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Technological greening, eco-efficiency, and no-regret strategy

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Abstract

In this paper we analyze the relationship between technological greening, eco-efficiency and no-regret strategies. By using a simple theoretical model, we evaluate the effects of technological greening on creation value, pollution level, and eco-efficiency. We show three contrasting effects of technological greening. First, technological greening may increase the pollution of a firm, and also of the whole industry. Second, the indicator of eco-efficiency can be misleading because it may improve in situations where pollution increases and/or profit decreases after technological greening. Third, technological greening that induces an improvement of the eco-efficiency indicator does not necessarily lead to a no-regret strategy. As a result, the indicator should not be used for decision making.

Keywords: technological greening, clean technology, eco-efficiency, environmental performance, rebound effect.

JEL Classification: L8, M2, Q5

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1 Introduction

In order to provide a comprehensive evaluation of both the environmental and the economic performance of firms, the World Business Council for Sustainable Development (WBCSD) elaborated in 1991 the concept of eco-efficiency, to be understood as the ratio of product value over environmental pressure (Schmidheiny, 1992). Broadly defined, eco-efficiency is also a management philosophy that encourages business to look for environmental improvements that yield joint economic benefits. As an example, Schmidheiny (1992) defines eco-efficient companies as “those which create ever more useful products and services while continuously reducing their consumption of resources and their pollution”. De Simone and Popoff (1997) extend the scope of this definition with four criteria: the definition of targets to reach, the dynamic assessment of environmental performance, the broad integration of environmental impacts, and the awareness of the firm’s impact on the Earth’s carrying capacity. Basically, the underlying idea behind all these definitions is that it is a good thing to produce more desirable output with less undesirable output.

In fact, very few papers in the literature address the issue of eco-efficiency from a theoretical perspective. Our purpose in this paper is to understand the relationship between technological greening, eco-efficiency, and no-regret strategies. Let us briefly define these three terms. *Technological greening* simply consists in the adoption of a less polluting technology. Thus, technological greening is good for the environment because it reduces the pollution level, but it can be costly to the firm since an advanced green technology is more expensive than an old dirty one. However, some authors believe that adopting a clean technology may yield competitive advantages, which leads on to the concept of no-regret strategy. A *no-regret strategy* is a strategy (here, investing or not in a green technology) such that the decrease in pollution is accompanied by an increase in profit. It can clearly be seen that the concept of *eco-efficiency* is the nexus of these two previous concepts. Furthermore, it is even considered by the WBCSD to be a tool for decision-making. Improving the value of the eco-efficiency indicator by technological greening means that more value is created with less pollution. In this paper we question this idea. Does the eco-efficiency indicator really capture all the effects of technological greening? Can it help in identifying no-regret decisions? In fact, we will see that the eco-efficiency indicator cannot be trusted.

Two strands of literature are of special relevance to our study. The first one deals with the relationship between environmental performance and economic performance. There exist two slightly different standpoints. Some authors argue that greater environmental performance systematically increases the firm's economic performance. Porter and Van Der Linde (1995), for example, consider that environmental performance is a key opportunity to foster a firm's competitive position, as it allows for increases in profitability or market share. Improving environmental performance may also lead to benefits from a managerial point of view. Hart (1995) or Russo and Fouts (1997) argue that an environmentally friendly technology may be a competitive advantage used as a resource-based strategy of the firm. A theoretical rationale for such no-regret options is provided by Bréchet and Jouvet (2009). The idea that greater environmental performance may foster economic performance has also been stressed by many empirical studies. Some papers show that better environmental performance increases the firm's value. For example, Dowell *et al.*, (2000) show that environmental performance (through compliance with environmental standards) is profitable to the firm. King and Lenox (2002) assess the positive relationship between environmental and economic performance through waste prevention, while Sinkin *et al.* (2008) study the impacts of ISO 14000 on a firm's value. Rennings *et al.* (2006) show the positive effect of environmental innovation on economic performance. All these results illustrate the idea that technological greening makes the firm better off, which coincides with an improvement in eco-efficiency.

On the other hand, some authors consider that an improvement in environmental performance does not systematically lead to an increase in economic performance *e.g.* Lankoski (2006). Palmer *et al.* (1995) show that stringent environmental regulation reduces a firm's profit because of the cost of environmental compliance. Boons and Wagner (2009) question the current assessment which states that innovation has an effect only on economic and ecological performance. The authors discuss the existence of a broader range of actions for innovation that explains this unclear relationship between innovation, environmental and economic performance. Bréchet and Michel (2007) formally show that the ranking of firms in terms of environmental performance depends not only on technological choice, but also on market equilibrium. In other words, the ranking cannot be reduced to the mere technological greening issue.

