Growth, Innovation and Environmental Policy: Clean *vs.* Dirty Technical Change

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Abstract

This paper focuses on a two sector endogenous growth model with environmental quality. Endogenous technological change creates either clean or dirty innovations, depending on relative profitability. The decentralized equilibrium does not attain neither optimal growth neither the optimal emissions rate. We show that R&D subsidies should be combined with a pollution tax to increase the rate of innovation and promote research towards cleaner technologies. The reduction of emissions intensity of aggregate output is achieved by changing the dirty-bias of technology in the economy. We study both first and second-best policies. We claim that pricing only emissions might not be enough, as the price required to give incentive, for instance, to low carbon technologies is too high, compromising growth.

Keywords: pollution; endogenous growth; innovation; environmental policy; decentralized equilibrium; optimal equilibrium;

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1 Introduction

The prospect of global climate change has emerged as a major issue in recent years. The relationship between global warming and increased concentration of greenhouse gases (GHGs) such as carbon dioxide CO_2, produced by the burning of fossil fuels, is suggested by much accumulated scientific evidence. In order to limit the global average temperature increase to less than 2^oC above pre-industrial levels, the Fourth Assessment Report of the IPCC [12] indicates that the peak of global emissions will have to occur around 2015, after which global emissions must go down substantially, between 50 and 85% in 2050 compared to 1990 levels.

International action is needed to respond to this challenge. More than a decade ago, the first international treaty on climate change, the Framework Convention on Climate Change (FCCC), was signed. Later on, in February 2005, the Kyoto Protocol became the first significant international effort to reduce GHG emissions. In the context of the EU, the Spring European Council, in March 2007, endorsed several measures to reduce emissions including an independent EU commitment of a 20% reduction in GHG emissions by 2020 compared to 1990 (European Council [16]). Moreover, and in contrast to the recent past, climate change is a high priority issue in the US Congress, where several bills have been discussed in the 110th US Congress targeting greenhouse gas emission control.

The reduction and stabilization of the GHG emissions makes technological change a central issue in policy design. In fact, as the IPCC Fourth Assessment Report shows, the use of technological change is responsible for a reduction in mitigation cost estimates measured either in carbon prices or in the effect on global GDP. Therefore, addressing climate change also requires a better understanding of the potential role played by technological change.

Integrated assessment studies have analyzed how to design caps on GHG emissions that would lead to stabilization of atmospheric concentrations of greenhouse gases. These studies have found that cost-effectiveness is achieved through relatively small emission reductions in the medium run, and much larger emission reduction in the more distant future. The cost of achieving significant greenhouse gas emissions reductions in the future will depend on the availability of low or zero cost emitting technologies.

Therefore, it is important to study environmental policy in a setting with endogenous technology. This allows to consider simultaneously the usual R&D distortions discussed by Stokey [19] and the role of R&D in decreasing the pollution externality.[1] The question of the type of technological change introduced by Acemoglu [1] gains a new meaning and relevance in this context.

In endogenous growth models which care for the environment, stagnation is avoided along the optimal path, either through increased abatement or through technological progress, as shown in Bovenberg and Smulders [5], Stokey [20], Elbasha and Roe [8], and Reis [17], among others. Therefore, the development of environmental friendly technologies protects the environment and, at the same time, drives economic growth, lowering the conflict between the two objectives.

The contribution of this paper is to study environmental policy in a model where the type of technological change - clean or polluting - is endogenous. To this end we consider a two sector endogenous growth model with clean and dirty innovations, in an economy that cares about the environment. Abstracting from environmental questions, there is evidence that in a market economy research tends to be under-provided relative to the social optimum.[2] Moreover, the extent to which research is environmental oriented and its policy implications are a matter of discussion. In particular, we examine how environmental policy affects both the rate and the type of technological change. The question is not only "Are there limits to growth?" as in Stokey [20], but also in what kind of innovations are we interested in and what incentives should policy give.

Other papers have focused on the importance of endogenous research in market economies with environmental damages, like Elbasha and Roe [8] and Grimaud [9]. Our paper differs from theirs since we consider both clean and dirty innovations. More recently, Ricci [18] and Hart [10], [11], analyze, in a vintage model, the effects of environmental regulation on the quantity

[1] Carraro and Siniscalco [6] present studies showing that large corporations typically adjust to environmental policy measures through innovation, rather than by switching inputs or reducing output. They also mention the fact that without innovation very high taxes are required to curb down CO_2 emissions.

[2] Jones and Williams [13], [14].

of research effort (how much research is performed), and on its quality (in an environmental dimension). We follow a different framework which focuses primarily on the relative productivity of dirty and clean technologies.

The structure of the modelled economy follows the work of Acemoglu [2] and Acemoglu and Zilibotti [3] where two types of innovations are carried out by profit maximizing firms. We assume two goods and two factors of production, one clean and one dirty. Pollution is a by-product of the dirty intensive good production. R&D firms develop new clean or dirty complementary intermediates depending on relative profitability.

Our purpose is to study how policy induced changes in the relative prices of the two goods affect the rate of innovation and the type of technical change. To this end, we focus on the induced impact on the relative productivity of dirty and clean technologies, a measure of the dirty-bias in the economy, similar to the skill-bias defined in Acemoglu and Zilibotti [3]. This is in contrast to Acemoglu's [2] biased technical change, where the relative factor rewards respond to changes in the relative endowments.

The solutions for the *laissez-faire* economy and the social planner's problem are compared. Emissions intensity of aggregate output is larger in the decentralized economy than in the optimal solution, as expected. In this paper, this result is related to the fact that the dirty-bias in the decentralized economy is higher than optimal.

We then identify the first-best regulatory instruments and show that the optimal policy encourages a change in the quality of research, in favor of the clean sector of the economy. In a second-best world, we show that in order to implement the efficient bias by using only an emissions tax, economic growth is sacrificed. This result may suggest that in the presence of a pollution externality there is an additional rationale to promote R&D.

The paper is organized as follows. The model is presented in Section 2. The decentralized equilibrium is derived in Section 3. In Section 4, the solution to the social planner's problem is discussed and compared to the decentralized solution. Section 5 focuses on policy implications. Section 6 summarizes the main conclusions. Technical details are presented in the appendices.

2 The Model

The economy is closed and produces an aggregate output from two commodities, which use primary factors of production and a set of differentiated intermediate inputs. The model builds in Acemoglu [2] and Acemoglu and Zilibotti [3], introducing preferences for environmental quality.

Consumers There are many identical infinitely lived consumers who get utility from consumption of aggregate output and environmental quality. Utility of a representative consumer is given by

$$U = \int_0^{\infty} (\log C + \mu \log Q)\, e^{-\rho t} dt \tag{1}$$

where C is consumption of the aggregate output, Q measures the quality of the environment, μ reflects environmental preferences and ρ is the rate of time preference. The utility function is increasing and strictly concave in C and Q as long as $\mu > 0$. The representative consumer values consumption more than environmental quality, such that $\mu < 1$. Consumers are endowed with two primary factors of production: a clean (L) one and a dirty (Z) one.[3]

Final output sector The aggregate output Y is produced from two goods, Y_L and Y_Z, through a Cobb-Douglas production function, as in Acemoglu and Zilibotti [3][4]

$$Y = Y_L^{\gamma} Y_Z^{1-\gamma} \tag{2}$$

where $\gamma \in (0,1)$ is the elasticity of aggregate output with respect to Y_L. Y_L is intensive in the clean factor, L, while Y_Z uses the dirty factor, Z, intensively. Y_L and Y_Z production functions are given by

$$Y_L = \frac{1}{1-\beta} \left(\int_0^{N_L} x_L(j)^{1-\beta} dj \right) L^{\beta} \quad \text{and} \quad Y_Z = \frac{1}{1-\beta} \left(\int_0^{N_Z} x_Z(j)^{1-\beta} dj \right) Z^{\beta} \tag{3}$$

[3] As Acemoglu [2] and Acemoglu and Zilibotti [3], we do not allow factor accumulation in order to simplify the analysis.

