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Environmental performance and equilibrium

Thierry Bréchet, Philippe Michel

July 2004

ENVIRONMENTAL
ECONOMICS & MANAGEMENT
MEMORANDUM

UCL
Université
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Center for Operations Research
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Thierry Bréchet* , Philippe Michel†

July 2004

Abstract

Firms' or industries' ranking in terms of environmental performance may be influenced by equilibrium and not only by ex ante technological characteristics. We adopt a natural definition of relative eco-efficiency between two industries operating within the same environmental constraint: the more eco-efficient one is the one that has the higher output level. We compare the relative eco-efficiency of two technologies characterizing two industries, and then of two firms within the same industry. We show that all these comparisons depend, through the equilibrium, on the environmental constraint imposed at the industry level. We also show that firm's profitability at the equilibrium depends on its eco-efficiency, but also on its labour elasticity and permits allocation: the more eco-efficient firm is not necessarily the more profitable one.

*Chair Lhoist Berghmans in Environmental Economics and Management, Center for Operations Research and Econometrics (CORE), Université catholique de Louvain, Voie du Roman Pays 34, B-1348 Louvain-la-Neuve, Belgium. E-mail: brechet@core.ucl.ac.be

†GREQAM, Université de la Méditerranée and EUREQua, Université Paris I, Institut Universitaire de France.

Key words: Eco-efficiency, benchmarking, tradable permits

JEL codes: D20; Q50

Acknowledgments: We thank Francisco Javier André Garcia, Marc Germain, Stéphane Lambrecht and Vincent van Steenberghe for usefull comments. Preliminary versions of this paper have been presented at the annual conference of the Environmental and Resource Economic Association, Budapest, June 2004 and at the Environmental Workshop at CORE.

1 Introduction

1.1 Motivation

Nowadays, environmental performance constitutes a strategic subject of concern for producers and policy makers. Both at micro and macro levels, complying with the numerous environmental constraints without endangering competitiveness is of crucial importance. In this context, eco-efficiency has become one of the buzzwords of our time, regarding economy and ecology as a key opportunity to enhance a firm or industry's competitive position in the market. The famous Porter hypothesis, originally expressed by Porter and van de Linder (1995), illustrates that challenge. Substantial progress has been made recently in measuring efficiency and identifying best practice, both at the industry and the country level. Three strands may be distinguished in the literature. First, efficiency measures in line with the pioneering work by Farrel (1957); a recent overview is given by Diewert and Nakamura (1999). Second, benchmarking procedures which consist of ranking firms or countries against 'best practice'. Benchmarking relies on a selection of purely quantitative measures: it does not necessarily embody the concept of efficiency. Third, as far as environmental issues are concerned, the question of the economic value of pollution raises: most of the previous studies only apply to positively priced outputs.

In contrast to the previous points, little or no attention has been paid to the rationale behind the concept of environmental performance in economic terms. This concept is generally broadly defined. For example, the term eco-efficiency, coined by the World Business Council for Sustainable Development (Schmidheiny, 1992) is defined as minimizing the quantity of undesirable output(s) per unit of desirable output. Such a definition relies on a quantitative measure of outputs, notwithstanding the economic and technological conditions prevailing on the markets, without any valuation of the environmental benefits and neglecting firms heterogeneity.

We show in this paper that such notions and practices may be misleading as far as environmental issues are concerned. The rational behind our argument is twofold. First, the definition of best practice, and consequently benchmarking with respect to this, strongly depends on the harshness of the environmental constraint, and thus on the corresponding market outcome. In other words, environmental performance is not just a matter of technological choice, but also of equilibrium. As a consequence, any change in the economic background may alter firms' ranking. Second, as far as the environment is concerned, the question of the economic value of pollution as an input is raised: how is it possible to evaluate the efficiency use of a public good? Most environmental goods are outside the market (no scarcity, no price) or, if a market does exist, full cost pricing is generally deficient. Consequently, a preliminary requirement for efficiency analyses for environmental issues would be to establish or restore competitive market conditions. The objective of this article is precisely to define properly eco-efficiency in economic terms and to point out policy implications.

1.2 Related literature

The term eco-efficiency was coined by the World Business Council for Sustainable Development in 1992 as 'a management strategy that links financial and environmental performance to create more value with less ecological impact' (Schmidheiny, 1992). This concept is similar to a variety of others used in business and environmental policy at industry level. It is advocated in many policy areas. The national environmental policy of the United States is under the Pollution Prevention Act of 1990, which defines Pollution Prevention as a reduction of wastes and pollutants through increased efficiency in the use of raw materials, energy, water and land. The Asian Productivity Organization launched a Green Productivity Program in 1994, a strategy for enhancing productivity and environmental performance. The key concept used by the European Commission behind its Benchmarking Enterprise Policy is eco-efficiency, defined as 'the value added divided by the quantity of input or emission of pollutants'. The same definition is used when 'Best Available Techniques' are defined under the Integrated Pollution Prevention and Control Directive (European Commission, 1996).

The economic literature on eco-efficiency and benchmarking is sparse. Yet, as pointed out by Diewert and Nakamura (1999), the process of benchmarking has long been used by private firms and its use in the public sector is now spreading. Hall and Winsten (1959) give an interesting early discussion of economists' perspectives on the various aspects of efficiency. In particular, they shed some light on the distinction between allocative, technical and managerial efficiency. What is particularly appealing for us in this paper is that the authors emphasise the confusion in the concepts and the need for efficiency comparisons (i.e. benchmarking). Yotopoulos and Lau (1973) disentangle allocative and technical efficiency, but their analysis only applies to measurable inputs. Forsund and Jansen (1977) focus on the comparison of the best practice function within an industry, because they think that this will give relevant information about future structural changes in the industry. However, they assume the same homothetic production function in different establishments, except for a random variable simulating differences in technical efficiency. Purely *ad hoc* justifications are given for these technical efficiency gaps.

Pittman (1983) and Zieschang (1984) point out that all multi-firm and multi-country comparisons involve the comparison of productive entities whose outputs are sold at positive prices and that the presence of unpriced undesirable outputs makes these comparisons misleading. Hence, Pittman assigns shadow prices to undesirable outputs to alleviate the absence of market prices and reveals substantial changes in the rankings for the steel industry. His conclusion is that ignoring undesirable outputs might yield misleading results *from a societal point of view.* Antweiler (2003) shows how a firm's position relative to other firms ('the best-of-class') determines its participation in abatement activity in the context of voluntary pollution abatement. But the question remains as to how to determine on which rung of the abatement ladder the firm is situated? This rung may change as soon as any other firm modifies its technology.

