Thünen-Series of Applied Economic Theory

Thünen-Reihe Angewandter Volkswirtschaftstheorie

Working Paper No. 106

Green R&D versus End-of-Pipe Emission Abatement: A Model of Directed Technical Change

Michael Rauscher

Universität Rostock
Wirtschafts- und Sozialwissenschaftliche Fakultät
Institut für Volkswirtschaftslehre
April 2009

Green R&D versus End-of-Pipe Emission Abatement: A Model of Directed Technical Change

Michael Rauscher

Universität Rostock, ifo-Institut München

Abstract

The paper looks at a model of directed technical change in an environmental-economics context. Firms can do conventional or "green" R&D or they can abate emissions at the end of pipe. The paper has two main foci. On the one hand, it investigates the impact of environmental regulation on the allocation of resources to conventional R&D, green R&D, and end-of-pipe abatement. On the other hand, it addresses the question whether stricter emission standards should be used to support green R&D and/or economic growth.

Keywords: economic growth and the environment, directed technical change

Acknowledgement

Research leading to this paper was supported by the German Federal Ministry of Education and Research in their programme on "Emergence, Diffusion, and Impact of Innovations towards Sustainability", grant no. 01UN0608. I benefitted from helpful discussions with Tilmann Rave and Ursula Triebswetter at the ifo Institute in Munich.

Green R&D versus End-of-Pipe Emission Abatement: A Model of Directed Technical Change

1 Introduction

Does strict environmental regulation foster innovation and economic growth? The so-called Porter hypothesis argues that it does. See Porter (1990) and Porter/van der Linde (1995). Standard economic theory in contrast suggests that tighter constraints such as stricter environmental product and process standards always deteriorate material well-being. In order to address the issue, I construct a simple dynamic environmental-economics model with research and development (R&D) into cleaner technologies of production. Firms adopting these cleaner technologies will spend less on end-of-pipe emission abatement. This benefit, though, comes at a cost since green R&D itself uses scarce resources which could be utilized profitably for other purposes in the economy as well. Thus, it is unclear whether, (i) tighter environmental standards will induce a shift from end-of-pipe to process-integrated emission abatement, (ii) tighter environmental standards will induce more R&D and growth, and (iii) whether, in a normative perspective, governments should implement stricter standards in a world with green R&D than in a world without. This paper is an attempt to answer the three questions.

The model is set up as follows. In a competitive market economy, two types of capital are accumulated, conventional capital, which pollutes the environment when used in production, and green capital, which doesn't. Remaining emissions can be abated at the end of the pipe, the abatement requirement – and, thus, the abatement cost, too - depending on the stringency of environmental regulation. Firms decide on how to allocate resources between conventional R&D, green R&D, and end-of-pipe abatement and the government determines the environmental standard. In order to introduce a motive for government interventions going beyond the mere internalization of pollution externalities, I assume that there are positive knowledge spillovers in the R&D sector.

There are different ways of modelling R&D in economics. This analysis will be carried out in an endogenous-growth framework, economic growth being driven by the accumulation of physical capital and technological know-how. For the sake of simplification, I will not distinguish between physical and knowledge capital but instead use aggregate variables encompassing both aspects of capital. The process of accumulation is modelled à la Jones (1995), where existing capital/knowledge advances the accumulation of new capital/ knowledge, albeit at a decreasing rate. Moreover, as already mentioned, knowledge spillovers across firms are taken into account. This approach is combined with modelling elements from the directed-technical-change literature, which was initiated by Acemoglu/Zilibotti (2001) and Acemoglu (2002) and applied to issues of environmental regulation by Ricci (2007), Balcão Reis/Cunha-e-Sá/ Leitão (2008), and Grimaud/Rouge (2008).[1] Grimaud/Rouge (2008) differs from the other two papers (and from this one as well) by looking at an exhaustible resource as an input. Balcão Reis/Cunha-e-Sá/Leitão (2008) do not consider knowledge spillovers across firms as a source of inefficiency, but assume monopolistic pricing by innovators. Moreover, I assume a constant level of emissions despite the fact that the economy grows, whereas Balcão Reis/Cunha-e-Sá/Leitão (2008) have growing emissions, which will certainly be unsustainable over an infinite time horizon. Ricci's (2007) model is closer to the one in this paper, but still differs in several ways. He assumes that technological change affects the emission intensity of capital whereas I distinguish between green and conventional capital. He assumes constant returns to knowledge in the generation of new knowledge, whereas I assume decreasing returns. Moreover, I consider the possibility of end-of-pipe abatement and address optimal environmental policies, which Ricci (2007) doesn't.

In one respect, the present paper differs from all the other ones mentioned above in that I employ an algebraically much simpler and, therefore, more conveniently tractable model of innovation and technical progress. For example, the model is solved for general production functions without taking recourse to Cobb-Douglas or CES specifications. The twist is to assume only one type of agent in the private sector of the economy, a capital-owning entrepreneur who does her R&D in-house, who save and consumes. Other papers, in contrast, assume up to four different groups of agents: households, which save and consume; capital owners, who accumulate capital; innovators, who do R&D; and entrepreneurs, who combine capital and technology in order to produce. If the markets on which these agents interact are perfectly competitive, then the simple homogenous-representative-agent model generates the same results as its more elaborated (and more intricate) general-equilibrium version with heterogeneous agents. The investigation is organized as follows. The next section presents the model. Section 3 looks at the private sector's optimum, derives the economy's growth path and derives some comparative statics. The fourth section is devoted to the government's

---

[1] There are many other papers on technological change and economic growth in the environmental-economics context, but I confine myself to the directed-technical-change literature because only this is directly relevant in the context of the present analysis.

optimum environmental policy in a second-best world. Section 5 looks at the first best and Section 6 summarizes.