[4] Acemoglu's [2] considers two types of goods as we do but an elasticity of substitution between them different from one. Acemoglu and Zilibotti [3] consider a Cobb-Douglas with a continuous of goods. The fact that we assume an elasticity of substitution of 1 implies that we only focus on the relative physical productivity of dirty and clean factors and not on the corresponding relative factor rewards. Thus, according to Acemoglu's [2] designation, we focus on factor-augmenting technical change and not in factor-biased technical change.

where $\beta \in (0,1)$, and L and Z are assumed to be supplied inelastically. The L-intensive good is produced from the clean factor and a range of L-complementary (L-augmenting) intermediates (x_L). The range of intermediate inputs of type x_L available at a given time period, is denoted by N_L. The amount of input j used is denoted by $x_L(j)$. The production function for Y_Z uses the dirty factor intensively and Z-complementary intermediates (x_Z). N_Z and $x_Z(j)$ are similar.[5]

A greater N_L enables the production of a greater level of Y_L for a given quantity of L, that is, it improves the productivity of the clean factor, while an increase in N_Z improves the productivity of the dirty factor. The ratio (N_Z/N_L) determines the relative productivity of dirty and clean technologies, which will be the measure of the dirty-bias in the economy, similar to the skill-bias in Acemoglu and Zilibotti [3]. For a given state of technology, that is, given N_L and N_Z, the production functions exhibit constant returns to scale. There will be aggregate increasing returns, when N_L and N_Z are increasing.

The markets for Y_L and Y_Z are perfectly competitive. The set of differentiated inputs are bought from the intermediate inputs sectors.

Intermediate inputs sectors Each input $j \in [0, N_L]$ and $j \in [0, N_Z]$ is supplied by a monopolist who faces a marginal cost, ψ, in terms of the final good, of producing intermediate inputs, which is the same for all intermediate inputs. The monopolist sets the price for the intermediate input, $\chi_L(j)$ or $\chi_Z(j)$.

R&D sector Technical change is modeled as the invention of new dirty and clean intermediates. It is assumed that only the final good is used as an input in this sector (lab equipment specification).The production functions for the innovations are

$$\dot{N}_L = \eta_L R_L \qquad \text{and} \qquad \dot{N}_Z = \eta_Z R_Z \tag{4}$$

where R_L and R_Z are spending on R&D for the clean and dirty factor-intensive good, respectively. One unit of final good spent on R&D directed at L-complementary intermediates will generate η_L new varieties of clean intermediates. $\dot{N}_Z$ is explained similarly.

[5]For example, we can think of Y as the production of energy, with Y_L as CO_2 free energy and Y_Z as fossil fuel energy.

Research is motivated by the future benefits which follow from the discovery of a new variety. A firm that discovers a new variety receives a patent on this intermediate input and becomes a monopolist. Thus, R&D firms develop new clean or dirty intermediates depending on relative profitability.

Budget constraint The budget constraint of the economy is

$$C + I + R = Y, \text{ that is}$$

$$C + \left[\psi \int_0^{N_L} x_L(j)\, dj + \psi \int_0^{N_Z} x_Z(j)\, dj\right] + (R_L + R_Z) = Y \qquad (5)$$

where I denotes investment, and R is total R&D expenditure.

Environmental quality We model the quality of the environment as a flow variable. Environmental damages are a by-product of the dirty sector. Environmental quality is measured by the inverse of emissions, E_Z,[6]

$$Q = \frac{1}{E_Z} = \frac{1}{\delta Y_Z}, \qquad 0 < \ \delta < 1 \qquad (6)$$

which are proportional to the production of Y_Z and δ is a technology parameter that quantifies the detrimental effect of Y_Z on the environment. When studying environmental policy we focus on emissions intensity (e.g., energy intensity), $\frac{E_Z}{Y}$.[7]

3 Decentralized equilibrium

In this section, we determine the decentralized equilibrium without government intervention. Agents take environmental quality as given. We assume that all agents have perfect foresight, so that at each moment of time the entire path of prices is known.

The markets for Y_L and Y_Z are competitive, so market clearing implies that their relative price p is given by

$$p = \frac{p_Z}{p_L} = \frac{\frac{\partial Y}{\partial Y_Z}}{\frac{\partial Y}{\partial Y_L}} \quad \text{where} \quad \frac{\frac{\partial Y}{\partial Y_Z}}{\frac{\partial Y}{\partial Y_L}} = \frac{1-\gamma}{\gamma}\left(\frac{Y_Z}{Y_L}\right)^{-1} \qquad (7)$$

[6] See, for example, Elbasha and Roe [8].

[7] This approach is followed, for example, by Canada, which has implemented a domestic trading system in which emission reduction credits can be traded to limit carbon emissions from much of the economy's energy and industrial sectors. The emission targets are expressed in terms of a reduction in emission intensity rather than in absolute levels of emissions reductions (Amano and Sedjo [4]).

The greater the supply of Y_Z relative to Y_L, the lower is its relative price p.

Let the price of the final good be the numéraire. In this case, the following relationship between the prices of the two goods holds

$$\frac{p_L^{\gamma} p_Z^{1-\gamma}}{\gamma^{\gamma} (1-\gamma)^{1-\gamma}} = 1 \tag{8}$$

Firms in the clean sector maximize profits, choosing L and $x_L(j)$, taking the price of their product, p_L, the price of the primary factor, ω_L, the prices of the intermediate inputs, $\chi_L(j)$, and the range of intermediate inputs, N_L, as given. Firms in the dirty sector face a similar problem. They maximize profits, treating environmental damages as exogenous.

From the first-order conditions of these problems, the rewards for the primary factors of production, ω_L and ω_Z, are obtained, as follows

$$\omega_L = \beta \frac{p_L Y_L}{L} \qquad \text{and} \qquad \omega_Z = \beta \frac{p_Z Y_Z}{Z}, \tag{9}$$

and the demand for each intermediate input is given by

$$x_L(j) = \left(\frac{p_L}{\chi_L(j)} \right)^{\frac{1}{\beta}} L \qquad \text{and} \qquad x_Z(j) = \left(\frac{p_Z}{\chi_Z(j)} \right)^{\frac{1}{\beta}} Z \tag{10}$$

The demand for each intermediate input is the same for all $j \in [0, N_L]$ and $j \in [0, N_Z]$.

Each monopolist in the intermediate goods sectors chooses prices, $\chi_L(j)$ and $\chi_Z(j)$, that maximize profits, taking into account the demand functions in (10). Since the demand curve for the intermediate input (10) is iso-elastic, profits are maximized by following the constant mark-up over marginal cost pricing rule $\chi_L(j) = \frac{\psi}{1-\beta}$, $j \in [0, N_L]$. To simplify the algebra, we normalize the marginal cost to $\psi = 1-\beta$. In equilibrium, prices are $\chi_L(j) = \chi_Z(j) = 1$.

Therefore, price, quantity and, hence, the level of profits are the same for all firms operating in each intermediate inputs sector. Using the prices and demands above, the monopolists' profits are

$$\pi_L = \beta p_L^{\frac{1}{\beta}} L \qquad \text{and} \qquad \pi_Z = \beta p_Z^{\frac{1}{\beta}} Z \tag{11}$$

R&D firms develop new clean or dirty intermediates depending on relative profitability given by the net present value of profits.

To maintain asset market equilibrium, the rate of return from holding equities (dividends plus changes in the value of the firms) must be equal to the rate of return on a one period loan, given by the interest rate r, that is

$$\frac{\pi_L}{V_L} + \frac{\dot{V}_L}{V_L} = r \qquad \text{and} \qquad \frac{\pi_Z}{V_Z} + \frac{\dot{V}_Z}{V_Z} = r \tag{12}$$

These equations relate the present value of future profits, V (the value of a firm in the intermediate inputs sector), to the flow of profits, π.

