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Standards, taxes and social welfare

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Standards, Taxes and Social Welfare

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Abstract

This paper ranks three widely used instruments to fight pollution under imperfect competition. We consider n symmetric and polluting firms that compete in quantity, have access to an exogenous cleaning technology and are subject to environmental regulation by means of either emission standards, performance standards or taxes. The environmental authority optimally chooses the instrument by maximizing social welfare. By solving the one- and the two-stage games, for exogenous and endogenous instruments respectively, we conclude that the standards dominate in terms of optimizing social welfare. In particular, the performance standard is the preferred instrument, while the tax is the least desirable policy for the regulator.

JEL codes: H21, H23, L13, Q52, Q58.

Keywords: Environmental regulation, Abatement cost, Emission standard, Performance standard, Pigouvian tax.

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1 Introduction

Environmental issues have become a serious and growing problem, since the 1950s (Pearce, 2002), a wide literature has emerged to develop and analyze possible regimes to face pollution and improve the quality of the environment. Requate (2005 and 2006) presents a thorough survey of many theoretical studies on several policies imposed to polluting firms, with the objetive of reduce damaging emissions sent to the atmosphere as a result of the production process. Many market structures are analyzed, including the Cournot oligopoly, which is the one that concerns to this work.[1] In his surveys, Requate (2005 and 2006) emphasizes the relevance of studying the implications on social welfare of the different policies used to reduce pollution. Along these lines, comparing the performance of three different regulatory instruments in terms of social welfare is the main purpose of this paper. The regulatory regimes under study are two command-and-control instruments, emission and performance standards, and a market-based one, taxes. The reasons for such choice are simple and presented below.

A natural instrument to fight pollution are taxes, a widely policy used to internalize externalities for perfect and imperfect competition. Barnett (1980) was one of the pioneers in introducing taxation for imperfect competition, in particular, for a monopolist. Levin (1985) introduces taxation for a Cournot oligopoly, he does not characterize the structure of the tax, instead, he compares the effect of such tax on perfect and imperfect competition. In contrast, Ebert (1992) describes the form of optimal taxes for Cournot oligopolies, and studies different ways to abate pollution.

On the other hand, standards are considered in this study because they are observed to be the dominant policy in practice, being the performance standard the most common, (Harrington et al. (2004), Hueth and Melkonyan (2009), Viscusi et al. (2000)) but also one of the least studied (Requate (2005)). There are several ways in the literature to rank policy instruments, one of them is analyzing their cost-effectiveness, i.e., which policy improves the environment at least cost. Market-based instruments, such as taxes, have been shown to be superior than command-and-control in terms of cost effectivity (Hahn and Stavins (1992), Requate (2005 and 2006)). In this work, we turn

[1] A very reduced list of studies on environmental regulation and imperfect competition includes Barnett (1980), Cropper and Oates (1992), Ebert (1992), Katsoulacos and Xepapadeas (1995), Levin (1985), Requate (1993 and 1997) and Simpson (1995).

to analyze the efficiency of standards and taxes, in the sense that we look for the instruments that provide the highest social welfare when they are endogenously chosen.

When considering taxes in this work, we assume that there is no abatement technology, since in such case, the tax leads to the first-best outcome (Ebert (1992)); allowing for cleaning technologies immediately takes us to a lower social welfare situation. On the contrary, when analyzing standards we consider that firms posses an exogenous abatement technology to comply the regulation, which corresponds to an end-of-pipe cleaning technology. In all cases, we abstract from any production costs to focus on the regulations and abatement technology effects.

Besides studying their cost-effectivity and efficiency in terms of maximizing social welfare, several authors have evaluated the performance of different environmental regimes by the incentives they provide to develop new and cleaner technologies. Requate (2005) presents a detailed survey on such studies, that were motivated by Kneese and Schulze (1975).[2]

Montero (2002b) is one of the few works that studies both performance standards and imperfect competition, it analyzes the incentives of four policy regimes on the R&D investment to improve the firms' abatement technology. To this end, the author considers a two-stage game, in the first stage, n symmetric firms decide how much to invest in R&D, and in the second one, the firms compete à la Cournot. The four instruments under study are: emission and performance standards, and two market-based instruments: tradeable and auctioned permits. Although his study suggests that command-and-control instruments may provide higher incentives for R&D investment, Montero (2002b) cannot predict a fully-fledged comparison among regimes.

Later on, Amir et. al. (2017) focus on the command-and-control instruments analyzed by Montero (2002b) and add a previous stage to the game that maximizes social welfare. Using a simple structure, with linear demand and linear abatement costs, Amir et. al. (2017) show that the performance standard is welfare superior than the emission standard, but such results are contingent on the particular primitives of their model.

