which implies that higher i means a higher wage. The individual preference rate for the future is denoted by $\beta^i \in]0,1[$.[10] We assume that this rate depends on the class i, i.e. the wage level, of each agent, respecting the following scheme: $\beta^i \geq \beta^{i-1}, \ \forall i \in I$. This assumption encompasses one side of the Keynes fundamental psychological law which states that the average propensity to save (i.e. the savings rate) increases when the income increases. As emphasized by Saez (2002), "*However, propensities to save vary widely across the population and empirical studies have shown that savings rates are correlated with education even controlling for income. Therefore, there is a strong presumption that higher income individuals save more not only because they have more income to save but also because they might have a better financial education and be more aware of the need to save for retirement.*" For example, Lawrance (1991) showed that subjective rates of time preference (identified from estimation of consumption Euler equations) are three to five percentage points higher for households with low permanent incomes than for those with high permanent incomes.

The utility function exhibits the usual properties: its two instantaneous components increase in their argument, are strictly concave and satisfy the Inada conditions. We also impose homotheticity. The real interest rate is r_{t+1}. The household's budget constraints are

$$\begin{cases} (1-\tau_t^i) w_t^i = c_t^{iy} + s_t^i \\ c_{t+1}^{io} = (1+r_{t+1}) s_t^i = R_{t+1} s_t^i \end{cases} \tag{2}$$

The household's problem is to maximize its lifetime utility (1) with respect to its intertemporal budget constraint given by (2). The first order conditions give

$$\frac{u'(c_t^{iy})}{v'(c_{t+1}^{io})} = R_{t+1} \beta^i \tag{3}$$

From these conditions, we can derive the optimal consumption and savings paths of the representative household, within the Diamond (1965) framework with a homothetic utility function:

$$\begin{cases} c_t^{iy} = c^y(R_{t+1}, w_t^i, \tau_t^i, \beta^i) \\ c_{t+1}^{io} = c^o(R_{t+1}, w_t^i, \tau_t^i, \beta^i) \\ s_t^i = s^i(R_{t+1}, w_t^i, \tau_t^i, \beta^i) \end{cases} \tag{4}$$

The usual results of comparative statics for w_t^i, τ_t^i and β^i hold. We also assume that the degree of intertemporal substitution between consumption when young and consumption when old should not be too small, so that the substitution

(*footnote continued*)
In contrast, in this paper, households' heterogeneity concerns their preferences too. The environmental tax bears on the polluting capital, which is closer to a polluter-payer principle.

[8] Our long term view allows us to assume full employment. Moreover, we focus on the efficiency double dividend (according to Goulder, 1995) and not on the employment double dividend.

[9] We do not introduce any direct effect of pollution on the household's welfare, but only the indirect one through the consequences on productivity of the degradation of environmental quality. Indeed, while the indirect effect impacts the wage gaps, a direct effect would have no impact on the welfare distribution among heterogeneous agents, because agents do not differ here by their preferences regarding the environmental quality.

[10] The assumption of intertemporal separability is not necessary and we could obtain the same results with a very general utility function such that $\beta^i = (\partial U(\cdot)/\partial c_{t+1}^{io})/(\partial U(\cdot)/\partial c_t^{iy})$.

effect will not be dominated too much by the income effect, due to changes in the rate of return R_{t+1} (de la Croix and Michel, 2002).

The production sector consists of competitive firms, each of them being characterized by the same production function $F(\cdot)$ with constant returns to scale. They use different kinds of labors characterized by their skills. Our model generalizes our work in Chiroleu-Assouline and Fodha (2011). Following Chao and Peck (2000) or Williams (2002) or Williams (2003), we assume that pollution has a negative impact on the total productivity of factors. This assumption is allowed by the abundant empirical evidence about the health effects of pollution (OECD, 2008) and the impact of workers' health on labor productivity (Bloom et al., 2004), specifically about the loss of productivity caused by the health effects of pollution (Ostro, 1983; Samakovlis et al., 2005; Pervin et al., 2008, for air pollution; Bosello et al., 2006 or Hübler et al., 2008, for the health effects of climate change). Weil (2007) provides an extensive review of the empirical evidence about the effects of health on productivity and estimates their impact on growth.[11] As a result, the total productivity of factors $A(P_t)$ is negatively affected by pollution P_t because pollution degrades the health of workers or the quality of natural resources ($\partial A(P)/\partial P \le 0$):

$$Y_t = A(P_t)F(K_t, \{L_{i,t}\})$$

The maximization problem of the representative firm is (taking the output price as *numeraire*)

$$\max_{K_t,\{L_{i,t}\}} \pi_t = A(P_t)F(K_t, \{L_{i,t}\}) - \sum_{i=1}^{I} w_t^i L_{i,t} - (1 + r_t + \tau_t^e)K_t$$

with π_t denoting the current net revenue. The depreciation rate of capital is equal to unity. We assume that pollution is due to capital stock in order to integrate in a very simple framework the fact that energy use is more likely to be a complement to capital than a substitute. The firm pays a tax $\tau^e \in [0, 1[$ proportional to the use of this factor. We hence suppose that there exists a constant technical relationship between capital stock employed and emission of pollutants.

Since markets are competitive, capital and labor earn their marginal products:

$$\begin{cases} A(P_t)F'_K - \tau_t^e = 1 + r_t \equiv R(K_t, \{L_{i,t}\}, A(P_t), \tau_t^e) \\ A(P_t)F'_{L^i} = w_t^i \equiv W^i(K_t, \{L_{i,t}\}, A(P_t)) \end{cases} \tag{5}$$

Let ε_L^i be the elasticity of output to labor, we have $\varepsilon_L^i = F'_{L^i} L_{i,t}/F(K_t, \{L_{i,t}\}) > 0\ \forall i,\ \forall t$.[12] We can then write $w_t^i = (Y_t/L_{i,t})\varepsilon_L^i$. Likewise, let ε_F be the elasticity of output to capital $\varepsilon_F = F'_K K_t/F(K_t, \{L_{i,t}\}) > 0$. We obtain $R(K_t, \{L_{i,t}\}, A(P_t), \tau_t^e) = (Y_t/K_t)\varepsilon_F - \tau_t^e$.
At the equilibrium of the labor markets (i.e. $L_{i,t} = q_i, \forall i \in I, \forall t$)), this yields

$$Y_t = A(P_t)F(K_t)$$

The ratio of wages is (using (5)), $\forall i \in I$:

$$\frac{w_t^i}{w_t^1} = \frac{F'_{L^i}}{F'_{L^1}} = \frac{\varepsilon_L^i}{\varepsilon_L^1}\frac{q^1}{q^i}$$

It needs to be recalled that the different labor classes are conventionally ranked by growing wages:

$$w_t^{i+1} > w_t^i \Leftrightarrow \frac{\varepsilon_L^{i+1}}{q_{i+1}} > \frac{\varepsilon_L^i}{q_i}$$

We assume that government spending (G) is entirely financed by current taxes. The government's budget constraint states that its purchases must be equal to, at each period, its tax revenues generated by the pollution tax and the labor tax:

$$\sum_{i=1}^{I} q_i \tau_t^i w_t^i + \tau_t^e K_t = G_t \tag{6}$$

We define a progressivity index of the labor tax, such as

$$\tau^i = \tau^1 + ab(i)$$

where τ^1 is the flat component of the tax rate, $b(i)$ defines the overall progressivity shape of the tax system and a is a positive parameter, called from now on the progressivity multiplier of the labor tax, which acts as an amplifier of the shape of progressivity. When $b(i)$ increases (resp. decreases) with the level of income, the income tax is progressive (resp. regressive). We focus here on the progressivity case and assume that $b(1) = 0$ and $b(i+1) > b(i)\ \forall i > 1$. We consider the general case for the characteristics of the tax progressivity. For example, the design of progressivity fits well the characteristics of the French tax system when $b(i+2) - b(i+1) < b(i+1) - b(i)$. As far as the overall progressivity shape of the tax system originates in the

[11] Our model addresses the specific issue of pollution due to industrial, highly capital-intensive sectors, that emit fine particles, NO_x or SO_x. These pollutants are harmful for the health of all agents, and especially of the workers employed by these sectors. This stylized model cannot describe the GHG case, since the carbon dioxide emissions have no direct effect on the health and productivity of workers and they are due to the use of fossil energies which can be substituted by carbon free inputs, such as capital or knowledge.