We will focus on the long-run balanced growth path of this economy, where prices and the interest rate are constant. Thus, the $\dot{V}$ terms are 0. Then, combining (11) and (12), yields

$$V_L = \frac{\beta p_L^{\frac{1}{\beta}} L}{r} \qquad \text{and} \qquad V_Z = \frac{\beta p_Z^{\frac{1}{\beta}} Z}{r} \tag{13}$$

The greater V_Z is relative to V_L, the greater are the incentives to develop dirty intermediates rather than clean ones. Since V_Z and V_L are increasing in prices, there are greater incentives to invent technologies producing more expensive goods.

There is free entry and exit in the R&D sector. Thus, in equilibrium, the value of a firm in the intermediate inputs sector (V_i, $i = L, Z$) must be equal to the cost of a new variety ($\frac{1}{\eta_i}$, $i = L, Z$).

We assume a balanced growth path (BGP), or steady-state equilibrium, where prices p_L and p_Z are constant, and N_L and N_Z, grow at the same constant rate. In equilibrium, along a BGP, all variables grow at the same rate: $\dot{Y}/Y = \dot{N}_L/N_L = \dot{N}_Z/N_Z = \dot{C}/C = \dot{Y}_Z/Y_Z = \dot{Y}_L/Y_L = g$. In order to generate growth, the number of new designs must be expanding over time. This occurs if the spending on R&D is increasing. More spending means more ideas, sustaining growth. In this case, the growth in ideas is clearly related to the final output growth ($\dot{R}_L/R_L = \dot{R}_Z/R_Z = g$).

There will be innovation in both sectors if the following condition holds

$$\eta_L V_L = \eta_Z V_Z \qquad \text{or} \qquad \eta_L \pi_L = \eta_Z \pi_Z \tag{14}$$

According to this condition, it is equally profitable to invest the development of L and Z-complementary intermediate inputs, so that along the BGP, N_L and N_Z can both grow. After substitution of (13), it implies

$$\frac{\eta_Z}{\eta_L} \left(\frac{p_Z}{p_L}\right)^{\frac{1}{\beta}} \frac{Z}{L} = 1 \tag{15}$$

This condition can be solved for the dirty-bias in the decentralized economy, (N_Z/N_L).

Substituting (10) into the production functions (3) we obtain the market productions of Y_L and Y_Z, given N_L and N_Z. Substituting these into (7) and solving for $p = p_Z/p_L$ we get the relative price of the two goods as a function of the relative productivity of dirty and clean technologies (N_Z/N_L), and of the relative factor supply, Z/L:

$$p = \left(\frac{1-\gamma}{\gamma}\right)^{\beta} \left(\frac{N_Z Z}{N_L L}\right)^{-\beta} \tag{16}$$

From (10) and (16), the relative demand of intermediate inputs as a function of (N_Z/N_L) is

$$\left(\frac{x_Z}{x_L}\right)^{DE} = \left(\frac{1-\gamma}{\gamma}\right) \left(\frac{N_Z}{N_L}\right)^{-1} \tag{17}$$

Substituting (16) in (15), and solving for (N_Z/N_L) we obtain

$$\left(\frac{N_Z}{N_L}\right)^{DE} = \left(\frac{\eta_Z}{\eta_L}\right) \left(\frac{1-\gamma}{\gamma}\right) \tag{18}$$

This equation defines the relative physical productivity of dirty and clean factors along the BGP, which is positively affected by the relative productivity of the R&D labs and the relative weight in the production of Y.

Substituting (18) in (17), we obtain the relative demand of intermediate inputs, with endogenous technology

$$\left(\frac{x_Z}{x_L}\right)^{DE} = \left(\frac{\eta_Z}{\eta_L}\right)^{-1} \tag{19}$$

From the maximization of (1), we obtain $\frac{\dot{C}}{C} = r - \rho$. Along a BGP, all variables grow at the same rate, $g = r - \rho$. This long-run growth rate is obtained in the following Proposition, in terms of the parameters of the model and the endowments of the economy.[8]

[8] We briefly analyze the stability properties of the model outside the BGP. The equilibrium condition for the relative profitability of innovations along the BGP is given by $\frac{\eta_Z V_Z}{\eta_L V_L} = 1$ (see (14)). If $\frac{\eta_Z V_Z}{\eta_L V_L} > 1$ (< 1) it will only be undertaken R&D in dirty complementary (clean complementary) intermediates. Since the relative profitability of creating dirty complementary intermediates $\frac{V_Z}{V_L}$ is decreasing in $\frac{N_Z}{N_L}$ (from (13) and (16)), the system is stable.

Proposition 1 *The long-run growth rate of the decentralized economy is given by*

$$g^{DE} = \beta \left(\gamma^{\gamma} (1-\gamma)^{1-\gamma} \right)^{\frac{1}{\beta}} (\eta_Z Z)^{1-\gamma} (\eta_L L)^{\gamma} - \rho \tag{20}$$

Proof. *The free-entry condition in R&D, $V_L = \frac{1}{\eta_L}$, together with (13), implies $\eta_L \beta p_L^{\frac{1}{\beta}} L = r$, in the steady-state. Using this condition together with (8), (16), to substitute for p_L, we obtain the growth rate of the economy for a given (N_Z/N_L),*

$$g = \eta_L \beta \left(\gamma^{\gamma} (1-\gamma)^{1-\gamma} \right)^{\frac{1}{\beta}} \left(\frac{\gamma}{1-\gamma} \right)^{1-\gamma} \left(\frac{N_Z Z}{N_L L} \right)^{1-\gamma} L - \rho \tag{21}$$

Combining (18) with (21), the result follows. ■

Consumer's utility depends on environmental quality, which is not taken into account by the producer of the polluting good. Besides the pollution externality there are also the distortions that result from the R&D activity. The next section addresses these issues by solving for the social planner's problem and comparing the optimal solution with the decentralized equilibrium.

4 The Social Planner's Problem

The social planner's problem for this economy can be stated as

$$Max \int_0^{\infty} (\log C + \mu \log Q) e^{-\rho t} dt \tag{22}$$

$$\text{s.t. } (2), (3), (4), (5), (6)$$

$$L = \bar{L}; \quad Z = \bar{Z} \quad \text{and} \quad N_L(0), N_Z(0) > 0 \text{ given}$$

Thus, the current value Hamiltonian for the social planner's problem is

$$\begin{aligned} H &= [\log C + \mu \log Q] + p_C \left[Y_L^{\gamma} Y_Z^{1-\gamma} - I - R_L - R_Z - C \right] \\ &+ r_L \left[\frac{1}{1-\beta} \left(\int_0^{N_L} x_L(j)^{1-\beta} dj \right) L^{\beta} - Y_L \right] \\ &+ r_Z \left[\frac{1}{1-\beta} \left(\int_0^{N_Z} x_Z(j)^{1-\beta} dj \right) Z^{\beta} - Y_Z \right] \\ &+ p_I \left[\psi \int_0^{N_L} x_L(j) dj + \psi \int_0^{N_Z} x_Z(j) dj - I \right] \\ &+ \lambda_L \eta_L R_L + \lambda_Z \eta_Z R_Z + p_Q \left[(\delta Y_Z)^{-1} - Q \right] \end{aligned} \tag{23}$$

where p_C, r_L, r_Z, p_I, λ_L, λ_Z, p_Q denote the shadow prices corresponding to the relevant constraints.

Solving the social planner's problem we obtain the efficient dirty-bias which is characterized in the next Proposition.

Proposition 2 *The efficient dirty-bias in the economy is*

$$\left(\frac{N_Z}{N_L}\right)^* = \kappa\left(\frac{\eta_Z}{\eta_L}\right)\left(\frac{1-\gamma}{\gamma}\right) = \kappa\left(\frac{N_Z}{N_L}\right)^{DE} \tag{24}$$

$$\text{where} \quad \kappa = \left(1 - \frac{\mu C}{\frac{\partial Y}{\partial Y_Z} Y_Z}\right), \qquad 0 < \kappa \leqslant 1 \tag{25}$$

represents the pollution externality. Since $\kappa < 1$, the efficient dirty-bias is smaller than the equilibrium one of the decentralized economy, given by (18).