In this paper we formally make the link between technological greening, eco-efficiency and no-regret strategy. Our contribution is to question whether an improvement of the eco-efficiency indicator due to technological greening necessarily leads to an increase in profits and a decrease in pollution. To this end, we develop a framework to understand the effects of technological greening on a firm's profit, a firm's emissions, emissions at the market level, and on the WBCSD indicator of eco-efficiency. By using a simple theoretical model we show that for a high tax level that gives a positive incentive for a less polluting technology, technological greening does not necessarily reduce emissions, either at the firm level or at the market level. However, the eco-efficiency indicator might improve, thus providing a wrong signal to decision-makers. These results do question the reliability of the indicator for decision-making. Indeed, we show that, after technological greening, the eco-efficiency indicator can increase when the firm experiences a profit loss and/or when the emission level increases. Finally, we show that the improvement of the eco-efficiency indicator is a necessary but not a sufficient condition for no-regret strategies.

The paper is organized as follows. In the next section we propose an overview of the use of the eco-efficiency indicator in business practice. In Section 3 the setting is presented. Section 4 analyzes the effects of technological greening on profit and emissions at the firm level. Section 5 discusses the cases of no-regret strategy and Section 6 analyzes the effects of technological greening on the eco-efficiency indicator. The last section is the conclusion.

2 Eco-efficiency in practice

Before beginning the theoretical analysis it is of interest to see to what extent the concept of eco-efficiency, and the related indicators, are used in practice.

Private and public sectors make wide use of eco-efficiency as an indicator to support decision-making. As guidance for managers and policy-makers in measuring and assessing a firm's performance, many institutional reports are based on the WBCSD concept, see *e.g.* Schmidheiny (1992), WBCSD (2000), Verfaillie and Bidwell (2001). Some institutions further develop managerial specificities linked to the indicator so as to widen its scope, for example in finance, accountancy or production areas. For example, the United Nations Conference on Trade And Development (Sturm *et al.*, 2003) and the widely used Global Reporting Initiative (GRI, 2006) provide a method to report environmental performance with respect to financial performance in an accountancy framework. Interestingly, both reports are divided into categories of materials (water use, energy use, global warming contribution, etc.) and assessment areas (economic, labor, environmental, social or human rights indicators).

At the business level, Ditz and Ranganathan (1997) wrote a report for the World Resources Institute that highlights the use of intensity measures for internal comparisons, but without providing any detail on the calculations. In addition to its 1991 seminal report, the WBCSD has also developed a classification of indicators into core and supplemental subdivisions, as presented by Verfaillie and Bidwell (2001). The first category of indicators is implementable, which makes comparisons between sectors or firms feasible. The second category consists in business-specific indicators which are designed to be used for internal purposes or for comparisons between plants in the same industry. This suggests that the generic concept of eco-efficiency cannot be generalized or, to put it in different terms, that eco-efficiency is sector-specific. We shall return to this point. In Canada, the National Round Table on the Environment and the Economy (NRTEE, 2001) has created a workbook defining indicators according to the life cycle approach (*from cradle to grave*). It classifies the indicators in energy use, waste intensity and water intensity. The eco-efficiency ratios are then calculated as the amount of resource consumed or as undesirable output over production level. See also Callens and Tyteca (1999) for more developed sets of indicators.

Finally, there also exists a literature on eco-efficiency that focuses on the implementation aspects at the company level. For example, BASF (Saling *et al.*, 2002) and Akzo Nobel (Cramer and van Lochem, 2001) have both published case studies on the eco-efficiency analysis of their production processes. Both use the eco-efficiency indicator in a broad sense, including life-cycle analysis. They have developed measurements for internal comparison among their own products. The methodology is not the same in the two case studies. BASF assesses eco-efficiency with diamond diagrams, because they want to encompass multi-pollutant products. Such a comparison is difficult because of the multidimensional problem (weightings, pollution preferences: is it better to produce a good that emits a lot of sulfur dioxide and little carbon dioxide, or the contrary?). The other firm, Akzo Nobel, assesses eco-efficiency by comparing six pilot projects corresponding to six business units differentiated by their innovation level. Both studies make use of eco-efficiency for internal comparison.

3 The setting

Our purpose is to develop a simple theoretical setting in order to understand the effects of technological greening at the firm and market levels. We consider a static, short term analysis. The industry is composed of a continuum of n heterogeneous firms. Each firm is indexed by $i \in F : \{1, ..., n\}$ and uses a production function $y_i = \sqrt{x_i}$, where y_i is the output and x_i is the input. Firms operate under perfect competition. The output price is p and the input price is normalized to 1. Let us denote by e_i the pollution level of firm i. Pollution is a joint product of output,

$e_i = y_i/b_i$, where b_i is the inverse of the emission/output intensity. We assume that firms acquired their initial technology before the enforcement of a regulation on environment. So the firms are differentiated by their polluting intensity $1/b_i$. By convention, the most polluting technology is $b_1 = 1$ and the cleanest one is $b_n = b_{max} > 1$. From now on, the regulator levies a uniform emission tax t on pollution. Firm i's problem writes as follows:

$$\max_{\{e_i\}} \qquad \pi_i = py_i - x_i - te_i, \forall i \in F.$$

The problem is solved by substituting y_i by e_i. The first-order condition gives the firm's optimal emission level (e_i^*), which yields the expressions for output (y_i^*) and profit (π_i^*) at the firm's optimum:

$$e_i^* = \frac{pb_i - t}{2b_i^2}, \tag{1}$$

$$y_i^* = \frac{pb_i - t}{2b_i},$$

$$\pi_i^* = \left(\frac{pb_i - t}{2b_i}\right)^2. \tag{2}$$

The impact of the emission tax on firm i's profit is $\triangle\pi_i = \pi_i^*(t > 0) - \pi_i^*(t = 0) = t(t - 2b_ip)/4b_i^2$. This expression shows that two effects interplay. On the one hand, the higher the tax level, the lower the profit (which is not surprising). But, on the other hand, for a given tax level, the lower b_i, the higher the profit decrease due to the tax. This means that a firm with a greener technology (*i.e.* a higher b_i) will experience a lower profit decrease if the tax is implemented. Does this suggests that, under some tax regulation, a firm always has an incentive to green its technology? And is it the case that technological greening is always good for the environment? In the sequel we will see that it is not always the case.

4 The effects of technological greening at the firm level

In this section we shall analyze the effects of technological greening at the firm level. Let us start by being precise about the terminology. We formally define *technological greening* as a marginal increase in b_i. Such an increase represents the adoption of a less polluting (or 'green') technology per unit of output. Technological greening is not free. It raises a cost given by ab_i, with $a > 0$. Because we consider marginal improvements of the technology, this cost corresponds to a marginal cost of adoption. This adoption cost is larger when the technology is already very clean (b_i is high). So the whole analysis will be conducted in marginal terms. We shall provide a comparative static analysis about the effect of improving a technology on profit and emissions.

4.1 The effects on firm's profit

The effect of technological greening on firm i's profit is given by the first derivative of equation (2) with respect to the technological parameter b_i, net of the adoption cost ab_i. This allows us to define a function φ of t, parametrized by b_i:

$$\varphi_i^*(t; b_i) \equiv \frac{\partial \pi_i^*}{\partial b_i} - ab_i = \frac{-t^2 + b_i pt - 2ab_i^4}{2b_i^3}.$$

The equation $\varphi_i^*(t; b_i) = 0$ provides us with an iso-profit frontier on which firm i's profit is unchanged after technological greening. The existence of real roots for $\varphi_i^*(t; b_i) = 0$, denoted by $\underline{t}_i$ and $\bar{t}_i$, relies on the assumption that a, the scale parameter of the greening cost, is not too large. Formally, we must have $a < p^2/8b_i^2, \forall i \in F$. The iso-profit frontier is described by functions that are defined by the roots of $\varphi_i^*(t; b_i) = 0$, in (b_i, t). In this space firm i's profit increases or decreases after technological greening, depending on *(i)* its initial technology, *(ii)* whether the emission tax is inside or outside a frontier $t(a, b_i, p)$ defined by $\underline{t}$ and $\bar{t}$. This leads us to our first result.

Proposition 1 *Firm i's profit can increase or decrease after technological greening, depending on the tax level and firm i's initial technology.*

Proof *See Appendix A.1*

The rationale behind this first proposition is twofold. Firstly, greening the technology entails a cost for the firm, and the cleaner the initial technology, the higher the cost increase. When the technology is already very efficient (large b_i) it may be too costly to improve it further in comparison with the savings on the tax bill. This is why profit can decrease when b_i is initially high (this corresponds to the right side of the φ_i frontier). Secondly, the higher the tax on pollution, the stronger the incentive for technological greening. Upgrading the technology is all the more profitable as the tax is high. However, for a very high tax level a firm with a low b_i may also experience a profit decrease. In such a situation, the emission reduction due to the technological greening does not compensate for the tax burden. To remain profitable, the firm should make a stronger innovation effort (even greater b_i).

Naturally, these two effects interplay and it may well be the case that the frontier φ_i is wide enough to make technological greening profitable for all initial technology levels.

4.2 The effects on firm's pollution

Let us now turn to the effect of technological greening on pollution. At the firm's optimum the emission level is given by equation (1). As previously, the effect of technological greening on firm's pollution is given by the first derivative of this expression with respect to b_i, which leads to the following function:

$$\psi_i^*(b_i, t) \equiv \frac{\partial e_i^*}{\partial b_i} = \frac{2t - b_i p}{2b_i^3}. \qquad (3)$$

The frontier $\psi_i^*(t; b_i) = 0$ is such that technological greening has no impact on firm i's pollution level. It gives us an iso-emission function, $\tilde{t}_i = b_i p/2$. Firm i's pollution increases or decreases with technological greening depending on *(i)* its initial technology and, *(ii)* whether the tax is above or below a frontier $t(b_i, p)$ given by $\tilde{t} = b_i p/2$. The following proposition summarizes the effect of technological greening on firm i's pollution.