[12] By assuming that ε_L^i is constant at each time, we restrict the analysis to Cobb–Douglas production functions. This ensures an invariant ranking of wages.

political process and is not so easy to change (from a progressive tax into a regressive one), we take $b(i)$ as exogenous and given.[13]

This yields, regarding the labor tax revenue:

$$\sum_{i=1}^{I} q_i \tau^i w^i = \sum_{i=1}^{I} \tau^i \varepsilon_L^i Y = Y\left(\tau^1 \sum_{i=1}^{I} \varepsilon_L^i + a \sum_{i=1}^{I} b(i)\varepsilon_L^i\right) \tag{7}$$

Let us define $\varepsilon_L = \sum_{i=1}^{I} \varepsilon_L^i > 0$ and B as the sum $\sum_{i=1}^{I} b(i)\varepsilon_L^i$. $B > 0$, which is constant for any given I and progressivity characteristics $\{b(i)\}_{1 \le i \le I}$.

As in our companion paper (Chiroleu-Assouline and Fodha, 2011) or in Heijdra et al. (2006), we assume capital-intensive sectors to be polluting sectors. To keep things simple, as we deal only with a one sector aggregate output, we assume that capital input is the main source of pollution (even if it is only a proxy). This can be justified either by the complementarity between capital and energy, or, from a broader view, because capital accumulation favors the production of pollution-intensive goods. For industrial pollution, this is consistent with evidence (Brown et al., 1992; Gale and Mendez, 1998; Antweiller et al., 2001).

The dynamics of pollution is described by the following law of motion:

$$P_t = (1-h)P_{t-1} + \phi K_{t-1} \equiv P(P_{t-1}, K_{t-1}) \tag{8}$$

where $\phi > 0$ stands for the emission rate of pollutants and h is the constant rate of natural absorption of pollution $(0 < h < 1)$.

In this economy, the capital stock in period t is formed by the sum of the young individuals' savings in period $t-1$. This equilibrium condition of the capital market is obtained by substituting the zero-profit condition, the government's budget constraint (6) and the household's budget constraints (2) into the equilibrium of the output good market. This is written as follows:

$$K_t = \sum_{i=1}^{I} q_i s_{t-1}^i$$

By substituting (4) and using (5), we finally obtain

$$K_t = \sum_{i=1}^{I} q_i s^i (W^i[K_{t-1}, \{q_i\}, A(P(P_{t-2}, K_{t-2}))], R\,[K_t, A(P(P_{t-1}, K_{t-1})), \tau_t^e], \tau_{t-1}^i, \beta^i) \tag{9}$$

The competitive equilibrium is thus described by the set $\{\{\hat{c}_t^{iy}, \hat{c}_t^{io}, \hat{s}_t^i\}_{i=1}^{i=I}, \hat{K}_t, \hat{Y}_t, \hat{P}, \hat{G}_t, \hat{w}_t, \hat{r}_t\}_{t=0}^{t=+\infty}$ satisfying equations $\{(4),(5),(6),(8),(9)\}_{t=0}^{t=+\infty}$. A steady state equilibrium is an allocation whereby capital and pollution are stationary, i.e. $\hat{K}$ and $\hat{P}$ are such that (using (8) and by substitution of (4) and (5) in (9)):

$$\hat{K} = \sum_{i=1}^{I} q_i \hat{s}^i \tag{10}$$

$$\hat{P} = \frac{\phi}{h}\hat{K} \tag{11}$$

For some given initial conditions $\{K_0, K_{-1}, P_{-1}\}$ and for a given triplet of tax policy instruments, $\{\tau^e, \tau^1, a\}$, we assume that there exists a long-term locally stable steady-state defined by $(\hat{K}, \hat{P})$ such that

$$\begin{aligned} \hat{K} &= K(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \\ \hat{P} &= P(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \end{aligned} \tag{12}$$

Using (5) and (10), one obtains the output value at the steady-state equilibrium:

$$\hat{Y} = Y(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \tag{13}$$

2.2. The abatement case

As pollution is caused by firms and harms their productivity, it would be rational for them to invest in abatement activities. In this subsection, we develop two extensions to account for these activities. We consider either adaptation or mitigation abatement:

(1) in the first case, we assume that the firm abates to fight against pollution and to increase the global productivity of factors. The abatement level does not depend upon the environmental taxation, i.e. the environmental tax is not an incentive to abate. The tax still relies on the polluting input and there is no substitute to the latter, as the labor supply is exogenous and there is no technical progress;

[13] This framework allows us to deal with only one parameter a to describe a large range of progressivity profiles. A more accurate way would have been to assume that $b(i)$ could be modified for each i. This would have led to dealing with $I+1$ instruments instead of 2.

(2) in the second case, we assume that the tax is levied on pollution emitted by the firm. In this case, the firm faces a trade-off between the payment of the pollution tax and the investment in abatement technology.

2.2.1. *Abatement as an adaptation strategy*

Assume that firms have access to private abatement and invest in abatement activities in order to maximize their profits. One direct way to take into account private abatement is to suppose that firms can allocate an endogenous fraction θ_t of their gross output to abatement activity (see for instance Copeland and Taylor, 2005). We can then define the net production of firms as follows:

$$y_t = (1-\theta_t)Y_t = (1-\theta_t)A(P_t)F(K_t,\{L_{i,t}\})$$

We keep on assuming that emitted pollution is an externality since at date t it is due to the use of capital stock in the past period $t-1$. The level of pollution that impacts the economy is then described by the following law of motion, where the emission rate of pollutants ϕ depends on θ_t:

$$P_t = (1-h)P_{t-1} + \phi(\theta_t)K_{t-1} \equiv P(\theta_t, P_{t-1}, K_{t-1}) \tag{14}$$

with $\phi(0)=1$, $\phi(1)=0$, $d\phi/d\theta<0$.