Proof. *The first-order conditions for a maximum are given by*

$$\frac{\partial H}{\partial Y_L} = p_C \frac{\partial Y}{\partial Y_L} - r_L = 0 \tag{26}$$

$$\frac{\partial H}{\partial Y_Z} = p_C \frac{\partial Y}{\partial Y_Z} - p_Q \frac{Q}{Y_Z} - r_Z = 0 \tag{27}$$

$$\frac{\partial H}{\partial C} = C^{-1} - p_C = 0 \tag{28}$$

$$\frac{\partial H}{\partial Q} = \mu Q^{-1} - p_Q = 0 \tag{29}$$

$$\frac{\partial H}{\partial x_L(j)} = r_L x_L(j)^{-\beta} L^\beta + p_I \psi = 0 \tag{30}$$

$$\frac{\partial H}{\partial x_Z(j)} = r_Z x_Z(j)^{-\beta} Z^\beta + p_I \psi = 0 \tag{31}$$

$$\frac{\partial H}{\partial I} = -p_C - p_I = 0 \tag{32}$$

$$\frac{\partial H}{\partial R_L} = -p_C + \lambda_L \eta_L = 0 \tag{33}$$

$$\frac{\partial H}{\partial R_Z} = -p_C + \lambda_Z \eta_Z = 0 \tag{34}$$

$$\dot{\lambda}_L = \rho\lambda_L - r_L \frac{1}{1-\beta} x_L^{1-\beta} L^\beta - p_I \psi x_L \tag{35}$$

$$\dot{\lambda}_Z = \rho\lambda_Z - r_Z \frac{1}{1-\beta} x_Z^{1-\beta} Z^\beta - p_I \psi x_Z \tag{36}$$

Also, the following transversality conditions must hold:

$$\lim_{t\longrightarrow\infty} \lambda_L N_L e^{-\rho t} = 0; \qquad \lim_{t\longrightarrow\infty} \lambda_Z N_Z e^{-\rho t} = 0 \tag{37}$$

Solving (30) and (31) for the demands of the intermediate inputs, and combining them with (32), (26), (27), (28) and (29), we obtain

$$x_L^*(j) = \left(\frac{r_L}{p_C\psi}\right)^{\frac{1}{\beta}} L = \left(\frac{\frac{\partial Y}{\partial Y_L}}{\psi}\right)^{\frac{1}{\beta}} L \tag{38}$$

$$x_Z^*(j) = \left(\frac{r_Z}{p_C\psi}\right)^{\frac{1}{\beta}} Z = \left(\frac{\frac{\partial Y}{\partial Y_Z} - \mu\frac{C}{Y_Z}}{\psi}\right)^{\frac{1}{\beta}} Z \tag{39}$$

The optimal demand for each input is the same for all $j \in [0, N_L]$ *and* $j \in [0, N_Z]$, *and it is constant along the BGP.*[9] ψ, *the marginal cost of producing intermediate inputs, corrects for the monopoly distortion. From (27), (28) and (29), the shadow price of the* Z*-intensive good is corrected for the pollution externality, as follows* $r_Z = \kappa p_C \frac{\partial Y}{\partial Y_Z}$. *From conditions (33) and (34),* $\frac{\dot{\lambda}_L}{\lambda_L} = \frac{\dot{\lambda}_Z}{\lambda_Z}$ *follows. Thus, equating (35) and (36), combined with (30), (31), (33), (34), (38), and (39) implies that*

$$\frac{\eta_Z}{\eta_L}\left(\frac{r_Z}{r_L}\right)^{\frac{1}{\beta}}\frac{Z}{L} = 1 \tag{40}$$

Substituting (38) and (39) into the production functions (3), we obtain the optimal Y_L *and* Y_Z, *given* N_L *and* N_Z. *Substituting these into the relative marginal product of* Y_Z, *given by (7), and solving, we get the efficient marginal rate of transformation between the two goods, as a function of both the relative productivity of dirty and clean technologies,* (N_Z/N_L), *and the relative factor supply,* (Z/L), *as follows*

$$\frac{\frac{\partial Y}{\partial Y_Z}}{\frac{\partial Y}{\partial Y_L}} = \kappa^{-(1-\beta)}\left(\frac{1-\gamma}{\gamma}\right)^{\beta}\left(\frac{N_Z Z}{N_L L}\right)^{-\beta} \tag{41}$$

Substituting (41) and r_L *and* r_Z *in (40), and solving for* (N_Z/N_L), *we get equation (24). Notice that when there is no externality, as in Acemoglu [2],* κ *is equal to* 1.[10] ■

This Proposition shows that the technology is too dirty-biased (higher N_Z/N_L) in the market economy relative to the optimum. The research effort is directed at new dirty complementary intermediates more than what

[9] In the first-order conditions (35) and (36) this is already assumed.

[10] κ is studied in detail in Appendix B.

is efficient, as the benefits of lower environmental damages are external. Moreover, the higher the environmental concern (the smaller κ), the lower the efficient dirty-bias. In the next section we look at policies that reduce the dirty-bias in the economy, promoting the innovation of new clean intermediates.

From (24) it follows that, in the market economy, the relative production of Y_Z is larger than the efficient one. Consequently, the emissions intensity of aggregate output is higher than optimal. The *laissez-faire* pollution level is higher than optimal, as expected.

From (38), (39) and (41), it follows that the relative demand of intermediate inputs as a function of (N_Z/N_L) is

$$\left(\frac{x_Z}{x_L}\right)^* = \kappa\left(\frac{1-\gamma}{\gamma}\right)\left(\frac{N_Z}{N_L}\right)^{-1} \tag{42}$$

Notice that for a given technology, internalizing pollution would imply a decrease on the relative demand of intermediate inputs. After taking into account endogenous technology, this demand is the same as in the decentralized economy (see (19)).

The long-run growth rate (and also the optimal growth rate of innovation) of this economy is summarized in the following Proposition.

Proposition 3 *The optimal long-run growth rate of the economy is given by*

$$g^* = \left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} \beta\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}} \kappa^{\frac{1-\gamma}{\beta}} (\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma - \rho \tag{43}$$

Proof. *From conditions (26), (28), (30), (33), (35), (38), together with (41) and the production function, (2), and the relative marginal product of Y_Z, given by (7), we obtain, after some algebra, the growth rate of the economy, for a given (N_Z/N_L),*

$$g = \eta_L\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} \beta\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}} \kappa^{\frac{(1-\gamma)(1-\beta)}{\beta}} \left(\frac{\gamma}{1-\gamma}\right)^{1-\gamma}\left(\frac{N_Z Z}{N_L L}\right)^{1-\gamma} L - \rho \tag{44}$$

Combining (24) with (44), the result follows. ■

The environmental externality influences the growth rate through (i) the adjustment on the intermediate inputs, and (ii) the incentives to innovation.

Before incorporating the efficient dirty-bias, the growth rate of the economy, given by (44), captures the externality through the adjustment on the intermediate inputs, for a given (N_Z/N_L). However, the externality is only fully accounted for after incorporating the optimal dirty-bias of technology, as shown in (43).

The optimal growth rate, (43), corrects for both the environmental externality (through κ) and the monopoly and R&D distortions (through $\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}$). The environmental externality ($\kappa < 1$) contributes to a decrease in g^* relative to g^{DE}, while the monopoly and R&D distortions ($\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} > 1$) work in the opposite way.[11]

If the correction for the monopoly and R&D distortions prevails, then $g^* > g^{DE}$. However, the optimal growth rate is lower than it would be without environmental externalities. In such case, when the environmental externality is not too large (large κ), the optimal solution is characterized by boosting growth and decreasing the dirty-bias in the economy. If the correction for the externality prevails, then $g^* < g^{DE}$. The decentralized growth rate will be larger than the optimal rate the stronger the effects of the environmental externality on welfare (the smaller κ). Proposition 4 summarizes the result.