Proposition 2 *Firm i's pollution can increase or decrease after technological greening, depending on the tax level and firm i's initial technology.*

Proof *See appendix A.2*

This result may seem counterintuitive. Actually, it may well be the case that, after having adopted a cleaner technology, the firm pollutes more. For a given tax level, unambiguously, technological greening reduces firm's emission output intensity. But it also allows for an increase in the marginal productivity of pollution, which results in an increase in the firm's production, *ceteris paribus*. The increase in output level can offset the improvement in pollution intensity, so that the firm's pollution level can increase. Such a situation is known in the energy economics literature as the *rebound effect* (see, *e.g.*, Greening *et al.*, 2000; Berkhout *et al.*, 2000). Gains in the efficiency of energy consumption can result in an effective reduction in the per unit price of energy services or an increase in market share such that, by the end, energy consumption increases, partially offsetting the impact of the efficiency gain. So the rebound effet can result from an equilibrium effect through prices, or through a productive effect. Because all prices are exogenous in our setting, only the latter effect comes out. Interestingly, this rebound effect appears when the tax on pollution is high enough. For a given b_i, the higher the tax, the stronger the reduction of the production cost after technological greening, and thus the stronger the increase in output.

5 Technological greening and no-regret strategy

At this stage of the paper, the puzzling result is that pollution level can increase after technological greening at the firm level. We have formally identified the situations for this to appear. Clearly, one may want to avoid such situations. Among the situations where pollution decreases (good news), it may happen that profit decreases (bad news). The purpose of this section is to identify the cases in which technological greening can yield a 'no-regret' strategy, that is, technological greenings leading to a profit increase and a pollution decrease. In this section we will see that such no-regret situations happen under different conditions at the firm level and at the aggregate level.

5.1 No regret at the firm level

Could it be possible that a firm has a positive incentive for technological greening and, by the end, that pollution increases? Conversely, could it be the case that technological greening reduces emissions while not providing a positive incentive to the firm? To answer these questions we shall combine the insights from the two previous analyzes. It is well-established in the literature that a pollution tax provides positive incentives for technological greening. Following this literature, the higher the tax, the stronger the incentive (see Requate 1995, 1998). Hereafter, following Bréchet and Jouvet (2008) we will see that it is not necessarily the case.

Our analysis is conducted by using the graphical illustration provided in Figure 1. We restrict ourselves to firms producing a positive output level ($y_i^*(t;b_i) \geq 0, \forall i$). We define the set domain as the space $(t;b_i)$ within the two following frontiers. The first frontier, defined by $t = b_i p$, is such that firms produce a positive output level when they are interior to the frontier (*i.e.* a smaller b_i and/or a smaller t). The second frontier is defined by b_{max}, the best available technology that has the lowest emission-output intensity. In Figure 1, one can also see the frontier related to the incentive for technological greening $\varphi_i^*(a, b_i, t) = 0$. A firm characterized by some $(t;b_i)$ and located inside the φ_i frontier will experience a profit increase after technological greening. Outside this frontier, the firm will experience a profit loss. The other frontier, $\psi_i^*(t;b_i) = 0$, is also displayed. Below that frontier, the firm's emissions decrease after technological greening; above, they increase. This function is increasing and linear with a slope $p/2$. The four frontiers gathered in Figure 1

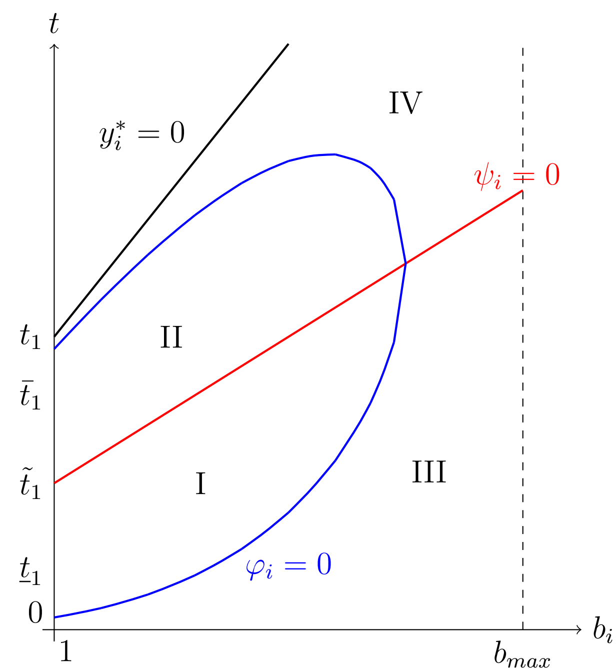

Figure 1: Combination of the effects of technological greening

split the domain into four areas labeled (I), (II), (III) and (IV).

In area (I), polluting emissions decrease with technological greening and profit increases. Here, technological greening corresponds to a no-regret strategy. In area (II), the firm experiences the rebound effect: technological greening yields a higher profit level, but pollution increases too. In this case, the positive incentive to improve the technology harms the environment. In area (III), polluting emissions decrease with technological greening, but profit does the same. In this case, the firm has no incentive for technological greening. At last, in area (IV), emissions increase with technological greening, but profit level decreases also. In other words, the initial technology is already efficient, so greening it even further is not profitable. This situation is not desirable because both the environment and the firm are worse-off.

