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Environmental Policy and Competitiveness: The Porter Hypothesis and the Composition of Capital[1]

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The Porter hypothesis suggests a win–win situation in the sense that environmental policy improves both environment and competitiveness. The suggestion received strong criticism from economists driven by the idea that if opportunities exist, firms do not have to be triggered by an extra cost. In this paper a model is developed which confirms this point but which also draws attention to some general mechanisms that relax the trade-off considerably. Downsizing and modernization of firms subject to environmental policy will increase average productivity and will have positive effects on the marginal decrease of profits and environmental damage. © 1999 Academic Press

1. INTRODUCTION

In an article that attracted the attention of both economists and policymakers, Porter [9] challenged the established notion that tough environmental policies imply private costs that harm the competitiveness of a country's industry, by claiming precisely the opposite. For policymakers (e.g., Gore [5]) this idea of a possible "win–win" option was like manna from heaven, because it relieved them of the difficult trade-off between environmental and other economic targets. Economists, however, are by nature sceptical about the idea of a "free lunch," and some also critized this so-called "Porter hypothesis" in the sense that attention is distracted from the cost-benefit analysis of environmental policy, which is in their view the most important issue (e.g., Palmer, Oates, and Portney [8]).

In short Porter's argument is that tough environmental regulation in the form of economic incentives can trigger innovation that may eventually increase a firm's competitiveness and may outweigh the short-run private costs of this regulation.

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His argument is mainly supported by a large number of case studies where firms under strict environmental regulation prove to be very successful (see, e.g., Porter and van der Linde [10]).

Empirical studies on competitiveness in the meaning of changes in the trade and investment patterns (e.g., Kalt [7], Tobey [13], Jaffe *et al*. [6]) do not find a significant adverse effect of more stringent environmental policies. The existing data are of course limited in their ability to measure the stringency of regulation but possible explanations mentioned are that the compliance costs are only a small fraction of total costs of production, that stringency differentials are small, and that investments follow the current state-of-the-art in technology even if this is not required by the environmental regulation in that country.

In the discussion following the appearance of the Porter hypothesis a number of attempts have been made to identify the mechanisms that can lead to a mitigation of the cost effect of environmental policy or can even lead to a win–win situation. The dominant argument is that firms are not aware of certain opportunities and that environmental policy might open the eyes. The revenues of these opportunities can then outweigh the costs of compliance. One line of thought is that the external shock through environmental regulation may reduce intrafirm inefficiencies and organizational failures (see, e.g., Gabel and Sinclair-Desgagné [4]), and may move the firm toward its production possibility frontier: the X-efficiency argument. A second idea is that firms create a first-mover advantage by the development of environmental technology which can be beneficial in later times when other countries also adopt a more stringent environmental policy. The standard counterargument is, of course, that in rational economic modelling it cannot be explained why firms do not see these opportunities by themselves, which at least implies that the argument does not have a general validity. It can be the case that innovation with the aim to reduce environmental pollution also lowers production costs and can therefore even be beneficial without considering environmental costs. For a rational firm, however, the conclusion must be that environmental policy is then not needed to trigger this innovation. The only arguments that remain in this discussion are the possibility of positive externalities of the additional R & D and the reduction of uncertainty to the firms about policy trends.

In the context of strategic trade models, where consumption takes place in a third country, increased competitiveness means a shift of profits from the foreign firm to the home firm. In a two-stage model where firms invest in R & D first and then choose output, it is possible to construct specific examples in which foreign R & D decreases and home profits increase under an environmental tax, but again this result has definitely no general validity (Simpson and Bradford III [12]). On the contrary, the basic story remains that governments have an incentive to distort the environmental tax downward from the Pigouvian level in order to lower the costs of the home firm and to shift profits to the home firm (Barrett [1], Ulph [14]), which is sometimes referred to as "ecological dumping" (e.g., Rauscher [11]).

The purpose of this paper is to explore the validity of the Porter hypothesis by considering firms' reactions with respect to both the type and the quantity of equipment in which they invest in response to changes in the production costs. First it is shown that an increase in production costs, brought about by environmental policy, triggers a restructuring of the capital stock in such a way that average productivity increases.[2] This can already be considered as an improvement of the competitiveness of the industry (Porter and van der Linde [10]), so that this part of the paper gives a formal basis to that point. It is, however, more interesting to see what happens to net profits, which is the focus of the second part of the paper. The analysis in the paper is based on a model where firms invest in machines of different ages. Younger machines are more productive and less polluting than older machines, but are more costly to buy and to install in the capital stock. Stricter environmental regulation, in the form of an increase in the emission tax, will reduce the number of machines of all ages and therefore the size of the firm. However, the same tax increase generally also reduces the average age of the capital stock and thus increases its productivity. It follows that two effects can be distinguished: a "downsizing" effect and a "modernization" effect. Downsizing refers to the reduction of the total capital stock.[3] Modernization refers to the reduction of the average age of this capital stock. Environmental regulation accelerates the removal of older machines from the capital stock which increases its productivity.[4] It is important to note here that in the actual practice of environmental policy, existing capital is often exempted from the new and stricter regulation. The effects analysed in this paper then only occur for the ages of the capital stock on which the higher tax is levied. As a consequence, modernization is less than in case all ages of the capital stock are subject to environmental regulation (e.g., Ellerman [3]).