Proposition 4 *The decentralized equilibrium growth rate, g^{DE}, can be smaller or higher than the optimal growth rate, g^*.*

So far, we have solved the model without taking into account that κ is endogenously determined. We will now show that taking into account the endogeneity of κ does not alter our results, giving additional insights. In order to obtain κ, we must derive the consumption to output ratio, $\frac{C}{Y}$, at the optimal solution. Notice that (25) can be rewritten as $\kappa = 1 - \frac{\mu}{(1-\gamma)}\frac{C}{Y}$. Substituting the consumption to output ratio in κ, we obtain,[12]

$$\kappa = 1 - \varphi(\kappa), \quad \text{where} \tag{45}$$

[11] Jones and Williams [13] present empirical evidence, using econometric estimates of returns to R&D, that socially optimal R&D investment is at least four times greater than actual spending (accounting for the current patent system and subsidies to research). Jones and Williams [14], using a calibrated model, and in the absence of taxes and subsidies, confirm the result of underinvestment in R&D and find that the main force promoting underinvestment is the surplus appropriability problem.

[12] See Appendix A for details. We follow Di Maria and Smulders [7], in a different context.

$$\varphi(\kappa) = \frac{\mu\rho}{(1-\gamma)(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^{\gamma}(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}\kappa^{\frac{1-\gamma}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^{\gamma}+(1-\gamma)\mu\rho}$$

Let $\kappa = \{\kappa_s\}$ represent the set of solutions for this equation.

In the model the effects of the environmental externality are captured by μ. When consumers do not value environmental quality ($\mu = 0$), from (45), it follows that κ is equal to 1. When environmental quality is as important to consumers' welfare as consumption ($\mu = 1$), then κ is negative. The more consumers value the environment (higher μ), and, therefore, the larger the environmental externality, the lower κ, and the lower the optimal growth rate of the economy.

Lemma 1 *At the equilibrium value of* κ_s, $\frac{\partial \kappa_s}{\partial \mu} < 0$.

Proof. *By analogy with stability analysis, we can show that* $\frac{\partial(1-\varphi(\kappa_s))}{\partial \kappa} < 1$ *iff* $\frac{\partial \kappa(\kappa_s)}{\partial \mu} < 0$. *In other words, at the equilibrium value of* κ_s, *as* $(1-\varphi(\kappa))$ *is positively sloped, it has to cut the 45-degree line from above. This result is shown in Appendix B.* ■

The comparative static results of the optimal growth rate, (43), taking into account the endogeneity of κ, are summarized in the following Proposition.[13]

Proposition 5 *The optimal growth rate is higher (i) the larger the country's endowment of* L *and* Z, *(ii) the smaller the cost of new intermediate inputs (larger* η_i, $i = L, Z$*), (iii) the smaller the rate of time preference (smaller* ρ*), and, (iv) the less consumers value the environment (lower* μ*).*

Proof. *Differentiating the optimal growth rate (43) with respect to the relevant parameter, the results follow. The same results apply to the decentralized growth rate.* ■

The comparison of the share of the clean (Y_L/Y) and dirty goods (Y_Z/Y) in the aggregate output in the decentralized equilibrium and in the optimum is summarized in the following Proposition.

Proposition 6 *The value of* Y_L/Y *in the long-run of the decentralized equilibrium is lower than the optimal one, and the opposite occurs with* Y_Z/Y *.*

[13] Also, we can show that the higher μ, the higher the consumption to output ratio, C/Y, and the lower the share of final good devoted to investment, I/Y, and to R&D expenditures, R/Y.

Also, the more consumers value the environment (the higher μ), the higher the difference between the decentralized and the optimal shares just mentioned.

Proof. *See Appendix C.* ■

The following Proposition presents the implications for the level of emissions per unit of output.

Proposition 7 *Emissions per unit of output are constant along the BGP and are higher in the laissez-faire economy than in the optimal solution according to*

$$\left(\frac{E_Z}{Y}\right)^* = \delta\frac{Y_Z}{Y} = \delta\kappa_s^\gamma\left(\frac{1-\gamma}{\gamma}\right)^\gamma\left(\frac{\eta_Z Z}{\eta_L L}\right)^{\beta\gamma} = \kappa_s^\gamma\left(\frac{E_Z}{Y}\right)^{DE}$$

Moreover, the more consumers value the environment (higher μ), the lower the optimal emissions intensity of aggregate output.

Summarizing, for a given (N_Z/N_L), the efficient relative production of the polluting good, and, thus, the efficient level of emissions intensity, is achieved by adjusting the production of intermediate inputs. The decentralized relative demand for dirty complementary intermediates is higher than the efficient one, as shown in (42). With endogenous technology, the internalization of the pollution externality also implies moving R&D towards new clean complementary intermediates and, therefore, increasing the relative physical productivity of the clean factor along the BGP.

The next section focuses on the policy implications determined by the fact that the decentralized growth path is different from the optimal one.

5 Policy Implications

Since the decentralized equilibrium growth path is different from the optimal one, and the dirty-bias in the decentralized economy is different from the efficient one, there is scope for government intervention. In this section we look for policy instruments that align both growth paths and allow for the efficient dirty-bias, thus, internalizing the environmental externality.

We begin by looking at the first-best policy. There are three distortions in the decentralized economy: (i) the surplus appropriability problem tends to generate too little research, (ii) intermediate goods are produced by monopolists, producing less than optimal, and, finally, (iii) because of the environmental externality, production of Y_Z is larger than optimal. Three market failures require three policy instruments: a technology policy instrument that takes the form of a subsidy to the R&D sector to encourage research, a subsidy to the producers of intermediate inputs to equate marginal costs to prices and neutralize the effect of monopoly pricing, and an environmental policy instrument on producers of Y_Z to internalize pollution externalities. In this last case, we consider an emission tax on the polluting good, which operates by closing the gap between private and social costs of the polluting activity. When optimally choosing the level of the policy instruments, the optimal allocation can be attained through a decentralized competitive market driven equilibrium.

We first assume that all these instruments are available to policy makers. However, because there might be insufficient policy instruments available to correct the multiple imperfections, we also look at second-best solutions. If growth is the most important target, we only need one policy instrument to align the two growth paths. However, one single instrument may not be enough to attain the optimal share of emissions in the aggregate output.

5.1 First-best policy

In order to determine the optimal policies, we introduce the policy instruments and compute the policy-ridden solution. The optimal level of the policy instruments is obtained by comparison with the social planner's solution.

Consider the following set of first-best instruments: (i) a proportional subsidy, $\phi^* > 1$, paid by the government to the R&D sector for each new design, which is assumed to be the same for new L and Z-complementary intermediates. The subsidy to the R&D sector decreases the costs of a new variety to $1/(\phi^* \eta_i)$, $i = L, Z$. This has impact on growth by increasing $\dot{N}_i$, $i = L, Z$; (ii) a subsidy, s^*, paid by the government to each producer of intermediate inputs, which is assumed to be the same for technology monopolists producing x_L and x_Z, and, finally, (iii) a unit emission tax, τ_Z^*, is levied on the polluting sector.

The optimal policy is summarized in the following Proposition.

Proposition 8 *The social optimum can be implemented through (i) a subsidy to the R&D sector given by $\phi^* = 1/\psi$, (ii) a subsidy to the producers of intermediate inputs given by $s^* = \beta$, and, (iii) a tax on emissions given by*

$$\begin{aligned}\tau_Z^* &= \frac{\mu}{\delta(1-\gamma)}\frac{C}{Y} \\ &= \frac{\mu\rho}{\delta(1-\gamma)\left[(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}\kappa_s^{\frac{1-\gamma}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma+\mu\rho\right]}\end{aligned}$$

Proof. *Comparing the policy-ridden solution given by*

$$g = \phi\frac{\psi(1-s)}{1-\beta}\left(\frac{1-\beta}{\psi(1-s)}\right)^{\frac{1}{\beta}}\beta\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}(1-\tau\delta)^{\frac{1-\gamma}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma-\rho$$

with the social planner's solution (43), the results follow. κ_s is the solution for equation (45) and $\frac{\partial\kappa_s}{\partial\mu} < 0$ holds. ■

The optimal tax increases with μ and decreases with the elasticity of Y with respect to the polluting good.