5.2 No regret at the aggregate level

Considering that it may happen that a firm has a positive incentive for technological greening but also that, as a result, its emission level increases, one may ask about the outcome at the market level. If all firms having a positive incentive to green their technology do it, can it happen that aggregate pollution level increases at the industry level? Is it possible that the emission increase of some firms is offset by the emission reduction of some other firms? We already know that pollution increase (after technological greening) happens for firms with a low b_i and when the tax level is high. So, one way to answer that question is to search whether there exists a tax level such that technological greening (with a positive incentive) leads to an increase in the aggregate pollution level. The effect of technological greening on the aggregate pollution level is:

$$\triangle e \equiv \int_{b_1(t)}^{b_2(t)} \partial e_i db, \forall t$$

Formally, we are looking for a tax level - if it exists - such that technological greening - with positive incentive - leads to an increase in the aggregate pollution level. Let us denote by b_1 and b_2 the technological boundaries within which the firms have a positive incentive for technological greening (see Section 4.1). Within these boundaries, for a given tax t, the aggregate effect of technological greening on aggregate emissions is thus given by:

$$\triangle e = \frac{b_2(t) - b_1(t)}{2b_1(t)b_2(t)} \left[t\frac{(b_1(t) + b_2(t))}{b_1(t)b_2(t)} - p \right]$$

As a consequence, aggregate emissions increase if $t > pb_1(t)b_2(t)/(b_1(t) + b_2(t))$. To understand how this condition shapes the result it is convenient to consider an numerical example. Let us consider three different tax levels such that $b_1(t) = 1$: $t = 3.5$, $t = 2.5$ and $t = 1.0$. Figure 2 illustrates the effect of technological greening both on the continuum of firms firm and at the aggregate level.[1] The horizontal-axis represents the continuum of technologies and the vertical axis represents the variation of the emission level after technological greening. Let $b_2(t)$ be the critical technology below which the incentive is positive. The aggregate variation in pollution is provided by the integral under and above these curves between b_1 and b_2. One can see that, for small and medium tax levels, aggregate emissions decrease after technological greening. With $t = 3.5$, the firms that initially had a very polluting technology (low b_i) experience a rebound effect, while the firms with a larger initial b_i pollute less. Aggregate emissions increase after technological greening when the first effect dominates the second one.

This result is summarized in the following proposition.

[1]Parameters value are: $p = 5$, $a = 0.5$.

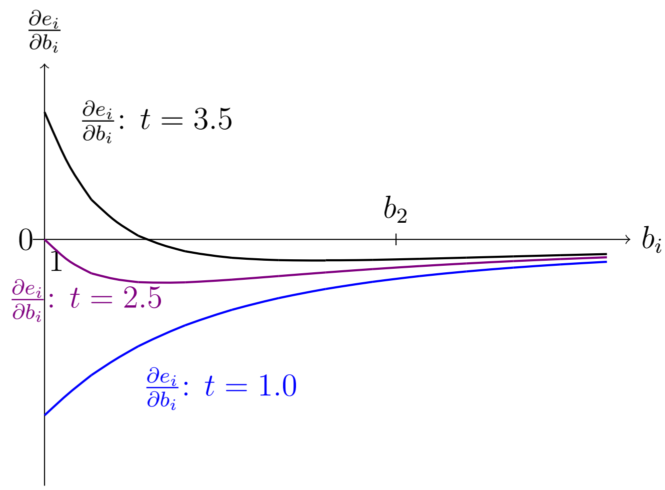

Figure 2: Effect of technological greening on firm's emissions, for three tax levels

Proposition 3 *Aggregate pollution increases after technological greening if the tax on pollution is high enough.*

Two major implications can be drawn from this result. First, it questions the very concept of *clean technology*. A firm with a larger b_i does not necessarily pollute less. Besides the mere technological issue (the choice of b_i), there exists an economical issue, that is, the way the firm makes use of the polluting factor within the production process and on the market. It appears that the relationship between a tight regulation that provides an incentive for innovation and pollution reduction is not straightforward. The incentive may be bad for the environment. Second, it also questions the reliability of the WBCSD eco-efficiency indicator in its ability to detect no-regret strategies. Scrutinizing further this issue is the purpose of our last section.

6 Is the eco-efficiency indicator reliable?

In this section we question the eco-efficiency indicator proposed by the WBCSD. In other words: is this indicator able to detect the situations where technological greening leads to a no-regret strategy (less pollution, more profit)? The indicator advised by the WBCSD consists in the ratio of created value over environmental impact. We shall interpret it as the ratio between profit level and emission level. This definition is consistent with current business practices (see Section 2). So we shall formally define the eco-efficiency indicator at the firm's optimum as ${I_i}^* = \pi_i^*/e_i^*$. The effect of technological greening on this indicator is given by its first derivative with respect to b_i:

$$\Lambda_i^*(b_i, t) \equiv \frac{\partial I_i}{\partial b_i} = \frac{(\partial \pi_i^* - ab_i)e_i^* - \pi_i^*(\partial e_i^*)}{(e_i^*)^2} = \frac{-pt + b_i p^2 - 4ab_i^3}{2(b_i p - t)}$$

The function $\Lambda_i^* = 0$ provides us with a frontier on which technological greening does not impact the indicator. This gives us a function $\breve{t}_i = (b_i p^2 - 4ab_i^3)/p$, which is concave to the origin[2] and equals zero for $b_i = p/(2\sqrt{a})$. Within the frontier, the indicator increases after technological greening; outside, it decreases. Our last proposition is thus the following.

