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Environmental Policy and Growth when Inputs are Differentiated in Pollution Intensity

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Summary

Environmental policy affects the distribution of market shares if intermediate goods are differentiated in pollution intensity. When innovations are environmental friendly, a tax on emissions skews demand towards new goods, which are the most productive. In this case along a balanced growth path the tax has to increase to keep the market shares of goods of different vintages constant. An increase in the burden of taxation lowers output on impact but, comparing balanced growth paths, we find that it spurs innovation. Through this channel environmental policy may increase the growth rate of the economy.

Keywords: Endogenous growth, environmental policy, induced technological change

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1 Introduction

Production activities have grown so much that they now play a primary role in the functioning of the ecosystem. Conservation of the ecosystem may constrain significantly further expansion of economic activity. The case of global warming is particularly important in the current international agenda of environmental policy. There is substantial agreement among the scientific community that climate change is exacerbated by emissions of green-house gases, such as methane and carbon dioxide (CO_2). Carbon emissions result from burning fossil fuel, the main source of primary energy. With the current technology and equipment, a reduction of emissions entails a fall in energy inputs which is likely to lower output below its potential level. Emissions can be controlled by imposing a tax or a quota on emissions (supported for instance by a market for pollution permits). We define this policy as a restrictive environmental policy.

A positive question arises: how does a restrictive environmental policy influence the prospects of economic growth? The answer is not so obvious as that concerning the impact on the current level of production, because in the long-run technology and equipment change.[1] Although no empirical work has yet attempted to provide an answer, in recent years a body of theoretical papers has addressed this question using models of endogenous growth. In these analysis emissions are formalized as an input or as a by-product. In any case environmental policy operates through a *direct channel* of transmission. It increases the cost of emissions inputs or forces firms to engage in abatement expenditure, and therefore it reduces the return on capital. As a result the rate of investment falls and this slows the rate of growth of output. In short, there exists a trade-off between economic growth and the protection of environmental quality.[2]

A number of analysis have explored the possibility that some other channels of transmission of environmental policy on growth can relax this trade-off. Most of these papers assume that environmental quality has strong external effects on the production sector or

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[1] The question may not be relevant for the design of environmental policy, given that the latter should target social welfare. Yet the answer is interesting on its own, at least in view of governments' reluctance to engage on stringent targets for the reduction of CO_2 emissions.

[2] See, for instance, Marrewijk et al. (1993) and Stokey (1998).

on utility. For instance, it is often assumed that improvements in environmental quality enhance either total factor productivity or productivity in the core sector for growth, such as human capital accumulation.[3] These kind of assumptions seem plausible for economies that rely heavily on the exploitation of natural resources or where pollution is so serious to weaken pupils's cognitive ability. In the case of most industrialized economies it is unlikely that improvements in the quality of the environment can have first order effects on factor productivity.[4]

This paper provides the rationale for an alternative channel of transmission of environmental policy on growth which tends to relax the trade-off between the protection of environmental quality and economic growth. This channel is independent of any externality resulting from improvements in environmental quality. Moreover, the mechanism of the growth process and of the environmental impact of production are designed to describe mainly industrialized economies. We adopt the framework of the schumpeterian growth theory, which model explicitly incentives to engage in productivity enhancing activities (hereafter R&D) (Grossman and Helpman 1991, Aghion and Howitt 1992). It is assumed that innovations improve the quality of capital goods on two dimensions: their productivity and pollution intensity. New goods are characterized by higher productivity and, possibly, lower pollution intensity than existing goods.[5] If innovations embody the same pollution intensity of the goods that they replace, emissions grow at the same rate as output. If instead innovations have a cleaner technology, emissions grow at a slower rate than output. The flow of services that capital goods provide are called intermediate

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[3] See for instance Bovenberg and Smulders, 1995, Smulders and Gradus, 1996, Gradus and Smulders, 1993, Kany and Ragot, 2001.

[4] Environmental policy may also affect growth if it influences households' saving behavior (e.g. Fisher and Marrewijk, 1998). In particular if consumption and environmental quality are complements, expected improvements in environmental quality induce households to save more to postpone consumption (Mohtadi, 1996, Michel and Rotillon, 1995). A way to rule out the trade-off consists in introducing increasing returns in pollution abatement, so that growth allows to increase the efficiency of abatement activities (e.g. Michel, 1993, and Xepapadeas, 1994, Andreoni and Levinson, 2001). In Hettich (1998) and Oueslati (2001) environmental policy fosters growth because it favors the accumulation of human capital by reducing consumption per unit of output in a context where consumption and leisure are normal goods.

[5] We do not allow for increased pollution intensity of capital goods. This assumption is plausible at least for industrialized economies, according to the stylized evidence reported in the table below.

goods. Their operating cost is composed of the rental rate of capital and the tax burden on emissions associated with their use. The relative weight of these components can be managed by the environmental policy-maker, and affects incentives to invest and the pace of growth if it varies across different vintages.

First, we analyze the case when the extent to which innovations are cleaner is exogenous, and in particular independent of environmental policy. This assumption allows us to focus on the description of an original channel of transmission through which environmental policy affects the pace of technological change and the rate of growth. We show that a tax on emissions has a *distortionary impact* on competition across sectors, when goods are differentiated in their pollution intensity. To the extent that there is a (negative) correlation between the productivity of goods and their pollution intensity, the tax on emissions acts as a prize to innovators. In fact, the tax on emissions increases the market share of new and most productive goods, and increases the relative pay-off to R&D investment. We find that, when goods are differentiated in emissions intensity, the green tax increases along a balanced growth path to keep the market shares of goods of different vintages constant. Furthermore an increase in the burden of emissions taxes reduces on impact the level of aggregate output, but increases the long-run rate of growth because it fosters R&D activity.[6]

	US	UK	Japan	S. Korea		Indonesia		Singapore	
	1960-96	1960-96	1960-96	1960-80	1980-96	1960-78	1978-96	1960-70	1970-96
CO$_2$/GDP†	-37%	-58%	-28%	+118%	-10%	+58%	-22%	+411%	-55%
Industry share‡	-34%	-30%	-15%	+95%	+8%	+137%	+22%	+84%	+16%

†: Thousand metric tons of CO$_2$ emissions from fossil-fuels and GDP at constant market prices. ‡: Industry value added as % of GDP.

Source: Oak Ridge National Laboratory, World Development Indicators (World Bank).

At first sight the assumption does not seem pertinent to countries undergoing a fast phase of industrialization. But this is due to the change in the sectoral composition of output, and does not imply that innovations are relatively dirty. In fact, Hettige et al. (1997) find that "the intensity of industrial pollution at the end-of-pipe declines strongly with income" in developing countries.

[6] Our argument is close to that presented by Xepapadeas and de Zeeuw (1999). They consider a vintage capital model in partial equilibrium, where new vintages are both more productive and less polluting. On the demand-for-capital side of the economy, an increase in emissions taxes induces firms to change the composition of their capital stock, reducing its average age and increasing its average productivity. The theory presented in the following sections incorporates this mechanism in a dynamic general equilibrium model, where the supply-of-capital side of the economy is endogenous on both its quality (designs of

Second, environmental policy is allowed to affect the extent to which innovations embody cleaner technologies, i.e. the *direction of R&D*. In this way we reintroduce the possibility that environmental policy has a negative impact on the growth rate. In fact emissions are an implicit input of production. Cleaner innovations are relatively less productive, because they use less of the complementary emissions input. Hence, as environmental policy induces R&D laboratories to design cleaner goods, the marginal effect of R&D on productivity growth decreases. This *direct input effect* runs in opposite direction to that due to the distortionary impact of emissions taxes (which tends to foster R&D). Solving numerically the model, we find that in general the direct effect dominates. However the distortionary impact of taxation is active and relaxes the growth-environmental trade-off.

This research is closely related to that of Stokey (1998), Aghion and Howitt (1998, ch.5), Grimaud (1999), Grimaud and Ricci (1999), which rationalize the trade-off. In those models emissions are an input in the final sector of the economy, independent of the mix of capital goods employed in production. Final sector firms control the pollution intensity in response to the relative price of pollutants. In the first part of the paper the pollution intensity is a technological state variable and its improvement is gradual. The reduction in the pollution intensity of aggregate output is therefore a smooth process resulting from the adoption of the state of the art knowledge by innovators. In this case old intermediate goods will be dirtier than new ones. This differentiation represents the crucial asymmetry driving the distortionary impact of environmental policy on which this analysis is focused. Nevertheless, when in the second part of the paper we allow firms to control the direction of R&D, the trade-off comes back into the picture.

The next section presents the model. Section 3 characterizes balanced growth paths. In section 4 we analyze the effect of environmental policy when the direction of R&D is exogenous. Section 5 considers the case when R&D laboratories choose endogenously the pollution intensity of innovations. We conclude in the last section.

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innovations) and quantity (saving-investment decision) dimensions.

2 The model economy

We extend the schumpeterian model of endogenous growth (as that of Aghion and Howitt 1998, p.85-92) to consider that production emits pollutants. Production takes place in three stages. First, labor is competitively engaged in research and development (R&D) activities aimed at designing higher-quality intermediate goods. Successful innovations are characterized by higher productivity and, possibly, by lower pollution intensity. The pollution intensity is a technological variable of the intermediate good, which is chosen by the R&D laboratory when it introduces the good on the market. This choice is irreversible and a lower pollution intensity implies a lower productivity of the good. Second, designs are protected by patents, so that intermediate goods are supplied under local monopoly power. These goods are produced employing capital. Their production also implies emissions of pollution. We assume a continuum of intermediate goods. Producers rent capital from households and pay a tax per unit of emissions resulting from their goods. Intermediate goods are combined with labor in the final sector to produce an homogeneous good, which can be consumed or invested.

In this section we first present the production functions of the final and intermediate sectors, and the environment. Next we study the behavior of the agents: the final sector, a representative intermediate good monopolist, the R&D sector, the consumers and the government.