The extra tax burden and the shift in investments and output are not profitable for the firm. This cost of environmental regulation is, however, mitigated by three effects: downsizing leads to an upward pressure on prices, modernization leads to a higher productivity of the capital stock, and downsizing and modernization together lead to lower emissions, so that an environmental target can be reached with a lower tax than in the absence of this effect. In this paper a situation with homogeneous capital, where only downsizing occurs, is compared to a situation with heterogeneous capital, where also modernization occurs. It is shown that the marginal decrease in profits is lower and the marginal decrease in emissions is higher in the second situation.

The implication for the debate on the Porter hypothesis is not that a win−win situation can be expected, but the trade-off between improving the environment and the competitiveness of the home industry is not as grim as it is sometimes suggested because of favourable changes in the composition of the capital stock.

Section 2 presents the basic model and Section 3 derives the optimal age distribution of the machines. In Section 4 the effects of an emission tax on productivity, profits, and emissions are given and a comparison is made with the case of homogeneous capital. Section 5 concludes the paper.

[2] A better environment will also have a positive effect on the productivity of other factors through clean air, clean water, improved health and so on, but this aspect will not be considered here.

[3] It is interesting to note here that Nabisco chairman and chief executive J. Greeniaus, when announcing the firm's downsizing, stated that it "was necessary to improve the company's competitive position and to accelerate 'strong sustainable earning growth' in the next century" (Financial Times, June 25, 1996).

[4] Environmental regulations in the 1970s unintentionally accelerated the modernization of the U.S. steel industry, although this does not mean that the premature scrapping of "obsolete" capital is socially beneficial, because such plants were presumably producing output whose value exceeded variable production costs (Jaffe *et al.* [6], based on U.S. Office of Technology Assessment [15]).

2. THE MODEL

Consider a firm that can invest in machines of different ages. Let $y \in [0, h]$ denote the age of the machine and introduce the following notation:

$v(y)$ is the output produced by a machine of age y, with $v'(y) \leq 0$. That is, a newer machine cannot produce less output than an older machine. New machines are more productive because they embody superior technology.

$c(y)$ is the running cost of a machine of age y, $c'(y) \geq 0$.

$s(y)$ are emissions of a machine of age y, $s'(y) \geq 0$. Older machines emit at least as much as newer machines. This might be the result of a natural deterioration in the condition of the machine with the passage of time, and/or the result of cleaner technologies being embodied in the new machines.

Let $x(t, y)$ be the number of machines of age y operating in year t. Then total output produced in year t is defined as

$$Q(t) = \int_0^h v(y)x(t, y)\, dy.$$

Assume that the firm has to pay an emission tax τ per unit emissions. Then the cost of running one machine is: $c(y) + \tau s(y)$. Therefore total running costs for year t are defined as

$$C(t) = \int_0^h [c(y) + \tau s(y)]x(t, y)\, dy.$$

In practice existing capital is often exempted from new and stricter environmental regulation. In the model this would imply that the tax τ is not levied on capital up to the maximum age h, which is analysed in this paper, but only on capital up to the age $k < h$. As a result, the downsizing and modernization effects, which are shown later on, only occur for that part of the capital stock. In a world with new source performance standards, $k = 0$ and the analysis in this paper breaks down. If $k > 0$ the effects will be there but will be smaller, and the older capital will not be affected. It follows that the results of this paper only apply to regulatory institutions where an emission tax is levied on all polluters or at least on the pollution of some part of the existing capital stock. The last situation occurs, for example, when regulations put a cap on the amount of money a firm may be required to spend to come into compliance with a new standard. Because the size of the necessary expenditure is usually correlated with the age of the capital stock, this cap in fact implies that capital above a certain age is exempted from the new regulation. The previous model can be used, but the age h should then be interpreted as the maximum age of machines on which the emission tax τ is actually levied. Finally, note that in practice economic incentive approaches to environmental regulation (primarily taxes and tradable permits) are gradually being adopted, so that an analysis based on an emission tax fits well with this development.

We assume that markets exist for machines of any age from 0 to h. This is a strong assumption but it is somewhat relaxed by introducing a capital adjustment cost later on. Let $b(y)$ be the cost of buying a machine of age y, with $b'(y) \leq 0$ (older machines cannot be more expensive than newer machines) and $b(h) = 0$ (a machine at the maximum age h is not worth anything). For the analysis in this paper it is assumed that the cost b of a used machine is given and that this cost does not depend on the other parameters of the model and the emission tax τ. In fact, none of the parameters of the model depends on the emission tax τ so that the firm can only react to the tax by adjusting the composition of the capital stock, which is the focus of this paper.

Let $u(y,t)$ be the number of machines of age y bought (if $u(y,t) > 0$) or sold (if $u(y,t) < 0$) in year t. The total cost or revenue to the firm from transactions in the machine market is defined as $b(y)u(y,t) + \frac{1}{2}[u(y,t)]^2$, with the second term reflecting the adjustment costs in buying or selling machines. These costs are, for example, adaptation costs or search costs. The quadratic form of this cost term leads to a simple expression for optimal purchases which is needed in order to make the rest of the analysis tractable.