The first-best policy, summarized in the previous Proposition, implements not only the optimal growth rate of the economy, but also the optimal emissions intensity of aggregate output as it induces the efficient demand for intermediates and the efficient dirty-bias in the economy. The tax decreases the demand of the dirty intermediates and, therefore, depresses the value of patents of new dirty complementary intermediates. This moves research towards new clean complementary intermediates, thus, increasing the clean-bias in the economy. Therefore, the optimal level of emissions per unit of output is achieved.

5.2 Second-best policies

Because policy makers may not have all the instruments available simultaneously, we also specify a second best optimum, where the social planner has available only one policy instrument. We assume that the primary target of the policy-maker is to align the market and the optimal growth paths, as long as the emissions intensity of aggregate output decreases, or, it is at the most the same as in the decentralized economy.

In this case, we consider a tax on the polluting good and two different kinds of subsidies to R&D. We compute the policy-ridden growth rate, then equate it to the optimal growth rate and solve for the optimal level of the policy variable.

(1) *Tax on the polluting good* If the pollution externality prevails over the remaining distortions in the model (that is, κ is small) and the regulator chooses to decrease growth ($g^{DE} > g^*$), a per unit emission tax, τ_Z, on the polluting sector can be considered. The growth rate of the regulated economy equates to the optimal one when

$$\tau_Z = \left[\frac{1}{\delta} - \frac{1}{\delta}\left(\frac{1}{\psi}\right)^{\frac{1}{1-\gamma}} \kappa_s\right] > 0 \tag{46}$$

Although the growth rate for the economy is optimal, the emissions intensity of aggregate output is not. The tax moves the economy towards the optimum, by adjusting (i) the relative demand of intermediates, for a given state of technology, and (ii) the dirty-bias (N_Z/N_L). However, since this second-best tax is smaller than the first-best one, it achieves neither the efficient demand of intermediates nor the efficient dirty-bias. There is a decrease in the relative production of Y_Z, and, thus, a decrease in the emissions per unit of output when compared to the *laissez-faire* economy. However, it remains above the efficient level. Therefore, implementing the efficient dirty bias through a tax on pollution compromises growth.

(2) *Subsidy to R&D* (i) Assuming a technology policy that subsidizes at the same rate both R&D sectors, that is, the subsidy is the same for new L and Z-complementary intermediates ($\phi = \phi_Z = \phi_L$), the optimal growth rate of the economy can be implemented through

$$\phi = \left[\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} \kappa_s^{\frac{1-\gamma}{\beta}}\right] > 1 \tag{47}$$

This policy instrument can be used when the monopoly and R&D distortions prevail over the environmental externality (that is, κ is large) and the regulator chooses to boost growth ($g^{DE} < g^*$). However, since the introduction of ϕ does not require any adjustment on the demand of intermediate inputs, for a given (N_Z/N_L), nor on the efficient dirty-bias, the relative production of Y_Z is the same as in the *laissez-faire* economy. Thus, emissions per unit of output are the same as in the *laissez-faire* economy, above the efficient level.

(ii) In contrast to the previous case, the government's technology policy may discriminate between the new designs by paying a different subsidy to each one, that is, $\phi_Z \neq \phi_L$. In order to achieve g^*, by computing the growth rate of the regulated economy, the following relationship between ϕ_Z and ϕ_L must hold:

$$\phi_Z = \left[\left(\frac{1}{\psi} \right)^{\frac{1}{\beta}} \kappa_s^{\frac{1-\gamma}{\beta}} \phi_L^{-\gamma} \right]^{\frac{1}{1-\gamma}} \tag{48}$$

Also, if $\phi_Z = \kappa_s \phi_L$ holds, the efficient dirty-bias is implemented. Solving this system of equations, we obtain $\phi_Z = \left(\frac{1}{\psi} \right)^{\frac{1}{\beta}} \kappa_s^{\frac{1-\gamma}{\beta}+\gamma}$ and $\phi_L = \left(\frac{1}{\psi} \right)^{\frac{1}{\beta}} \kappa_s^{\frac{(1-\gamma)(1-\beta)}{\beta}}$, for which both the optimal growth rate of the economy and the efficient dirty-bias in the economy are obtained. Since $\kappa_s < 1$, $\phi_Z < \phi_L$, implying that the new Z-complementary intermediates become relatively more costly than the new L-complementary intermediates. This will encourage research towards new clean complementary intermediates, therefore, increasing the clean-bias in the economy.

Differentiating R&D subsidies towards the clean sector corrects for the technology externalities and at the same time reduces emissions. However, there is no adjustment on the demand of intermediate inputs, for a given (N_Z/N_L). Moreover, after endogeneizing for technical change, the relative demand of dirty complementary intermediates is higher than the optimal one. Therefore, although the efficient dirty-bias is implemented, the production of Y_Z is higher than the efficient one, and, consequently, the emissions intensity also is. However, the economy moves towards the optimum and attains a lower share of emissions in the aggregate output than in the decentralized equilibrium.

In summary, despite that the optimal growth rate can be achieved using all these second-best instruments, only the tax on emissions, $\tau_Z > 0$, or the differentiated subsidies to research, $(\phi_Z) < (\phi_L)$, are able to decrease emissions per unit of output. A common subsidy to both types of research keeps the same emissions intensity as in the *laissez-faire* economy.

6 Conclusions

In this paper we develop an endogenous growth model for a closed economy that incorporates the welfare effects of environmental quality and innovation. The aggregate output is produced from two goods, and two factors of production, one clean and one dirty. In this economy, technological change extends the range of two types of intermediate inputs: clean and dirty complementary intermediates.

We study the trade-off between environmental quality and growth when the type of technological change is endogenous. As expected, the more consumers value the environment, the lower the optimal growth rate. This suggests that different levels of concern about the environment can help explaining the differences in environmental policies, and, thus, in growth rates across countries.

Because there are a negative externality from pollution and distortions caused by the monopoly power and the R&D activity, the decentralized growth rate can be higher or smaller than the optimal rate. We study the problem of implementing the optimal path. There are three distortions in the decentralized economy: the surplus appropriability problem, the monopoly power by intermediate inputs producers and pollution. The first-best policy is implemented through a subsidy to the R&D sector to encourage research, a subsidy to the producers of intermediate inputs to neutralize the effect of monopoly pricing, and an emissions tax on the polluting good to eliminate the distortion due to pollution. We compute the levels of the three policy instruments which allow implementing the optimal solution.

The regulator wishes to decrease the relative production of dirty intermediates and encourage environmentally oriented research. In the market economy, research effort directed at new dirty intermediates relative to new clean intermediates is larger than the efficient one. The pollution tax affects both the balance of production between clean and dirty intermediates and the efficient dirty-bias in the economy. It has a distortionary impact on the two sectors of intermediates. It decreases the demand of the dirty intermediates and, therefore, depresses the value of patents of new dirty complementary intermediates. Since R&D firms develop new clean or dirty complementary intermediates depending on relative profitability, this encourages research towards new clean complementary intermediates, and, therefore, moves the dirty-bias towards its efficient level.

In summary, to implement the efficient dirty-bias and the optimal level of emissions per unit of output the pollution tax must be complemented by subsidies to R&D and to the monopolists that produce the intermediate goods. The environmental policy instruments encourage research of new clean factor-complementary intermediates and allow the regulated economy to choose the efficient dirty-bias. The reduction in the emissions intensity of aggregate output is possible by decreasing both the use of the dirty complementary intermediates, in the short-run, and the dirty-bias in the economy, in the long-run.