2 The Model

Let us consider an economy consisting of a continuum of identical firms run by capital-owning entrepreneurs who use identical technologies to produce a homogenous GDP good. The representative capitalist-entrepreneur maximizes the present value of future utility, the discount rate being δ,

$$\int_0^\infty (ln\, C(t) + u(\varepsilon))e^{-\delta t} dt\,,$$

where $lnC(t)$ is the utility derived from consumption or dividend income at time t,[2] ε is environmental quality as determined by an ambient standard set by the government and $u(.)$ is an increasing and concave utility function. Like in Acemoglu/Zilibotti (2001), Acemoglu (2002), Ricci (2007), Balcão Reis/Cunha-e-Sá/Leitão (2008), and Grimaud/Rouge (2008), and there are two types of capital. Firms use conventional capital, $K(t)$, and green capital, $G(t)$, to produce an output $F(K(t),G(t))$, where $F(.,.)$ is a well-behaved neoclassical production function with constant returns to-scale (CRS) satisfying the Inada conditions. Output is used for consumption, for investment in capital of either type, and for end-of-pipe emission abatement:

$$F(K(t),G(t)) - C(t) - (R_K(t) + R_G(t))w - \chi(\varepsilon)K(t) = 0\,. \tag{1}$$

$R_K(t)$ and $R_G(t)$ denote research and development to generate new capital of types K and G, respectively, with w as a constant and exogenous opportunity cost of research. In the real world, $R_K(t)$ and $R_G(t)$ may be approximated by numbers of patents. In contrast to the other directed-technical-change models, innovation takes place within the firm. Environmental regulation is of the command-and-control type. The government sets the environmental standard, ε, which is constant and taken as a binding constraint by the firm. The cost of achieving this environmental standard is proportional to installed conventional capital, $K(t)$, and it is increasing and convex in the strictness of environmental regulation, i.e. $\chi'>0$, $\chi''>0$.

[2] By taking the log of consumption, I assume a special utility function with a unit elasticity of intertemporal substitution. One can show that the qualitative results of this paper go through for the more general case as well as long as the elasticity is not too large, the critical value being larger than 1. Given that realistic estimates of the elasticity of intertemporal substitution are in the range 0.7 to 0.8 (Hall 1988, Guvenen 2006), the error made by assuming a unit elasticity seems tolerable.

Unlike other models of endogenous growth in environmental economics where steady-state emissions grow over time, I assume that spending a constant share of GDP on abatement suffices to keep emissions constant. The empirical evidence cited in Brock/Taylor (2004) suggests that the abatement cost share has indeed been almost constant in most industrialized countries in the 1980s and 1990s and that emissions have not increased (but instead even declined) during this period.

The accumulation of conventional and green capital is modelled à la Jones (1995)[3] in equations (2) and (3), where dots above variables denote derivatives with respect to time and the functions $A(.,.,.)$ and $B(.,.,.)$ are concave, have CRS, positive first derivatives and satisfy the Inada conditions:

$$\dot{K}(t) = A\big(K(t), K^*(t), R_K(t)\big). \tag{2}$$

$$\dot{G}(t) = B\big(G(t), G^*(t), R_G(t)\big). \tag{3}$$

Knowledge spillovers are modelled via $K^*(t)$ and $G^*(t)$, which denote the economy-wide stocks of conventional and green capital, respectively. Ex post they are equal to the stocks employed by the representative firm: $K^*(t)=K(t)$ and $G^*(t)=G(t)$. Ex ante, however, producers take $K^*(t)$ and $G^*(t)$ as exogenously given. Some other papers, e.g. Sue Wing (2006) and Ricci (2007), assume spillovers in R&D flows whereas I assume that the spillover is due to knowledge stocks, which I think is more plausible. Finally, it the initial levels of the two stocks, K_0 and G_0, are given historically. Since the two types of capital are perfectly malleable in this model, K and G are summable.[4] As a normalization, assume that $K_0+G_0=1$.

Summarizing the model, the economy is characterized by CRS in the accumulable factors and will, therefore, grow at a constant rate. Conventional capital enhances output but pollutes the environment. Reductions of pollution are possible at some cost with an end-of-pipe clean-up technology, which is modeled only rudimentarily via a cost function. Alternatively, producers can invest in green capital, which is a substitute for conventional capital in production but does not pollute the environment. This green investment is tantamount to an

3 Jones (1995) assumes that R&D is done by labour, which is inelastically supplied in the economy, whereas I assume that R&D expenditure is a share of GDP.