It appears from the literature that the identification of best practice and benchmarking procedures usually relies on *ex ante* descriptions of the technological and managerial characteristics of the firms or industries. We argue that eco-efficiency should be evaluated *ex post*, i.e. taking into account market outcomes.

From an economic viewpoint, free disposal leads to nil shadow prices: there is no reason for a firm to hold back from using such an input. This also occurs, at least partially, whenever the market price does not reflect the social value, this being understood as including both private and external costs. Clearly, in such a context, the concept of efficiency becomes meaningless. One solution for introducing scarcity is to define property rights on collective goods: committing polluters to emissions ceilings boils down to assigning emissions rights among them by restraining the use of the resource at the global level. We shall consider a market on which firms' emissions quotas are defined and tradable permits are issued by the regulator. Montgomery (1972) has shown, and it is now well-established, that such a market is efficient under competitive conditions.

In this paper we show that, restricting ourselves to a short-term analysis with well-behaved entrepreneurs, the rung on the ladder of eco-efficiency may change with market outcomes as soon as firms are heterogeneous. Here eco-efficiency is defined from a social point of view, thanks to an emissions commitment and trading scheme. Consequently, what should be considered as best practice in the industry may also change. Moreover, we show that the most profitable firm is not necessarily the most eco-efficient one. We generalise the results of Jouvet *et al.* (2003) by introducing firms' heterogeneity with regard to factor elasticities.

The paper proceeds as follows. In section 2 we present the model of an industry committed with pollution abatement under a trading scheme in which firms are heterogeneous. Section 3 characterizes the equilibrium. In section 4 we analyse the relationship between environmental performance and equilibrium, both at the industry and firm levels. Section 5 shows that the links between eco-efficiency and profitability are not straightforward. Conclusions and policy implications are discussed in Section 6.

2 The model

We study the partial equilibrium of an industry composed by I firms indexed by i using capital, labor and the environment. No specific assumption has to be made on this pollutant except that it must be a global pollution within the industry considered. Firms operate under perfect competition. They produce the same good, but according different technologies. All these technologies, however, are assumed to be of Cobb-Douglas type. An industry is defined by the set of the technologies of the I firms (A_i, b_i, α_i), the cost of labor (w) and the (inverse) demand curve of the produced good $P(Y)$.

2.1 The firms and their technology

Each firm i has a potential level of production given by a Cobb-Douglas technology combining capital and labour

$$\widehat{Y}_i = A_i K_i^{1-\alpha_i} L_i^{\alpha_i} \tag{1}$$

where A_i is a scale parameter and α_i the labour elasticity $(0 < \alpha_i < 1)$. Actual output is given by

$$Y_i = z_i \widehat{Y}_i = z_i A_i K_i^{1-\alpha_i} L_i^{\alpha_i} \tag{2}$$

where z_i $(0 \leqslant z_i \leqslant 1)$ stands for the utilization rate of potential output. It may also be seen as an index of the technology used (see Stockey, 1998). Pollution intensity is assumed to vary with the utilization rate

$$\frac{E_i}{Y_i} = b_i z_i \tag{3}$$

where b_i is the emission - output ratio in the absence of emissions constraint $(b_i > 0)$. This equation is equivalent to

$$E_i = b_i z_i^2 A_i K_i^{1-\alpha_i} L_i^{\alpha_i} \tag{4}$$

Remark 1 *This specification is equivalent to a three factors production function. Eliminating z_i by sustitution between equations (2) and (4) leads to*

$$Y_i = \left(\frac{E_i}{b_i}\right)^{\frac{1}{2}} \left(A_i K_i^{1-\alpha_i} L_i^{\alpha_i}\right)^{\frac{1}{2}} \equiv G_i\left(K_i, L_i, E_i\right)$$

which corresponds to a first degree homogenous Cobb-Douglas production function with capital, labour and emissions. This form only applies whenever $z_i < 1$*. With* $z_i \leqslant 1$ *the production function becomes*

$$Y_i = \min \left\{ A_i K_i^{1-\alpha_i} L_i^{\alpha_i}, G_i\left(K_i, L_i, E_i\right) \right\}$$

2.2 Firms' behavior

In the short run, the capital stock K_i is given and considered as fixed. Enforcement for pollution abatement is set by implementing a market of tradable emission permits among the firms. Let $\overline{E}_i$ be the firm i's freely allocated emission permits. Once given, these permits can be bought or sold by the firms on the market at a price q. On all markets, firms operate under perfect competition. Given the price of output p, the labour cost w and the price of permits q, firm i maximizes its profit given by $\pi_i = pY_i - wL_i - q(E_i - \overline{E}_i)$. Thus, it chooses z_i and L_i as solution of

$$\max_{0 \leqslant z_i \leqslant 1, L_i \geqslant 0} \pi_i = A_i K_i^{1-\alpha_i} L_i^{\alpha_i} \left(pz_i - qb_i z_i^2\right) - wL_i + q\overline{E}_i \tag{5}$$

The first-order conditions for an interior solution lead to

$$p = 2qb_i z_i \tag{6}$$

$$w = \alpha_i A_i K_i^{1-\alpha_i} L_i^{\alpha_i - 1} \left(pz_i - qb_i z_i^2\right) \tag{7}$$

Using (6), the second condition writes

$$w = \frac{1}{2} p z_i \alpha_i A_i K_i^{1-\alpha_i} L_i^{\alpha_i - 1} \tag{8}$$

Condition (6) implies that the condition for an interior solution ($z_i < 1$) must fit $p/q < 2b_i$.

2.3 The equilibrium

We study the partial equilibrium in the industry with I firms with a given labour cost w, a given inverse demand function $P(Y)$ and a given total amount of emission rights[1] $\overline{E} = \sum_{i=1}^{I} \overline{E}_i$. We assume that $P(.)$ is a decreasing continous function defined on the set of positive real numbers $\mathbb{R}_{++}$: $P(Y) < 0$ for all $Y > 0$. We only consider interior equilibria, i.e. such that all firms are constrained on their emissions ($z_i < 1$, $\forall i = 1, ...I$). An interior equilibrium within this industry is defined as follows.

Definition 1 *An interior equilibrium is defined by*

(i) the output price (p^*) and the permits price (q^*),

(ii) the firms' utilization rates z_i^* ($0 < z_i^* < 1$) and quantities $Y_i^* > 0$, $L_i^* > 0$ and $E_i^* > 0$ satisfying (2), (3), (6) and (7),

(iii) aggregate quantities $Y^* = \sum_{i=1}^{I} Y_i^*$ and $E^* = \sum_{i=1}^{I} E_i^*$ satisfying $p^* = P(Y^*)$ and $E^* = \overline{E}$.