The firm chooses to buy or to sell machines of different ages in order to maximize profits, with p the price of output. That is, the firm chooses at each point in time an age distribution of machines to maximize profits,[5]

$$\max_{\{u(t,y)\}} \int_0^\infty \int_0^h \big[pv(y)x(t,y) - [c(y) + \tau s(y)]x(t,y) - \big[b(y)u(t,y) + \tfrac{1}{2}u^2(t,y)\big]\big]\, dy\, dt$$

$$\text{subject to } \frac{\partial x(t,y)}{\partial t} = -\frac{\partial x(t,y)}{\partial y} + u(t,y),$$

$$x(0,0) = 0,\ x(t,y) \geq 0,\ \forall t, y. \tag{1}$$

This is an infinite horizon optimal control problem with transition dynamics described by a linear partial differential equation (Carlson, Haurie, and Leizarowitz [2]). The transition equation indicates that the rate of change in the number of machines of a given age, y, is determined by two factors. These are the reduction in the number of machines of that age as machines become older (the first term of the transition equation), and the reduction or increase in the number of machines brought about by the sale or acquisition of machines of the given age y (the second term of the transition equation). The number of machines of each age at each time has to be nonnegative, while the initial condition on the number of machines implies that the firm starts with no new machines in the capital stock.

The generalized Hamiltonian function for this problem is given as

$$H = pv(y)x(t,y) - [c(y) + \tau s(y)]x(t,y) - \big[b(y)u(t,y) + \tfrac{1}{2}u^2(t,y)\big] + \lambda(t,y)\left[-\frac{\partial x(t,y)}{\partial y} + u(t,y)\right].$$

[5]We take a discount rate equal to zero because the analysis would otherwise become more complex without adding anything to the purpose of this paper.

The first-order conditions for optimality, besides the transition dynamics in (1), are

$$\frac{\partial H}{\partial u} = 0, \quad \text{or} \quad u(y,t) = \lambda(y,t) - b(y),$$

$$\frac{\partial \lambda(y,t)}{\partial t} = -\frac{\partial H}{\partial x} + \frac{\partial}{\partial y}\frac{\partial H}{\partial x_y}, \qquad x_y = \frac{\partial x}{\partial y},$$

or

$$\frac{\partial \lambda(y,t)}{\partial t} = -pv(y) + [c(y) + \tau s(y)] - \frac{\partial \lambda(y,t)}{\partial y}.$$

In order to obtain tractable analytical results from the preceding optimality conditions, we consider the firm at the steady state, in which case $\partial x/\partial t = 0$ and $\partial \lambda/\partial t = 0$. By suppressing t and then denoting $\partial \lambda/\partial y = \dot{\lambda}$, and $\partial x/\partial y = \dot{x}$, the optimality conditions at the steady state can be written as

$$u(y) = \lambda(y) - b(y), \tag{2}$$

$$\dot{\lambda}(y) = -pv(y) + [c(y) + \tau s(y)], \tag{3.1}$$

$$\dot{x}(y) = u(y). \tag{3.2}$$

The optimality conditions corresponding to the steady state are equivalent to the optimality conditions of the optimal steady-state problem (OSSP) associated with problem (1). The OSSP is defined (Carlson, Haurie, and Leizarowitz [2]) as

$$\max_{\{u(y)\}} \int_0^h \Big[pv(y)x(t,y) - [c(y) + \tau s(y)]x(t,y) - \big[b(y)u(t,y) + \tfrac{1}{2}u^2(t,y)\big]\Big]\, dy$$

$$\text{subject to } \dot{x}(y) = u(y), \qquad x(0) = 0, \qquad x(y) \geq 0, \forall y.$$

The OSSP problem is an optimal control problem defined over ages $y \in [0, h]$, with as state variable the number of machines of a given age and as control variable the sales or acquisitions of machines of this same age. The OSSP problem can be thought of as a situation where the firm chooses the optimal age distribution of the machines in steady state, which results from some exogenous shock.

In our model the exogenous shock is a change in the emission tax that changes the optimal age distribution of the machines. In order to determine the effects from changes in the tax parameter we examine next the optimal age distribution of the machines as determined by the optimality conditions (2), (3.1), and (3.2).

3. THE OPTIMAL AGE DISTRIBUTION

Integrating (3.1) we obtain

$$\lambda(y) = \int_0^y [-pv(\rho) + c(\rho) + \tau s(\rho)]\, d\rho + A_1. \tag{4}$$

The boundary condition of this fixed-horizon optimal control problem, $\lambda(h) = 0$, yields the constant of integration in (4),

$$A_1 = -\int_0^h [-pv(\rho) + c(\rho) + \tau s(\rho)]\, d\rho.$$

Therefore, $\lambda(y)$ is given by

$$\lambda(y) = \int_y^h [pv(\rho) - c(\rho) - \tau s(\rho)]\, d\rho. \quad (5)$$

The value of λ as given by (5) reflects the benefits from installing one machine of age y and keeping it until it becomes of maximum age. From (2) the optimal sales or acquisitions of machines of age y is given by

$$u^*(y) = \lambda(y) - b(y) = \int_y^h [pv(\rho) - c(\rho) - \tau s(\rho)]\, d\rho - b(y). \quad (6)$$

Note that

$$u^*(y) \gtreqless 0, \quad \text{as } \lambda(y) \gtreqless b(y),$$

which is intuitively clear because λ denotes the benefits and b denotes the price of new machines.