4 Malleability is due to the fact that the rates of investment, $R_K(t)$ and $R_G(t)$, enter the budget constraint in a linear fashion. Thus, it is possible to turn capital of type K into capital of type G or vice versa in an instant by letting one rate of investment go to infinity and the other one to minus infinity.

investment in process-integrated pollution abatement – as opposed to end-of-pipe abatement. Knowledge spillovers across firms (but, as a simplification of the model, not across conventional and green R&D) generate externalities that require government intervention. Finally, perfect malleability ensures that the economy can jump to its steady-state capital allocation instantaneously at *t*=0 such that transitional dynamics do not have to be considered.

3 Solution of the Model

For the sake of notational brevity, I omit arguments of functions in much of the remainder of the paper as long as this does not cause ambiguities. The current-value Hamiltonian is

$$H = lnC + u(\varepsilon) + \xi[F(K,G) - C - (R_K + R_G)w - \chi(\varepsilon)K] + \alpha A(K,K^*,R_K) + \beta B(G,G^*,R_K)$$

and the first-order conditions are

$$C^{-1} = \xi , \tag{4}$$

$$\alpha A_R = \beta B_R = w\xi , \tag{5}$$

$$\dot{\alpha} = (\delta - A_K)\alpha - (F_K - \chi)\xi , \tag{6}$$

$$\dot{\beta} = (\delta - B_G)\beta - \xi F_G , \tag{7}$$

where subscripts denote partial derivatives multivariate functions and where the arguments of all functions have been omitted. I consider a balanced growth path with all time-dependent variables growing at the same rate. Due to the CRS assumption, all first derivatives in equations (5) to (7) are then constant. Establishing growth rates in equations (4) and (5) and using (5) to substitute for ξ in (6) and (7) yields

$$\hat{C} = A_K + w^{-1}A_R(F_K - \chi) - \delta = B_G + w^{-1}B_R F_G - \delta . \tag{8}$$

Equation (8) contains two standard results of economic growth theory. The first one is a variant of Ramsey's rule of optimum saving. The economy's growth rate equals the elasticity of intertemporal substitution (which is one in this model) times the marginal productivity of capital minus the discount rate. Here the marginal productivity of capital has two components since accumulation of capital does not only enhance production but also the future accumulation of capital. The second result is an indifference condition: the two types of capital are equally productive in the optimum.

Since all variables grow at the same rate along the balanced growth path, the ratios of the time-dependent variables are fixed. Define $c=C/K$, $g=G/K$, $r_K=R_K/K$, $r_G=R_G/G$, $k^*=K^*/K$, and $g^*=G^*/G$. Note that $k^*=g^*=1$ ex post. Moreover, from the properties of CRS functions, $f(g)\equiv F\left(1,\frac{K}{G}\right)=\frac{F(K,G)}{K}$, $a(k^*,r_K)\equiv A\left(1,\frac{K^*}{K},\frac{R_K}{K}\right)=\frac{A(K,K^*,R_K)}{K}$, and $b(g^*,r_K)\equiv B\left(1,\frac{G^*}{G},\frac{R_G}{G}\right)=\frac{B(G,G^*,R_K)}{G}$. Then, $A_R=a_r$, $A_K=a-a_{k^*}-r_K a_r$, $B_R=b_r$, $B_G=b-b_{g^*}-r_G b_r$, $F_G=f'$, and $F_K=f-gf'$. Using all this in equation (8), we get three conditions that determine the steady-state growth path (see the appendix for their derivation).

$$a(1,r_K)=b(1,r_G), \tag{9}$$

$$\left(r_G+\frac{\delta+b_{g^*}(1,r_G)}{b_r(1,r_G)}\right)w=f'(g), \tag{10}$$

$$\left(r_K+\frac{\delta+a_{k^*}(1,r_K)}{a_r(1,r_K)}\right)w=f(g)-gf'(g)-\chi(\varepsilon). \tag{11}$$

These equations determine g, r_G, and r_K.[5] Equation (9) states that G and K grow at the same rate. Equations (10) and (11) state that the marginal productivities of G and K (right-hand sides) equal the marginal cost of supplying G and K (left-hand sides), which is increasing in the cost of R&D, in the discount rate, and the non-internalized knowledge spillover and decreasing in the productivity of R&D in the creation of new capital. Due to malleability, firms can relocate capital instantaneously at time 0 such that the green-to-conventional-capital ratio, g, implied by equations (9) to (11) is valid from the beginning and there are no transitional dynamics. With the normalization $K_0+G_0=1$, the allocation of capital at time $t=0$ turns out to be

$$K(0)=\frac{1}{1+g} \quad \text{and} \quad G(0)=\frac{g}{1+g}. \tag{12}$$

---

[5] It is this step where the logarithmic utility function leads to considerable simplifications. Equations (10) and (11) would be more complex with an elasticity of intertemporal utility not equalling 1.