3 Existence and uniqueness of equilibrium

Let us first consider the equilibrium condition on the output market. We shall demonstrate that this condition is equivalent to a relation linking total output Y to the equilibrium price ratio $v = p/q$.

[1] We assume that the permits are freely allocated to the firms. The study of the equilibrium would be the same if the permits were auctionned.

3.1 The emission - output price ratio

Starting from $Y_i = z_i A_i K_i^{1-\alpha_i} L_i^{\alpha_i}$ and rearranging (8) such that

$$L_i^{1-\alpha_i} = \frac{p\alpha_i}{2w} z_i A_i K_i^{1-\alpha_i} \tag{9}$$

we get

$$Y_i = \left(z_i A_i K_i^{1-\alpha_i}\right)^{\frac{1}{1-\alpha_i}} \left(\frac{p\alpha_i}{2w}\right)^{\frac{\alpha_i}{1-\alpha_i}} \tag{10}$$

Using (6) we obtain

$$Y_i = \mu_i K_i \left(\frac{p}{q}\right)^{\frac{1}{1-\alpha_i}} \left(\frac{p}{w}\right)^{\frac{\alpha_i}{1-\alpha_i}} \tag{11}$$

where

$$\mu_i = A_i^{\frac{1}{1-\alpha_i}} \left(\frac{1}{2b_i}\right)^{\frac{1}{1-\alpha_i}} \left(\frac{\alpha_i}{2}\right)^{\frac{\alpha_i}{1-\alpha_i}} \tag{12}$$

It must be noticed that μ_i only depends on the technological characteristics of the firm i. Hence, the condition for equilibrium on the output market yields to the following condition on $v = p/q = P(Y)/q$

$$1 = \sum_{i=1}^{I} \frac{Y_i}{Y} = \sum_{i=1}^{I} \mu_i K_i v^{\frac{1}{1-\alpha_i}} \frac{1}{Y} \left(\frac{P(Y)}{w}\right)^{\frac{\alpha_i}{1-\alpha_i}} \equiv \Phi\left(v, Y\right) \tag{13}$$

with μ_i, K_i and w as given.

Proposition 1 *The condition for equilibrium on the output market defines the ratio $v = p/q$ as a function $V(.)$ of total output. This function is increasing and continous on $\mathbb{R}_{++}$. So equation (13) reads $v = V(Y)$.*

Proof. For all $Y > 0$, $\Phi\left(v, Y\right)$ is an increasing function of v: this function increases from 0 to $+\infty$ when v increases from 0 to $+\infty$. So there exists one and only one solution $v = V(Y) > 0$ for the equation $\Phi(v, Y) = 1$. From the implicit functions theorem, $V(Y)$ is continue and increasing in Y since $\Phi(v, Y)$ is continous and decreasing in Y. ■

It may be pointed out that (13) gives an explicit expression of the function $V(Y)$ only when all the firms have the same price elasticity for labour ($\alpha_i = \alpha$, $\forall \alpha_i$).

3.2 Emissions at equilibrium

In shaping the equilibrium on the market of tradable permits, it is worth noting that, with $0 < z_i < 1$, all the ratios E_i/Y_i are equal since, from (6), we have

$$\frac{E_i}{Y_i} = b_i z_i = \frac{p}{2q} = \frac{v}{2} \tag{14}$$

For any given individual emissions permits allocation $\overline{E}_i$, each firm will buy or sold permits so as (14) is ensured. However, the equilibrium only depends on the overall permits allocation. It clearly appears now that changing this overall allocation (i.e. the global emissions constraint) will have consequences both on the price of the permits and on the price on the output. The equality of the emission - output ratios among the firms results from the assumption of the equality of these individual ratios with respect to the utilization rate of potential output. This assumption allows us to obtain a relation at the aggregate level between the emission - output ratio and the permits and output price ratio at equilibrium.

3.3 Existence and uniqueness

From proposition 1 we know that, at equilibrium, we have $v = V(Y)$ and that the emissions level in the industry is such that

$$\frac{E}{Y} = \frac{V(Y)}{2} \tag{15}$$

Proposition 2 *There exists a upper bound B such that, for all $\overline{E} < B$, there exists a unique interior equilibrium. The total production Y^* corresponding to this equilibrium is defined by $V(Y^*)\,Y^* = 2\overline{E}$ and the firm i's utilization rate writes*

$$z_i^* = \frac{V(Y^*)}{2b_i}$$

The equilibrium is independant from the initial allocation of permits among the firms.

Proof. Provided (15) the equilibrium on the market of permits $E = \overline{E}$ reads

$$\overline{E} = \frac{V(Y)\,Y}{2} \tag{16}$$

Since $V(Y)\,Y$ is an increasing function of Y, increasing from 0 to $+\infty$ when Y increases from 0 to $+\infty$, (16) defines a function $\mathcal{Y}\left(\overline{E}\right)$ which increases from 0 to $+\infty$ when $\overline{E}$ increases from 0 to $+\infty$. The corresponding value of z_i stands

$$z_i = \frac{V\left(\mathcal{Y}\left(\overline{E}\right)\right)}{2b_i}$$

The condition $z_i < 1$ holds if and only if $V\left(\mathcal{Y}\left(\overline{E}\right)\right) < 2b_i$. We define B with the following condition

$$V\left(\mathcal{Y}\left(B\right)\right) = 2\min b_i$$

Thus, for all $\overline{E} < B$ there exists $Y^* = \mathcal{Y}\left(\overline{E}\right)$ with $z_i^* < 1$ for all i. The corresponding values of z_i^*, L_i^* (given by (9)) and Y_i^* (given by (10)) define an equilibrium with $p^* = P(Y^*)$ and $q^* = P(Y^*)/V(Y^*)$. ■

4 Environmental performance at equilibrium

An economy $\mathcal{E}$ is defined by the technology of the firms $(A_i, b_i, \alpha_i)_{i\in I}$, their stock of capital $(K_i)_{i\in I}$, the wage rate w and the inverse demand function $P(.)$. Considering the function $\Phi\left(v, Y\right)$ given from relation (13), we define

$$\Psi(Y) = \Phi\left(\frac{2\overline{E}}{Y}, Y\right) \tag{17}$$

$\Psi(Y)$ is a decreasing function of Y which decreases from $+\infty$ to 0 when Y increases from 0 to $+\infty$. Considering $\overline{E} < B$, there exists a unique equilibrium for which total production $Y^* = \mathcal{Y}\left(\overline{E}\right)$ is the solution of $\Psi(Y) = 1$. Prices at equilibrium are $p^* = P(Y^*)$ and $q^* = p^*/v^*$ where the ratio $v^* = V(Y^*)$ is equal to $2\overline{E}/Y^*$. The firm i's output level is given by (11)

$$Y_i^* = \mu_i K_i \left(v^*\right)^{\frac{1}{1-\alpha_i}} \left(\frac{p^*}{w}\right)^{\frac{\alpha_i}{1-\alpha_i}} \tag{18}$$