The stock of machines of age y is partly determined by sales and acquisitions of machines of that age and partly inherited from sales and acquisitions in the past. The set of stocks of all ages is the optimal age distribution of machines and can be calculated from (3.2). Note that the initial stock is 0 and that the result can be viewed as a function of the tax parameter τ. This yields

$$x^*(y, \tau) = \int_0^y \left[\int_z^h [pv(\rho) - c(\rho) - \tau s(\rho)]\, d\rho - b(z) \right] dz. \quad (7)$$

The marginal changes of these stocks with respect to the tax rate τ are given by

$$\frac{\partial x^*(y, \tau)}{\partial \tau} = -\int_0^y \int_z^h s(\rho)\, d\rho\, dz < 0.$$

Therefore, an increase in the emission tax reduces the number of machines of each age in the capital stock, which implies that the age distribution of machines is shifted downward. This is the downsizing effect of the emission taxes. Furthermore, because total emissions are defined as

$$S(\tau) = \int_0^h s(y) x^*(y, \tau)\, dy,$$

we have that

$$\frac{dS(\tau)}{d\tau} < 0.$$

The important questions, however, are (i) whether this downsizing effect is accompanied by a modernization effect, or a change in the shape of the age distribution of machines, that increases the productivity of the capital stock, and (ii) how the increase in the emission tax affects firm's profits.

4. PRODUCTIVITY EFFECTS OF EMISSION TAXES

Suppose that the firm has optimized the age distribution of its capital stock, so that the number of machines for each age is given by (7). The proportion of machines of age y in the aggregate optimal capital stock of the firm is defined as

$$f(y,\tau) = \frac{x(y,\tau)}{\int_0^h x(y,\tau)\,dy}.$$

Note that $f(y,\tau)$ is a density function, because $f(y,\tau) \in [0,1]$, $\int_0^h f(y,\tau)\,dy = 1$. The average age of the optimal capital stock is defined as

$$g(\tau) = \int_0^h y f(y,\tau)\,dy = \frac{\int_0^h y x(y,\tau)\,dy}{\int_0^h x(y,\tau)\,dy}.$$

The basic question is under which conditions an increase in the tax rate reduces the average age of the capital stock, or $dg(\tau)/d\tau < 0$.

PROPOSITION 1. *A stricter environmental policy reduces the average age of the optimal capital stock if and only if the average age of the optimal capital stock before the tax increase is less than the average age of the change in the capital stock* (*which is a reduction as the firm downsizes in response to an increase in the tax rate*), *or*

$$\frac{\int_0^h y x(y,\tau)\,dy}{\int_0^h x(y,\tau)\,dy} < \frac{\int_0^h y(\partial x(y,\tau)/\partial\tau)\,dy}{\int_0^h (\partial x(y,\tau)/\partial\tau)\,dy}.$$

For a proof see the Appendix.

The proposition is intuitively clear, because removing on average more older machines reduces the average age, but the formulation is useful for what follows.

Under the condition of the foregoing proposition the downsizing of the firm also causes modernization of the capital stock. The optimal average age is reduced, as the tax increase removes the relatively older machines from the capital stock.

To analyse the productivity effects from a reduction in the average age, we define the average productivity of the capital stock as

$$\pi(\tau) = \frac{\int_0^h v(y)x(y,\tau)\,dy}{\int_0^h x(y,\tau)\,dy}.$$

Using a decreasing linear productivity function, defined as $v(y) = \alpha - \beta y$ with $\beta > 0$, we have that

$$\frac{d\pi}{d\tau} = -\beta \frac{d}{d\tau} \frac{\int_0^h yx(y,\tau)\,dy}{\int_0^h x(y,\tau)\,dy} = -\beta \frac{dg(\tau)}{d\tau}.$$

In that case, stricter environmental policy, in the form of a higher tax rate, increases the productivity of the capital stock when the average age of the capital stock is reduced. The earlier proposition gives the condition for this to take place. We will investigate this condition for general linear functional forms for the variables of the problem. The linearity assumption might not always be realistic but the analysis becomes already quite complex. To investigate whether the results are generalizable to nonlinear functional forms is left for further research.

Consider the case where

$$v(y) = a_0 + a_1(h - y),$$
$$c(y) = c,$$
$$b(y) = b(h - y),$$
$$s(y) = s_0 + s_1 y,$$

where all the parameters are nonnegative and at least a_1 or s_1 is strictly positive.

This implies that acquisition costs b decline linearly with age y of the machines and running costs c of the machines are constant. Output v is linearly decreasing with age y while emissions s are linearly increasing, with at least one of them in a strict way. The following proposition can then be stated.