The maximization problem of the representative firm turns to

$$\max_{K_t,\{L_{i,t}\},\theta_t} \pi_t = (1-\theta_t)A(P_t)F(K_t,\{L_{i,t}\}) - \sum_{i=1}^{I} w_t^i L_{i,t} - (1+r_t+\tau_t^e)K_t$$
$$\text{s.t. } P_t = \phi(\theta_t)K_{t-1}$$

By substitution of pollution into the profit function, we obtain

$$\max_{K_t,\{L_{i,t}\},\theta_t} \pi_t = (1-\theta_t)A((1-h)P_{t-1} + \phi(\theta_t)K_{t-1})F(K_t,\{L_{i,t}\}) - \sum_{i=1}^{I} w_t^i L_{i,t} - (1+r_t+\tau_t^e)K_t$$

Recall that K_{t-1} is given for the firms at date t. Since markets are competitive, capital and labor earn their marginal products:

$$\begin{cases} (1-\theta_t)A(\phi(\theta_t)K_{t-1})F'_K - \tau_t^e = 1+r_t \equiv R(K_t,\{L_{i,t}\},A(P_t),\tau_t^e,\theta_t) \\ (1-\theta_t)A(\phi(\theta_t)K_{t-1})F'_{L^i} = w_t^i \equiv W^i(K_t,\{L_{i,t}\},A(P_t),\theta_t) \end{cases} \tag{15}$$

Concerning the abatement effort, we have

$$\frac{\partial \pi_t}{\partial \theta_t} = K_{t-1}\phi'_\theta A'_P F\big(K_t,\{L_{i,t}\}\big) - A_t F\big(K_t,\{L_{i,t}\}\big) - \theta_t K_{t-1}\phi'_\theta A'_P F\big(K_t,\{L_{i,t}\}\big) = 0$$
$$\Leftrightarrow \theta_t = \frac{\varepsilon_{\phi/\theta_t}\varepsilon_{A/P}}{1+\varepsilon_{\phi/\theta_t}\varepsilon_{A/P}}$$

with $\varepsilon_{A/P} = -A'_P P_t/A_t > 0$ and $\varepsilon_{\phi/\theta_t} = -\theta_t\phi'_\theta/\phi(\theta_t) > 0$.

Positive abatement modifies the equilibrium value of the aggregate variables, and we have

$$\begin{cases} \hat{K}^\theta = K(\tau^e,\tau^1,a,\{b(i)\},\{\beta^i\}) \\ \hat{P}^\theta = P(\tau^e,\tau^1,a,\{b(i)\},\{\beta^i\}) \\ \hat{Y}^\theta = Y(\tau^e,\tau^1,a,\{b(i)\},\{\beta^i\}) \\ \hat{\theta} = \theta(\tau^e,\tau^1,a,\{b(i)\},\{\beta^i\}) \end{cases}$$

2.2.2. *Abatement as a mitigation strategy induced by the environmental tax*

In this case, we assume that the firm can invest in abatement in order to decrease its emission of pollutants and hence, to pay less tax. The pollutant emission rate depends on the effort of abatement θ_t. The evolution of pollution is now:

$$P_t = (1-h)P_{t-1} + \phi(\theta_{t-1})K_{t-1}$$

and the program of the firm is written as follows:

$$\max_{K_t,\{L_i\},\theta_t} \pi_t = (1-\theta_t)A((1-h)P_{t-1} + \phi(\theta_{t-1})K_{t-1})F(K_t,\{L_{i,t}\}) - \sum_{i=1}^{I} w_t^i L_{i,t} - (1+r_t+\tau_t^e\phi(\theta_t))K_t$$

The first order conditions determine the optimal abatement effort:

$$\frac{\partial \pi_t}{\partial \theta_t} = -A(P_t)F\big(K_t, \{L_{i,t}\}\big) - \tau_t^e \phi_t' K_t = 0$$
$$\Leftrightarrow \theta_t = \frac{P_{t+1}}{Y_t}\tau_t^e \varepsilon_{\phi/\theta_t}$$

The abatement effort depends on the environmental tax level, in a positive and linear way ($d\theta/d\tau^e = (P_{t+1}/Y_t)\varepsilon_{\phi/\theta_t} > 0$). As in the previous section, abatement has a direct impact on the aggregate value of the equilibrium. At the steady-state equilibrium, any increase in the environmental tax will also increase the abatement investment, which will decrease the pollution stock and shift up the global productivity of factors. Abatement will also have consequences on the government's budget:

$$\sum_{i=1}^{I} q_i \tau_t^i w_t^i + \tau_t^e \phi(\theta_t(\tau_t^e))K_t = G_t$$

and on the values of the steady-state equilibrium:

$$\begin{cases} \hat{K}^{\theta(\tau^e)} = K(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \\ \hat{P}^{\theta(\tau^e)} = P(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \\ \hat{Y}^{\theta(\tau^e)} = Y(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \\ \hat{\theta}(\tau^e) = \theta(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}) \end{cases}$$

In both cases, abatement will have important consequences on the aggregate variables (productivity, production and pollution for instance) without affecting qualitatively the households' behavior. The following sections will rely on our basic model and we give some insights into the consequences of abatement on the budget-neutral tax reform in the next section (and in Appendix A).

3. The specification of the budget-neutral tax reform

We study a budget-neutral environmental tax reform, based on an exogenous increase of the environmental tax rate, leaving the amount of government spending, and consequently the level of the tax revenues unchanged ex post. This increase $d\tau^e$ of the environmental tax rate can be compensated by a change of the labor tax rates $d\tau^i$ by two potential means: (i) a homogenous variation of all labor tax rates through the flat rate component ($d\tau^1$) or (ii) a variation in the progressivity of the labor tax (through a variation of the progressivity multiplier da). At the steady-state equilibrium, the government's budget constraint is (using (6) and (7)):

$$(\tau^1 \varepsilon_L + aB)\hat{Y} + \tau^e \hat{K} = \hat{G} \tag{16}$$

Let us first define the following elasticities (in absolute values) computed at the steady-state equilibrium: $\varepsilon_A = |\hat{K}\hat{A}_K'/\hat{A}| > 0$ the elasticity of the total factor productivity w.r.t. the stock of capital (through pollution); $\varepsilon_{\tau^1} = |\tau^1 \hat{K}_{\tau^1}'/\hat{K}| > 0$, $\varepsilon_{\tau^e} = |\tau^e \hat{K}_{\tau^e}'/\hat{K}| > 0$ and $\varepsilon_a = |a\hat{K}_a'/\hat{K}| > 0$ measure respectively the elasticity of the steady-state equilibrium stock of capital w. r.t. A, τ^1, τ^e and a. One can easily show that $\hat{K}_{\tau^1}' < 0$ and $\hat{K}_a' < 0$ because the labor tax increases lower the steady state savings. But, as with the environmental tax, the sign of $\hat{K}_{\tau^e}'$ is a priori undetermined because of the impact of τ^e on the capital cost ((5)). In our framework, the environmental tax can be justified only if it decreases pollution, which induces the following assumption and corresponds to an efficiency property of the pollution tax.

Assumption H1. $\hat{K}_{\tau^e}' < 0$.

The link between the variations of the pollution tax and of the characteristics of the labor tax is obtained through the differentiation of constraint (16), which is quite direct (using (12) and (13)).

Any budget-neutral tax reform is then characterized by the following relationship between $d\tau^e$, $d\tau^1$ and da (with $dG = dq_i = d\alpha_i = 0$):

$$\left(\varepsilon_L \frac{\hat{Y}}{\hat{K}} - \frac{\varepsilon_{\tau^1}}{\tau^1} C\right) d\tau^1 + \left(B\frac{\hat{Y}}{\hat{K}} - \frac{\varepsilon_a}{a} C\right) da + \left(1 - \frac{\varepsilon_{\tau^e}}{\tau^e} C\right) d\tau^e = 0 \tag{17}$$

where $C = (1-\varepsilon_A/\varepsilon_F)(R+\tau^e)(\tau^1\varepsilon_L + aB) + \tau^e$, constant, summarizing the overall tax base effect of the reform.