2.1 Production and the environment

Final output is produced employing labor and a continuum of intermediate inputs according to the production function:

$$Y_\tau = (1 - n_\tau)^{1-\alpha} \int_0^1 Z_{j\tau} A_{j\tau} x_{j\tau}^\alpha dj \tag{1}$$

where $\alpha \in (0, 1)$; labor supply is fixed and normalized to unit mass; a share $(1 - n)$ of labor is employed in production and n in R&D activities (if labor market clears); $x_{j\tau}$ is the quantity of intermediate good $j \in [0, 1]$ used at date τ. The technology embodied in intermediate goods is described by a two-dimensional vector characterized by parameters

A and Z. $A_{j\tau}$ is the implicit labor productivity index and $Z_{j\tau}$ the pollution intensity index of intermediate good j at date τ. As shown in the production function (1), the productivity of good j at date τ depends on the product $Z_{j\tau}A_{j\tau}$. The link between parameter Z and productivity is explained at the end of this subsection.

Intermediate goods are produced employing capital, according to:

$$x_{j\tau} = \frac{K_{j\tau}}{A_{j\tau}} \tag{2}$$

Thus, intermediate goods are services from capital goods, and the more productive the good the higher its capital intensity.

The flow of emissions, P_j, associated to the use of a capital good depends on its pollution intensity index at date τ, $Z_{j\tau}$, and are given by, $\forall\ j \in [0,1]$:

$$P_{j\tau} = Z_{j\tau}^{1/\alpha\beta} K_{j\tau} \tag{3}$$

with $\beta \in (0,1)$. Thus aggregate emissions, P, can be defined as follows:

$$P_\tau = \int_0^1 P_{j\tau}dj = \int_0^1 Z_{j\tau}^{1/\alpha\beta} K_{j\tau}dj \tag{4}$$

Substituting for $K_{j\tau}$ from (3) into (2), we see that good j is produced out of emissions:

$$x_{j\tau} = \frac{P_{j\tau}}{Z_{j\tau}^{1/\alpha\beta} A_{j\tau}} \ .$$

(3) can be written as:

$$Z_{j\tau} = \left(\frac{P_{j\tau}}{K_{j\tau}}\right)^{\alpha\beta}$$

Thus $Z_{j\tau}$ is a measure of the emissions-capital ratio characteristic of good j at date τ. This means that for any given technology Z_j, substitution of capital for emissions cannot take place, e.g. in response to a shift in their relative price. Substitution can take place only with the introduction of a new technology in sector j, say $Z_j^{'}$. The pollution intensity is reduced if the new technology satisfies $Z_j^{'} < Z_j$. Nevertheless a new technology can be introduced only through R&D. At the industry level substitution is therefore costly and discontinuous over time.

Emissions are implicit inputs that are combined with intermediate inputs according to their pollution intensity. Substituting for $Z_{j\tau}$ above and $x_{j\tau}$ from (2) into (1), we get:

$$Y_\tau = \int_0^1 \left[(1-n_\tau)A_{j\tau}\right]^{1-\alpha} \left[P_{j\tau}^{\beta} K_{j\tau}^{1-\beta}\right]^{\alpha} dj$$

We can think of equipment machines which are employed in the process of production. Labor is required to operate them, and their use implies some pollution. The productivity of labor and dirtiness of the process of production depend on the design of machines, according to their technological parameters A and Z. The productivity of intermediate goods is increasing in the pollution intensity index because emissions represent an implicit input complementary to capital.

2.2 Prices and green tax

The price of final output is normalized to unity. We denote by w the wage, by p_j the price of intermediate input $j \in [0,1]$, by r the rate of return on savings, by V_τ the value of an innovation introduced at date τ. Moreover, the government levies a tax per unit of emissions, h, on intermediate goods producers to price emissions associated to their sales.

2.3 The final sector

The instantaneous profits of the fictitious competitive final firm are:

$$\psi_\tau = (1-n_\tau)^{1-\alpha} \int_0^1 Z_{j\tau} A_{j\tau} x_{j\tau}^{\alpha} dj - w_\tau (1-n_\tau) - \int_0^1 p_{j\tau} x_{j\tau} dj$$

Therefore the (inverse) demand for labor from the final sector is given by:

$$w_\tau = (1-\alpha)(1-n_\tau)^{-\alpha} \int_0^1 Z_{j\tau} A_{j\tau} x_{j\tau}^{\alpha} dj \tag{5}$$

and the (inverse) demand for intermediate inputs is given by, $\forall j \in [0,1]$:

$$p_{j\tau} = A_{j\tau} Z_{j\tau} \alpha (1-n_\tau)^{1-\alpha} x_{j\tau}^{\alpha-1} \tag{6}$$

2.4 The intermediate goods monopolists

Consider the problem of the monopolist in sector j characterized by technology $\{A_j, Z_j\}$. It rents from households A_j units of capital and is subject to a green tax burden $h_\tau P_{j\tau}/x_{j\tau} = h_\tau A_j Z_j^{1/\alpha\beta}$ per unit produced, from (2) and (3). Hence, the monopolist maximizes instantaneous profits $\Pi_{j\tau} = [p_{j\tau} - A_j(r_\tau + h_\tau Z_j^{1/\alpha\beta})]x_{j\tau}$. Substituting for the demand from the final sector, (6), and proceeding for maximization, we obtain partial equilibrium sales, the pricing rule and profits of the monopolist in sector j:[7]

$$\hat{x}_{j\tau} = (1 - n_\tau)\left(\frac{\alpha^2 Z_j}{r_\tau + h_\tau Z_j^{1/\alpha\beta}}\right)^{\frac{1}{1-\alpha}} \tag{7}$$

$$\hat{p}_{j\tau} = A_j \frac{r_\tau + h_\tau Z_j^{1/\alpha\beta}}{\alpha}$$

$$\hat{\Pi}_{j\tau} = A_j \frac{1-\alpha}{\alpha}\left[r_\tau + h_\tau Z_j^{1/\alpha\beta}\right]\hat{x}_{j\tau} \tag{8}$$

Notice that profits are:

- increasing in the *total productivity* index $A_j Z_j^{\frac{1}{1-\alpha}}$ of good j;
- decreasing in the *marginal cost* of firm j: $m_{j\tau} = [r_\tau + h_\tau Z_j^{1/\alpha\beta}]$

The green tax depresses sales and profits and more so the dirtier the good (the higher the Z_j). The crucial feature of the model is that the green tax has an heterogenous impact on profits across goods, when they are differentiated in pollution intensities.

2.5 The R&D stage

Any firm in the competitive R&D sector targets improvements on one particular intermediate good. The R&D activity is modeled as a Poisson process with instantaneous arrival rate λn_j, where n_j is the mass of labor employed in R&D in sector j and $\lambda > 0$ is a productivity parameter. Each innovation improves the quality of the intermediate good on both dimensions, A and Z. Namely, an innovation allows the patent holder to produce the intermediate good characterized by the leading-edge technology, that is the highest of all A's, denoted by $\bar{A}$, and the lowest of all Z's, denoted by $\underline{Z}$, at the date of arrival of the innovation (an intersectoral spillover). Each innovation contributes marginally to the improvement of the leading-edge technology on the two dimensions. This intertemporal

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[7] Results do not change if the green tax were levied on the final sector. The demand for good j is in this case $p_{j\tau} = A_j[\alpha(1-n_\tau)^{1-\alpha} Z_j x_{j\tau}^{\alpha-1} - h_\tau Z_j^{1/\alpha\beta}]$. The monopolist maximizes $\pi = (p_{j\tau} - A_j r_\tau)x_{j\tau}$. Sales and profits are given by (7) and (8), the price is lower, i.e. $p_{j\tau} = A_j[r_\tau/\alpha + (1-\alpha)h_\tau Z_j^{1/\alpha\beta}/\alpha]$.

spillover is modeled by assuming that the rate of growth of the leading-edge technology is proportional to the aggregate flow of innovations $\lambda n = \int_0^1 \lambda n_j dj$:

$$\frac{\dot{\bar{A}}_\tau}{\bar{A}_\tau} = \gamma \lambda n_\tau \qquad \gamma > 0 \tag{9}$$

$$\frac{\dot{\underline{Z}}_\tau}{\underline{Z}_\tau} = \zeta \lambda n_\tau \qquad \zeta \leq 0 \tag{10}$$

ζ is the aggregate index of the *direction of R&D*, because it measures to what extent innovations are environmental friendly. If $\zeta = 0$ innovations have the same pollution intensity as the goods that they replace, and emissions associated to their use are larger because innovations are more capital intensive. Instead, innovations are cleaner if $\zeta < 0$, that is if their pollution intensity is lower. Whether the emissions associated to the use of new goods are lower than those generated by old goods depends on size of ζ. Notice that in any case, as soon as $\zeta < 0$ the emissions intensity is correlated to the productivity of goods. Hence, a tax on emissions is a policy tool that allows to discriminate goods indirectly according to their productivity, if $\zeta < 0$.

Figure 1 plots the marginal impact of R&D employment on the growth rate of three technological parameters as function of ζ. Line $dg_{\bar{A}}/dn = \gamma\lambda$ represents the growth rate of the leading-edge implicit labor productivity index, $\bar{A}$, which is independent of ζ. Line $dg_{\underline{Z}}/dn = \zeta\lambda$ depicts the growth rate of the leading-edge pollution intensity, $\underline{Z}$. Line $dg_{TP}/dn = \gamma\lambda + \zeta\lambda/(1-\alpha)$ is the growth rate of the total productivity index of the leading-edge good, $\bar{A}\underline{Z}^{\frac{1}{1-\alpha}}$. It is clear that ζ measures the direction of technological change. In fact, its value determines whether and by how much R&D improves the total productivity and the cleanliness of goods.[8]

Free entry in R&D ensures that at equilibrium the following arbitrage condition holds:

$$n_\tau \in (0,1) \quad \Rightarrow \quad w_\tau = \lambda V_\tau \tag{11}$$

where V_τ is the value of an innovation arrived at date τ. If R&D activity takes place at all, then its marginal cost (the wage) equals its expected marginal return.

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[8] Notice that targeting cleaner innovations does not affect the cost of R&D, neither the difficulty of R&D, as instead is the case in Verdier (1995). Yet increasing the degree of cleanliness targeted reduces the total productivity of innovations. This trade-off is equivalent to the case of explicit R&D cost (see foonote).