PROPOSITION 2. *Under the assumptions made earlier about the functional forms of output, running costs, acquisition costs, and emissions, an increase in the emission tax reduces the optimal average age of the capital stock and increases its average productivity. For a proof see the Appendix.*

Thus when the downsizing effect is accompanied by a modernization effect a stricter environmental policy can increase the average productivity of the capital stock. It should be noticed, however, that the increase in productivity cannot be solely attributed to a stricter environmental policy. In case, for example, that running costs c increase linearly with age y of the machines, it can be shown that in the absence of environmental policy, an exogenous upward shock to these costs also increases productivity. The result appears again because of a more general mechanism which is associated with a downsizing of the industry due to an increase in costs and an accompanying modernization of the capital stock in the course of the downsizing process. As with X-efficiency, the positive effects may be caused by an external shock in general and not exclusively one in relation with an environmental problem.

A stricter environmental policy can thus increase the average productivity of capital and reduce emissions at the same time. These effects can, however, not be regarded as a win–win situation unless the effects of emission taxes on profits are positive as well.

5. PROFIT EFFECTS OF EMISSION TAXES

In order to analyse the profit effects of emission taxes, we consider a case where the firm subject to the environmental tax represents the home industry. This industry competes with a similar industry in another country which is not subject to the environmental tax τ.

Given the price p and the steady-state optimal age distribution of machines given by (7) total output for the home industry is given by

$$\int_0^h v(y)x^*(y,\tau)\,dy = \int_0^h\int_0^y\int_z^h v(y)[pv(\rho) - c(\rho) - \tau s(\rho)]\,d\rho\,dz\,dy - \int_0^h\int_0^y v(y)b(z)\,dz\,dy.$$

Suppose that the demand for the output of the home industry and the industry abroad comes from a third country according to the linear demand schedule,

$$p = \bar{p} - \int_0^h v(y)x^*(y,\tau)\,dy - \int_0^h v(y)x^*(y,0)\,dy.$$

The equilibrium price becomes

$$p^* = p_1\tau + p_0,$$

where

$$p_0 = \frac{\bar{p} + \int_0^h\int_0^y\int_z^h 2v(y)c(\rho)\,d\rho\,dz\,dy + \int_0^h\int_0^y 2v(y)b(z)\,dz\,dy}{1 + \int_0^h\int_0^y\int_z^h 2v(y)v(\rho)\,d\rho\,dz\,dy},$$

and

$$p_1 = \frac{\int_0^h\int_0^y\int_z^h v(y)s(\rho)\,d\rho\,dz\,dy}{1 + \int_0^h\int_0^y\int_z^h 2v(y)v(\rho)\,d\rho\,dz\,dy}.$$

Using these expressions the steady-state optimal age distribution of machines becomes

$$x^*(y,\tau) = \left[\int_0^y\int_z^h [p_1 v(\rho) - s(\rho)]\,d\rho\,dz\right]\tau + x^*(y,0),$$

where

$$x^*(y,0) = \int_0^y \left[\int_z^h [p_0 v(\rho) - c(\rho)]\, d\rho - b(z) \right] dz,$$

with $[\int_0^y \int_z^h [p_1 v(\rho) - s(\rho)]\, d\rho\, dz]\tau < 0$ indicating the reduction in the capital stock of the home industry due to the downsizing effect of the environmental tax.

The environmental tax τ has a price effect and a cost effect. The change in the steady-state profits can be split into two parts. A change $\Delta\Pi_1$ as a result of the changes in the price, the cost of emission taxes, and the age distribution of machines, and a change $\Delta\Pi_2$ as a result of the changes in the transactions on the machine market.

The first change in profits becomes

$$\begin{aligned}\Delta\Pi_1(\tau) = {} & \left[\int_0^h [p_1 v(y) - s(y)] \int_0^y \int_z^h [p_1 v(\rho) - s(\rho)]\, d\rho\, dz\, dy \right] \tau^2 \\ & + \left[\int_0^h [p_0 v(y) - c(y)] \int_0^y \int_z^h [p_1 v(\rho) - s(\rho)]\, d\rho\, dz\, dy \right. \\ & \left. + \int_0^h [p_1 v(y) - s(y)]\, x^*(y,0)\, dy \right] \tau.\end{aligned}$$

Because the net result from transactions on the machine market is given by

$$\tfrac{1}{2} b^2(y) - \tfrac{1}{2} \left[\int_y^h [p v(\rho) - c(\rho) - \tau s(\rho)]\, d\rho \right]^2,$$

the second change in profits becomes

$$\begin{aligned}\Delta\Pi_2(\tau) = {} & -\tfrac{1}{2} \left[\int_0^h \left[\int_y^h [p_1 v(\rho) - s(\rho)]\, d\rho \right]^2 dy \right] \tau^2 \\ & - \left[\int_0^h \int_y^h [p_1 v(\rho) - s(\rho)]\, d\rho \int_y^h [p_0 v(\rho) - c(\rho)]\, d\rho\, dy \right] \tau.\end{aligned}$$