In equilibrium, emissions by unit of output are equal among the firms and verify

$$\frac{E_i^*}{Y_i^*} = b_i z_i^* = \frac{v^*}{2} = \frac{\overline{E}}{Y^*} \tag{19}$$

4.1 Comparing two economies

In order to compare different set of technologies in the industry producing a given good, we assume that the wage rate, the inverse demand function and the number of firms are given. The only difference holds on technological parameters. Let us consider two economies, $\mathcal{E}$ and $\widetilde{\mathcal{E}}$, with I firms characterized by the following technological parameters (A_i, b_i, α_i) and $(\widetilde{A}_i, \widetilde{b}_i, \widetilde{\alpha}_i)$, $i = 1...I$, all the other characteristics being identical between the two economies. Let $\Psi(.)$ and $\widetilde{\Psi}(.)$ be the functions (17) corresponding to the two economies. Given $\overline{E}$ satisfying both $\overline{E} < B$ and $\overline{E} < \widetilde{B}$, the unique equilibrium output levels Y^* and $\widetilde{Y}^*$ are solutions of the two following equations

$$\Psi(Y^*) = \Phi\left(\frac{2\overline{E}}{Y^*}, Y^*\right) = 1 \text{ and } \widetilde{\Psi}(\widetilde{Y}^*) = \widetilde{\Phi}\left(\frac{2\overline{E}}{\widetilde{Y}^*}, \widetilde{Y}^*\right) = 1 \qquad (20)$$

Considering the fact that these two economies have the same characteristics except the firm's technological parameters, we can compare the eco-efficiency of these two economies by comparing their respective output level for a same level of emissions constraint $\overline{E}$. In the following, we shall always assume that $\overline{E}$ verifies both $\overline{E} < B$ and $\overline{E} < \widetilde{B}$ such that we get interior solutions, which entails that output levels are determined from (20). We are now able to define what we shall call *relative eco-efficiency.*

Definition 2 *For a given $\overline{E}$, the economy $\widetilde{\mathcal{E}}$ is more eco-efficient than the economy $\mathcal{E}$ if its output level at equilibrium is larger, i.e. $\widetilde{Y}^* > Y^*$.*

This definition simply defines *relative eco-efficiency* between the two economies by comparing the output level at equilibrium for the same emissions ceiling. This also means that the ratio of the aggregate production on the aggregate emissions is larger in the more eco-efficient economy. The formal conditions for being *more eco-efficient* are set below.

Proposition 3 *$\widetilde{\mathcal{E}}$ is more eco-efficient than $\mathcal{E}$ if and only if $\widetilde{\Psi}(Y^*) > 1$ and if and only if $\Psi(\widetilde{Y}^*) < 1$. The property $\widetilde{Y}^* > Y^*$ implies that*

(i) in $\widetilde{\mathcal{E}}$ the price ratio at equilibrium $\widetilde{v}^* = \widetilde{p}^*/\widetilde{q}^*$ is smaller than the one in $\mathcal{E}$, $v^* = p^*/q^*$

(ii) in $\widetilde{\mathcal{E}}$ the emission-output ratios $\widetilde{E}_i^*/\widetilde{Y}_i^*$ (which are equal among firms and equal to $\overline{E}/\widetilde{Y}^*$) are smaller than in $\mathcal{E}$ (where $E_i^*/Y_i^* = \overline{E}/Y^*$)

(iii) for any firm i having the same technological characteristics in $\widetilde{\mathcal{E}}$ and $\mathcal{E}$, that is to say $(\widetilde{A}_i, \widetilde{b}_i, \widetilde{\alpha}_i) = (A_i, b_i, \alpha_i)$, this firm's output level and utilization rate at equilibrium are lower in $\widetilde{\mathcal{E}}$ than in $\mathcal{E}$ ($\widetilde{Y}_i^* < Y_i^*$ and $\widetilde{z}_i^* < z_i^*$).

Proof. The condition $\widetilde{\Psi}(Y^*) > 1 = \widetilde{\Psi}(\widetilde{Y}^*)$ is equivalent to $Y^* < \widetilde{Y}^*$ because $\widetilde{\Psi}(.)$ is decreasing. Similarly, $\Psi(\widetilde{Y}^*) < 1 = \Psi(Y^*)$ is equivalent to $\widetilde{Y}^* > Y^*$.

Whenever $\widetilde{Y}^* > Y^*$, we know from (19) that prices at equilibrium satisfy

$$\widetilde{v}^* = \frac{2\overline{E}}{\widetilde{Y}^*} < \frac{2\overline{E}}{Y^*} = v^*$$

so that we get

$$\frac{\widetilde{E}_i^*}{\widetilde{Y}_i^*} = \frac{\widetilde{v}^*}{2} < \frac{v^*}{2} = \frac{E_i^*}{Y_i^*} \quad \forall i \in I$$

From (19) we also have

$$\widetilde{b}_i \widetilde{z}_i^* = \frac{\widetilde{v}^*}{2} < \frac{v^*}{2} = b_i z_i^*$$

So if $\widetilde{b}_i = b_i$ then we have $\widetilde{z}_i^* < z_i^*$ (and this is independent from the fact that $\widetilde{\alpha}_i$ may eventually be equal or different from α_i).

Finally, whenever all the parameters are identical for a particular firm i $((\widetilde{A}_i, \widetilde{b}_i, \widetilde{\alpha}_i) = (A_i, b_i, \alpha_i))$, then μ_i given by (12) is equal to $\widetilde{\mu}_i$ and from (18) we obtain

$$\widetilde{Y}_i^* = \mu_i K_i \left(\widetilde{v}^*\right)^{\frac{1}{1-\alpha_i}} \left(\frac{\widetilde{p}^*}{w}\right)^{\frac{\alpha_i}{1-\alpha_i}} < Y_i^*$$

since $\widetilde{v}^* < v^*$ and $\widetilde{p}^* = P\left(\widetilde{Y}^*\right) < p^* = P\left(Y^*\right)$. ■