An innovation is worth the present value of the expected stream of profits:

$$V_\tau = \int_\tau^\infty e^{-\int_\tau^t r_s ds} e^{-\lambda \int_\tau^t n_s ds} \hat{\Pi}_t(\bar{A}_\tau, \underline{Z}_\tau) dt$$

where $\hat{\Pi}_t(\bar{A}_\tau, \underline{Z}_\tau)$ denotes profits at date t of a monopoly characterized by the technology $\{\bar{A}_\tau, \underline{Z}_\tau\}$. The first discount factor takes into account the opportunity cost, i.e. the return on savings. The second discount factor is the probability of survival of the monopoly, because the next innovation in the sector makes its patent obsolete.

2.6 Consumers and the government

The representative consumer chooses the path of consumption to maximize the present value stream of instantaneous isoelastic utilities, subject to a dynamic budget constraint:[9]

$$\max_{\{c\}_0^\infty} \int_0^\infty e^{-\rho\tau} \frac{c_\tau^{1-\varepsilon}}{1-\varepsilon} d\tau$$

$$\dot{W} = w_\tau + r_\tau W_\tau - c_\tau + T_\tau$$

where W is financial wealth and T are transfers from the government. The solution links the rate of growth of consumption to the rate of return on savings and preference parameters, according to the Ramsey rule:

$$g_c = \frac{r_\tau - \rho}{\varepsilon} \tag{12}$$

where g_i denotes the rate of growth of variable i. To rule out trivial paths of savings, the solution must satisfy the no-Ponzi game condition:

$$\lim_{\tau \to \infty} e^{-\int_0^\tau r_s ds} W_\tau = 0$$

Finally, we need to impose a budget constraint on the government. To be simple but without loss of generality, we assume that the budget is held balanced at any given date:

$$h_\tau P_\tau = T_\tau$$

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[9] With this formalization of the utility function we abstract from the impact that environmental policy may have on the saving behavior.

3 Balanced growth path analysis

Along a balanced growth path, n and ζ must be constant for $\bar{A}$ and $\underline{Z}$ to grow at constant rates from (9) and (10). Furthermore, the law of motion of capital, $\dot{K}_\tau = Y_\tau - c_\tau$, implies that capital, output and consumption grow at the common rate $g = g_c$. Finally, according to the Ramsey rule (12) g is constant only if r is constant. Hence, we obtain the following:

Proposition 1 *There exists a balanced growth path if the green tax increases according to the following policy rule:*

$$g_h = -\frac{g_{\underline{Z}}}{\alpha\beta} = \frac{-\zeta}{\alpha\beta}\lambda n \tag{13}$$

Along this path output growth is function of n *and* ζ *according to:*

$$g = \left(\gamma + \frac{\zeta}{1-\alpha}\right)\lambda n \tag{14}$$

Therefore, growth is positive only if:

$$\zeta \in \left(\left(\alpha - 1\right)\gamma, 0\right] \tag{15}$$

Proof. First, we compute the value of an innovation using (7) and (8):

$$\begin{aligned} V_\tau &= \frac{1-\alpha}{\alpha}\bar{A}_\tau \left(\alpha^2 \underline{Z}_\tau\right)^{\frac{1}{1-\alpha}} (1-n) \int_\tau^\infty e^{-(r+\lambda n)(t-\tau)} \left[r + h_t \underline{Z}_\tau^{1/\alpha\beta}\right]^{\frac{-\alpha}{1-\alpha}} dt \\ &= \bar{\Pi}_\tau \int_\tau^\infty e^{-(r+\lambda n)(t-\tau)} \left[\frac{r + h_\tau \underline{Z}_\tau^{1/\alpha\beta}}{r + h_t \underline{Z}_\tau^{1/\alpha\beta}}\right]^{\frac{\alpha}{1-\alpha}} dt \\ &= \bar{\Pi}_\tau \int_\tau^\infty e^{-(r+\lambda n)(t-\tau)} \left(\frac{\bar{m}_\tau}{m_t}\right)^{\frac{\alpha}{1-\alpha}} dt \end{aligned} \tag{16}$$

Where $\bar{\Pi}_\tau$ and $\bar{m}_\tau$ denote initial profits and marginal cost of an innovator at date τ, and m_t denotes the marginal cost at future dates $t > \tau$ of the firm innovating at τ. The latter increases over time, and thus profits are crowded-out, if and only if the green tax, h, increases. The integral in the first expression is constant over time if the marginal cost of the leading-edge monopolist, $\bar{m}_\tau$, is constant, that is if $h_\tau \underline{Z}_\tau^{1/\alpha\beta}$ is independent of τ. This is ensured by policy rule (13).

For n to be constant the arbitrage condition (11) must hold at all times for the equilibrium level of n. Under policy (13) the value of patents (proportional to the right-hand-side of (11)) grows at the same rate as the initial profit of innovators, that is: $g_V = g_{\bar{A}} + \frac{1}{1-\alpha} g_{\underline{Z}}$. The left-hand-side of (11) is increasing with the wage. From (5), the latter is the productivity of labor in the final sector, i.e. $w_\tau = (1-\alpha) Y_\tau / (1-n)$, so that it increases at the rate of output growth, hence $g_w = g$ for n constant. Logdifferentiating the arbitrage condition (11), we obtain:

$$g = g_w = g_V = g_{\bar{A}} + \frac{1}{1-\alpha} g_{\underline{Z}}$$

(14) is derived using (9) and (10). ■

Along a balanced growth path, the green tax increases at a constant rate if innovations are environmental friendly. This is the case when the emissions-capital ratio of innovations is lower than that of the goods they replace, i.e. when $\zeta < 0$.[10] To understand this result suppose that the green tax is held constant although innovations are environmental friendly. In this case the weight of the green tax burden over marginal cost for innovations would fall over time. Then innovations would become increasingly competitive relative to existing intermediate goods. As a result the market share of innovations would increase progressively. This is incompatible with the concept of balanced growth.[11]

The crucial feature of environmental policy in this economy is that it affects the relative costs across goods of different vintage. Define $H = h_\tau \underline{Z}_\tau^{1/\alpha\beta}$. Under policy rule (13) the marginal cost of the leading-edge good is constant and equal to $\bar{m} = r + H$. Then the marginal cost increases with the age of the technology, so that at some later date $t > \tau$ it is equal to $m_t = r + e^{g_h (t-\tau)} H$. Hence the distribution of intermediate goods according to their technological age is characterized by the marginal cost of the leading-edge sector relative to that of firms of age s:

$$\frac{\bar{m}}{m_s} = \frac{r + H}{r + e^{g_h s} H}$$

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[10] That the tax per unit of emissions increases along balanced growth paths with declining pollution intensity of output is a result common to all models with emissions inputs. In fact, as P/Y declines, the marginal product of emissions increases, and this is reflected in their implicit price.

[11] As the market share of innovations increases, so does the value of innovations (which is forward looking) relative to the cost of innovation (which reflects the current cross-sectoral distribution of market shares). Then the incentive to engage in R&D grows faster than its cost, and R&D activity intensifies over time (n grows).

Older technologies are less competitive than new ones because of their relative dirtiness, implying a larger burden of green taxes. The ratio would indeed be constant in the absence of environmental friendly technological progress (i.e. $\zeta = 0$ and $g_h = 0$) or in the absence of taxation ($h = 0$). This effect of environmental policy is called the "green crowding-out" effect, because the policy reduces the competitiveness of aging technologies and crowds out their profit generating capacity.

The loss of competitiveness follows the path illustrated in figure 2. Under policy rule (13), the distribution of market shares across goods of different technological ages is time invariant. Therefore the two competitiveness-loss functions (one backward looking, $\bar{m}/m_s$, and one forward looking, $\bar{m}_\tau/m_t$ in (16)) are independent of τ and coincide for $s \equiv (t-\tau)$.

3.1 The aggregate economy

Let us first normalize aggregate variables in terms of the leading-edge output, $\bar{x}_\tau$.[12] We can compute aggregate demand for capital from the intermediate goods sector by integrating over the space of goods the rearranged production function (2), to obtain:

$$K_\tau = \bar{A}_\tau \bar{x}_\tau \Gamma \tag{17}$$

where:[13]

$$\Gamma = \int_0^1 \frac{A_{j\tau} x_{j\tau}}{\bar{A}_\tau \bar{x}_\tau} dj = \lambda n \int_0^\infty e^{-(\lambda n + g)s} \left(\frac{\bar{m}}{m_s} \right)^{\frac{1}{1-\alpha}} ds \tag{18}$$

Similarly, the flow of aggregate emissions of pollutants can be written as:

$$P_\tau = \underline{Z}_\tau^{\frac{1}{\alpha\beta}} \bar{A}_\tau \bar{x}_\tau \Lambda \tag{19}$$

where:

$$\Lambda = \int_0^1 \frac{Z_{j\tau}^{1/\alpha\beta} A_{j\tau} x_{j\tau}}{\underline{Z}_\tau^{1/\alpha\beta} \bar{A}_\tau \bar{x}_\tau} dj = \lambda n \int_0^\infty e^{-\left(\lambda n + g + \frac{\zeta}{\alpha\beta}\lambda n\right)s} \left(\frac{\bar{m}}{m_s} \right)^{\frac{1}{1-\alpha}} ds \tag{20}$$

Finally, output can be computed as:

$$Y_\tau = (1-n)^{1-\alpha} \underline{Z}_\tau \bar{A}_\tau \bar{x}_\tau^\alpha \Delta \tag{21}$$

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[12] Aggregate variables coincide with average variables due to the normalization of the mass of sectors.