In order to obtain a tractable expression for the total change in profits $\Delta\Pi(\tau)$, Lemma 1 from the Appendix is used. By renaming y into ρ and by renaming z into y in the right-hand side of Lemma 1 it is easy to see that the second term of $\Delta\Pi_1$ and the second term of $\Delta\Pi_2$ cancel out, and that the total change in the steady-state profits can be written as

$$\Delta\Pi(\tau) = \pi_1 \tau^2 + \pi_0 \tau, \tag{8}$$

where

$$\pi_1 = \tfrac{1}{2} \int_0^h \int_0^y \int_z^h [p_1 v(y) - s(y)][p_1 v(\rho) - s(\rho)]\, d\rho\, dz\, dy,$$

and

$$\pi_0 = \int_0^h [p_1 v(y) - s(y)]\, x^*(y,0)\, dy.$$

Thus the change in profits is a quadratic function of the environmental tax τ, with $\Delta\Pi(0) = 0$. With an increasing environmental tax τ the profits Π decrease monotonically until the steady-state optimal age distribution of machines has decreased to zero. In the interval from $\tau = 0$ until the value $\tau_{\max} > 0$, at which the resulting machine distribution is zero, the change in profits is negative and decreasing in the environmental tax τ,

$$\frac{d\Delta\Pi(\tau)}{d\tau} = \int_0^h [p_1 v(y) - s(y)] x^*(y, \tau)\, dy < 0.$$

With an increasing environmental tax τ total emissions S also decrease according to[6]

$$\frac{dS(\tau)}{d\tau} = \int_0^h \int_0^y \int_z^h s(y)[p_1 v(\rho) - s(\rho)]\, d\rho\, dz\, dy < 0.$$

Having established that stricter environmental policy reduces both profits and emissions in the home industry, we now turn to examine the relative effects of a stricter environmental policy when the downsizing of the home industry is or is not accompanied by a modernization of the capital stock. We compare two cases: In the first, the benchmark case, the productivity of the machines is constant and therefore no modernization is possible. In the second case the newer machines have a higher productivity so that a stricter environmental policy can generate a modernization effect. Emissions are kept constant over age in the two cases. It would be more realistic to assume that older machines emit more than newer machines, but this would only strengthen the results that follow.

Consider as a benchmark the case where all machines have the same productivity $v(y) = a$, the same running costs $c(y) = c\ (= 0)$, the same emissions $s(y) = s$, and acquisition costs $b(y) = b(h - y)$ to reflect that newer machines last longer. The benchmark is compared with the case where the machines' productivity decreases with age according to $v(y) = a_0 + a_1(h - y)$. It is easy to show that this specification leads to the same total output and equilibrium price p_0 before tax as in the benchmark case, if the parameters of the specification satisfy

$$a_0 = da, \qquad a_1 = \frac{8}{3h}(1 - d)a, \qquad d \in [0, 1),$$

and the acquisition costs become

$$b(y) = b_1(h - y), \qquad b_1 = b + \left(\tfrac{1}{15}\right)(1 - d)^2 p_0 a.$$

It is to be expected that the parameter of the acquisition costs is higher for a downward sloping productivity than for a constant productivity. From Proposition 2 it follows that an increase in the emission tax, for these specifications, increases the average productivity of the capital stock through the modernization effect.

[6] Note that in order to determine the optimal tax it is necessary to determine the costs of total emissions to society. The purpose of this paper is, however, to analyse the effect of a nonhomogeneous capital stock, for which such a valuation is not necessary.

Suppose that now an environmental tax τ is levied.
In the benchmark case the equilibrium price becomes $p^b = p_1^b \tau + p_0$ with

$$p_1^b = \frac{\frac{1}{3} a s h^3}{1 + \frac{2}{3} a^2 h^3},$$

while for the varying productivity case the equilibrium price becomes $p^v = p_1^v \tau + p_0$ with

$$p_1^v = \frac{\frac{1}{3} a s h^3}{1 + \frac{2}{3}\left[1 + \left(\frac{1}{15}\right)(1-d)^2\right] a^2 h^3}.$$

Using this framework the following proposition can be stated

PROPOSITION 3. *Let $dS^b(\tau)/d\tau$, $dS^v(\tau)/d\tau$, and $d\Pi^b(\tau)/d\tau$, $d\Pi^v(\tau)/d\tau$ denote the marginal decreases in emissions and profits by a stricter environmental policy in the home country, in the benchmark and varying productivity cases, respectively. Then under the assumptions made previously,*

$$\left|\frac{dS^v(\tau)}{d\tau}\right| > \left|\frac{dS^b(\tau)}{d\tau}\right| \quad \textit{and} \quad \left|\frac{d\Pi^v(\tau)}{d\tau}\right| < \left|\frac{d\Pi^b(\tau)}{d\tau}\right|.$$

For a proof see the Appendix.

Thus when the industry can change the composition of its capital stock by buying newer more productive machines, and this action is induced by a stricter environmental policy the reduction in emissions is larger and the reduction in profits is smaller as compared to the case where no such action is possible. Therefore it can be stated that when the downsizing of the home industry due to a stricter environmental policy is accompanied by modernization of its capital stock, there are smaller losses in profits and there are greater gains in emission reductions relative to the case where modernization is not possible.