In the abatement cases, the tax base is modified as shown in Appendix A.

Assumption H2. We assume that $1 \geq \varepsilon_F - \varepsilon_A > 0$.

$\varepsilon_F - \varepsilon_A$ is the total measure of the sensitivity of output to capital stock through the direct effect ε_F of capital stock as an input, and the indirect effect ε_A, which corresponds to the impact of capital stock on global factor productivity, via the evolution of pollution. The direct contribution of capital to output is therefore assumed to be greater than the indirect one.

The reverse ($\varepsilon_F < \varepsilon_A$) would be of negligible economic interest because any rise in τ^e would result in a decrease of K allowing an increase of Y. Under Assumption H2, we can easily show that $C \geq \tau^e \geq 0$.

We will study two polar cases for specifying a budget-neutral environmental tax reform:

- uniform variation of all labor tax rates, with invariant progressivity ($da=0$):

$$d\tau^1 = -\frac{1-\frac{\varepsilon_{\tau^e}}{\tau^e}C}{\varepsilon_L\frac{\widehat{Y}}{\widehat{K}}-\frac{\varepsilon_{\tau^1}}{\tau^1}C}d\tau^e = -\Lambda\, d\tau^e \tag{18}$$

- variation of the progressivity, with invariant flat rate component of the tax rate ($d\tau^1=0$):

$$da = -\frac{1-\frac{\varepsilon_{\tau^e}}{\tau^e}C}{B\frac{\widehat{Y}}{\widehat{K}}-\frac{\varepsilon_a}{a}C}d\tau^e = -\Omega\, d\tau^e \tag{19}$$

Proposition 1. *The sign of the budget-neutral tax reform multipliers Λ and Ω is a priori undetermined and depends on the initial tax rates and on the values of the various elasticities.*

Proof. (i) The common numerator of both tax reform multipliers measures the effect of the change in pollution tax rate on its revenue. There is both a value effect (the tax revenue increases with the tax rate, for an unchanged stock of capital) and a tax base effect (the stock of capital decreases, and so does the output; as the tax rate increases, so the tax base erodes). These two effects work in opposite ways. As a result, this term might be positive or negative.

(ii) The denominator of each of these multipliers measures the effect of the change in labor tax rate on its revenue. There is also both a value effect (the tax revenue increases with the tax rate, for unchanged wages) and an overall tax base effect proportional to C (in the case of an increase in the tax rates, wages decrease and hence the tax base is eroded). They too work in opposite ways. As a result, this term too might be positive or negative. As the numerator and the denominator of both tax reform multipliers can be either positive or negative, the sign of the necessary change in the labor tax components is also undetermined. □

Assumption H3. *We focus on the Laffer-efficiency case, where the sign of the budget-neutral tax reform multipliers Λ and Ω is positive.*

Using (17), Assumption H3 implies

$$\text{sign}\left[1-\frac{\varepsilon_{\tau^e}}{\tau^e}C\right] = \text{sign}\left[\varepsilon_L\frac{\widehat{Y}}{\widehat{K}}-\frac{\varepsilon_{\tau^1}}{\tau^1}C\right] = \text{sign}\left[B\frac{\widehat{Y}}{\widehat{K}}-\frac{\varepsilon_a}{a}C\right].$$

The case of tax inefficiencies is of minor interest in our model since it corresponds to a weak pollution externality, inducing very low environmental tax revenues, or to a very strong sensitivity of capital stock to the environmental tax variation. Under Assumption H3, we do not consider these very specific and extreme cases. Nevertheless, considering the latter cases would not change our results, it would only shed light on some particular results.

4. Welfare analysis

As in previous papers (Chiroleu-Assouline and Fodha, 2006, 2011), we examine here the welfare effects of the tax change for a generation during its life-cycle, once the final steady-state equilibrium is reached. In this section, the welfare issue is thus a long term one.

The welfare effects of small tax changes are measured by the marginal *excess burden* defined as the *compensatory income variation*, denoted dR_c, i.e. the additional income that needs to be provided to the representative household to keep its utility at its initial level. It stands for the excess welfare loss of the consumers over and above the tax revenues collected by the government and can be interpreted as the hidden costs of financing public spending: a positive value for the marginal excess burden indicates a loss in welfare after the tax reform.

Let us determine the compensatory income variation which, after the tax reform, would leave the level of life-cycle utility unchanged ($dU=0$):

$$\frac{\partial U}{\partial c^{iy}}dc^{iy}+\frac{\partial U}{\partial c^{io}}dc^{io}=0$$

We use the first-order condition of the representative household′s program, which gives, using (2) and (3):

$$Rdc^{iy} + dc^{io} = 0$$

The intertemporal budget constraint of household i is written as follows:

$$\left(1-\tau^i\right)w^i = c^{iy} + \frac{1}{R}c^{io}$$

Applying the definition of the compensatory income variation dR_c^i:

$$\left(1-\tau^i\right)dw^i - w^i\left(d\tau^1 + b(i)\,da\right) + dR_c^i = -\frac{1}{R^2}c^{io}\,dR$$

by using (2) this leads to

$$dR_c^i = -\left(1-\tau^i\right)dw^i + w^i\left(d\tau^1 + b(i)\,da\right) - \frac{s^i}{R}\,dR \tag{20}$$

Unlike Bovenberg and de Mooij (1994) and the major part of the literature on this subject, it is here impossible to distinguish an environmental component and a non-environmental one, because pollution and production affect each other and the two impacts on welfare are not separable. We are thus constrained to depart from the usual definition of the double dividend (Goulder, 1995) because of this non-separability[14]: a "double dividend"will be characterized by the simultaneous decrease of pollution (which stands for the usual first dividend) and an increase in welfare (which depends here also on the pollution level).

The increase in welfare is verified for any variations of consumptions such that $\partial U/\partial c^{iy}\,dc^{iy} + \partial U/\partial c^{io}\,dc^{io} > 0$. This property plays an important role in our results. The first dividend requires a decrease of the capital stock inducing a decrease of the output, but this does not prevent the obtaining of the economic dividend. This originates from the impacts of K on W and R: $dW/dK > 0$ and $dR/dK \gtrless 0$. Such a decrease in the capital stock has a negative impact on both consumption through the wage rate effect, but it could be compensated by the positive influence on consumption when the household is old through the interest rate effect.

We now compute these two impacts of the capital stock on the input prices. Concerning the wage rate, we have (from (5)), in case of tax increases

$$d\hat{w}^i = -(\varepsilon_F - \varepsilon_A)\hat{w}^i\left[\frac{\varepsilon_{\tau^1}}{\tau^1}\,d\tau^1 + \frac{\varepsilon_{\tau^e}}{\tau^e}\,d\tau^e + \frac{\varepsilon_a}{a}\,da\right] < 0 \tag{21}$$

The impact of any tax increase on wages is unambiguously negative. This effect hurts all households′ welfare through two channels. It first decreases the wage rate, which is a base effect that increases the compensatory income variation. Secondly, this policy also reduces the net income as the tax rate increases, the latter acts as a rate effect that also increases the compensatory income variation.