We also discuss second-best policies, assuming that the primary target of the policy makers is to align the market and the optimal growth paths. We consider, in alternative, a tax on emissions and a differentiated subsidy to R&D, according to the type of research. These policies decrease the share of emissions in the aggregate output, moving it towards the optimum, but its optimal level is not achieved. Our results suggest that pricing only emissions might not be enough, as the price required to give incentive to low-carbon technologies is too high, sacrificing growth.

Moreover, in order to provide incentives for firms to invest in the development of those technologies, credible commitments to meeting long-run emissions targets without imposing unnecessarily high near-term costs have to be provided. The fact that the caps to be set in the future are those that are relevant for innovation, and that, as discussed in Montgomery and Smith [15], it is not possible to credibly impose in the present strict future targets gives additional relevance to policies that increase government funding or incentives for private funding of research directed to cleaner technologies (grants and tax incentives, prizes, R&D consortia).

Appendix A - Share of output devoted to C

In order to obtain C/Y, we need to make use of the final good resource constraint (5). From this condition, $\frac{C}{Y} = 1 - \frac{I}{Y} - \frac{R}{Y}$. Thus, we need to determine I/Y and R/Y.

The total cost of producing L and Z-complementary intermediates is $I = \psi x_L^* (j) N_L + \psi x_Z^* (j) N_Z$. Substituting (38) and (39) into the production functions (3), and solving for the total amount of intermediates purchased ($x_i^* (j) N_i$), we obtain $x_i^* (j) N_i = \left(\frac{r_i}{p_C \psi}\right) Y_i (1-\beta)$. Together with (26) and (27), we obtain $I = (1-\beta) Y_L \frac{\partial Y}{\partial Y_L} + (1-\beta) Y_Z \left(\frac{\partial Y}{\partial Y_Z} - \mu \frac{C}{Y_Z}\right)$. As $Y = Y_L \frac{\partial Y}{\partial Y_L} + Y_Z \frac{\partial Y}{\partial Y_Z}$, the share of final good invested in intermediate inputs is given by $\frac{I}{Y} = (1-\beta)\left(1 - \mu \frac{C}{Y}\right)$.

From (4), R&D expenditures in each sector can be written as $R_i = g^* N_i / \eta_i$. From (28), (30), (33), (35), (38) and the production function for Y_L after substituting for x_L^*, we find that $\frac{N_L}{\eta_L} = \frac{Y_L \beta (1-\beta)}{g^* + \rho} \left(\frac{r_L}{p_C \psi}\right)$. $\frac{N_Z}{\eta_Z}$ can be obtained similarly. Thus, total expenditure in R&D can be written as $R = \frac{Y_L \beta g^*}{g^* + \rho} \frac{\partial Y}{\partial Y_L} + \frac{Y_Z \beta g^*}{g^* + \rho} \left(\frac{\partial Y}{\partial Y_Z} - \mu \frac{C}{Y_Z}\right)$ which implies that $\frac{R}{Y} = \frac{\beta g^*}{g^* + \rho} \left(1 - \mu \frac{C}{Y}\right)$.

Finally, from (5), we obtain the consumption to output ratio as

$$\frac{C}{Y} = \frac{\beta - \frac{\beta g^*}{g^* + \rho}}{1 - \mu \left[(1-\beta) + \frac{\beta g^*}{g^* + \rho}\right]} \tag{49}$$

$$= \frac{\rho}{(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} \left(\gamma^\gamma (1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}} \kappa^{\frac{1-\gamma}{\beta}} (\eta_Z Z)^{1-\gamma} (\eta_L L)^\gamma + \mu\rho}$$

after substituting for g^*, given by (43).[14]

Appendix B - Proof (Lemma 1)

Assume $A = \left(\frac{1}{\psi}\right)^{\frac{1}{\beta}} \left(\gamma^\gamma (1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}} (\eta_Z Z)^{1-\gamma} (\eta_L L)^\gamma$

$\frac{\partial(1-\varphi(\kappa_s))}{\partial \kappa} < 1 \Longleftrightarrow \frac{\partial \kappa(\kappa_s)}{\partial \mu} < 0$

where

$$\frac{\partial(1-\varphi(\kappa_s))}{\partial \kappa} = \frac{(1-\gamma)^2 A \beta^{-1} \frac{1-\mu}{\mu} \kappa_s^{\frac{1-\gamma}{\beta} - 1} \rho}{\left[(1-\gamma) A \frac{1-\mu}{\mu} \kappa_s^{\frac{1-\gamma}{\beta}} + (1-\gamma)\rho\right]^2}$$

[14]It can be shown that $\frac{I}{Y}$, $\frac{R}{Y}$ and $\frac{C}{Y} \in (0,1)$.

and

$$\frac{\partial\kappa(\kappa_s)}{\partial\mu}=\frac{-(1-\gamma)\mu^{-2}A\kappa_s^{\frac{1-\gamma}{\beta}}\rho}{\left[(1-\gamma)A\frac{1-\mu}{\mu}\kappa_s^{\frac{1-\gamma}{\beta}}+(1-\gamma)\rho\right]^2-(1-\gamma)^2A\beta^{-1}\frac{1-\mu}{\mu}\kappa_s^{\frac{1-\gamma}{\beta}-1}\rho}$$

Notice that $\frac{\partial(1-\varphi(\kappa_s))}{\partial\kappa}<1$ is equivalent to have the denominator of $\frac{\partial\kappa(\kappa_s)}{\partial\mu}$ positive. Since the numerator of $\frac{\partial\kappa(\kappa_s)}{\partial\mu}$ is negative, then $\frac{\partial\kappa(\kappa_s)}{\partial\mu}<0$. On the other hand, if $\frac{\partial\kappa(\kappa_s)}{\partial\mu}<0$, since the numerator is negative, then the denominator has to be positive, implying that $\frac{\partial(1-\varphi(\kappa_s))}{\partial\kappa}<1$.

The solution can be shown graphically. When $1-\gamma\leqslant\beta$ (that is, when the share of Y_Z on Y is smaller or equal than the share of Z on Y_Z), $1-\varphi(\kappa)$ is concave. Figure 1 illustrates the left hand side and the right hand side of equation (45), for a given μ, when $1-\gamma\leqslant\beta$.

When $1-\gamma>\beta$, $1-\varphi(\kappa)$ is convex for $\kappa<\hat{\kappa}$, and concave for $\kappa>\hat{\kappa}$.[15] Figure 2 illustrates this case.

In both cases, as μ increases, $1-\varphi(\kappa)$ crosses the horizontal axis at a higher κ.[16] Also, when $1-\gamma>\beta$, the inflection point, $\hat{\kappa}$, is increasing in μ. Thus, the right hand side of equation (45) moves to the right.

There is a solution for equation (45) as long as $\exists\ \kappa : 1-\varphi(\kappa)>\kappa$, that is, $(1-\gamma)(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma\kappa^{\frac{1-\gamma}{\beta}}(1-\kappa)-(1-\gamma)\mu\rho\kappa-\gamma\mu\rho>0$.

We assume a positive optimal growth rate of the economy, $g^*>0$, that is, $\kappa>\left[\frac{\rho}{\beta A}\right]^{\frac{\beta}{1-\gamma}}$, where $A=\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma$.

This means that $\mu<\frac{\left(\frac{\rho}{\beta A}\right)(1-\gamma)A\left[1-\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}\right]}{\left(\frac{\rho}{\beta A}\right)(1-\gamma)A\left[1-\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}\right]+\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}(1-\gamma)\rho+\gamma\rho}<1$. In other words, the solution we are considering is only possible for environmental preferences such that $0<\mu<\frac{\left(\frac{\rho}{\beta A}\right)(1-\gamma)A\left[1-\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}\right]}{\left(\frac{\rho}{\beta A}\right)(1-\gamma)A\left[1-\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}\right]+\left(\frac{\rho}{\beta A}\right)^{\frac{\beta}{1-\gamma}}(1-\gamma)\rho+\gamma\rho}$. A very high environmental concern by consumers would imply either zero

[15] The inflection point is $\hat{\kappa}=\left[\frac{\mu\rho(1-\gamma-\beta)}{(1-\gamma+\beta)(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma}\right]^{\frac{\beta}{1-\gamma}}$.