6. CONCLUSIONS

Using a model in which firms can invest in machines with different characteristics, where newer machines are more productive and "cleaner" but also more expensive than older machines, we isolated two effects resulting from the introduction of a stricter environmental policy in the form of a tax on emissions: A productivity effect and a profit–emission effect.

The productivity effect implies that if the downsizing of the firm due to the stricter environmental policy is accompanied by a modernization effect, which means a reduction in the average age of the capital stock, then the average productivity of the capital stock increases.

The profit–emission effect indicates that profits and emissions decrease with a stricter environmental policy. However, in the case that the capital stock can be composed of newer more productive machines and older less productive machines the effect of an environmental tax is better in two ways, as compared to the case where modernization of the capital stock is not possible: the marginal decrease in emissions is higher and the marginal decrease in profits is lower.

Therefore, our results indicate that although a stricter environmental policy cannot be expected to provide a win−win situation in the sense of both reducing emissions and increasing profitability in an industry, we may expect increased productivity of the capital stock along with a relatively less severe impact on profits and more emission reductions, when the stricter policy induces modernization of the capital stock. The trade-off between environmental conditions and profits of the home industry remains but is less sharp because of downsizing and modernization of the industry.

APPENDIX A

Proof of Proposition 1. The proposition follows by taking the derivative,

$$\frac{dg(\tau)}{d\tau} = \frac{d}{d\tau}\frac{\int_0^h yx(y,\tau)\,dy}{\int_0^h x(y,\tau)\,dy}$$

setting the numerator less than zero and rearranging terms, where it should be noted that the change in the capital stock is negative. ■

LEMMA 1. *The following holds*:

$$\int_0^h \int_0^y \int_z^h f(y)g(\rho)\,d\rho\,dz\,dy = \int_0^h \left(\int_z^h f(y)\,dy\right)\left(\int_z^h g(\rho)\,d\rho\right) dz.$$

Proof. Change the order of integration of z and y. ■

Proof of Proposition 2. First, the terms of the two ratios of the condition of Proposition 1 are developed separately. The first term becomes

$$\Omega_1 = \int_0^h x(y,\tau)\,dy = \int_0^h \int_0^y \int_z^h [pv(\rho) - c(\rho) - \tau s(\rho)]\,d\rho\,dz\,dy$$
$$- \int_0^h \int_0^y b(z)\,dz\,dy.$$

By Lemma 1 and then changing the order of integration, the first part of this expression for Ω_1 can be written as

$$\int_0^h \int_z^h (h-z)[pv(\rho) - c(\rho) - \tau s(\rho)]\,d\rho\,dz$$
$$= \int_0^h \int_0^\rho (h-z)[pv(\rho) - c(\rho) - \tau s(\rho)]\,dz\,d\rho$$
$$= \int_0^h \left(h\rho - \tfrac{1}{2}\rho^2\right)[pv(\rho) - c(\rho) - \tau s(\rho)]\,d\rho.$$

By changing the order of integration, the second part of Ω_1 can be written as

$$\int_0^h \int_0^y b(z)\,dz\,dy = \int_0^h \int_z^h b(z)\,dy\,dz = \int_0^h (h-z)b(z)\,dz.$$

Combining these two results we obtain

$$\Omega_1 = \int_0^h \left[\left(h\rho - \tfrac{1}{2}\rho^2\right)[pv(\rho) - c(\rho) - \tau s(\rho)] - (h-\rho)b(\rho)\right] d\rho.$$

Similarly, the second term becomes

$$\begin{aligned}\Omega_2 &= \int_0^h yx(y,\tau)\,dy \\ &= \int_0^h \left[\tfrac{1}{2}\left(h^2\rho - \tfrac{1}{3}\rho^3\right)[pv(\rho) - c(\rho) - \tau s(\rho)] - \tfrac{1}{2}(h^2-\rho^2)b(\rho)\right] d\rho.\end{aligned}$$

Furthermore,

$$\Omega_3 = \int_0^h \frac{\partial x(y,\tau)}{\partial \tau} = -\int_0^h \int_0^y \int_z^h s(\rho)\,d\rho\,dz\,dy,$$

or, by using Lemma 1 and then changing the order of integration,

$$\begin{aligned}\Omega_3 &= -\int_0^h \int_z^h (h-z)s(\rho)\,d\rho\,dz \\ &= -\int_0^h \int_0^\rho (h-z)s(\rho)\,dz\,d\rho = -\int_0^h \left(h\rho - \tfrac{1}{2}\rho^2\right)s(\rho)\,d\rho.\end{aligned}$$

Similarly,

$$\Omega_4 = \int_0^h y\frac{\partial x(y,\tau)}{\partial \tau}dy = -\int_0^h \tfrac{1}{2}\left(h^2\rho - \tfrac{1}{3}\rho^3\right)s(\rho)\,d\rho.$$