Remark 2 *The inequality of the ratios* $\widetilde{p}^*/\widetilde{q}^* < p^*/q^*$ *does not allow to conclude on the changing in the price of permits due to the fact that the larger production level in* $\widetilde{\mathcal{E}}$ *implies a lower equilibrium price for output* $\widetilde{p}^* < p^*$*. However, if the price elasticity of demand is low enough, we will get* $\widetilde{q}^* > q^*$*. More precisely*

$$\frac{\widetilde{q}^*}{q^*} = \frac{\widetilde{p}^*}{p^*}\frac{v^*}{\widetilde{v}^*} = \frac{P\left(\widetilde{Y}^*\right)\widetilde{Y}^*}{P\left(Y^*\right)Y^*}$$

is larger than 1 whenever total receipt $P\left(Y\right)Y$ *is an increasing function of output* Y*. It may also be shown that, for the same output level, emissions would be lower in the economy* $\widetilde{\mathcal{E}}$*. This means that* Y^* *is an equilibrium level of output with a more restrictive emission constraint.*

4.2 Comparing two technologies

We shall now compare two technologies in terms of environmental performance. In other words, we are looking for the firm which, among the I firms considered within the industry, could be labelled as the most eco-efficient, opening the door to an interpetation in terms of 'best environmental practices' and relevant benchmarking among the firms. Let us consider a benchmark technology for a given firm i, $\mathcal{T}_i = (A_i, b_i, \alpha_i)$, and an alternative technology $\widetilde{\mathcal{T}}_i = (\widetilde{A}_i, \widetilde{b}_i, \widetilde{\alpha}_i)$ for the same firm. We assume that all the other firms

$j \neq i$ have the same individual technology $\mathcal{T}_j = (A_j, b_j, \alpha_j)$, $\forall j \neq i$. We note the two corresponding economies $\mathcal{E}(\mathcal{T}_i)$ and $\mathcal{E}(\widetilde{\mathcal{T}}_i)$.

Definition 3 *For a given environmental constraint $\overline{E}$, the technology $\widetilde{\mathcal{T}}_i$ is more eco-efficient than the technology $\mathcal{T}_i$ if the economy $\mathcal{E}(\widetilde{\mathcal{T}}_i)$ is more eco-efficient than the economy $\mathcal{E}(\mathcal{T}_i)$.*

As proved with proposition 3, the condition $\widetilde{Y}^* > Y^*$ boils down to $\widetilde{\Psi}(Y^*) > 1 = \Psi(Y^*)$. In this case, the output level of all the firms $j \neq i$ is lower ($\widetilde{Y}_j^* < Y_j^*, \forall j \neq i$) and their output intensity is lower too ($\widetilde{z}_j^* < z_j^*$). So necessarily the output of the firm i is larger in $\widetilde{\mathcal{E}}$ than in $\mathcal{E}$ and the increase of its own output is larger than the decrease of all the other firms' output (because we have $\widetilde{Y}^* > Y^*$).

In the following difference

$$\widetilde{\Psi}(Y) - \Psi(Y) = \widetilde{\Phi}\left(\frac{2\overline{E}}{Y}, Y\right) - \Phi\left(\frac{2\overline{E}}{Y}, Y\right) \tag{21}$$

only the terms indexed by i may differ, so we can re-arrange it as follows

$$\widetilde{\Psi}(Y) - \Psi(Y) = \frac{K_i}{Y}\left(\widetilde{\mathcal{S}}_i\left(Y, \overline{E}\right) - \mathcal{S}_i\left(Y, \overline{E}\right)\right) \tag{22}$$

where

$$\mathcal{S}_i\left(Y, \overline{E}\right) = \mu_i \left(\frac{2\overline{E}}{Y}\right)^{\frac{1}{1-\alpha_i}} \left(\frac{P(Y)}{w}\right)^{\frac{\alpha_i}{1-\alpha_i}} \tag{23}$$

Naturally, $\widetilde{\mathcal{S}}_i\left(Y, \overline{E}\right)$ is defined in the same way but with $\widetilde{\mu}_i$ and $\widetilde{\alpha}_i$.

Proposition 4 *For a given environmental constraint $\overline{E}$, the technology $\widetilde{\mathcal{T}}_i = (\widetilde{A}_i, \widetilde{b}_i, \widetilde{\alpha}_i)$ is more eco-efficient than $\mathcal{T}_i$ if and only if $\widetilde{\mathcal{S}}_i\left(Y^*, \overline{E}\right) > \mathcal{S}_i\left(Y^*, \overline{E}\right)$, where Y^* is the output level at equilibrium in $\mathcal{E}$.*
In the particular case where $\widetilde{\alpha}_i = \alpha_i$, this condition yields to $\widetilde{A}_i \widetilde{b}_i^{-\frac{1}{\beta}} > A_i b_i^{-\frac{1}{\beta}}$, which is independant from $\overline{E}$, from the technology of the other firms and from the equilibrium.

Proof. We have $\widetilde{Y}^* > Y^* \iff \widetilde{\Psi}(Y^*) > \Psi(Y^*) = 1$ and the difference $\widetilde{\Psi}(Y^*) - \Psi(Y^*)$ has the sign of $\widetilde{\mathcal{S}}_i\left(Y^*, \overline{E}\right) - \mathcal{S}_i\left(Y^*, \overline{E}\right)$. In the case where $\widetilde{\alpha}_i = \alpha_i$ in (23), factors μ_i and $\widetilde{\mu}_i$ are equal and the difference $\widetilde{\mathcal{S}}_i\left(Y^*, \overline{E}\right) - \mathcal{S}_i\left(Y^*, \overline{E}\right)$ has the sign of

$$\widetilde{\mu}_i - \mu_i = \left(\left(\widetilde{A}_i\widetilde{b}_i\right)^{\frac{1}{1-\alpha_i}} - \left(A_ib_i\right)^{\frac{1}{1-\alpha_i}}\right)\left(\tfrac{1}{2}\right)^{\frac{1}{1-\alpha_i}}\left(\tfrac{\alpha_i}{2}\right)^{\frac{\alpha_i}{1-\alpha_i}}$$

and we have $\widetilde{\mu}_i - \mu_i > 0$ if and only if $\widetilde{A}_i\widetilde{b}_i^{-\frac{1}{\beta}} > A_ib_i^{-\frac{1}{\beta}}$. ■

We are consistent with the results provided by Jouvet, Michel and Rotillon (2003): as soon as the elasticities α_i are the same for all the firms, comparing environmental efficiency between firms reverts to comparing the value of $A_ib_i^{-\frac{1}{\beta}}$. This result also applies when one is comparing two different technologies, as soon as the elasticity is the same $((\widetilde{A}_i, \widetilde{b}_i, \alpha_i)$ and (A_i, b_i, α_i) for firm i). As soon as the elasticities differ among the firms, the previous condition also depends on $\overline{E}$: this means that, for different values of $\overline{E}$, the firms' ranking in terms of environmental efficiency may be altered. Consequently, the fact that a firm may be labelled as more eco-efficient than another one depends not only on its own technological features but also on the equilibrium prevailing on all the markets it is operating on. A numerical illustration is provided in the next section. The comparison of two technologies $\mathcal{T}_i$ and $\widetilde{\mathcal{T}}_i$ has been defined by comparing two economies in which only these technologies differ (definition 2). Now, the result of proposition 4 allows us to compare two technologies within a single economy.