[16] $1-\varphi(\kappa)$ crosses the horizontal axis at

$\bar{\kappa}=\left[\frac{\mu\rho\gamma}{(1-\gamma)(1-\mu)\left(\frac{1}{\psi}\right)^{\frac{1}{\beta}}\left(\gamma^\gamma(1-\gamma)^{1-\gamma}\right)^{\frac{1}{\beta}}(\eta_Z Z)^{1-\gamma}(\eta_L L)^\gamma}\right]^{\frac{\beta}{1-\gamma}}$. Since $\frac{\partial\bar{\kappa}}{\partial\mu}>0$, the result follows.

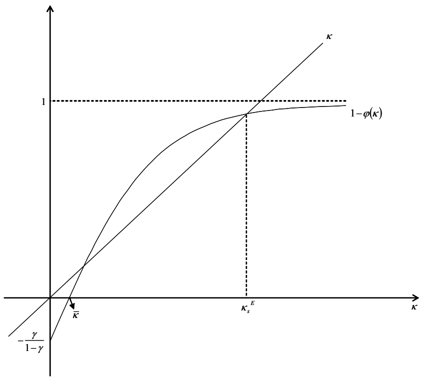

Figure 1: $\kappa = 1 - \varphi(\kappa)$ (eq. (45)), when $1 - \gamma \leqslant \beta$

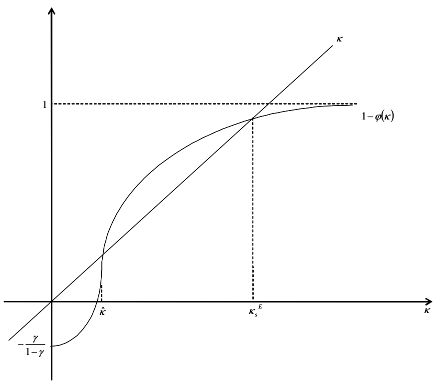

Figure 2: $\kappa = 1 - \varphi(\kappa)$ (eq. (45)), when $1 - \gamma > \beta$

or negative growth.

As well, from the maximization of the utility function, it has to be the case that $g^* < \frac{\rho}{1-\mu}$. If this condition holds for $\mu = 0$, it also holds for positive values of μ.

Appendix C - Proof (Proposition 6)

Notice that the share of the clean good in the final output is given by the inverse of $\frac{Y}{Y_L} = \left(\frac{Y_Z}{Y_L}\right)^{1-\gamma}$, that is, from (7), by $\frac{Y}{Y_L} = \left(\frac{1-\gamma}{\gamma}\left(\frac{\frac{\partial Y}{\partial Y_Z}}{\frac{\partial Y}{\partial Y_L}}\right)^{-1}\right)^{1-\gamma}$. After substituting for the efficient marginal rate of transformation between the two goods, with endogenous technical change (equation (41), and (N_Z/N_L)

from equation (24)), we obtain $\left(\frac{Y}{Y_L}\right)^* = \left(\kappa_s \frac{1-\gamma}{\gamma}\left(\frac{\eta_Z Z}{\eta_L L}\right)^\beta\right)^{1-\gamma} = \kappa_s^{1-\gamma}\left(\frac{Y}{Y_L}\right)^{DE}$.
Likewise, we have that $\left(\frac{Y}{Y_Z}\right)^* = \left(\frac{Y_Z}{Y_L}\right)^{-\gamma} = \left(\kappa_s \frac{1-\gamma}{\gamma}\left(\frac{\eta_Z Z}{\eta_L L}\right)^\beta\right)^{-\gamma} = \kappa_s^{-\gamma}\left(\frac{Y}{Y_Z}\right)^{DE}$.
Since $0 < \kappa_s < 1$, it follows that $\left(\frac{Y}{Y_L}\right)^* < \left(\frac{Y}{Y_L}\right)^{DE}$ and $\left(\frac{Y}{Y_Z}\right)^* > \left(\frac{Y}{Y_Z}\right)^{DE}$.
By differentiating $\frac{Y}{Y_L}$ and $\frac{Y}{Y_Z}$ with respect to μ, it follows that Y_L becomes relatively more important on the production of the final output the higher μ is, and the opposite occurs with Y_Z.

References

[1] Acemoglu, D., 1998, "Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality", *Quarterly Journal of Economics* **CXIII**, 1055-1090

[2] Acemoglu, D., 2002, "Directed Technical Change", *Review of Economic Studies* **69**, 781-809.

[3] Acemoglu, D. and F. Zilibotti, 2001, "Productivity Differences", *Quarterly Journal of Economics*, 563-606.

[4] Amano, M and R. A. Sedjo, 2006, "Forest Sequestration: Performance in Selected Countries in the Kyoto Period and the Potential Role of Sequestration in Post-Kyoto Agreements", Resources for the Future.

[5] Bovenberg, A. L. and S. Smulders, 1995, "Environmental Quality and Pollution-Augmenting Technological Change in a Two-sector Endogenous Growth Model", *Journal of Public Economics* **57**, 369-391.

[6] Carraro, C and D. Siniscalco, 1994, "Environmental Policy Reconsidered: The Role of Technological Innovation", *European Economic Review* **38**, 545-555.

[7] Di Maria, C. and S. Smulders, 2004, "Trade Pessimists vs Technology Optimists: Induced Technical Change and Pollution Havens", *Advances in Economic Analysis & Policy*, Vol. 4, No. 2, Article 7. http://www.bepress.com/bejeap/advances/vol4/iss2/art7

[8] Elbasha, E. H. and T. L. Roe, 1996, "On Endogenous Growth: The Implications of Environmental Externalities", *Journal of Environmental Economics and Management* **31**, 240-268.

[9] Grimaud, A., 1999, "Pollution Permits and Sustainable Growth in a Shumpeterian Model", *Journal of Environmental Economics and Management* **38**, 249-266.

[10] Hart, R., 2004, "Growth, Environment and Innovation-A Model with Production Vintages and Environmentally Oriented Research", *Journal of Environmental Economics and Management* **48**, 1078-1098.

[11] Hart, R., 2004, "Can Environmental Regulations Boost Growth?", Paper presented at SURED Conference, Ascona, Switzerland, June 2004.

[12] IPCC, 2007, Summary for Policymakers. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press. Chapter 2.7.

[13] Jones, C. I. and J. C. Williams, 1998, "Measuring the Social Return to R&D", *The Quarterly Journal of Economics* **113**, 1119-1135.

[14] Jones, C. I. and J. C. Williams, 2000, "Too Much of a Good Thing? The Economics of Investment in R&D", *Journal of Economic Growth* **5**, 65-85.

[15] Montgomery, W. D. and A. E. Smith, 2007, "Price, Quantity and Technology Strategies for Climate Change Policy". In: *Human-Induced Climate Change*, edited by M. E. Schlesinger, H. S. Kheshgi, J. Smith, F. C. de la Chesnaye, J. M. Reilly, T. Wilson, C. Kolstad, Cambridge University Press.

[16] Presidency Conclusions of the Brussels European Council, 8/9 March 2007. http://www.consilium.europa.eu/uedocs/cms_Data/docs/pressdata/en/ec/93135.pdf

[17] Reis, A., 2001, "Endogenous Growth and the Possibility of Eliminating Pollution", *Journal of Environmental Economics and Management* **42**, 360-373.

[18] Ricci, F., 2007, "Environmental Policy and Growth when Inputs are Differentiated in Pollution Intensity", *Environmental and Resource Economics* **38** (3), 285-310.

[19] Stokey, N., 1995, "R&D and Economic Growth", *Review of Economic Studies* **62**

[20] Stokey, N., 1998, "Are There Limits to Growth?", *International Economic Review* **39**, 1-31.