To derive the impact of environmental regulation on g, r_G, and r_K, totally differentiate equations (9) to (11):

$$\begin{pmatrix} a_r & -b_r & 0 \\ 0 & w\left(1+\frac{b_{g^*r}}{b_r}-(\delta+b_{g^*})\frac{b_{rr}}{b_r^{\,2}}\right) & -f'' \\ w\left(1+\frac{a_{k^*r}}{a_r}-(\delta+a_{k^*})\frac{a_{rr}}{a_r^{\,2}}\right) & 0 & gf'' \end{pmatrix}\begin{pmatrix} dr_K \\ dr_G \\ dg \end{pmatrix}=\begin{pmatrix} 0 \\ 0 \\ -\chi' d\varepsilon \end{pmatrix}$$

and the comparative statics of the steady state are

$$\frac{dr_K}{d\varepsilon}=\frac{-b_r\chi'/w}{\left(1+\frac{a_{k^*r}}{a_r}-(\delta+a_{k^*})\frac{a_{rr}}{a_r^{\,2}}\right)b_r+\left(1+\frac{b_{g^*r}}{b_r}-(\delta+b_{g^*})\frac{b_{rr}}{b_r^{\,2}}\right)ga_r}<0, \tag{13a}$$

$$\frac{dr_G}{d\varepsilon}=\frac{-a_r\chi'/w}{\left(1+\frac{a_{k^*r}}{a_r}-(\delta+a_{k^*})\frac{a_{rr}}{a_r^{\,2}}\right)b_r+\left(1+\frac{b_{g^*r}}{b_r}-(\delta+b_{g^*})\frac{b_{rr}}{b_r^{\,2}}\right)ga_r}<0, \tag{13b}$$

$$\frac{dg}{d\varepsilon}=\frac{-\left(1+\frac{b_{g^*r}}{b_r}-(\delta+b_{g^*})\frac{b_{rr}}{b_r^{\,2}}\right)\frac{a_r\chi'}{f''}}{\left(1+\frac{a_{k^*r}}{a_r}-(\delta+a_{k^*})\frac{a_{rr}}{a_r^{\,2}}\right)b_r+\left(1+\frac{b_{g^*r}}{b_r}-(\delta+b_{g^*})\frac{b_{rr}}{b_r^{\,2}}\right)ga_r}>0 \tag{13c}$$

Stricter environmental standards induce declines in the steady-state rates of investment in both conventional and green capital (equations (13a,b)), but the share of green capital in total capital rises (equation (13c)). Given that a change in ε will induce an instantaneous shift in the composition of capital at time 0, we have that $G(0)$ will rise whereas $K(0)$ will be reduced according to equations (12). Translated into the real world, where perfect malleability does not exist, the implication is that stricter environmental regulation tends to induce additional green R&D in the short run, but generally reduces the rate of innovation in the longer term. The latter implies that the steady-state economic growth rate is negatively affected by stricter environmental policy: $da/d\varepsilon = db/d\varepsilon < 0$. This confirms Ricci's (2007) finding.

The economic intuition behind the results is straightforward. Tighter environmental standards raise the cost of using conventional capital and it is therefore substituted by green capital such that g is increased. The higher cost of using conventional capital reduces the incentive to accumulate this capital in the longer term. Due to the shift from conventional to green capital, the marginal productivity of green capital is reduced ($f''<0$) and this reduces the incentive to invest in this type of capital as well.

r_K and r_G measure rates of investment related to the corresponding capital stocks, e.g. number of new patents as a share of the cumulative number of patents. Alternatively, one might wish to look at R&D expenditure as a share of GDP. The following three equations present the effects of stricter environmental regulation on the R&D expenditure shares of K-type and G-type capital and on the share of end-of-pipe abatement cost in GDP, respectively.

$$\frac{d(wr_K/f)}{d\varepsilon}=\frac{w}{f}\left(\frac{dr_K}{d\varepsilon}-r_K\frac{f'}{f}\frac{dg}{d\varepsilon}\right)<0, \tag{14a}$$

$$\frac{d(wgr_G/f)}{d\varepsilon}=\frac{w}{f}\left(g\frac{dr_G}{d\varepsilon}+r_G\left(1-\frac{gf'}{f}\right)\frac{dg}{d\varepsilon}\right), \tag{14b}$$

$$\frac{d(\chi/f)}{d\varepsilon}=\frac{\chi}{f}\left(\frac{\chi'}{\chi}-\frac{f'}{f}\frac{dg}{d\varepsilon}\right). \tag{14c}$$

Equation (14a) shows that the share of GDP spent on conventional R&D will unambiguously decline. The effects on the GDP shares of green R&D and end-of-pipe abatement are ambiguous. How resources are allocated to end-of-pipe abatement versus integrated technology, depends on the parameters of the model, in particular on the productivity of green capital and on the cost of using end-of-pipe technologies. The ratio of green capital to resources spent on end-of-pipe abatement is

$$\frac{d(g/\chi)}{d\varepsilon}=\frac{1}{\chi}\left(\frac{dg}{d\varepsilon}-\frac{g\chi'}{\chi}\right)=-\frac{\chi' f}{gf''\chi^2}\left(\gamma\frac{\chi}{f}+\frac{gf''}{f'}\frac{gf'}{f}\right), \tag{14d}$$

with $\gamma\in(0,1)$ being defined in the appendix. It is seen that a shift from end-of-pipe to process-integrated abatement is likely if the cost of end-of-pipe abatement measured as a share of GDP is high, if the elasticities $|gf''/f'|$ and gf'/f are small and (from closer inspection of γ) if the spillovers in green R&D are large and those in conventional R&D are small.