We now turn to the impact of the policy on the interest rate:

$$d\hat{R} = \left[\hat{R} + \tau^e\right]\left[1-(\varepsilon_F - \varepsilon_A)\right]\left(\varepsilon_{\tau^1}\frac{d\tau^1}{\tau^1} + \varepsilon_{\tau^e}\frac{d\tau^e}{\tau^e} + \varepsilon_a\frac{da}{a}\right) - d\tau^e \gtreqless 0 \tag{22}$$

The impact of labor tax increases on the interest rate is unambiguously positive. Indeed, these tax rate increases lower the equilibrium level of the capital stock. This drop induces a higher marginal productivity of capital, which in turn increases the interest rate. And the drop in capital stock reduces pollution stock as well, and therefore raises the global productivity of factors, which in turn increases the interest rate.

Both effects appear similarly in the case of a capital tax rate increase, but its final impact on the interest rate is *a priori* undetermined because of the increase of the cost of capital which pushes down the steady state interest rate.

We finally obtain

$$dR_c^i = Z^i\left(\varepsilon_{\tau^1}\frac{d\tau^1}{\tau^1} + \varepsilon_{\tau^e}\frac{d\tau^e}{\tau^e} + \varepsilon_a\frac{da}{a}\right) + \hat{w}^i\left(d\tau^1 + b(i)\cdot da\right) + \frac{\hat{s}^i}{\hat{R}}\,d\tau^e$$

with $Z^i = (1-\tau^i)\hat{w}^i(\varepsilon_F - \varepsilon_A) - (\hat{R} + \tau^e)(1-[\varepsilon_F - \varepsilon_A])\hat{s}^i/\hat{R}$. Although the compensatory income variation dR_c^i measures the monetary effect of the gross welfare variation, we also need to compute this variation relatively to the initial wage rate in order to assess the regressivity properties of the tax reform.

Let us define $\Delta(x^i)$ as the difference between the values of the variable x between two successive classes of households $i+1$ and i: $\Delta(x^i) = x^{i+1} - x^i$ for any variable x.

[14] The reasons for this improper definition of the double dividend can be drawn from Goulder (1995) about Bovenberg and de Mooij (1997). In our model, it becomes difficult to separate the gross costs, defined as the effect of the environmental tax on welfare, abstracting from welfare changes linked to changes in the environmental quality, and environmental benefits of tax policies. Any increase of welfare cannot be interpreted as a case of second dividend, strictly speaking, because it involves benefit-side issues. This is not a case of negative gross costs. Rather, following Goulder (1995), we should say that our result supports the notion that when production-related environmental benefits are taken into account, environmental taxes sometimes can lead to higher welfare as well as a cleaner environment.

Definition 1. A tax is welfare regressive if and only if an increase of its rate implies a relative compensatory income variation $dR_c^i/\hat{w}^i$ decreasing with i, or equivalently $\Delta(dR_c^i/\hat{w}^i) = dR_c^{i+1}/\hat{w}^{i+1} - dR_c^i/\hat{w}^i \le 0$.[15]

Proposition 2. *Any increase of the single environmental tax implies a welfare loss for household i:*

$$\text{(i)} \qquad \forall \frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i} \quad \textit{when } 1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e} \ge 0 \ \ (\textit{i.e. } d\hat{R}/d\tau^e \le 0);$$

$$\text{(ii) } \textit{for } \frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i} \le \left| \frac{\frac{\hat{R}}{\tau^e}(\varepsilon_F-\varepsilon_A)\varepsilon_{\tau^e}}{1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}} \right| \quad \textit{when } 1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e} < 0 \ (\textit{i.e. } d\hat{R}/d\tau^e > 0).$$

Obviously, the ratio $\hat{s}^i/(1-\tau^i)\hat{w}^i$ is positively and directly determined[16] by the value of β^i which increases with i.

Corollary 3. *When* $1-[1+\hat{R}/\tau^e][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e} < 0$, *household i such that*

$$\frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i} > \left| \frac{\frac{\hat{R}}{\tau^e}(\varepsilon_F-\varepsilon_A)\varepsilon_{\tau^e}}{1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}} \right|$$

benefits from the environmental tax increase.

Proof. Let us compute this effect for agent i:

$$\frac{dR_c^i}{(1-\tau^i)\hat{w}^i\, d\tau^e} = \frac{Z^i}{(1-\tau^i)\hat{w}^i}\frac{\varepsilon_{\tau^e}}{\tau^e} + \frac{1}{(1-\tau^i)\hat{w}^i}\frac{\hat{s}^i}{\hat{R}}$$

$$= (\varepsilon_F-\varepsilon_A)\frac{\varepsilon_{\tau^e}}{\tau^e} + \frac{1}{\hat{R}}\frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i}\left(1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}\right)$$

A welfare loss corresponds to $dR_c^i \ge 0$. □

The conditions defined in Proposition 2 induce a welfare loss despite a specific effect due to the life-cycle assumption. As the propensity to save the richest households is higher, their consumption when old is also relatively higher. Indeed the increase of the environmental tax lowers the capital stock, hence increasing the rate of return on savings. The benefit of this effect is greater when the share of savings is high. Finally, the environmental tax decreases the welfare if the savings rate $\hat{s}^i/\hat{w}^i$ is lower than the threshold defined by

$$\left| \frac{\frac{\hat{R}}{\tau^e}(1-\tau^i)(\varepsilon_F-\varepsilon_A)\varepsilon_{\tau^e}}{1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}} \right|.$$

[15] In our paper, the welfare loss imposed by any tax rate increase is the *sacrifice* mentioned by Musgrave and Thin (1948), and a tax is called welfare regressive if its increase imposes a higher relative sacrifice to the poorest households than to the richest ones (similar but not identical to the *proportional sacrifice* defined by Young (1987) as a proportion of the ex ante utility).

[16] For several specifications of the preferences of the households, $\hat{s}^i/(1-\tau^i)\hat{w}^i$ is equal to β^i. More generally, $\hat{s}^i/\hat{w}^i$ is positively correlated to β^i. Notice that $1/(1-\tau^i)$ is also increasing with i. As we have $\hat{w}^{i+1} \ge \hat{w}^i$ and $\beta^{i+1} \ge \beta^i$, we then have

$$\frac{\hat{s}^{i+1}}{(1-\tau^{i+1})\hat{w}^{i+1}} \ge \frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i} \quad \text{and} \quad \frac{\hat{s}^{i+1}}{\hat{w}^{i+1}} \ge \frac{\hat{s}^i}{\hat{w}^i}$$

From (20), we can derive the interpretation of this threshold expressed here according to all parameters and steady-state variables: when $d\hat{R}/d\tau^e > 0$, the environmental tax implies a welfare loss for households such that

$$\frac{\hat{s}^i}{(1-\tau^i)\hat{w}^i} \le \left| \frac{dw^i/w^i}{d\hat{R}/\hat{R}} \right|$$

i.e. by dividing the denominator and the numerator by $d\tau^e/\tau^e$, such that their propensity to save is less than the ratio of the elasticity of their wage to the environmental tax divided by the elasticity of the interest rate to the environmental tax.