[13] See appendix 7.1 for the derivation of Γ, Λ and Δ.

where:

$$\Delta = \int_0^1 \frac{Z_{j\tau} A_{j\tau} x_{j\tau}^{\alpha}}{\underline{Z}_{\tau} \bar{A}_{\tau} \bar{x}_{\tau}^{\alpha}} dj = \lambda n \int_0^{\infty} e^{-(\lambda n + g)s} \left(\frac{\bar{m}}{m_s} \right)^{\frac{\alpha}{1-\alpha}} ds \tag{22}$$

Output in (21) is written as proportional to output produced using the leading-edge good times the aggregation factor Δ, which measures the relative contribution to production of older goods. This is computed in (22) by taking into account the mass of existing goods of age s, their total productivity gap, and their use. Any technology is initially adopted by a mass λn of goods, out of which only a proportion $e^{-\lambda n s}$ of goods of age s survives at date τ. Older goods are less productive than the leading-edge good, and their productivity gap is ruled by the growth rate of total productivity, $AZ^{1/(1-\alpha)}$, which equals g by (14). Finally, sales of older goods are affected by environmental policy according to the competitiveness-loss function $\bar{m}/m_s$.

The aggregation factors Γ, Λ and Δ are constant along a balanced growth path, and are characterized by the following properties (see appendix 7.1 for the proof):

1. $\Gamma < 1, \ \forall \zeta \leq 0$
2. $\Lambda > \Gamma, \ \forall \zeta < 0$
3. $\Lambda > \Delta > \Gamma, \ \forall \zeta < 0$, since $\Delta = \frac{r}{\bar{m}} \Gamma + \frac{H}{\bar{m}} \Lambda$,
4. $\Delta \Gamma^{-\alpha} < \left(1 + \gamma + \frac{\zeta}{1-\alpha}\right)^{\alpha - 1} < 1, \ \forall \zeta < 0$
5. $\Gamma = \Lambda = \Delta = \int_0^1 A_{j\tau}/\bar{A}_{\tau} dj = (1+\gamma)^{-1} < 1, \ \text{iff } \zeta = 0$

Substituting for $\bar{x}_{\tau}$ from (17) into (19), aggregate emissions are:

$$P_{\tau} = \underline{Z}_{\tau}^{\frac{1}{\alpha\beta}} K_{\tau} \frac{\Lambda}{\Gamma} \tag{23}$$

Property 2 implies that $\forall \zeta < 0$:

$$P_{\tau} \geq \underline{Z}_{\tau}^{\frac{1}{\alpha\beta}} K_{\tau}$$

which means that aggregate emissions are greater that if all capital were of the less polluting kind. Equation (23) can also be written as:

$$\underline{Z}_{\tau} = \left(\frac{P_{\tau} \Gamma}{K_{\tau} \Lambda} \right)^{\alpha\beta} \tag{24}$$

Thus the leading-edge pollution intensity also measures the pollution intensity of aggregate output. If $\zeta < 0$ the pollution intensity declines continuously for the economy as a whole, although the process is discontinuous at the firm level.

Next, substituting for $\bar{x}_\tau$ using (17) into (21), we obtain the following expression for aggregate output:

$$Y_\tau = \underline{Z}_\tau \left[(1-n)\bar{A}_\tau\right]^{1-\alpha} K_\tau^\alpha \frac{\Delta}{\Gamma^\alpha} \tag{25}$$

Finally, substituting for $\underline{Z}$ from (24) into (25), we can write emissions explicitly as inputs into the production function:

$$Y_\tau = \Delta \left[(1-n)\bar{A}_\tau\right]^{1-\alpha} \left[\left(\frac{P_\tau}{\Lambda}\right)^\beta \left(\frac{K_\tau}{\Gamma}\right)^{1-\beta}\right]^\alpha \tag{26}$$

It is clear then that the lower are emissions inputs the lower is output. Moreover, equation (26) shows that emissions are combined with services from capital goods, with unitary elasticity of substitution, and then this composite good is combined with labor.

To conclude on the aggregate picture of the economy, we find that the green tax revenue grows at the same rate as output. In fact, the green tax revenue grows at rate $g_h + g_P$ which equals g from (23) under policy (13). Hence, transfers to households grow at this rate to keep the budget balanced. This property provides a simple implementation rule for policy (13): set the tax level to maintain constant the weight of the green tex revenue over output.

3.2 General equilibrium

The dynamic general equilibrium is determined when the labor market clears and workers are indifferent between working in final sector firms and in R&D firms. The equilibrium level of R&D employment, n, equates the marginal product of labor in the final sector (5) to the expected marginal return to R&D from the arbitrage condition (11):

$$(1-\alpha)(1-n)^{-\alpha}\underline{Z}_\tau \bar{A}_\tau \bar{x}_\tau^\alpha \Delta = \lambda V_\tau$$

Substituting for V_τ using (16) and simplifying the condition is:

$$(1-n)^{-\alpha}\underline{Z}_\tau \bar{x}_\tau^\alpha \Delta = \frac{\lambda}{\alpha}(r+H)\bar{x}_\tau \int_\tau^\infty e^{-(r+\lambda n)(t-\tau)} \left(\frac{\bar{m}_\tau}{m_{t-\tau}}\right)^{\frac{\alpha}{1-\alpha}} dt \tag{E}$$

Figure 3 depicts the left-hand-side of equation (E) at a given date τ as an upward sloping, and the right-hand-side as a downward sloping schedule in the (n,value) space.[14] The equilibrium level of R&D, n^e, is determined at the intersection of the two schedules.

The left-hand-side is proportional to the marginal product of labor in the final sector. Due to diminishing returns, the marginal product of labor in the final sector tends to infinity as all labor is employed in R&D. The right-hand-side is proportional to the value of an innovation. The first factor before the integral, is proportional to the initial instantaneous profit of the innovator which is decreasing in n (see 16).[15] Also the integral is strictly decreasing in n. This is straightforward for the discount factor and the survival probability. Furthermore, competitiveness loss proceeds at a faster pace, because the greater is the rate of innovation, the faster the green tax will be increasing, according to policy rule (13). The expected flow of profits is therefore crowded-out at a faster rate.

It follows that, if at $n = 0$, the expected return to R&D is larger than the cost, there exists a unique equilibrium level of R&D activity, $n^e > 0$. Substituting for $\bar{x}_\tau$ and Δ using (7) and (22) in (E), and simplifying, n^e is defined as the implicit solution of:

$$\frac{n}{\alpha(1-n)} \int_0^\infty e^{-(g+\lambda n)s} \left(\frac{\bar{m}}{m_s}\right)^{\frac{\alpha}{1-\alpha}} ds = \lambda \int_0^\infty e^{-(r+\lambda n)t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}} dt \tag{27}$$

4 The impact of environmental policy with exogenous direction of R&D

Let us assume that the aggregate index of the direction of R&D, ζ, is exogenous, and in particular independent of environmental policy. Under policy rule (13) $g_h = -\lambda n\zeta/\alpha\beta$ always, and therefore the policy tool of interest is the level of the green tax burden levied on the leading-edge producer: H. We find the following result.

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[14] Both the LHS and the RHS in figure 3 shift downwards over time. However they cross at a constant level of n (see 27).

[15] An increase in n has two negative effects on this profit rate (see 8). First, lower labor inputs in the final sector reduce the marginal product of intermediate inputs, and thus depress demand (from 6). Second, the faster the growth rate, the higher the interest rate (from 12) and thus the marginal cost.

Proposition 2 *Along a balanced growth path a marginal increase in the green tax burden levied on innovations, H, reduces on impact the level of aggregate output:*

$$\frac{\partial Y_\tau}{\partial H_\tau} < 0$$

as long as R&D employment, n, does not decrease. This negative impact is greater the more environmental friendly are innovations, i.e. the lower is ζ.

Proof. The proof consists in differentiating output as given by (21) and comparing the case $\zeta = 0$ with $\zeta < 0$. See appendix 7.2. ■

The result is not surprising since we know from (26) that emissions are inputs in the aggregate production function. Thus the higher their relative price, the lower will be their employment and the lower aggregate output. This input effect is active even in the absence of differentiation in the pollution intensity. However when there is differentiation the impact is magnified because the policy change affects older (i.e. dirtier) goods more heavily. That is, the increase in the green tax burden shifts downwards the competitiveness-loss schedule, and older sectors suffer from a greater loss in sales. This asymmetric impact of green taxes across goods leads us to the main result of the paper.

Proposition 3 *A marginal increase in the green tax burden levied on innovations, H, increases the balanced growth path R&D employment if innovations are environmental friendly. That is:*

$$\frac{\partial n^e}{\partial H} > 0 \qquad \text{if } \zeta < 0$$

Therefore the rate of growth of the economy, g^e, is increasing in H (see 14).

Proof. The proof (see appendix 7.3) shows that, at the original equilibrium level of n, the left-hand-side of the equilibrium condition (E) falls more than its right-hand-side. These shifts of the schedules result in a new equilibrium with higher n. ■

A larger burden of green taxes reduces directly the innovator's prospective profits and the value of innovations. The larger burden of taxation however, also translates into lower aggregate output and lower demand for labor from the final sector, which reduces the cost of R&D. The proposition establishes that the fall in wages outweighs the fall in the value of innovations, when these are environmental friendly. As a result R&D activity increases at equilibrium.

The asymmetric impact of the tax on the cost of and reward to R&D is due to the fact that an increase in the green tax burden "punishes" relatively more older technologies, or in other words skews relative sales in favor of modern intermediate goods, because they are cleaner.[16] Consider the reduced form (27) of the equilibrium condition. The downward shift of the competitiveness-loss schedule affects both sides of the equation. The left-hand-side represents the demand for labor from the final sector, which depends upon the distribution of sales across vintages. The reduction of the market share of relatively old goods is discounted according to their productivity gap, that is at rate g. The right-hand-side represents the demand for labor from the R&D sector, proportional to the value of an innovation. The latter depends upon the expected evolution of the market share of the patent owner. The expected fall in the future market share reduces the value of the patent according to the discount rate r. Recall that along a balance growth path $r > g$ (the no-Ponzi game condition). Since the negative impact of an increase in the green tax burden falls more heavily on older sectors and on future profits for innovators, $r > g$ implies that the loss affects more the demand for labor from the final than from the R&D sector. In other words, the current situation of the labor market depends less on expected future events than on past events, as summarized by the distribution of technologies across vintages.