4. Welfare Effects and Second-Best Environmental Policy

Given the fact that there are two knowledge spillovers and an environmental externality in the model, the government would need three instruments to achieve the first-best optimum: two subsidies to improve the incentives to do conventional and green R&D and an environmental standard to deal with the environmental externality. However, I will initially look at a second-best world in which environmental regulation is the only policy variable. The first best will be addressed afterwards. The second best is interesting not only from a theoretical viewpoint, it is also very relevant from a policy perspective. An argument often made in favour of strict environmental policies is that they spur R&D and accelerate innovation. However, this makes sense only if the appropriate instruments, which support R&D and innovation directly, are not or not sufficiently used.

Given the economy's constant growth rate, $a(1,r_K)= b(1,r_G)$, the utility function can be rewritten (details in the third part of the appendix)

$$\int_0^\infty e^{-\delta t}\left(ln\,C(t)+u(\varepsilon)\right)dt=\frac{a(1,r_K)}{\delta^2}+\frac{u(\varepsilon)+ln\,c-ln(1+g)}{\delta},$$

where (12) was used to substitute $(1+g)^{-1}$ for $K(0)$. The consumption-to-capital ratio, c, is determined via equation (1) such that

$$c=f(g)-(r_K+gr_G)w-\chi(\varepsilon), \tag{15}$$

and by using (10) and (11), we have

$$c=w\left(\frac{\delta+a_{k*}(1,r_K)}{a_r(1,r_K)}+g\frac{\delta+b_{g*}(1,r_G)}{b_r(1,r_G)}\right), \tag{15'}$$

According to (15'), the consumption-to-capital ratio is increasing in the discount rate and in the non-internalized technology spillovers. This is an expected result: the lack of internalization of the positive R&D externality will make the economy more myopic. It is also intuitive that an increase in the R&D productivities a_r and b_r makes the economy shift resources from consumption to R&D expenditure and thereby lowers c. By similar reasoning the positive impact of the direct cost of R&D effort, w, on c appears plausible. The effect of tighter environmental regulation on c is ambiguous.

Inserting (15) into the welfare function, taking the derivative with respect to ε, and using equations (10), (13a), (13b), and (15') to simplify terms where appropriate (details in the appendix), we have

$$Cu' = \chi' K + \frac{wK}{1+g}\left(\frac{\delta + a_{k*}}{a_r} - \frac{\delta + b_{g*}}{b_r}\right)\frac{dg}{d\varepsilon} + \frac{\chi' K}{\Delta\delta}\left(b_r a_{k*} + g a_r b_{g*}\right). \tag{16}$$

where $\Delta>0$ is the denominator of the comparative-statics expressions in equations (13a) to (13c) and $dg/d\varepsilon$ is given by equation (13c). Condition (16) contains several terms that are familiar from environmental economics. Noting that $1/C$ is the marginal utility of consumption, $Cu'(\varepsilon)$ on the left-hand side is the marginal rate of substitution between environmental quality and consumption, i.e. the marginal environmental damage. In a static world without R&D directed at cleaner technologies, it would equal the marginal cost of end-of-pipe abatement. This is the first term on the right-hand side of equation (16), $\chi' K$. The remainder of equation (16) contains effects of knowledge spillovers and of costs of developing cleaner integrated technologies. Let us divide by K and take $cu'=\chi'$ as a benchmark. This case is depicted in Figure 1 by solid lines, the marginal abatement cost increasing and the marginal environmental damage declining in ε (and, thus, increasing in pollution). Additional terms on the right-hand side of equation (16) shift the χ' line either upwards or downwards. The dotted