Proposition 4 *The eco-efficiency indicator can increase or decrease after technological greening, depending on the tax level and the initial technology.*

Proof *See appendix A.3*

To summarize the reliability of the eco-efficiency indicator we have gathered the effects of technological greening on the indicator with those on profit and emissions of firm i in the same figure. This $\Lambda_i^* = 0$ frontier divides areas (II) and (III) into four subdomains that are named (IIa), (IIb), (IIIa), (IIIb). For a given tax level below the frontier $\Lambda_i^* = 0$, the eco-efficiency indicator increases after technological greening, above it decreases. Table 1 displays the effects of technological greening on the two arguments of the eco-efficiency indicator; it must be used in combination with Figure 3.

In area (I) and (IV) the eco-efficiency indicator behaves according to the intuition and gives the right signal to the decision maker. On the one hand, the firm and the environment are getting better in (I), which means that technological greening increases profits and decreases pollution (a no-regret strategy). On the other hand, things are getting worse in (IV) for both the firm and the environment, which is signaled by the eco-efficiency indicator. So both in cases (I) and (IV) the eco-efficiency indicator can be trusted.

Unfortunately, in all other areas the eco-efficiency indicator gives a 'go' signal for technological greening, while it worsens the situation both for the firm and for the environment.

[2]It belongs to the domain.

	π^*	e^*	I_i
I	$\nearrow$	$\searrow$	$\nearrow$
IIa	$\nearrow$	$\nearrow$	$\nearrow$
IIb	$\nearrow$	$\nearrow$	$\searrow$
IIIa	$\searrow$	$\searrow$	$\nearrow$
IIIb	$\searrow$	$\searrow$	$\searrow$
IV	$\searrow$	$\nearrow$	$\searrow$

Table 1: A comprehensive view of the effects of technological greening - Complement to Figure 3

Area (II) is mixed: profit and emissions increase with technological greening. However, this zone is divided into two. In area (IIa), the eco-efficiency indicator gives a positive signal for technological greening, thus giving a wrong information to decision-makers: the firm will be better-off, but it will pollute more (rebound effect). The indicator is enhanced because the profit increase is stronger than the emission increase, and this is due to the high marginal benefit of technological greening (high tax on emission/low initial technology level).

In area (IIb), the eco-efficiency indicator gives a 'no-go' signal for technological greening because the emission increase is stronger than the profit increase. In that case, the indicator decreases despite an increase of profit.

In area (III), both profit and emissions decrease after technological greening. Again, the effects on eco-efficiency splits the zone into two. In areas (IIIa), the indicator gives a 'go' signal. By cleaning its technology the firm will reduce its emission level (no rebound effect in that area), but it will be worse-off in terms of profit. The reason here is that the firm is already very clean and the cost of pollution, relative to the cost of adoption, is not high enough. Adopting a cleaner technology would be too expensive in comparison with its productive benefits. Still, the indicator gets higher because the emission reduction is stronger than the profit loss.

In area (IIIb), the indicator gives a 'no-go' signal for technological greening because the profit loss is stronger than the emission reduction. The eco-efficiency indicator decreases despite the emission reduction.

By combining all the previous results we are able to state the general following corollary.

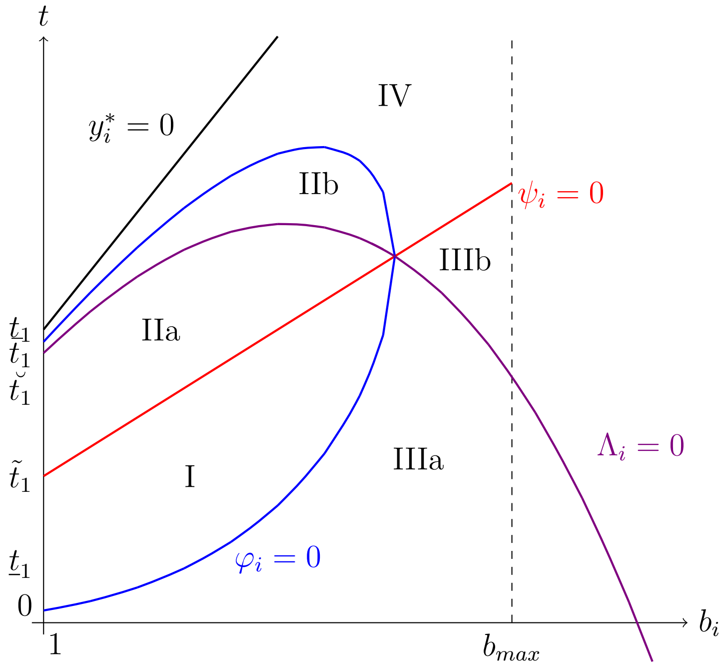

Figure 3: Global effects of technological greening

Corollary *An improvement in the eco-efficiency indicator is a necessary but not a sufficient condition for a no-regret strategy.*

This latter corollary shows that the eco-efficiency indicator, as defined by the World Business Council, is not an adequate indicator for decision-making, neither at the firm level nor at the market level.