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[16] The level of the green tax burden affects the dynamics of the system only to the extent that it modifies the distribution of market shares across goods of different vintage, i.e. the shape of the competitiveness-loss schedule. Suppose that the marginal cost consists exclusively of the green tax burden. Then the competitiveness-loss function is $\bar{m}/m_t = e^{-g_h t}$, with g_h exogenous in this setting. Using (16) and (8) we compute: $V_\tau = \left[\bar{A}_\tau H \bar{x}_\tau \left(1-\alpha\right)/\alpha\right] / \left[\lambda n + r - \zeta\lambda n / \left[\beta\left(1-\alpha\right)\right]\right]$. To evaluate wages $w = \left(1-\alpha\right) Y / \left(1-n\right)$, we can solve explicitly Δ and use (21) to get $w_\tau = \left[\left(1-\alpha\right)\left(1-n\right)^{-\alpha} \bar{A}_\tau \underline{Z}_\tau \bar{x}_\tau^{\alpha}\right] / \left[1+\gamma-(1-\beta)\zeta/\beta(1-\alpha)\right]$. Insert these values in the equilibrium condition $w = \lambda V$. Simplify using (7) and (12) to write the rate of interest as function of the growth rate: $r = \rho + \varepsilon g$. We have:

$$\bar{n} = \frac{[1+\gamma-(1-\beta)\zeta/\beta(1-\alpha)] - \rho/\alpha\lambda}{[1+\gamma-(1-\beta)\zeta/\beta(1-\alpha)]\,[1/\alpha+1] + (\varepsilon-1)/\alpha[\gamma+\zeta(1-\alpha)]}$$

The equilibrium R&D employment is independent of the level of the tax burden H.

The main lesson that we want to retain from this result is that environmental policies are in general not neutral with respect to the cross-sectoral distribution of demand. Green taxes skew sales towards cleaner intermediate goods. If innovations are environmental friendly, environmental policy fosters innovative activities and leads to faster productivity growth (given ζ). The result can be interpreted along the lines proposed by Xepapadeas and Zeeuw (1999). An increase in the green tax reduces the average age of capital goods in use, increasing the average productivity of capital. As in any endogenous growth model, higher return on capital fosters investment and increases the growth rate.

5 The impact of environmental policy with endogenous direction of R&D

In this section variable ζ is allowed to respond to changes in environmental policy. This variable measures the direction of R&D, determining whether and to what extent innovations are cleaner than the goods that they replace. At the same time, however, variable ζ also determines the marginal effect of R&D on the growth of total productivity of intermediate goods. This is because emissions are implicit inputs, complementary to capital. Therefore, when ζ is allowed to vary, it entails a trade-off between total productivity and the cleanliness of intermediate goods.[17]

Consider the problem of a R&D firm that has obtained an innovation at date τ with attached implicit labor productivity $\bar{A}_\tau$. Suppose that it can choose to adopt any pollution intensity for its innovation out of the technological menu $Z \in \left[\omega \bar{Z}, \bar{Z}\right]$, with $\omega < 1$ and $\bar{Z}$

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[17] One can reinterpret the trade-off as resulting from an explicit cost of targeting cleaner innovations at the level of the R&D firm (the assumption of Verdier, 1995). Consider an R&D firm that is employing $\hat{n}$ researchers. Its expected instantaneous improvement in total productivity of its blueprint is $\bar{A}_\tau \bar{Z}_\tau^{\frac{1}{1-\alpha}} \lambda \hat{n}$ if it targets $\bar{Z}_\tau$, but only $\bar{A}_\tau \underline{Z}_\tau^{\frac{1}{1-\alpha}} \lambda \hat{n}$ if it targets $\underline{Z}_\tau < \bar{Z}_\tau$. Therefore, if the R&D firm targets the same expected improvement in total productivity, it needs to employ $n/\hat{n} = \left(\bar{Z}_\tau / \underline{Z}_\tau\right)^{\frac{1}{1-\alpha}}$ more researchers. This cost function is convex with respect to the targeted improvement in cleanliness. Notice that at the sectoral level the interval of time between innovations is $1/\lambda n$, so that the R&D cost function above can be written as $e^{\frac{-\zeta}{1-\alpha}}$ at the aggregate level, if $\bar{Z}_\tau$ is the pollution intensity inherited from the incumbent (i.e; prevailing for $\zeta = 0$).

denoting the technology inherited from the incumbent firm. There can be three regimes according to whether the problem has a corner or an interior solution. Improving the cleanliness of the innovation ($Z < \bar{Z}$) affects its value in two opposite directions:

- profits are reduced because the total productivity of the innovation, $\bar{A}_\tau Z^{\frac{1}{1-\alpha}}$, falls;
- if emissions are taxed, profits increase because the marginal cost, $h_\tau Z^{\frac{1}{\alpha\beta}}$, is reduced. This gain is increasing in the expected rate of growth of the green tax, g_h.

Denoting by $\underline{Z}_\tau$ the solution, when it is interior it must satisfy the implicit function:[18]

$$\int_\tau^\infty e^{-(r+\lambda n)(t-\tau)} \left(\frac{r+h_\tau \underline{Z}_\tau^{1/\alpha\beta}}{r+e^{g_h(t-\tau)}h_\tau \underline{Z}_\tau^{1/\alpha\beta}}\right)^{\frac{\alpha}{1-\alpha}} \left[\frac{e^{g_h(t-\tau)}h_\tau \underline{Z}_\tau^{1/\alpha\beta}}{r+e^{g_h(t-\tau)}h_\tau \underline{Z}_\tau^{1/\alpha\beta}} - \beta\right] dt = 0 \qquad (28)$$

Environmental policy is here defined by the level of the green tax and by a commitment concerning its rate of growth: $\{h_\tau, g_h\}$. Notice that R&D firms choose the pollution intensity target taking into account the level of the green tax, h_τ. As a result the tax burden levied on innovations cannot be considered any longer as a free policy tool. Moreover, policy tool g_h is also constrained by policy rule (13) to ensure that the economy evolves on a balanced path. Yet, the direction of R&D may be influenced itself by the commitment on g_h through (28) and the identity $\zeta = \ln(\underline{Z}/\bar{Z})$ (see footnote 18).

The first regime is characterized by commitment to $g_h = 0$, which is compatible with balanced growth only as long as innovations are not environmental friendly ($\zeta = 0$). This requires that innovators adopt the inherited pollution intensity, $\bar{Z}$, which is the case only if $h < r\bar{Z}^{\frac{-1}{\alpha\beta}}\beta/(1-\beta)$ according to (28). For this set of balanced growth paths, pollution intensity is eventually uniform across goods since $\forall\tau\ \underline{Z}_\tau = \bar{Z}$. As a result, a once and for all increase in the green tax level increases the tax burden levied on innovations, reduces the level of production on impact, but has no long run effect on R&D employment and growth (proposition 3). The dynamics of the system is unaffected by this shift in environmental policy, and it coincides with that prevailing in the absence of any policy at all.

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[18] The first order condition (28) is obtained by differentiating the value of the innovation as given in (16) and simplifying. Both aggregate variables n and ζ are taken as given at this stage, but they must be coherent with the choice of the representative R&D firm. In particular, ζ reflects the improvement in cleanliness that is chosen according to (28). In fact, on a balanced path innovations arrive in each sector on average every interval of time $1/\lambda n$, so that $\bar{Z}_\tau = e^{-g_{\underline{Z}}\frac{1}{\lambda n}}\underline{Z}_\tau = e^{-\zeta}\underline{Z}_\tau$, that is $\zeta = \ln\left(\underline{Z}_\tau/\bar{Z}_\tau\right)$.

The second set of balanced paths is obtained when the authorities commit to a positive but "moderate" g_h. For any initial inherited technology, eventually the tax induces R&D firms to adopt cleaner technologies. As innovations are environmental friendly, pollution intensity becomes heterogenous across goods ($\zeta < 0$). In the case of an interior solution for the direction of R&D, the equilibrium condition (27) and the first order condition (28) define a system of implicit functions, whose solution is a couple $\{n, \underline{Z}_\tau\}$. Numerical solutions are derived to characterize the balanced growth paths prevailing for different policies $\{h_\tau, g_h\}$. Figures 4, 5 and 6 plot the results.[19] Notice that the level of the tax affects only the level of the pollution intensity index (fig. $4a$), but not the tax burden levied on innovations (fig. $4b$).[20] Instead the latter is a decreasing function of g_h. A commitment to a higher g_h augments the incentive to adopt cleaner technologies, a choice that lowers the total productivity of innovations. This translates directly in slower productivity growth. As shown in figure 5, the simulations confirm that this direct channel of transmission of environmental policy on growth dominates the indirect effect. The latter runs through the permanent change of the distribution of market shares across vintages. The rise in g_h affects this distribution in two ways: the relative weight of the initial tax burden falls (lower H/r), but the tax burden increases faster with age (higher g_h and lower ζ). The competitiveness loss schedule shifts downwards and favors relatively innovations. The case of high elasticity of intertemporal substitution emphasizes the power of the distortionary impact of environmental policy running through this channel of transmission. Figure 6 compares the set of balanced paths prevailing for different values of ε, the inverse of the elasticity of intertemporal substitution. Notice that in the case with $\varepsilon = .9$, R&D employment is smaller than its *laisser-faire* level ($g_h = 0$) for low values of g_h, but greater for high values. The result is interesting because the case $\varepsilon < 1$ usually implies that a fall in the return on savings reduces equilibrium investment, and R&D employment is a form of investment in this economy (Grimaud and Ricci, 1999). Here, the distortionary impact of green taxes is strong enough to reverse the outcome.

Finally, the third regime is attained when the technology menu constraint is binding

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[19] The figures draw the results for a particular value of parameters. Changing the parameters affects the scale of the results but not their qualitative features.