It follows that the condition of Proposition 1, $\Omega_2/\Omega_1 < \Omega_4/\Omega_3$, becomes

$$\frac{\int_0^h \left[\tfrac{1}{2}\left(h^2\rho - \tfrac{1}{3}\rho^3\right)[pv(\rho) - c(\rho)] - \tfrac{1}{2}(h^2-\rho^2)b(\rho)\right] d\rho}{\int_0^h \left[\left(h\rho - \tfrac{1}{2}\rho^2\right)[pv(\rho) - c(\rho)] - (h-\rho)b(\rho)\right] d\rho} < \frac{\int_0^h \tfrac{1}{2}\left(h^2\rho - \tfrac{1}{3}\rho^3\right)s(\rho)\,d\rho}{\int_0^h \left(h\rho - \tfrac{1}{2}\rho^2\right)s(\rho)\,d\rho}.$$

For $v(\rho) = a$, $c(\rho) = c$, $b(\rho) = b(h-\rho)$, and $s(\rho) = s$ both the left-hand side and the right-hand side of this inequality are equal to $5h/8$. Furthermore, it is easy to see that for $s(\rho) = s_0 + s_1\rho$ with $s_1 > 0$ the right-hand side is larger than $5h/8$ and that for $v(\rho) = a_0 + a_1\rho$ with $a_1 > 0$ the left-hand side is smaller than $5h/8$. ■

Proof of Proposition 3. By straightforward calculations we obtain

$$\frac{dS^b(\tau)}{d\tau} = -\frac{1+\frac{1}{3}a^2h^3}{1+\frac{2}{3}a^2h^3}\,\tfrac{1}{3}s^2h^3,$$

while

$$\frac{dS^v(\tau)}{d\tau} = -\frac{1+\frac{1}{3}\left[1+\left(\frac{2}{15}\right)(1-d^2)\right]a^2h^3}{1+\frac{2}{3}\left[1+\left(\frac{1}{15}\right)(1-d)^2\right]a^2h^3}\,\tfrac{1}{3}s^2h^3.$$

Thus it follows that the marginal decrease in total emissions is larger in the case with the varying productivity than in the benchmark case.

Furthermore, straightforward calculations show that in the benchmark case the marginal change in steady-state profits becomes

$$\frac{d\Pi^b(\tau)}{d\tau} = \frac{d\Delta\Pi^b(\tau)}{d\tau} = \tfrac{1}{3}sh^3\left[\left[\frac{1+\frac{1}{3}a^2h^3}{1+\frac{2}{3}a^2h^3}\right]^2 s\tau - \frac{1+\frac{1}{3}a^2h^3}{1+\frac{2}{3}a^2h^3}(p_0a-c-b)\right],$$

while for the varying productivity case the result is

$$\frac{d\Pi^v(\tau)}{d\tau} = \frac{d\Delta\Pi^v(\tau)}{d\tau} = \hat{\pi}\tau + \tilde{\pi},$$

where

$$\hat{\pi} = \left(\tfrac{1}{45}\right)(1-d)^2p_1^{v2}a^2h^3 + \left[\frac{1+\frac{1}{3}\left[1+\left(\frac{2}{15}\right)(1-d^2)\right]a^2h^3}{1+\frac{2}{3}\left[1+\left(\frac{1}{15}\right)(1-d)^2\right]a^2h^3}\right]^2\tfrac{1}{3}s^2h^3,$$

and

$$\tilde{\pi} = -\tfrac{1}{3}sh^3\left[\frac{1+\frac{1}{3}\left[1+\left(\frac{1}{15}\right)(1-d^2)\right]a^2h^3}{1+\frac{2}{3}\left[1+\left(\frac{1}{15}\right)(1-d)^2\right]a^2h^3}p_0a - \frac{1+\frac{1}{3}\left[1+\left(\frac{2}{15}\right)(1-d^2)\right]a^2h^3}{1+\frac{2}{3}\left[1+\left(\frac{1}{15}\right)(1-d)^2\right]a^2h^3}(c+b_1)\right].$$

Thus it follows that the marginal decrease in profits is already smaller for $\tau = 0$ in the varying productivity case as compared to the benchmark, and the difference grows with an increasing environmental tax. ■

APPENDIX B: LIST OF SYMBOLS

y	age of a machine
h	maximum age of a machine
t	time
$v(y)$	output of a machine of age y
a_0, a_1, d, a	parameters of $v(y)$

$c(y)$	running cost of a machine of age y
c	parameter of $c(y)$
$s(y)$	emissions of a machine of age y
s_0, s_1	parameters of $s(y)$
$x(t, y)$	number of machines of age y operating in year t
$Q(t)$	total output in year t
τ	emission tax per unit emissions
$C(t)$	total running costs for year t
S	total emissions
$b(y)$	buying cost of a machine of age y
b, b_1	parameters of $b(y)$
$u(y, t)$	number of machines of age y bought or sold in year t
p	price of output
p_0, p_1	parameters of the equilibrium price
H	generalized Hamiltonian
$\lambda(y, t)$	adjoint state or benefits from installing one machine of age y at time t
A_1	constant of integration
*	optimal
$f(y)$	proportion of machines of age y in the optimal capital stock
g	average age of the optimal capital stock
π	average productivity of the capital stock
α, β	productivity parameters
Δ	change
Π	profits
π_0, π_1	parameters of change in steady-state profits
$_b$	benchmark case
$_v$	varying productivity case

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