Definition 4 *In an economy $\mathcal{E}$ with an environmental constraint $\overline{E}$, the technology of the firm i (A_i, b_i, α_i) is more eco-efficient than the technology of the firm j (A_j, b_j, α_j) if $\mathcal{S}_i\left(Y^*, \overline{E}\right) > \mathcal{S}_j\left(Y^*, \overline{E}\right)$.*

As stated in proposition 4, this definition may be interpretated as follows: if the firm j were adopting the firm i's technology, keeping constant its capital stock K_j and all the other firms being unchanged, then total output at equilibrium would increase in the economy. At the new equilibrium, the output level of firm j would be increased and the output level of all the other firms would be decreased. Furthermore, considering (18) we have

$$\mathcal{S}_i\left(Y^*, \overline{E}\right) = \frac{Y_i^*}{K_i} \tag{24}$$

One criterion of firm i's environmental performance at equilibrium when emissions are constrained at the global level is its output level per unit of capital.

4.3 A numerical illustration

A numerical illustration is given hereafter. We first consider an economy $\mathcal{E}$ with two firms ($i = 1, 2$) having the same technology, that is to say $\mathcal{T}_i = (A_i, b_i, \alpha_i), \forall i = 1, 2$. The inverse demand function writes $p = hY^{-y}$ (with $h > 0$ and $y > 0$). The values for the parameters and exogeneous variables are the following: $K_i = A_i = b_i = 1$, $\alpha_i = 0.8$, $h = 5$ and $y = 0.3$. The computable model is set as follows: Y_i^* is calculated from equation (20) with μ_i provided from equation (14); equilibrium on the output and permits markets is verified through equations (10) and (15). The numerical simulation gives that equilibrium level of output without environmental constraint is $Y^0 = E^0 = 7.10$ (since $b_i = 1$) with $Y_1^0 = Y_2^0 = 3.55$. As soon as an environmental constraint $\overline{E}$ is imposed on the industry (numerically, $0 < \overline{E} < 7.10$), the output level is reduced in the industry. This reduction is the same for the two firms since they are identical. The stronger the emission constraint, the larger the loss of output.

Now, let us consider a change in the technology of firm 2. Economy $\widetilde{\mathcal{E}}$ will differ from economy $\mathcal{E}$ by the fact that $\widetilde{\alpha}_2 = 0.3$, all other things being unchanged. The same environmental contraint has now differentiated impacts on the two economies and on the two firms: the simulations show that the rankings in terms of eco-efficiency depends on the harshness of the constraint.

Figure 1 displays the difference between global output levels in the two economies (in percentage) with respect to the environmental constraint $(\overline{E})$. A threshold appears at $\overline{E} = 4.22$. Above this threshold we have $Y^* > \widetilde{Y}^*$ whereas $Y^* < \widetilde{Y}^*$ below, revealing that the economy $\mathcal{E}$ is *more eco-efficient* than the economy $\widetilde{\mathcal{E}}$ when the environmental constraint is not too strong.

< Figure 1 here>

Figure 2 displays firms output levels with respect to $\overline{E}$ at equilibrium in the two economies $\mathcal{E}$ and $\widetilde{\mathcal{E}}$. At the equilibrium in $\mathcal{E}$, output decreases are the same $(Y_1^* = Y_2^*)$ while they differ in economy $\widetilde{\mathcal{E}}$: the curves $\widetilde{Y}_1^*$ and $\widetilde{Y}_2^*$ are crossing at the threshold $\overline{E} = 4.22$. Firm 1 is *more eco-efficient* than firm 2 for slight abatement constraints $(4.22 < \overline{E} < 7.10)$ but it is the other way round for more stringent abatements $(0 < \overline{E} < 4.22)$. It may be noticed that, when initial allocations are equal $(\overline{E}_1 = \overline{E}_2 = \overline{E}/2)$, the most eco-efficient firm has the higher output level and buys emission permits to the less eco-efficient one.

< Figure 2 here>

5 Eco-efficiency and capital profitability

Up to now we restricted ourselves to a short term analysis with capital stock as given. Under that context we have shown that comparing eco-efficiency among the firms at a given equilibrium boils down to comparing their output - capital ratios. Now we shall take into account the fact that the capital profitability is influenced by the initial allocation of permits among the firms.

5.1 Capital profitability at equilibrium

Let us define capital profitability as the net receipt divided by the capital stock.

Proposition 5 *The firm i's capital profitability at equilibrium satisfies*

$$\frac{\pi_i}{K_i} = \frac{1-\alpha_i}{2} p^* S_i \left(Y^*, \overline{E} \right) + q^* \frac{\overline{E}_i}{K_i} \tag{25}$$

Proof. In equilibrium the two following relations hold from (9) and (14)

$$wL_i^* = \frac{\alpha_i}{2} p^* Y_i^* \quad \text{and} \quad q^* E_i^* = \frac{1}{2} p^* Y_i^*$$

So the profit of firm i, given by $\pi_i = p^* Y_i^* - wL_i^* - q^* \left(E_i^* - \overline{E}_i \right)$, writes

$$\pi_i = \frac{1-\alpha_i}{2} p^* Y_i^* + q^* \overline{E}_i$$

and with (24) we obtain (25). ■

Hence, there are three reasons for which the ordering in terms of capital profitability may differ from the ordering in terms of eco-efficiency: the technical efficiency (S_i), the value of the labor elasticity α_i and the relative permits endowment $\overline{E}_i / K_i$.

5.2 Eco-efficiency *versus* capital profitability

The case where elasticities are identical among the firms has been considered by Jouvet *et al.* (2003). In this particular case, the ranking in terms of eco-efficiency strictly determines the ranking in terms of profitability whenever the initial permits allocations per unit of capital respect the same ranking. In particular, if the initial allocations satisfy $\overline{E}_i/K_i = \overline{E}_j/K_j \;\; \forall i$ and j, then we have $\pi_i^*/K_i > \pi_j^*/K_j$ if and only if $S_i\left(Y^*, \overline{E}\right) > S_j\left(Y^*, \overline{E}\right)$: the ranking in terms of profitability fits with the ranking in terms of eco-efficiency. As soon as the elasticities differ, it becomes possible to get both $S_i\left(Y^*, \overline{E}\right) > S_j\left(Y^*, \overline{E}\right)$ and $(1-\alpha_i)\, S_i\left(Y^*, \overline{E}\right) < (1-\alpha_j)\, S_j\left(Y^*, \overline{E}\right)$. In other words, even if $\overline{E}_i/K_i = \overline{E}_j/K_j \;\; \forall i$ and j, we are not sure that the most eco-efficient firm will have the higher profitability.