[20] This result implies $d\underline{Z} = -\alpha\beta(\underline{Z}/h)dh$, even though it cannot be proved analytically.

from below. Once g_h has reached the critical level $\bar{g}_h = -\lambda n(\ln\omega)/\alpha\beta$, the commitment to increase it further is not credible because it is incompatible with balanced growth.[21] In this case, g_h is high enough to ensure that innovators adopt the cleanest possible technology ($\omega\bar{Z}$), which follows a deterministic process. In other words the direction of R&D is exogenously bounded from below by a minimum value of ζ. This means that the economy is in the case studied in the previous section, where a once and for all increase in the green tax skews permanently the market shares towards recent vintages. In this case, a restrictive environmental policy improves incentives to engage in R&D, induces environmental friendly technological progress but does not entail any compression of innovations' total productivity. As a result, the policy fosters the pace of growth. This statement must now be qualified because the growth rate of the economy is enhanced starting from its lowest possible level, which is attained for the extreme feasible g_h and a low h.

We conclude that a restrictive environmental policy may have a positive impact on growth only if the feasible improvements in the cleanliness of innovations are constrained.

6 Conclusion

In the theory presented in this paper, economic growth results from the design of new, more productive, capital goods by profit seeking agents, the R&D firms. Emissions represent implicit inputs complementary to capital. Hence if new goods are designed as cleaner, their productivity is below its potential level. If the tax on emissions is large enough, innovations are relatively clean. This has two implications. First, the contribution of innovation to the growth in productivity is weakened. Second, capital goods are differentiated in pollution intensity. The latter effect gives scope for taxation to distort the distribution of market shares across goods of different vintages. In particular, the green tax increases the market share of relatively modern goods (which are the most productive and the least polluting), and this effect improves incentives to engage in R&D activities.

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[21] For $\bar{g}_h$ we have $\zeta = \ln\omega$, and (15) reads $\omega > e^{-(1-\alpha)\gamma}$ for $g > 0$.

The crucial assumption underlying this result is that R&D is labor intensive.[22]

In short, a restrictive environmental policy affects the economic growth through two channels of transmission, that operate in two opposite directions: the first channel lowers the marginal impact of innovation on productivity growth, while the second channel spurs innovation. The second channel is likely to dominate only if R&D firms have little scope for reducing the pollution intensity of innovations.

The main contribution of this paper concerns the mechanism of trasmission of environmental policy in the decentralized economy. Ricci (2000) presents the welfare analysis of balanced growth path and finds it very close to that of Aghion and Howitt (1998, ch.5). The only difference worth noticing is that here reducing the pollution intensity of output requires R&D activity, while in the Aghion and Howitt model pollution intensity is a control variable. Hence, the optimal R&D employment is larger in the former than in the latter model. As a consequence the optimal rate of growth of output is larger and that of emissions is lower in our model than in the case considered by Aghion and Howitt.

Finally, we would like to point out that the distortionary impact of green taxes highlights a more general property of the schumpeterian model of growth. In fact, in the multi-sector model of vertical innovation where labor is the sole input in R&D, any policy that affects heterogeneously the producers of intermediate goods has an impact on the equilibrium growth of output (Ricci, 2001). Various policies influence the distribution of market shares across goods of different vintages. Some policy measures favor directly innovations as they enter the market, such as tax breaks for new firms or fiscal incentives to adopt new equipment. Other policies may affect the competitiveness of relatively old sectors. We can think of support schemes for declining sectors, and *vice versa* of policies that ease exit from relatively inefficient sectors. We believe that this additional property confirms the fact that the schumpeterian theory of growth is a fruitful tool for policy analysis.

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[22] In fact, in this case the tax reduces the cost of R&D along with its pay-off.

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7 Appendix

7.1 The aggregation factors Γ, Λ and Δ

Let us define :

- $a_j = \frac{A_j}{\bar{A}} \in (0,1]$, an index measuring the productivity gap of good j relative to the leading-edge technology at a given date τ. The greater a_j, the smaller the gap. Ex-ante this is a stochastic variable;

- $z_j = \frac{\underline{Z}}{Z_j} \in (0,1]$, measuring the (inverse) gap in pollution intensity of good j relative to the leading-edge technology at a given date τ. The greater z_j, the smaller the gap. This too is a stochastic variable.

- $M_j = \frac{\bar{m}}{m_j} \in (0,1]$,the ratio of the marginal cost in sector j relative to that prevailing in the leading-edge sector, at any given date τ. By the definition of m we have:

  $$M(z_j) = \frac{r+H}{r+Hz_{j,\tau}^{-1/\alpha\beta}}$$

  implying $M(1) = 1$ and $M' > 0$

- The sales of any good j relative to the leading-edge sector can be expressed as:

  $$X(z_{j\tau}) = \frac{\hat{x}_{j\tau}}{\bar{x}_\tau} = \left(\frac{r+H}{z_{j\tau}\left[r+Hz_{j,\tau}^{-1/\alpha\beta}\right]}\right)^{\frac{1}{1-\alpha}} = \left(\frac{M_{j\tau}}{z_{j\tau}}\right)^{\frac{1}{1-\alpha}}$$

- We define:

  $$\Gamma = \int_0^1 a_j X(z_j)dj$$

  The integral has no mathematical sense because a and z are distributed stochastically (and *a priori* discontinuously) over the space of goods $[0,1]$. However along a balanced growth path at any date τ it is possible to reshuffle the goods by order of decreasing technological gap, i.e. according to their age s. Any technology is adopted initially by a mass λn of firms, out of which only a proportion $e^{-\lambda ns}$ of those with age s survives at date τ. Furthermore, the productivity gap for firms of age s is: $\frac{\bar{A}_{\tau-s}}{\bar{A}_\tau} = e^{-g_{\bar{A}}s} = e^{-\lambda n\gamma s}$;

and the pollution intensity gap is: $\frac{\underline{Z}_\tau}{\underline{Z}_{\tau-s}} = e^{g_{\underline{Z}} s} = e^{\lambda n \zeta s}$. Finally, under policy rule (13) older goods sell less, according the competitiveness-loss function, $\bar{m}/m_s$. We have:

$$\begin{aligned}
\Gamma &= \int_0^1 a_j z_j^{\frac{-1}{1-\alpha}} \left(M(z_j)\right)^{\frac{1}{1-\alpha}} dj \\
&= \int_0^\infty \lambda n e^{-\lambda n s} \frac{\bar{A}_{\tau-s}}{\bar{A}_\tau} \left(\frac{\underline{Z}_{\tau-s}}{\underline{Z}_\tau}\right)^{\frac{1}{1-\alpha}} \left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}} ds \\
&= \lambda n \int_0^\infty e^{-\left(\lambda n + \lambda n \gamma + \frac{\lambda n \zeta}{1-\alpha}\right)s} \left(\frac{r+H}{r+e^{g_h s}H}\right)^{\frac{1}{1-\alpha}} ds \\
&= \lambda n \int_0^\infty e^{-(\lambda n + g)s} \left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}} ds
\end{aligned}$$

- We define:

$$\Lambda = \int_0^1 z_j^{-1/\alpha\beta} a_j X(z_j) dj$$

and proceeding as above:

$$\begin{aligned}
\Lambda &= \lambda n \int_0^\infty e^{-(\lambda n + g)s} e^{-g_{\underline{Z}} s/\alpha\beta} \left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}} ds \\
&= \lambda n \int_0^\infty e^{-\left(\lambda n + g + \frac{\zeta}{\alpha\beta}\lambda n\right)s} \left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}} ds
\end{aligned}$$

- We define:

$$\Delta = \int_0^1 \frac{a_j}{z_j} [X(z_j)]^\alpha dj$$

and again:

$$\begin{aligned}
\Delta &= \lambda n \int_0^\infty e^{-(\lambda n + \lambda n \gamma + \lambda n \zeta)s} \left(\frac{\underline{Z}_{\tau-s}}{\underline{Z}_\tau}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{\bar{m}}{m_s}\right)^{\frac{\alpha}{1-\alpha}} ds \\
&= \lambda n \int_0^\infty e^{-(\lambda n + g)s} \left(\frac{\bar{m}}{m_s}\right)^{\frac{\alpha}{1-\alpha}} ds
\end{aligned}$$

We have the following properties :

Property 1 : $\Gamma < 1$,

From the definition of Γ, of a and of X, we have that:

$$A_j \hat{x}_j < \bar{A}\bar{x} \quad \forall j \in [0,1] \quad \text{but one} \quad \Rightarrow \quad \Gamma < 1$$

Consider any sector of age $s > 0$, using (7) we have:

$$
\begin{aligned}
A_{s\tau}\hat{x}_{s\tau} &= \bar{A}_{\tau-s}\hat{x}_{s\tau} \\
&= \bar{A}_{\tau}e^{-g_{\bar{A}}s}(1-n)\left(\frac{\alpha^2\underline{Z}_{\tau}e^{-g_{\underline{Z}}s}}{r+e^{\frac{-g_{\underline{Z}}}{\alpha\beta}s}H}\right)^{\frac{1}{1-\alpha}} \\
&= e^{-gs}\bar{A}_{\tau}(1-n)\left(\frac{\alpha^2\underline{Z}_{\tau}}{r+e^{\frac{-\zeta}{\alpha\beta}\lambda ns}H}\right)^{\frac{1}{1-\alpha}} \\
&< e^{-gs}\bar{A}_{\tau}(1-n)\left(\frac{\alpha^2\underline{Z}_{\tau}}{r+H}\right)^{\frac{1}{1-\alpha}} \\
&< \bar{A}_{\tau}\bar{x}_{\tau}
\end{aligned}
$$

Property 2 : $\Lambda > \Gamma$ if $\zeta < 0$ since $z_j^{-1/\alpha\beta} \in [1, \infty)$;

Property 3 : $\Lambda > \Delta > \Gamma$, if $\zeta < 0$

Indeed :

$$
\begin{aligned}
\Delta &= \int_0^1 \frac{a_j}{z_j}[X(z_j)]^{\alpha}dj \\
&= \int_0^1 a_j z_j^{\frac{-1}{1-\alpha}}\left(\frac{\bar{m}}{m_j}\right)^{\frac{1}{1-\alpha}}\left(\frac{r+Hz_j^{-1/\alpha\beta}}{r+H}\right)dj \\
&= \frac{r}{r+H}\Gamma + \frac{H}{r+H}\Lambda
\end{aligned}
$$

Thus : $\Delta - \Lambda = \frac{r}{r+H}(\Gamma - \Lambda) < 0$, by property 2;

Property 4 : $\Delta\Gamma^{-\alpha} \leq (1+\gamma+\zeta/(1-\alpha))^{\alpha-1} < 1$.