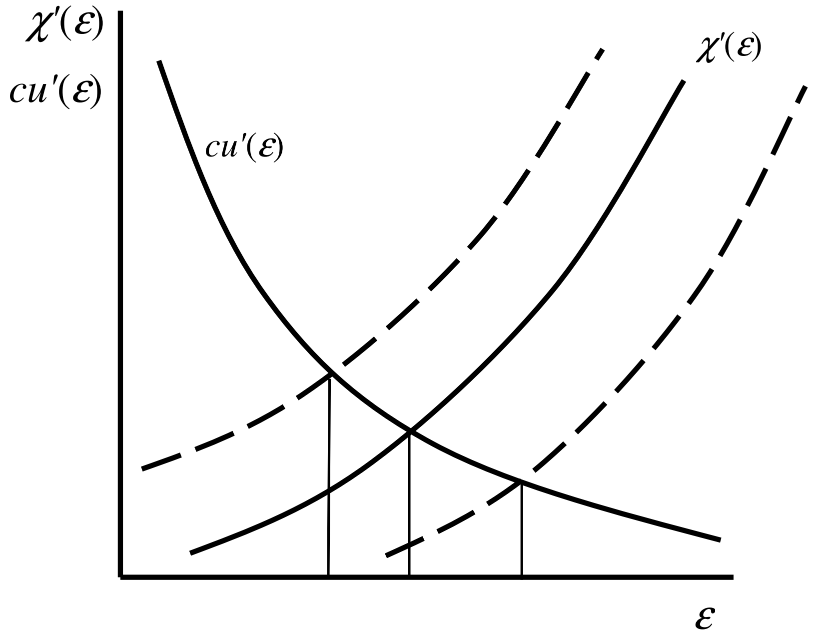

Figure 1: Marginal environmental damage and marginal abatement cost

lines in Figure 1 show that upward shifts imply laxer environmental regulation and that downward shifts imply an increase of ε. Let us start from the last term on the right-hand side of equation (16). It is positive and vanishes only in the absence of knowledge spillovers. This term contains the growth component of the R&D externalities. Without internalization, the income share spent on R&D is too low, the economic growth rate is too low as well and, as the first-best instruments are not available, the optimum response is to relax environmental regulation. The second term on the right-hand side of equation contains the composition effect arising from the relocation of capital from type *K* to type *G*. It is increasing in the direct cost of R&D effort, *w*, and in the discount rate, it contains the productivities of conventional and green R&D, a_r and b_r, respectively, and it contains the spillovers a_{k*} and b_{g*}. Everything else being equal, an increase in a_{k*} will induce an upward shift in the χ' line and induce a reduction in ε, whereas an increase in b_{g*} shifts the curve downwards and leads to stricter environmental standards.[6] In the case of highly asymmetric spillovers with $b_{g*} \gg a_{k*}$, the optimum environmental regulation may be stricter than in the benchmark scenario where the environmental standard addresses the environmental externality only. The underlying reason is that a market economy under laisser faire does not generate enough green capital. A stricter environmental standard induces the desired shift from *K* to *G*, albeit at the cost of lowering the economic growth rate.

The results derived from condition (16) can be summarized as follows:

- Large knowledge spillovers in general reduce growth and make firms behave too myopically. In order to correct for this and to boost economic growth, the environmental standard should be relaxed.

- If the *G* spillover is large compared to the *K* spillover, this leads to unfavourably low stocks of green capital. The desirable shift from conventional to green capital can be achieved by stricter environmental standards than in the benchmark case.

In general, the combined effect is ambiguous. Optimal environmental standards may be stricter or laxer than those internalizing the pure environmental externality. Although both scenarios are theoretically feasible, the case of tighter standards is probably less relevant in practice. It requires that spillovers are highly asymmetric, the green sector being subject to

---

6 Note that $dg/d\varepsilon$ contains spillover terms, too. Closer inspection of equation (13c) reveals that $dg/d\varepsilon$ is increasing in b_{g*} and decreasing in a_{k*}. These additional effects may reinforce or mitigate those originating from the occurrence of the spillover terms in the expression in brackets in front of $dg/d\varepsilon$.

substantial cross-fertilization amongst firms whereas spillovers are small to negligible in the conventional sector. Otherwise, the growth effect will dominate and result in laxer environmental standards.

5. The First-Best Policy

A first-best policy uses three instruments to address the three externalities prevailing in this model. Assume that subsidies are paid to firms for the accumulation of conventional and green capital, the subidy rates being s_K and s_G, respectively. The optimality conditions (10) and (11) are changed slightly by adding s_G and s_K on the right-hand sides of equation (10) and (11), respectively. The optimum subsidy rates are

$$s_G = \frac{b_{g*}}{b_r}, \tag{17}$$

$$s_K = \frac{a_{k*}}{a_r}. \tag{18}$$

Inspection of the comparative statics shows that both subsidies raise the R&D rates and, thus, the rate of economic growth as well. This confirms the result obtained by See Balcão Reis/ Cunha-e-Sá/Leitão (2008). If the positive knowledge externalities are large and the negative environmental externality is small, then the optimally managed economy grows at a larger rate than the laisser-faire economy. If, however, the environmental externality dominates the knowledge spillover, the result is reversed.

The environmental regulation in the first-best optimum is determined by

$$Cu' = \chi' K + \frac{\delta w K}{1+g}\left(\frac{1}{a_r} - \frac{1}{b_r}\right)\frac{dg}{d\varepsilon}, \tag{19}$$

which is condition (16) without the knowledge-spillover terms. The first term on the right-hand side is clear, the second one still deserves an explanation. It measures the intertemporal component of marginal abatement cost, which arises from the change in capital allocation induced by a change in environmental policy. For the interpretation of the term in brackets, remember that the factor price frontier, known from neoclassical production theory, establishes a negative relationship between the marginal productivities in a CRS production function. This implies that the marginal productivities of accumulated capital of type K and type G (including the productivity effect of the spillover) in the generation of new knowledge are increasing in the inverse R&D productivities, $1/a_r$ and $1/b_r$, respectively. Thus, the term in brackets is positive (negative) if $A_K+A_{K^*}$ is large (small) compared to $B_G+B_{G^*}$. Everything else being equal, the marginal cost of abatement is large if conventional capital is very productive in the generation of new conventional capital and it is small if green capital is very productive in the generation of new green capital In the former case the optimum environmental standard should be lax; in the latter case it should be strict.