Corollary 4. *If the single environmental tax imposes a welfare loss, it is also welfare regressive when*

(i) $$1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e} \ge 0 \quad \textit{if and only if} \quad \frac{\Delta(\hat{s}^i/\hat{w}^i)}{\Delta(\tau^i)} < \frac{\frac{\hat{R}}{\tau^e}(\varepsilon_F-\varepsilon_A)\varepsilon_{\tau^e}}{\left[1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}\right]};$$

(ii) $$1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e} < 0.$$

Proof. The environmental tax is welfare regressive if and only if the poorest households bear the heaviest burden of the increase of the environmental tax, i.e. $\Delta(dR_c^i/\hat{w}^i) \le 0$, i.e.

$$-\frac{\varepsilon_{\tau^e}}{\tau^e}(\varepsilon_F-\varepsilon_A)\Delta\tau^i + \left[1-\left[1+\frac{\hat{R}}{\tau^e}\right][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}\right]\frac{\Delta(\hat{s}^i/\hat{w}^i)}{\hat{R}} \le 0.$$

As β^i and τ^i increase with i, according to Assumption H2, the sign of $\Delta(dR_c^i)$ depends on the sign of $[1-[1+\hat{R}/\tau^e][1-(\varepsilon_F-\varepsilon_A)]\varepsilon_{\tau^e}]$ that is on the impact of the environmental tax on the interest rate.[17] □

Combining the sufficient conditions for welfare loss and welfare regressivity, we obtain that when $d\hat{R}/d\tau^e > 0$, the environmental tax only affects the welfare of the poorest households and is unconditionally welfare regressive. Also, when $d\hat{R}/d\tau^e \le 0$, it affects all households and may be welfare regressive for specific combinations of initial tax rates and elasticities.

Proposition 5. (i) *The increase of the single flat wage tax* ($d\tau^1 > 0$) *causes a welfare loss if and only if*

$$\frac{\hat{s}^i}{\hat{w}^i} \le \frac{\hat{R}\left[1\Big/\frac{\varepsilon_{\tau^1}}{\tau^1}+(1-\tau^i)(\varepsilon_F-\varepsilon_A)\right]}{[\hat{R}+\tau^e][1-(\varepsilon_F-\varepsilon_A)]}.$$

(ii) *It is welfare regressive, i.e. it penalizes more heavily the lowest wage-earners.*

Proof. Let us compute this effect for agent i:

$$\frac{dR_c^i}{\hat{w}^i\, d\tau^1} = \frac{Z^i}{\hat{w}^i}\frac{\varepsilon_{\tau^1}}{\tau^1}+1 = \frac{dR_c^i}{\hat{w}^i\, d\tau^1} = \frac{\varepsilon_{\tau^1}}{\tau^1}\left(1-\tau^i\right)(\varepsilon_F-\varepsilon_A)+1-[1-(\varepsilon_F-\varepsilon_A)]\left[\hat{R}+\tau^e\right]\frac{1}{\hat{R}}\frac{\hat{s}^i}{\hat{w}^i}\frac{\varepsilon_{\tau^1}}{\tau^1}$$

The condition $dR_c^i \ge 0$ gives the threshold for welfare loss and, as τ^i and $\hat{s}^i/\hat{w}^i$ both increase with i, this tax is always welfare regressive. □

Proposition 6. *An increase of the single progressivity multiplier of the wage tax* ($da > 0$) *deteriorates the welfare of agents i if and only if*

$$\frac{\hat{s}^i}{\hat{w}^i} \le \frac{\hat{R}\left[b(i)\Big/\frac{\varepsilon_a}{a}+(1-\tau^i)(\varepsilon_F-\varepsilon_A)\right]}{[\hat{R}+\tau^e][1-(\varepsilon_F-\varepsilon_A)]}.$$

Proof. Let us compute this effect for agent i:

$$\frac{dR_c^i}{\hat{w}^i\, da} = \frac{Z^i}{\hat{w}^i}\frac{\varepsilon_a}{a}+b(i) = \left[\left(1-\tau^i\right)(\varepsilon_F-\varepsilon_A)-[1-(\varepsilon_F-\varepsilon_A)]\left[\hat{R}+\tau^e\right]\frac{1}{\hat{R}}\frac{\hat{s}^i}{\hat{w}^i}\right]\frac{\varepsilon_a}{a}+b(i)$$

The condition $dR_c^i \ge 0$ gives the threshold for welfare loss. □

Obviously, the total effect of such an increase in the progressivity multiplier a can be either progressive or regressive, depending on the relative strengths of the regressivity of $Z^i/\hat{w}^i$ and the progressivity characteristics of $b(i)$.

[17] This result is in line with Dissou and Siddiqui (2014) who show, in a different framework, that the regressivity or progressivity of the carbon tax depends on the effects of the tax on the factors′ prices, namely the interest rate because labor supply is also exogenous.

Remark 1. Regarding our welfare analysis, all the previous results still hold if $\varepsilon_A = 0$, basically because the productivity effect of pollution is assumed to be a second order effect (Assumption H2).

For an economy where productivity is insensitive to pollution ($\varepsilon_A = 0$) and where the pollution would affect household's welfare in an additive way, as in the standard literature, the previous analysis would stand for the analysis of the effects of the environmental tax reform on the economic share of overall welfare, and the double dividend could be defined in the standard way, as a simultaneous improvement of the economic share of overall welfare and of the environmental one (through the decrease of pollution).

5. The environmental effects of the tax reform

As steady-state pollution depends only on steady-state capital, we find straightforwardly that the first dividend (*i.e.* a decrease of pollution) is reached if $d\hat{P} = (\phi/h)\, d\hat{K} < 0$. This condition is rewritten as (see (12))

$$d\hat{K} = -\left[\varepsilon_{\tau^1}\frac{\hat{K}}{\tau^1}\, d\tau^1 + \varepsilon_{\tau^e}\frac{\hat{K}}{\tau^e}\, d\tau^e + \varepsilon_a\frac{\hat{K}}{a}\, da\right] < 0$$

$$\Leftrightarrow \frac{\varepsilon_{\tau^1}}{\tau^1}\Lambda + \frac{\varepsilon_a}{a}\Omega < \frac{\varepsilon_{\tau^e}}{\tau^e}$$

$$\Leftrightarrow \left(1 - \frac{\varepsilon_{\tau^e}}{\tau^e}C\right)\left[\frac{\frac{\varepsilon_{\tau^1}}{\tau^1}}{\varepsilon_L\frac{\hat{Y}}{\hat{K}} - \frac{\varepsilon_{\tau^1}}{\tau^1}C} + \frac{\frac{\varepsilon_a}{a}}{B\frac{\hat{Y}}{\hat{K}} - \frac{\varepsilon_a}{a}C}\right] < \frac{\varepsilon_{\tau^e}}{\tau^e}$$

The Laffer-efficiency Assumption H3 does not guarantee that the environmental dividend occurs. It would need a low positive impact on capital, because of the decrease of the wage tax, compared to the negative impact of the environmental tax.

Proposition 7. *The environmental tax reform ensures the environmental dividend if and only if*

(i) $\Lambda < (\varepsilon_{\tau^e}/\tau^e)/(\varepsilon_{\tau^1}/\tau^1)$ *when the revenue is recycled only through a decrease of the flat wage tax*;
(ii) $\Omega < (\varepsilon_{\tau^e}/\tau^e)/(\varepsilon_a/a)$ *when the revenue is recycled only through a decrease of the progressivity multiplier of the wage tax*;
(iii) $(\varepsilon_{\tau^1}/\tau^1)\Lambda + (\varepsilon_a/a)\Omega < \varepsilon_{\tau^e}/\tau^e$ *when the revenue is recycled through a decrease of both the flat wage tax and the progressivity multiplier of the wage tax.*

With respect to the environmental objective of the policy, the tax reform should not involve too strong a decrease of the labor tax rate, in order to limit its boost to economic growth.