Define $G = \gamma + \zeta/(1-\alpha)$. By Jensen's inequality:

$$
\begin{aligned}
[\Delta(1+G)]^{\frac{1}{\alpha}} &= \left\{\lambda n\int_0^{\infty}(1+G)e^{-(1+G)\lambda ns}\left[\left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}}\right]^{\alpha}ds\right\}^{\frac{1}{\alpha}} \leq \\
&\leq \lambda n\int_0^{\infty}(1+G)e^{-(1+G)\lambda ns}\left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}}ds = \Gamma(1+G)
\end{aligned}
$$

Property 5 : $\Gamma = \Delta = \Lambda = \int_0^1 a_j dj = (1+\gamma)^{-1}$ if $\zeta = 0$

If there is no differentiation in pollution intensity, that is if $\zeta = 0$, then $z_j = 1\ \forall j \in [0,1]$, and $g_h = 0$ by policy rule (13) so that $X(z_j) = 1\ \forall j \in [0,1]$. The result is immediate from the definitions of Γ, Λ and Δ.

7.2 Proof of proposition 2

To prove the proposition, we differentiate output given by (21) with respect to $H \equiv h\underline{Z}^{1/\alpha\beta}$, holding n constant. Use of the equilibrium sales of intermediate goods (7), the definitions of Δ and Λ (22) and (20), and the first definitions in appendix 7.1. We have:

$$
\begin{aligned}
\frac{\partial Y}{\partial H} &= (1-n)^{1-\alpha}\underline{Z}_{\mathcal{T}}\bar{A}_{\mathcal{T}}\bar{x}_{\mathcal{T}}^{\alpha}\left[\frac{\partial \Delta}{\partial H}+\frac{\alpha\Delta}{\bar{x}_{\mathcal{T}}}\frac{\partial \bar{x}_{\mathcal{T}}}{\partial H}\right] \qquad (29)\\
&= \frac{\alpha(1-n)^{1-\alpha}\underline{Z}_{\mathcal{T}}\bar{A}_{\mathcal{T}}\bar{x}_{\mathcal{T}}^{\alpha}}{(1-\alpha)\left[r+H\right]}\left[\int_0^1 \frac{a_j}{z_j}\left(\frac{\hat{x}_{j\mathcal{T}}}{\bar{x}_{\mathcal{T}}}\right)^{\alpha}\frac{(1-z_j^{-1/\alpha\beta})r}{\left[r+Hz_j^{-1/\alpha\beta}\right]}dj-\Delta\right]\\
&= \frac{\bar{A}_{\mathcal{T}}\bar{x}_{\mathcal{T}}}{\alpha(1-\alpha)}\int_0^1 \frac{a_j}{z_j}\left(\frac{\hat{x}_{j\mathcal{T}}}{\bar{x}_{\mathcal{T}}}\right)^{\alpha}\left[\frac{\left(1-z_j^{-1/\alpha\beta}\right)r}{\left[r+Hz_j^{-1/\alpha\beta}\right]}-1\right]dj\\
&= \frac{-\bar{A}_{\mathcal{T}}\bar{x}_{\mathcal{T}}}{\alpha(1-\alpha)}\int_0^1 z_j^{-1/\alpha\beta}a_j\left(\frac{\hat{x}_{j\mathcal{T}}}{\bar{x}_{\mathcal{T}}}\right)dj=\frac{-\bar{A}_{\mathcal{T}}\bar{x}_{\mathcal{T}}\Lambda}{\alpha(1-\alpha)}<0
\end{aligned}
$$

The fall in output is lower when pollution intensity is uniform across sectors, $\zeta = 0$. In this case $\partial\Delta/\partial H = 0$ according to property 5, so that the first term in brackets on the second line is nil. The latter is negative whenever $\zeta < 0$, since $z_j^{-1/\alpha\beta} > 1$ for all goods j but one. The fall in output is reinforced if R&D activity increases on impact, because less labor is available for production.

7.3 Proof of proposition 3

To prove the result we show that, at the original equilibrium level of n, the left-hand-side (LHS) of the equilibrium condition (E) falls more than the right-hand-side (RHS). These shifts of the schedules depicted in figure 4.b result in a new equilibrium level of R&D employment, n, higher than the original one.

The LHS of (E) can also be written as $Y_{\mathcal{T}}/\left[(1-n)\bar{A}_{\mathcal{T}}\right]$ and therefore falls along with output. Using (29) from appendix 7.2 we obtain:

$$
\frac{\partial LHS}{\partial H}=\frac{-\bar{x}_{\mathcal{T}}\Lambda}{\alpha(1-\alpha)(1-n)} \qquad \text{(L)}
$$

The RHS of (E) is equal to $\lambda V_{\mathcal{T}}/\left[\bar{A}_{\mathcal{T}}\left(1-\alpha\right)\right]$. We can first compute the impact of a marginal change in H on the value of innovations V_τ as expressed in the first line of (16). This is:

$$\begin{aligned}\frac{\partial V_\tau}{\partial H} &= \frac{1-\alpha}{\alpha}\bar{A}_\tau\left(\alpha^2\underline{Z}_\tau\right)^{\frac{1}{1-\alpha}}(1-n) \\ &\quad \int_0^\infty e^{-(r+\lambda n)t}\left(\frac{-\alpha}{1-\alpha}\right)e^{g_h t}\left[r+e^{g_h t}H\right]^{\frac{-\alpha}{1-\alpha}-1}dt \\ &= -\bar{x}_\tau\bar{A}_\tau\int_0^\infty e^{-(r+\lambda n)t}e^{g_h t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}}dt<0\end{aligned}$$

And therefore:

$$\frac{\partial RHS}{\partial H}=-\frac{\lambda\bar{x}_\tau}{(1-\alpha)}\int_0^\infty e^{-(r+\lambda n)t}e^{g_h t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}}dt \tag{R}$$

The increase in H reduces more the LHS than the RHS if (L) is smaller than (R). Rearranging using the definition of Λ (20) and (14) :

$$\frac{n}{\alpha(1-n)}>\frac{\int_0^\infty e^{-(r+\lambda n)t}e^{g_h t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}}dt}{\int_0^\infty e^{-(g+\lambda n)s}e^{g_h s}\left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}}ds}$$

We can substitute the left-hand-side of this last inequality by its value prevailing at the original equilibrium, given by the equilibrium condition (E), which rearranged gives:

$$\frac{n}{\alpha(1-n)}=\frac{\int_0^\infty e^{-(r+\lambda n)t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}}dt}{\Delta/\lambda n}=\frac{\int_0^\infty e^{-(r+\lambda n)t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}}dt}{\int_0^\infty e^{-(g+\lambda n)s}\left(\frac{\bar{m}}{m_s}\right)^{\frac{\alpha}{1-\alpha}}ds}$$

That the LHS of (E) falls more than the RHS around the original equilibrium if (L) is smaller than (R) implies:

$$\frac{\int_0^\infty e^{-(g+\lambda n)s}e^{g_h s}\left(\frac{\bar{m}}{m_s}\right)^{\frac{1}{1-\alpha}}ds}{\int_0^\infty e^{-(g+\lambda n)s}\left(\frac{\bar{m}}{m_s}\right)^{\frac{\alpha}{1-\alpha}}ds}>\frac{\int_0^\infty e^{-(r+\lambda n)t}e^{g_h t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}}dt}{\int_0^\infty e^{-(r+\lambda n)t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}}dt} \tag{I}$$

The two sides of (I) are equal if $\zeta=0$ since this implies $\bar{m}/m_t=1\ \forall t$ and $g_h=0$. The difference between the two sides of the inequality lies in the discount rate of the integrands. We now show that the ratio of the two integrals is decreasing in the discount rate. It is easy to show that $\forall\ t$ (or s) >0 :

$$e^{g_h t}\left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}}>\left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}}$$

Let us denote the ratio of the two functions by Ψ:

$$\Psi(t)=e^{g_h t}\frac{r+H}{r+e^{g_h t}H}$$

Then we have that Ψ is increasing for $r > 0$:

$$\frac{\partial \Psi(t)}{\partial t} \propto 1 - \frac{e^{g_h t} H}{r + e^{g_h t} H} > 0$$

Now consider a generic discount rate δ, and define the ratio of the integrals in (I) as:

$$\begin{aligned} f(\delta) &= \frac{\int_0^\infty e^{-\delta t} e^{g_h t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{1}{1-\alpha}} dt}{\int_0^\infty e^{-\delta t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}} dt} \\ &= \frac{\int_0^\infty e^{-\delta t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}} \Psi(t) dt}{\int_0^\infty e^{-\delta t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}} dt} \\ &= \int_0^\infty \Omega(t, \delta) \Psi(t) dt \end{aligned}$$

where:

$$\Omega(t, \delta) = \frac{e^{-\delta t} \left(\frac{\bar{m}}{m_t}\right)^{\frac{\alpha}{1-\alpha}}}{\int_0^\infty e^{-\delta u} \left(\frac{\bar{m}}{m_u}\right)^{\frac{\alpha}{1-\alpha}} du}$$

is a normalized weight function, characterized by:

$$\frac{\partial \Omega}{\partial \delta} \propto \int_0^\infty u e^{-\delta u} \left(\frac{\bar{m}}{m_u}\right)^{\frac{\alpha}{1-\alpha}} du - t \int_0^\infty e^{-\delta u} \left(\frac{\bar{m}}{m_u}\right)^{\frac{\alpha}{1-\alpha}} du$$

Therefore $\exists$

$$\tilde{t} = \frac{\int_0^\infty u e^{-\delta u} \left(\frac{\bar{m}}{m_u}\right)^{\frac{\alpha}{1-\alpha}} du}{\int_0^\infty e^{-\delta u} \left(\frac{\bar{m}}{m_u}\right)^{\frac{\alpha}{1-\alpha}} du}$$

such that:

$$\frac{\partial \Omega}{\partial \delta} > 0 \quad \forall t < \tilde{t} \quad \text{and} \quad \frac{\partial \Omega}{\partial \delta} < 0 \quad \forall t > \tilde{t}$$

This means that an increase in the discount rate δ shifts the weight from high values of t to low values of t. Since $\Psi(t)$ is increasing, this implies that:

$$\frac{\partial f(\delta)}{\partial \delta} < 0$$

Inequality (I) holds as long as the discount rate on its left-hand-side, $g + \lambda n$, is lower than the one on its right-hand-side, $r + \lambda n$, that is whenever $r > g$. Notice that this is always the case at equilibrium for the no-Ponzi game condition to hold. This condition states that the present value of households' financial wealth, W, is nil asymptotically. Along a balanced growth path W grows with income, so:

$$\lim_{t\to\infty} e^{-rt}W_t = \lim_{t\to\infty} e^{-(r-g)t}W_0 = 0 \qquad \Leftrightarrow \qquad r > g$$

We have established that in the neighborhood of the equilibrium defined by (E): $r > g \Rightarrow$ (I) holds $\Rightarrow \partial LHS/\partial H < \partial RHS/\partial H < 0 \Rightarrow \partial n^e/\partial H > 0$.