6. Summary

The investigation of this simple endogenous-growth model has produced the following insights

- Conventional capital tends to be replaced by green capital if environmental standards are tightened.
- In the short run, tighter environmental standards foster green R&D.
- In the long-run steady-state, R&D rates are reduced by tighter environmental standards, both for conventional as well as for green capital.
- The steady-state growth rate of the economy is declining in tighter environmental standards.
- End-of-pipe abatement tends to be replaced by process-integrated abatement if its cost is high and if green R&D is subject to substantial knowledge spillovers compared to conventional R&D.
- A second-best optimum environmental policy that takes knowledge spillovers into account is likely to be too lax compared to the benchmark of marginal damage equals marginal abatement cost. The converse is theoretically possible if green R&D is subject to substantially larger positive externalities than conventional R&D.
- The first-best policy combines subsidization of capital accumulation with an environmental standard that equates marginal environmental damage and marginal abatement cost. The marginal abatement cost includes an intertemporal component which is small if the productivity of green capital in the generation of new green capital is large

and large if the productivity of conventional capital in the generation of new conventional capital is large.

Coming back to the question posed in the beginning, this model does not support the dynamic version of Porter's hypothesis. Everything else being equal, tighter environmental standards retard rather than accelerate long-term economic growth despite potentially substantial spillovers in the green R&D sector. This is like in Ricci's (2007) paper. In general, it seems difficult to construct models of directed technical change such that the balanced growth rate of the economy is increased by tighter environmental regulation. For a special modelling strategy, see Hart (2007), but also Ricci's (2007) critique of Hart's approach.[7] As an alternative, one might think of models with non-balanced growth paths, in which substantial knowledge spillovers in the green sector drive the economy's R&D and its long-term growth while the share of conventional capital goes to zero. This may be an interesting road of future research in theoretical environmental economics, but is an open question whether such a dominance of green capital over conventional capital is realistic. On the empirical side, it would be interesting to test other predictions of this paper, particularly those concerning the crowding out of conventional by green R&D and about the expenditure shares going into green R&D versus end-of-pipe abatement. Given the limited availability of data and the problem to distinguish process-integrated from end-of-pipe abatement in practice, existing studies like Frondel/Horbach/Rennings (2007) had to be more moderate in their ambitions. With better data, however, theory-driven empirical research might in the future further enhance our understanding of the forces that drive environmental innovation and the policy instruments suitable to supporting them.

7 Of course, one can get higher growth rates from stricter environmental standards if environmental quality has a positive impact on factor productivities, but this is not the Porter hypothesis.

References

Acemoglu, D, 2002, Directed Technical Change, Review of Economic Studies 69, 781-809.

Acemoglu, D., F. Zilibotti, 2001, Productivity Differences, Quarterly Journal of Economics 116, 563-606.

Balcão Reis, A., M.A. Cunha-e-Sá, A Leitão, 2008, Growth, Innovation and Environmental Policy: Clean vs. Dirty Technical Change, Paper presented at the 2nd Annual Meeting of the Portuguese Economic Journal.

Brock W.A., S.M. Taylor, 2004, The Green Solow Model, Cambridge, MA: NBER Working Paper 10557.

Frondel, M., J. Horbach und K. Rennings, 2007, End-of-Pipe or Cleaner Production? An Empirical Comparison of Environmental Innovation Decisions across OECD Countries, Business Strategy and the Environment 16, 571-584

Grimaud, A., L. Rouge, 2008, Environment, Directed Technical Change and Economic Policy, Environmental and Resource Economics 41, 439-463.

Guvenen, F., 2006, Reconciling Conflicting Evidence on the Elasticity of Intertemporal Substitution: A Macroeconomic Perspective, Journal of Monetary Economics 53, 1451-1472

Hall, R.E, 1988, Intertemporal Substitution in Consumption, Journal of Political Economy 96, 339-357.

Hart, R., 2007, Can Environmental Regulations Boost Growth?, in L. Bretschger, S. Smulders, eds, Sustainable Resource Use and Economic Dynamics, Dordrecht: Springer, 53-71.

Jones, C.I., 1995, R&D-Based Models of Economic Growth, Journal of Political Economy, 103, 759-784.

Porter, M.E., 1991, America's Green Strategy, Scientific American, 264 (4), 168.

Porter, M.E., van der Linde, C., 1995, Toward a New Conception of the Environment-Competitiveness Relationship, Journal of Economic Perspectives 9 (4), 97-118.

Ricci, F., 2008, Environmental Policy and Growth when Inputs Are Differentiated in Pollution Intensity, Environmental and Resource Economics 37, 285-310.

Sue Wing, I, 2006, Representing Induced Technological Change in Models for Climate Policy Analysis, Energy Economics 28, 539-562.

Appendix

Some results in this paper are a bit cumbersome to be derived. Here are derivations step by step.

A.1 Derivation of Equations 9 and 10

The starting point is equation (8).

$$\hat{C} = A_K + w^{-1} A_R (F_K - \chi) - \delta = B_G + w^{-1} B_R F_G - \delta . \tag{8}$$

Note that $\hat{C} = A / K = B / G$ because of equal growth rates and rewrite (8) such that

$$\frac{B}{G} = B_G + w^{-1} B_R F_G - \delta ,$$

$$\frac{A}{K} = A_K + w^{-1} A_R (F_K - \chi) - \delta .$$

Moving to lower-case letters for functions in intensive form, we have

$$b = b - b_{g*} - r_G b_r + w^{-1} b_r f' - \delta ,$$

$$a = a - a_{k*} - r_K a_r + w^{-1} a_r (f - gf' - \chi) - \delta .$$

Rearranging terms gives (10) and (11).