This difference may be interpretated as the difference in the marginal productivity of capital between firms i and j. Indeed, with $Y_i^* = z_i^* A_i K_i^{1-\alpha_i} \left(L_i^*\right)^{\alpha_i}$ the partial marginal effect of K_i on Y_i^* writes

$$\frac{\partial Y_i^*}{\partial K_i} = (1-\alpha_i)\, \frac{Y_i^*}{K_i} = (1-\alpha_i)\, S_i\left(Y^*, \overline{E}\right) \tag{26}$$

If we consider the example took in section 4.3 with equal initial allocations of permits among the two firms, only the last term in equation (25) would be identical between the firms. The difference in profitability would not only come from the difference in eco-efficiency (S_i) but also in capital elasticities $(1-\alpha_i)$. Numerically, the difference in elasticities dominates the difference in eco-efficiency for any emissions constraint at the industry level and we always get $\widetilde{\pi}_2/K_2 > \widetilde{\pi}_1/K_1$ (see figure 3).

<Figure 3 here>

6 Conclusion and policy implications

In this paper we examine how firms' or industries' ranking in terms of eco-efficiency is influenced by market outcome, that is to say here by the global emissions constraint imposed on the industry. We adopt a quite natural definition of relative eco-efficiency between two industries operating within the same environmental constraint: the more eco-efficient one is the one with the higher output level. The analysis of this condition allows us to compare the relative eco-efficiency of two technologies characterising two different industries, and also to compare two firms within the same industry. We show that all these comparisons depend, through the equilibrium, on the environmental constraint imposed at the industry level.

In our model, firms' heterogeneity arises from three parameters: a scale parameter, technological pollution intensity parameter and labour elasticity. Wage rate and capital stock are given for each firm. For a given global emissions ceiling imposed at the industry level we characterise the equilibrium on the output and permits markets and derive their relative price ratio as a function of total output. This shows how equilibrium is altered when global output level is modified. When the industry experiences an emissions constraint, we show that there exists a unique equilibrium such that firms' utilisation rates depend both on their technological features and on the equilibrium price ratio. One assumption on the technologies in our model implies that the emissions output ratios are the same among firms. This property allows us to aggregate these ratios, which leads to interesting conclusions. It seems quite natural to define eco-efficiency at the industry level as follows: an industry is more eco-efficient than another one whenever its output level at equilibrium is higher under the same environmental constraint.

When comparing two economies, we demonstrate that the most eco-efficient one has both the smallest output/permit price ratio and the smallest emissions/output ratio. This reveals that, even if the emissions/output ratio is not an adequate indicator of eco-efficiency at the firm level, it can be at the industry level. Importantly, one firm having the same technology in these two economies will have a smaller output level in the most eco-efficient one.

It is possible to apply this definition to compare the eco-efficiency of two technologies. This is done by comparing two economies that only differ by a single firm's technology, and is achieved by comparing the technological coefficients and the equilibrium between the two economies. In the particular case where the labour elasticities are the same, this comparison boils down to comparing the technologies independently of the equilibrium, which is no longer the case when the elasticities differ. This result also allows us to compare firms within a single industry. Given an environmental constraint at the industry level, a technology is more eco-efficient than another one if, whenever a firm adopts it, industry output level is higher. Moreover, at the new equilibrium, this firm's output level will increase whereas the output level of all the other firms will decrease. Finally, we show that the ordering in terms of capital profitability might differ from the ordering in terms of eco-efficiency depending on the value of the capital elasticity and the relative permits endowment.

A numerical illustration shows that the firm's ranking in terms of eco-efficiency does depend on the environmental constraint imposed at the industry level, proving that this ranking depends on the equilibrium. Finally we see that a firm's profitability at equilibrium depends on its eco-efficiency, but also on its labour elasticity and permits allocation. In other words, even under the same emissions constraint, the most eco-efficient firm is not necessarily the most profitable one.

Our paper provides an economic rationale for the concept of eco-efficiency. The policy implications are of great importance as soon as eco-efficiency measures and benchmarking procedures are involved in economic policy, and we show that this is an increasingly common practice nowadays. Eco-efficiency (defined as the largest output level under a given environmental constraint) cannot be considered independently of the market conditions: it is only at equilibrium that eco-efficiency can be properly evaluated. This is particularly true as far as the environment is concerned. A comprehensive evaluation of efficiency from a social point of view requires the environmental concerns to be fully internalised; a suitably-designed tradable permits system allows that. In comparison with a tax, tradable permits offer the advantage of highlighting the necessity of an emissions ceiling and being efficient both from an economic and an environmental point of view. However, the issue of individual allocation rules remains open, beyond the scope of the efficiency analysis. We see that, even if it has no effect on the equilibrium in our model (which it would have in a general equilibrium context), the allocation rule does affect the individual firm's profitability. Consequently, current practices based on *ex ante* benchmarking procedures should be used with caution. In particular, we show that considering the emissions/output ratio as an indicator of eco-efficiency or marginal abatement cost at the firm's level is really misleading. Furthermore, a free allocation rule based on past emissions (the so-called 'grandfathering' rule) is nothing but a gift to the most polluting firms before environmental regulation. From these two arguments we plead for *(i)* an improvement of the benchmarking procedures to encompass economic dimensions and *(ii)* auctions when tradable emission permits are implemented. Meeting these two requirements will help achieving efficient environmental protection under efficient economic conditions, leading to socially optimal policies.