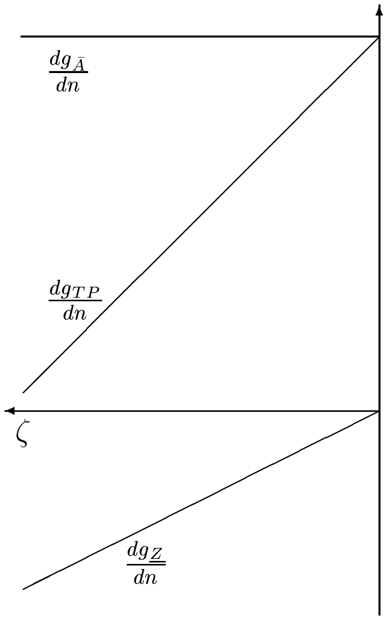

Figure 1: The direction of R&D

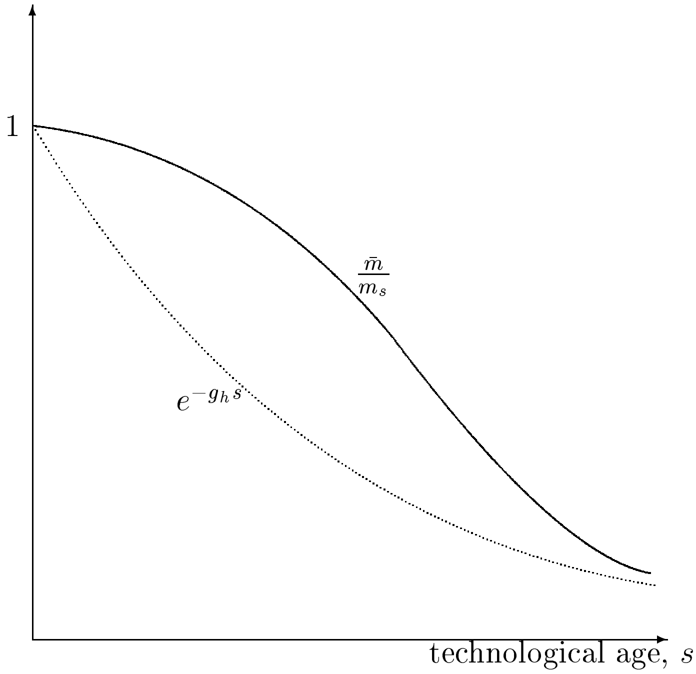

Figure 2: Competitiveness-loss or "green crowding-out" effect

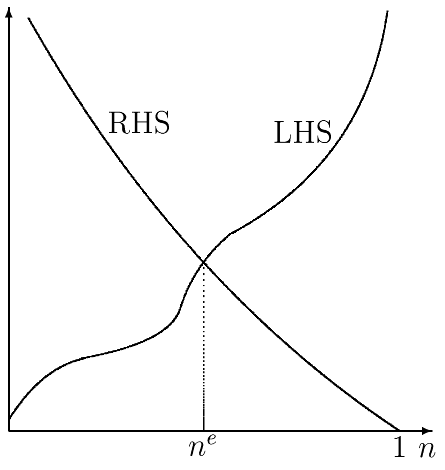

Figure 3: The equilibrium condition (E)

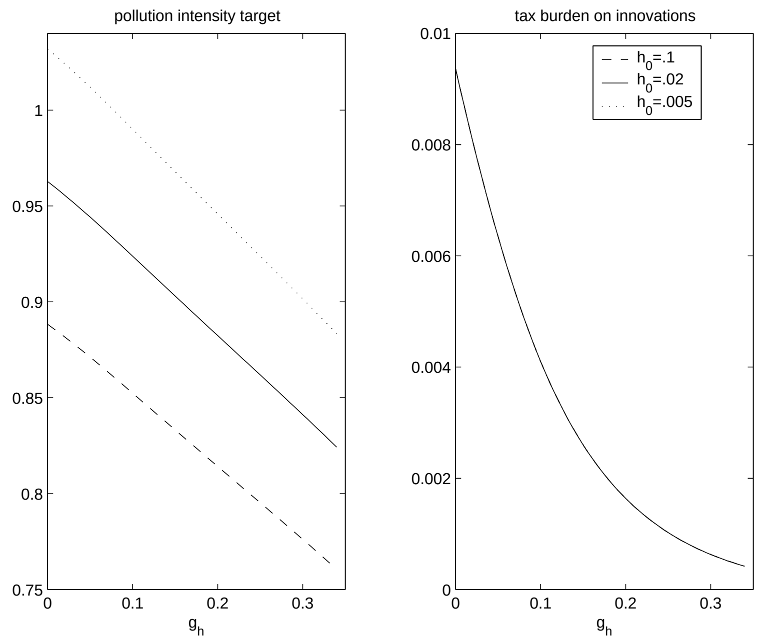

Figure 4: Endogenous direction of R&D: the role of the tax level.

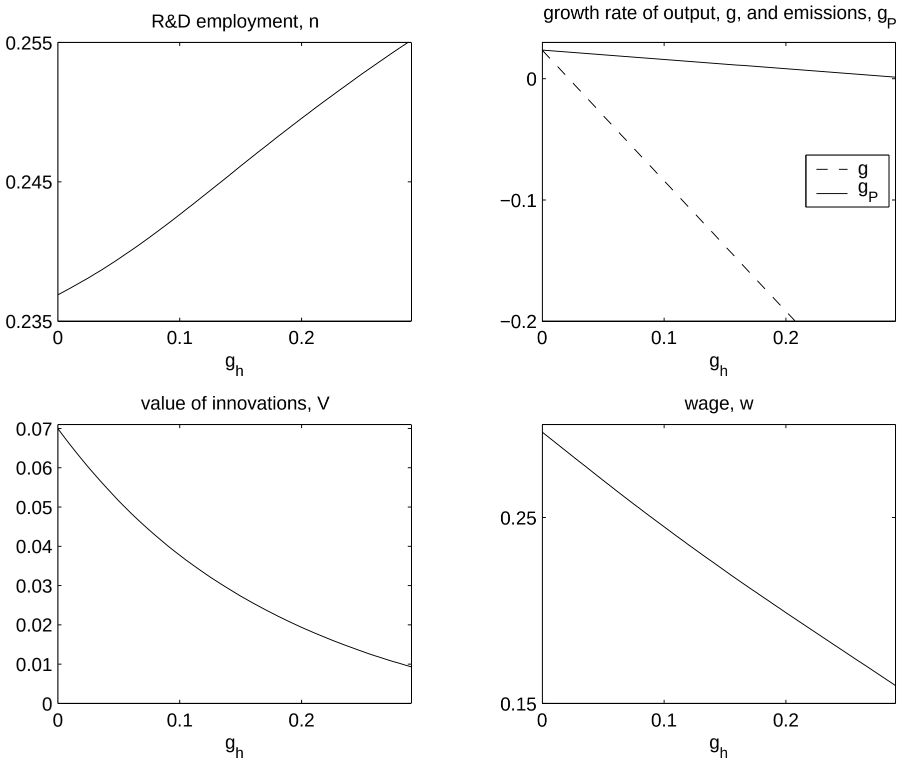

Figure 5: Endogenous direction of R&D: equilibria as function of g_h.

Parameter values: $\alpha = .4$, $\beta = .125$, $\lambda = .5$, $\gamma = .2$, $\rho = .03$, $\varepsilon = 1.5$, $h = 02$, $A = 1$.

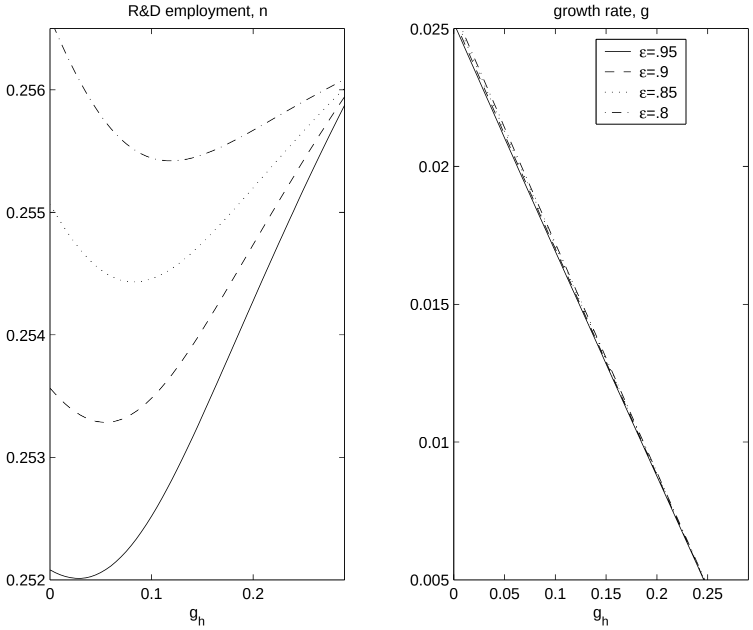

Figure 6: Endogenous direction of R&D: the distortionary impact of green taxes.

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