A 2 Derivation of Equation (14d)

Taking the derivative of g/χ with respect to ε yields

$$\frac{d(g/\chi)}{d\varepsilon} = \frac{1}{\chi}\left(\frac{dg}{d\varepsilon} - \frac{g\chi'}{\chi}\right).$$

Define

$$\gamma = \frac{1+\frac{b_{g^*r}}{b_r}-\left(\delta+b_{g^*}\right)\frac{b_{rr}}{b_r^{\,2}}}{1+\frac{b_{g^*r}}{b_r}-\left(\delta+b_{g^*}\right)\frac{b_{rr}}{b_r^{\,2}}+\left(1+\frac{a_{k^*r}}{a_r}-\left(\delta+a_{k^*}\right)\frac{a_{rr}}{a_r^{\,2}}\right)\frac{b_r}{ga_r}} .$$

and replace $\frac{dg}{d\varepsilon}$ by $-\frac{\gamma\chi'}{gf''}$.

$$\frac{d(g/\chi)}{d\varepsilon}=\frac{1}{\chi}\left(-\frac{\gamma\chi'}{gf''}-\frac{g\chi'}{\chi}\right)=-\frac{\chi'}{\chi^2 gf''}\left(\gamma\chi+g^2 f''\right)=-\frac{\chi' f}{\chi^2 gf''}\left(\gamma\frac{\chi}{f}+\frac{gf''}{f'}\frac{gf'}{f}\right).$$

A3 Derivation of Equation 16

We start from welfare:

$$\int_0^\infty e^{-\delta t}\left(ln\,C(t)+u(\varepsilon)\right)dt=\int_0^\infty e^{-\delta t}\left(at+ln\,C(0)+u(\varepsilon)\right)dt=\frac{a}{\delta^2}+\frac{u(\varepsilon)+ln\,c+ln\,K(0)}{\delta}.$$

Note that $\int_0^\infty at\,e^{-\delta t}dt=a/\delta^2$, which follows from partial integration (or from looking into a comprehensive mathematics formulary). Using $K(0)=(1+g)^{-1}$ and $c=f(g)-(r_K+gr_G)w-\chi(\varepsilon)$, utility can be rewritten as

$$\int_0^\infty e^{-\delta t}\left(ln\,C(t)+u(\varepsilon)\right)dt=\frac{a(1,r_K)}{\delta^2}+\frac{u(\varepsilon)+ln\left(f(g)-(r_K+gr_G)w-\chi(\varepsilon)\right)-ln(1+g)}{\delta}.$$

Differentiating with respect to ε, setting the result equal to zero and multiplying by δ yields

$$u'+\frac{1}{c}\left((f'-r_G w)\frac{dg}{d\varepsilon}-w\frac{dr_K}{d\varepsilon}-wg\frac{dr_G}{d\varepsilon}-\chi'\right)+\frac{a_r}{\delta}\frac{dr_K}{d\varepsilon}-\frac{1}{1+g}\frac{dg}{d\varepsilon}=0.$$

Multiply by c and rearrange terms:

$$cu' = \chi' + \left(\frac{c}{1+g} - \left(f' - r_G w \right) \right) \frac{dg}{d\varepsilon} + \left(w - \frac{c a_r}{\delta} \right) \frac{dr_K}{d\varepsilon} + wg \frac{dr_G}{d\varepsilon} .$$

From (13a) and (13b), we can use $\frac{dr_K}{d\varepsilon} = \frac{-b_r \chi' / w}{\mathit{\Delta}}$ and $\frac{dr_G}{d\varepsilon} = \frac{-a_r \chi' / w}{\mathit{\Delta}}$, where $\mathit{\Delta}$ is used to replace the bulky term in the numerators of equations (13a) and (13b). Moreover, we can use (10) to substitute for (f'-$r_G w$):

$$cu' = \chi' + \left(\frac{c}{1+g} - \frac{w\left(\delta + b_{g*}\right)}{b_r} \right) \frac{dg}{d\varepsilon} - \left(1 - \frac{c a_r}{\delta w} \right) \frac{b_r \chi'}{\mathit{\Delta}} - g \frac{a_r \chi'}{\mathit{\Delta}} .$$

Now use (15') to substitute for c on the right-hand side

$$cu' = \chi' + \frac{w}{1+g} \left(\frac{\delta + a_{k*}}{a_r} + g \frac{\delta + b_{g*}}{b_r} - (1+g) \frac{\delta + b_{g*}}{b_r} \right) \frac{dg}{d\varepsilon} + \left(\left(\frac{\delta + a_{k*}}{a_r} + g \frac{\delta + b_{g*}}{b_r} \right) \frac{a_r}{\delta} - 1 \right) \frac{b_r \chi}{\mathit{\Delta}} - g \frac{a_r \chi}{\mathit{\Delta}} .$$

Collecting and rearranging terms then yields

$$cu' = \chi' + \frac{w}{1+g} \left(\frac{\delta + a_{k*}}{a_r} - \frac{\delta + b_{g*}}{b_r} \right) \frac{dg}{d\varepsilon} + \frac{\chi'}{\mathit{\Delta}\delta} \left(b_r a_{k*} + g a_r b_{g*} \right).$$

Finally multiply by K to obtain (16) with Cu' on the left-hand side.