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Figure 1. Difference (in %) between total output level in the two economies w.r.t. the environmental constraint $(\widetilde{Y}^* / Y^* - 1)$

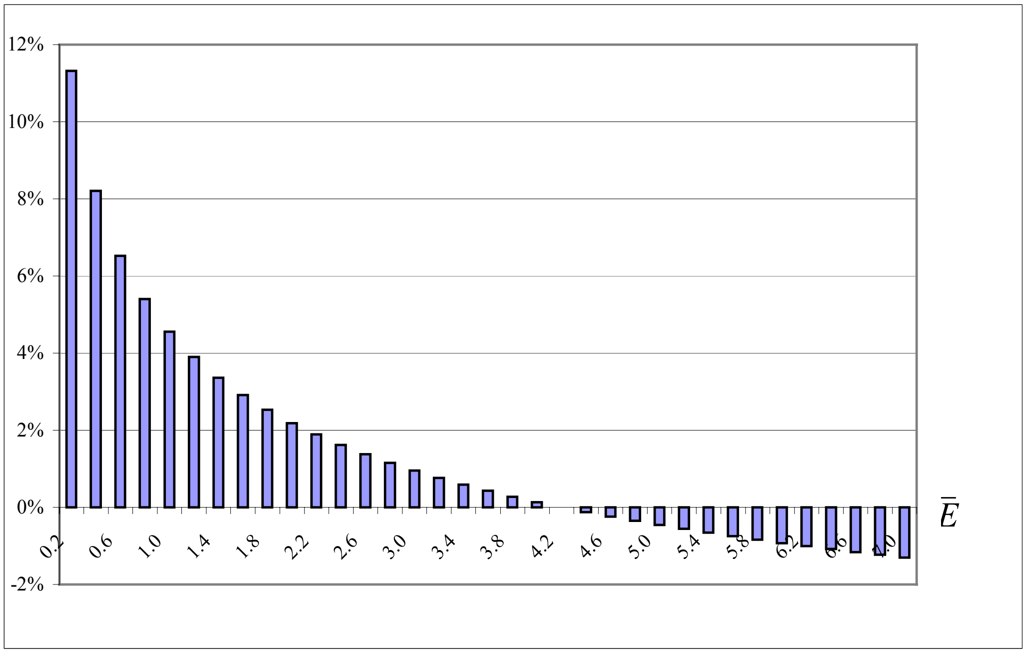


Figure 2. Firms' output level in the two economies w.r.t. the environmental constraint

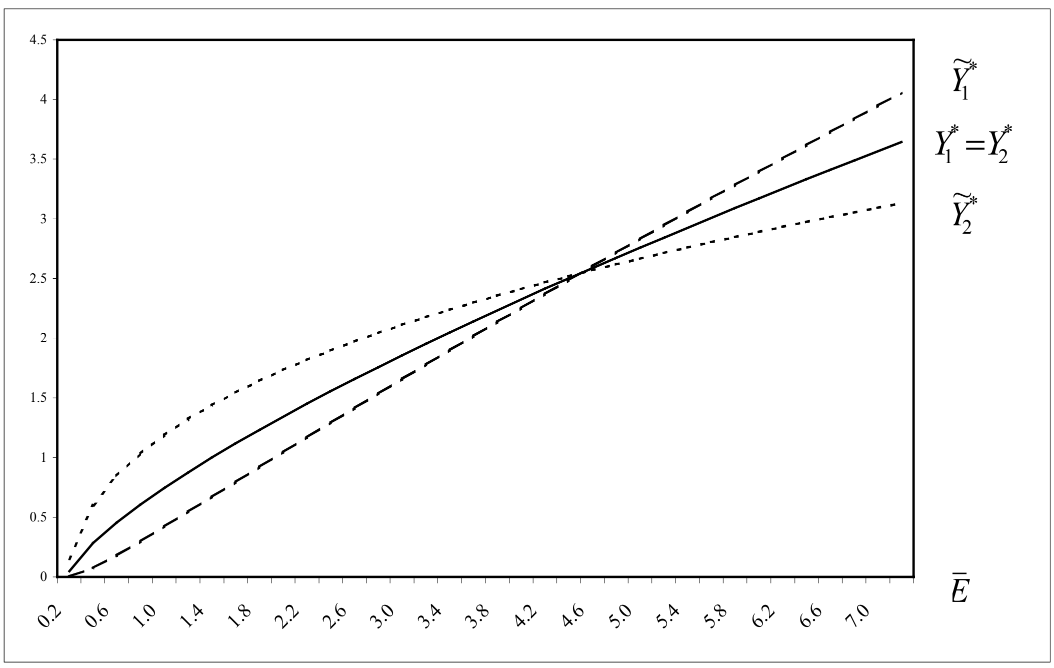
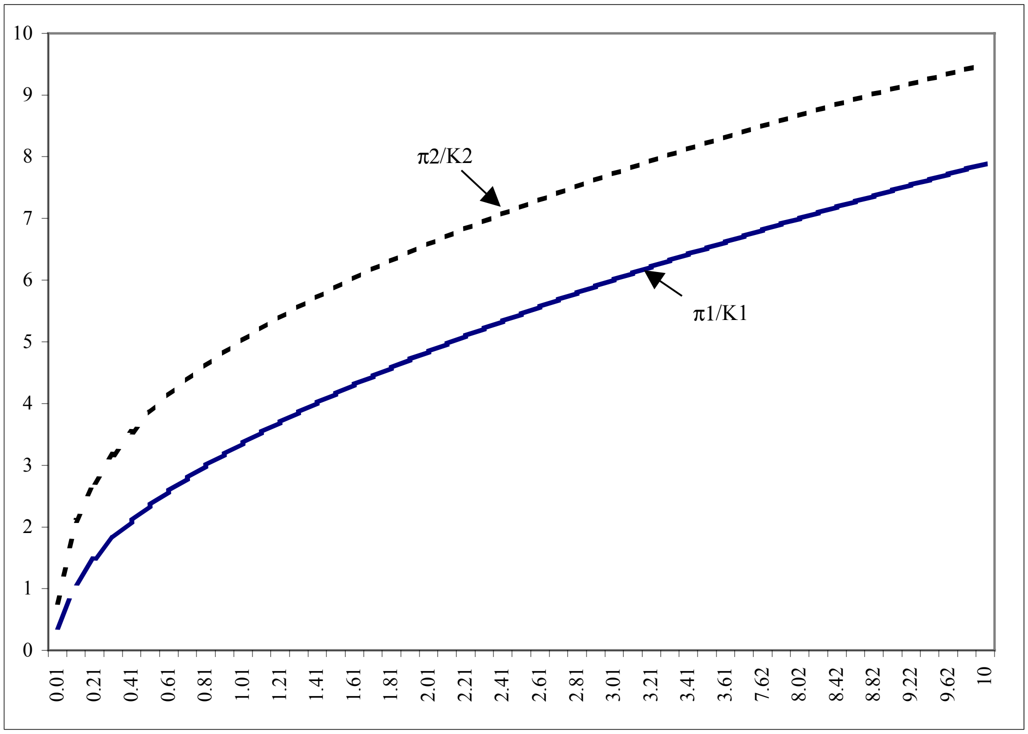


Figure 3. Firms' profitability in the two economies w.r.t. the environmental constraint



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Chair Lhoist Berghmans in Environmental Economics and Management
Center for Operations Research & Econometrics (CORE)
Université catholique de Louvain (UCL)
Voie du Roman Pays 34
B-1348 Louvain-la-Neuve, Belgium

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