7 Conclusion

In this paper we provide a framework to understand the effects of technological greening on firm's profit, firm's emission, market emissions, and on the indicator of eco-efficiency. We show why eco-efficieny is at the nexus between technological greening (adopting a less polluting technology) and no-regret strategies (lower pollution level and higher profits). With a simple theoretical model we highlight that technological greening may raise conflicting effects. First, a high tax level on pollution that provides the firm with a positive incentive for technological greening may also lead to an increase in emissions, both at the firm level or at the market level. Second, technological greening can lower the firm's profit if the initial technology is already very efficient. Third, these conflicting effects are not systematically detected by the eco-efficiency indicator, as defined by the WBCSD. In other words, eco-efficiency cannot be trusted as an indicator for decision-making. More formally, we show that eco-efficiency is a necessary, but not a sufficient condition for identifying no-regret strategies. It may give a 'go' signal to the firm for technological greening in cases where the firm will experience a profit decrease and a pollution increase.

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A Appendix

A.1 Proof of Proposition 1

The effect of technological greening on profit is given by the first derivative of the profit level (2) with respect to the technological parameter b_i. Let us define the following:

$$\begin{aligned}
\varphi_i^*(b,t) = \frac{\partial \pi_i^*}{\partial b_i} - ab_i &= \frac{-t^2 + b_i pt - 2ab_i^4}{2b_i^3} = 0 \\
\Leftrightarrow \quad \underline{t}_i &= \frac{1}{2}(b_i p - \sqrt{b_i^2 p^2 - 8ab_i^4}) \\
\text{and} \quad \bar{t}_i &= \frac{1}{2}(b_i p + \sqrt{b_i^2 p^2 - 8ab_i^4})
\end{aligned}$$

This φ_i function allows us to define a frontier on which the effect of technological greening on the profit level is zero, $\varphi_i^*(b_i,t) = 0$. There exist cases where real roots of $\varphi_i^*(b_i,t) = 0$ do not exist. The very existence of real roots for $\varphi_i^*(b_i,t) = 0$, denoted by $\underline{t}_i$ and $\bar{t}_i$, relies on the following assumption:

Assumption We suppose a condition on a for which an environmental technological amelioration allow an improvement of the profit level. Otherwise $\underline{t}_i$ and $\bar{t}_i$ do not exist which means an environmental technological amelioration decrease the profit level.

$$b_i^2 p^2 - 8ab_i^4 > 0 \qquad \Leftrightarrow \qquad a < \frac{p^2}{8b_i^2}$$

Both of the roots belong to the set domain, $\bar{t}_i < \tilde{t}$ and $\underline{t}_i < \tilde{t}$. For $b_i = 1$, we have:

$$\begin{aligned}
\bar{t}_1 &< t_1 \\
\frac{1}{2}(p + \sqrt{p^2 - 8a}) &< p
\end{aligned}$$

$$\begin{aligned}
\underline{t}_1 &< t_1 \\
\frac{1}{2}(p - \sqrt{p^2 - 16a}) &< p
\end{aligned}$$

Calculating the first and the second derivatives of the function $\underline{t}_i = \frac{1}{2}(b_i p - \sqrt{b_i^2 p^2 - 8ab_i^4})$, we determine that the curve is increasing and convex to the origin.

$$\begin{aligned}
\frac{\partial \underline{t}_i}{\partial b_i} &= \frac{1}{2}\left(p - \frac{-32ab_i^3 + 2b_i p^2}{2\sqrt{-8ab_i^4 + b_i^2 p^2}}\right) > 0 \\
\frac{\partial^2 \underline{t}_i}{\partial b_i^2} &= \frac{4b_i^2(16a^2 b_i^2 - 3ap^2)}{(8ab^2 - p^2)\sqrt{b_i^2 p^2 - 8ab^4}} > 0
\end{aligned}$$

Calculating the first and the second derivatives of the function $\bar{t}_i = \frac{1}{2}(b_i p + \sqrt{b_i^2 p^2 - 8ab_i^4})$, we determine that the curve is decreasing and concave to the origin.

$$\frac{\partial \bar{t}_i}{\partial b_i} = \frac{1}{2}\left(p + \frac{-32ab_i^3 + 2b_i p^2}{2\sqrt{-8ab_i^4 + b_i^2 p^2}}\right) < 0$$
$$\frac{\partial^2 \bar{t}_i}{\partial b_i^2} = -\frac{4b_i^2(16a^2 b_i^2 - 3ap^2)}{(8ab^2 - p^2)\sqrt{b_i^2 p^2 - 8ab^4}} < 0$$

A.2 Proof of Proposition 2

The effect of technological greening on pollution is given by the first derivative of the emissions (1) with respect to the technological parameter b_i which is given by:

$$\frac{\partial e_i^*}{\partial b_i} = \psi_i^*(b_i, t) = \frac{2t - b_i p}{2b_i^3} = 0 \Leftrightarrow \quad \tilde{t} = \frac{b_i p}{2} = 0$$

The function $\tilde{t}_i$ is linear and increasing in b_i.