6. The welfare effects of the tax reform under conditions of regressivity

Since we intend to focus on the worst case, we assume that the single environmental tax is both welfare reducing for all households and regressive, even if the environmental dividend is obtained (i.e. conditions (i)–(iii) of Proposition 7 are verified).
As each policy does not affect all classes equally, it may be asked which one would be preferred by each class of workers.

Proposition 8. *When the impact on the steady-state capital stock of the compensating variation of* τ^1 *is greater than the impact of the compensating variation of* a, (i) *the revenue recycling of the budget-neutral environmental tax reform preferred by the workers of the lowest classes consists of a decrease in the flat rate component of the tax rate* τ^1 (ii) *but the one preferred by the workers of the highest classes consists of a decrease in the progressivity of the wage tax rate.*

Proof. Let us compare the compensatory income variations associated with each policy.

- *First case* ($dR^i_{(\tau^1)}$): uniform variation of all labor tax rates (with invariant progressivity): $da = 0$ and $d\tau^1 = -\Lambda\, d\tau^e$

$$\frac{dR_c^i(\tau^1)}{d\tau^e} = -Z^i\left[\frac{\varepsilon_{\tau^1}}{\tau^1}\Lambda - \frac{\varepsilon_{\tau^e}}{\tau^e}\right] - \hat{w}^i\Lambda + \frac{\hat{s}^i}{\hat{R}}$$

$$\Longleftrightarrow \frac{dR_c^i(\tau^1)}{\hat{w}^i\, d\tau^e} = -\underbrace{\frac{Z^i}{\hat{w}^i}}_{+}\underbrace{\left[\frac{\varepsilon_{\tau^1}}{\tau^1}\Lambda - \frac{\varepsilon_{\tau^e}}{\tau^e}\right]}_{-} - \underbrace{\Lambda}_{+} + \frac{1}{\hat{R}}\frac{\hat{s}^i}{\hat{w}^i}$$

The sign of this compensatory income variation is not the same whatever the class of households. By substituting the value of Z^i into the latter condition, we show that this recycling option induces a relatively higher welfare loss for the richest households than for the poorest ones:

$$\frac{dR_c^i(\tau^1)}{\hat{w}^i\, d\tau^e} > 0 \Longleftrightarrow \frac{\hat{s}^i}{\hat{w}^i} \leq \frac{\hat{R}\left[\Lambda + (1-\tau^i)(\varepsilon_F - \varepsilon_A)\left(\frac{\varepsilon_{\tau^1}}{\tau^1}\Lambda - \frac{\varepsilon_{\tau^e}}{\tau^e}\right)\right]}{1 + \left[\hat{R} + \tau^e\right][1 - (\varepsilon_F - \varepsilon_A)]\left(\frac{\varepsilon_{\tau^1}}{\tau^1}\Lambda - \frac{\varepsilon_{\tau^e}}{\tau^e}\right)}$$

- *Second case* ($dR^i_{(a)}$): variation of the progressivity (with invariant flat rate component): $d\tau^1 = 0$, $da_i = b(i)da$ and $da = -\Omega d\tau^e$

$$\frac{dR_c^i(a)}{d\tau^e} = -\underbrace{Z^i}_{+}\underbrace{\left[\frac{\varepsilon_a}{a}\Omega - \frac{\varepsilon_{\tau^e}}{\tau^e}\right]}_{-} - \underbrace{\hat{w}^i b(i)\Omega}_{+} + \frac{\hat{s}^i}{\hat{R}}$$

$$\Longleftrightarrow \frac{dR_c^i(a)}{\hat{w}^i\, d\tau^e} = -\underbrace{\frac{Z^i}{\hat{w}^i}}_{+}\underbrace{\left[\frac{\varepsilon_a}{a}\Omega - \frac{\varepsilon_{\tau^e}}{\tau^e}\right]}_{-} - \underbrace{b(i)\Omega}_{+} + \frac{1}{\hat{R}}\frac{\hat{s}^i}{\hat{w}^i}$$

A similar reasoning applies here: since $Z^i/\hat{w}^i$ decreases with i, while $\hat{s}^i/\hat{w}^i$ and $b(i)$ increase when i increases unlike Ω which is constant, this recycling option induces a relatively higher welfare loss (that may turn into a welfare gain) for the poorest households than for the richest ones.

The signs of these compensatory income variations depend on the values of the characteristics of the economy ($b(i), \varepsilon_F, \varepsilon_A, \varepsilon_a, \varepsilon_{\tau^e}$) and of the initial tax rates (τ^e, τ^i, a). The result above suggests that, in the case where some classes of workers suffer from a deterioration of their welfare after the above tax reforms, an appropriate policy mix could be designed in order to leave the welfare of each class of workers not deteriorated by the environmental tax reform: it would consist in an increase of the progressivity index together with a decrease of the flat rate component of the wage tax rate.

Assume that the budget-neutral tax reform is defined by $d\tau^1 < 0$ and $da = -\mu\, d\tau^1$ with $\mu > 0$ hence $da > 0$. Such a compensation for the increase in the environmental tax rate will imply a greater decrease of τ^1 than above, because the degree of progressivity is raised. $\mu = -da/d\tau^1$ could be named the *transformation ratio of the flat tax rate into progressivity of the compensating labor tax.*

Proposition 9. *For economies where a decrease in the wage flat tax τ^1 does not suffice to re-establish the welfare of some classes of workers, the minimal transformation ratio of the flat tax rate into progressivity $\overline{\mu}$ may be chosen, in order to ensure that all classes will be better off with the environmental tax reform.*

Proof. Let us specify the link implied by such a policy between the increase in the environmental tax rate and the decrease in the flat component of the wage tax:

$$d\tau_e = -\frac{1}{\Lambda}\, d\tau^1 - \frac{1}{\Omega}\, da = -\frac{1}{\Omega}\left(\frac{\Omega}{\Lambda} - \mu\right) d\tau^1$$

The compensatory income variation of the budget-neutral mix policy is

$$dR^i_{(\mu)} = -\left[\left(Z^i\frac{\varepsilon_{\tau^1}}{\tau^1} + \hat{w}^i\right) - \left(Z^i\frac{\varepsilon_a}{a} + \hat{w}^i b(i)\right)\mu\right]\frac{\Lambda}{\left(\frac{\Lambda}{\Omega} - \mu\right)} + \left(\frac{Z^i\frac{\varepsilon_{\tau^e}}{\tau^e} + \hat{s}^i}{\hat{R}}\right)$$

- $dR^i_{(\mu)} \lesseqgtr 0$, $\forall i = 1, \ldots I$.
- $dR^i_{(\mu)}$ is neither monotonous in $b(i)$, nor in μ, $\forall i$.
- If $dR^i_{(\tau^1)} < 0$, $\forall i = 1, \ldots I$, all classes will be better off even with $\mu = 0$.

If $\exists i, dR^i_{(\tau^1)} > 0$, as the function $dR^i_{(\mu)}$ is bound for each μ, there is one $\bar{\imath}$ which maximizes it:

$$\bar{\imath} = \text{INT}\,[\arg\max dR^i_{(\mu)}]$$

One can choose $\overline{\mu} > 0$ in order to nullify $dR^{\bar{\imath}}_{(\mu)}$: this ensures that all classes will be better off (their compensatory income

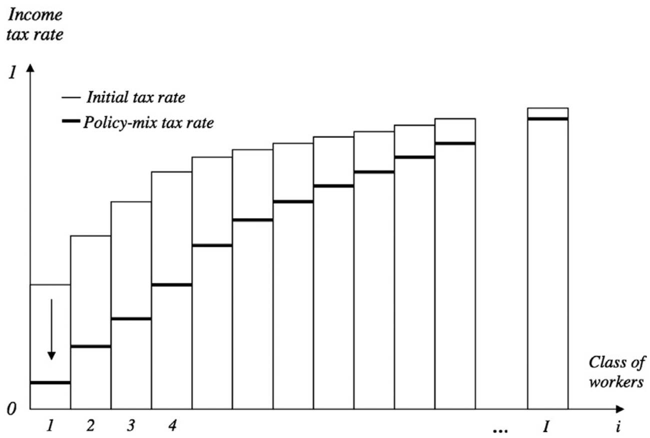

Fig. 1. Profile of the labor tax rates before and after the environmental tax reform.

variations are all negative or null):

$$\overline{\mu} = \frac{Z^{\bar{\imath}}\dfrac{\mathcal{E}_{\tau^1}}{\tau^1} + \hat{w}^{\bar{\imath}} - \dfrac{1}{\Omega}\left(\dfrac{Z^{\bar{\imath}}\frac{\mathcal{E}_{\tau^e}}{\tau^e} + \hat{S}^{\bar{\imath}}}{\hat{R}}\right)}{Z^{\bar{\imath}}\dfrac{\mathcal{E}_a}{a} + \hat{w}^{\bar{\imath}} b(\bar{\imath}) - \dfrac{1}{\Lambda}\left(\dfrac{Z^{\bar{\imath}}\frac{\mathcal{E}_{\tau^e}}{\tau^e} + \hat{S}^{\bar{\imath}}}{\hat{R}}\right)} \qquad \square$$

This policy mix aims to reduce the pre-existing distortions of the tax system, in a second-best world, but not to reach an optimal outcome. Therefore $\overline{\mu}$ comes from our Pareto-improving criterion but not from any optimality criterion. Fig. 1 shows the qualitative impact of such a policy mix on the design of the wage tax.

The government can thus combine variations of the two parts of the wage tax rate and design a policy-mix system: by increasing the tax burden for the upper tax brackets, it is possible to earn greater tax revenues than through the environmental tax alone, and then to decrease more the income tax of the lowest tax rate bracket. Therefore, all classes are less taxed but even the poorest class would benefit from the environmental tax reform. The increase in the welfare of the upper-income classes will be reduced, but is still high, compared to the lower-income classes.

7. Conclusion

In this paper, we have shown in a general framework that a budget-neutral environmental tax reform may result in a double dividend, when the economy is characterized by heterogeneous agents (old and young), many classes of employees (heterogeneous labor) and productivity affected by pollution.

We have analyzed the distributional effects of several tax policies between different categories of households and put forward an appropriate policy mix to compensate them, in order to ensure non-decreasing welfare for each class of workers.

We have also emphasized that the conditions for obtaining a double dividend depend on the distributive properties of the labor taxes. Hence, we have shown that: (i) an increase of the single environmental tax may deteriorate the welfare of all and may be regressive; and (ii) under some conditions, the low-pay workers prefer a budget-neutral environmental tax reform, achieved through a decrease in the flat rate component, whereas the high-pay workers prefer a decrease in progressivity. In our general framework, we focus on the specific case of an economy with a Laffer-efficient tax system, where the environmental tax reform results in a first dividend but causes higher welfare losses for the lowest-pay households. We have demonstrated that whatever the degree of regressivity of the environmental tax alone, it is possible to re-design a recycling mechanism to obtain not only a double dividend but also a Pareto-improving tax reform by modifying the progressivity characteristics of the tax system, instead of lump-sum transfers or any other form of homogeneous compensation. The mechanisms underlying this result can be summarized as follows. The primary consequence of the environmental tax is the decrease of the pollution resulting from the decrease of the capital stock, which also implies a reduction of the output because the reform leaves constant the other production factors (labor). The cost of this environmental benefit consists of a fall in the wages of all agents, which can produce distributional effects since wage earners will lose. Moreover, to reduce capital, total savings in the economy have to be reduced, which is likely to hurt households that prefer to save. These negative effects on total life-cycle consumption can be somehow counterbalanced by the rise of the interest rate (due to the drop in the capital stock), which benefits the second-period consumption. One contribution of the paper is to highlight these non-trivial distributional effects.

The heterogeneity characteristics of the economy and the progressivity of the labor tax allow the government to obtain more revenues from the environmental policy. The increase of the progressivity of the labor tax permits a greater decrease of its flat rate component, without compromising the environmental benefit. Moreover, it enables the redistribution of welfare between the agents, in order to fulfill our Pareto-improvement criterion. We finally show how a Pareto-improving budget-neutral tax reform can be achieved by simultaneously decreasing the flat rate component of the income tax and increasing its progressivity according to the ratio that ensures no welfare loss even for the most heavily affected households.

It may be observed that even if productivity is insensitive to pollution and/or if pollution would affect households′ welfare in an additive way, our results would still be robust and contribute to the standard double dividend literature. Nevertheless, our results stem from the assumption of inelastic labor supply. If we consider endogenous labor supply, it is likely to modify the conditions for the success of the progressive budget-neutral tax reform. Indeed, the leisure-consumption trade-off would soften the variations in wages induced by the capital stock decrease and hence would temper the changes in the income tax rate structure.

One of the reasons for the failure of the French carbon tax (so-called Carbon Contribution) in 2010 was that the intended revenue-recycling process was hardly understood by the taxpayers and did not manage to make the reform acceptable. But in fact, a careful design of a broader tax reform could have achieved this goal by alleviating the effect of the carbon tax on the poorest agents and by increasing the fairness of such a policy. This kind of revenue recycling should be considered by policymakers, as it allows all obstacles to the acceptance of environmental tax reform to be eliminated.

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Appendix A

In the case of an adaptation abatement strategy, as the optimal level of abatement does not depend on the environmental tax, the definition of the budget equilibrium is not affected. Finally, the distributional analysis and the definition of the Pareto improving policy-mix are unchanged.

In the case of a mitigation abatement strategy, the government′s budget equilibrium turns out to

$$(\tau^1 \varepsilon_L + aB)\hat{Y}(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}, \theta(\tau^e)) + \tau^e \phi(\theta(\tau^e))\hat{K}(\tau^e, \tau^1, a, \{b(i)\}, \{\beta^i\}, \theta(\tau^e)) = \hat{G}$$

Basically, we have new elements in this equilibrium and we only focus on these changes (comparatively to the "no abatement" case). The total differentiation of the budget constraint is modified regarding the environmental tax side, which then becomes:

$$[\varepsilon_{Y/\theta}\varepsilon_{\theta/\tau^e}\tau^e\hat{Y} + \phi\hat{K} + \varepsilon_{\phi/\theta}\varepsilon_{\theta/\tau^e}\hat{K} + \tau^e\phi\varepsilon_{K/\theta}\varepsilon_{K/\tau^e}\tau^e\hat{K}]\, d\tau^e$$

But as in the "no abatement case", all these terms are constant and positive, which implies that the abatement investment will change the aggregate level of the steady-state equilibrium, but will not impact the consequences for households. However, this assumption on abatement influences the likelihood of the success of the environmental policy. Indeed, as the environmental tax revenues are lower, the decrease of the labor tax is also lower.

Despite the consequences of abatement activities on the aggregate variables, they do not compromise the results about the distribution properties of the environmental tax policy.

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