Location of the frontier within the set domain

A frontier $\tilde{t}_i = \frac{b_i p}{2}$ is defined such that the effects of technological greening on pollution level is null: $\psi_i^*(b_i, t) = 0$. Under our assumption this function of iso-emissions ($\tilde{t}_i = \frac{b_i p}{2}$) belongs to the set domain $\tilde{t}_1 < t_1 \quad \Leftrightarrow \quad p/2 < p$. The function $\tilde{t}_i = b_i p/2$ is located above the frontier $\underline{t}_i = \frac{1}{2}(b_i p - \sqrt{b_i^2 p^2 - 8ab_i^4})$ for b_1:

$$\tilde{t}_1 > \underline{t}_1 \quad \Leftrightarrow \quad \frac{p}{2} > \frac{1}{2}(p - \sqrt{p^2 - 8a}) \Rightarrow 0 > -\sqrt{p^2 - 8a}$$

Crossing point

The function $\tilde{t}(a, b_i, p)$ crosses the roots $\bar{t}$ and $\underline{t}$ at a particular value of b_i such that $b_i = \frac{p}{\sqrt{8a}}$:

$$\bar{t}(a, b_i, p) = \tilde{t}(a, b_i, p) \quad \Leftrightarrow \quad \frac{1}{2}(b_i p + \sqrt{b_i^2 p^2 - 8ab_i^4}) = \frac{b_i p}{2} \Rightarrow b_i = \frac{p}{\sqrt{8a}}$$

$$\underline{t}(a, b_i, p) = \tilde{t}(a, b_i, p) \quad \Leftrightarrow \quad \frac{1}{2}(b_i p - \sqrt{b_i^2 p^2 - 8ab_i^4}) = \frac{b_i p}{2} \Rightarrow b_i = \frac{p}{\sqrt{8a}}$$

A.3 Proof of Proposition 4

The effect of technological greening on the eco-efficiency indicator is given by the first derivative of I_i *w.r.t.* $b - i$,

$$\Lambda_i^*(b_i, t) \equiv \frac{\partial I_i}{\partial b_i} = \frac{(\partial \pi_i^* - ab_i)e_i^* - \pi_i^*(\partial e_i^*)}{(e_i^*)^2} = \frac{-pt + b_i p^2 - 4ab_i^3}{2(b_i p - t)} = 0 \Leftrightarrow \quad \breve{t} = \frac{b_i p^2 - 4ab_i^3}{p}$$

The function $\breve{t}$ is increasing and concave in b_i and equals zero for $b_i = p/(2\sqrt{a})$.

Location of the frontier within the set domain

The frontier $\breve{t}_i = \frac{b_i p^2 - 4ab_i^3}{p}$ is such that the effect of technological greening on eco-efficiency indicator level is nill, $\Lambda_i^*(b_i, t) = 0$. This function $\breve{t}_i = (b_i p^2 - 4ab_i^3)/p$ belongs to the set domain

$$t_1 > \breve{t}_1 \quad \Leftrightarrow \quad p > \frac{p^2 - 4a}{p} \Rightarrow \qquad 0 > -4a$$

The function $\breve{t} = (b_i p^2 - 4ab_i^3)/p$ for $b_i = 1$ gives us $\breve{t} = (p^2 - 4a)/p$ and it is located between $\bar{t}_1$ and $\tilde{t}_1$.

$$\bar{t}_1 > \breve{t}_1 \quad \Leftrightarrow \quad \frac{1}{2}(p + \sqrt{p^2 - 8a}) > \frac{p^2 - 4a}{p} \Rightarrow \qquad p > \sqrt{8}$$

Assuming that $a < (p^2)/(8b_i^2)$ allows us to set a condition on p for b_1. It confirms that $\bar{t}_1 > \breve{t}_1$: $a < (p^2)/(8b_i^2) \quad \Leftrightarrow \quad p > \sqrt{8a}$. Considering this assumption on a we can also confirm that $\breve{t}_1 > \tilde{t}_1$: $\quad \Leftrightarrow \quad (p^2 - 4a)/p > p/2 \Leftrightarrow p > \sqrt{8a}$.

Crossing point

The function $\breve{t}(a, b_i, p)$ crosses $\tilde{t}(a, b_i, p)$ and thus $\bar{t}(a, b_i, p)$ and $\underline{t}(a, b_i, p)$ at $b_i = p/(\sqrt{8a})$ (see Appendix A.2) such that

$$\breve{t}(a, b_i, p) = \tilde{t}(a, b_i, p) \quad \Leftrightarrow \quad \frac{b_i p^2 - 4ab_i^3}{p} = \frac{b_i p}{2} \Rightarrow b_i = \frac{p}{\sqrt{8a}}$$

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