Works like Montero (2002b) and Amir et. al. (2017) suggest that given a two- or three-stage game, a general ranking of environmental regulations in terms of their effects on R&D investment,

[2]Incentives for technology adoption and innovation have been studied for perfect and imperfect competition. A very brief list of studies that allow for market power of the polluting firms includes Amir et. al. (2017), Carlsson (2000), Fischer et. al. (2003), Montero (2002a and 2002b).

production and social welfare is not a simple task. But no analysis has been done to the game where the abatement technology is fixed and cannot be modified by means of R&D. This paper fills such gap in the literature; we study taxes, emission and performance standards when their choice is endogenous and we find powerful and clear-cut public policy results. In particular, standards are shown to be welfare superior than taxes, being the performance standard more desirable.

For the command-and-control instruments under study, we consider a two-stage game that entails a regulator that chooses an optimal standard, absolute or relative, by maximizing social welfare in the first stage. After knowing the standard and its level, the symmetric firms engage in quantity competition in the second stage. In this part, we compare the equilibrium variables of interest, such as quantity produced, final and abated emissions, industry profits, consumer surplus and social welfare. This comparison allows us to rank the standards in terms of social welfare.

Then, we introduce taxes for being a common market-based instrument. As in Ebert (1992), we introduce the optimal tax that induces the highest social welfare, finally, we compare such welfare with that induced by the dominant standard, i.e., by the performance standard. We conclude that the performance standard is unambiguously superior to the other instruments in terms of social welfare, which is a preponderant result in terms of environmental policy. The relevance of our findings relies on their generality, since only usual assumptions are made along the paper, then, the results are robust to any plausible specification of the market and industry.

The following section introduces the model, including definitions of standards and taxes. Section 3 presents the standards assessment, considering the cases where the regimes are exogenous (one-stage game) and endogenous (two-stage game). Studying the one-stage game becomes really useful to analyze the two-stage game, which is of particular interest to us. Section 3 ranks standards and taxes in terms of social welfare. Conclusions are in Section 5 and the last one contains all the proofs.

2 Preliminaries

We consider an industry with n symmetric firms that compete in quantity. Firm $i = 1, ..., n$ produces $q_i \geq 0$ units of output, and the price of the output is given by the inverse demand function $P(Q)$, where $P : [0, \infty) \to [0, \infty)$ and $Q = q_1 + q_2 + ... + q_n$ is the total output produced in the industry. For simplicity, we assume that the production is costless and concentrate on the role of the abatement technology and environmental instruments.

Without regulation, every unit of output produced generates a unit of polluting emission. The emissions sent to the atmosphere cause a damage measured by the function $D : [0, \infty) \to [0, \infty)$, which is increasing in pollution.

Since production harms society through pollution, the firms are subject to environmental regulation. In this study we analyze three instruments that the regulator may choose: emission standards, performance standards and taxes. These instruments are described in detail below.

For the command-and-control instruments (the standards), the firms can abate y units of pollution at cost $C(y)$, $C : [0, \infty) \to [0, \infty)$, which will be referred to as cost of abatement. We assume that $C(0) = 0$ and that the more units of pollution the firms abate, the higher the cost will be; we also assume that such abatement cost increases at an increasing rate. Thus, we assume the following assumptions throughout this study that are standard in the literature:

(A1) $P(\cdot)$ is continuously differentiable and $P'(\cdot) < 0$;

(A2) $D(\cdot)$ is continuously differentiable and $D'(\cdot) > 0$;

(A3) $C(\cdot)$ is twice continuously differentiable, $C(0) = 0$, $C'(\cdot) > 0$ and $C''(\cdot) \geq 0$.

Now we describe the three regulatory instruments studied in this paper and how they influence the firms' decisions. Since the firms are symmetric, we assume that they are subject to the same regulation, in terms of instruments and levels.

2.1 Emission standards

In this case, the regulator chooses the maximum amount of emissions that each firm is allowed to generate, let us call this amount e, which is strictly greater than zero. Since the cost of abatement is strictly increasing, the firms will choose to pollute as much as they can, and firm i will send e emissions to the atmosphere. As a consequence, the firm must abate $q_i - e$ emissions and its optimization problem becomes:

$$\max_{q_i} q_i P(q_i + q_{-i}) - C(q_i - e),$$

where q_{-i} denotes the output produced by the firms other than firm i, i.e., $q_{-i} = Q - q_i$.

Assuming differentiability and an interior solution, the first order condition (FOC) of the firm is given by

$$q_iP'(q_i + q_{-i}) + P(q_i + q_{-i}) - C'(q_i - e) = 0. \tag{1}$$

Let us suppose that $e > 0$ is such that a symmetric equilibrium exists, and under such equilibrium every firm produces q^e. To make the problem economically interesting, we assume that $e < q^e$, otherwise, the firms will not have to abate any pollution and the regulation will not play any role in modifying the firms' behavior.

2.2 Performance standards

With this instrument, the regulator sets the the relative amount of pollution that firm i can generate, at most, fraction h of their production; thus, $0 < h < 1$. Similar to Section 2.1, since $C' > 0$, the firms will pollute as much as they are allowed by the regulation. This means that the final emissions of firm i will be q_ih and the abatement, $q_i(1 - h)$.

Firm i solves

$$\max_{q_i} q_iP(q_i + q_{-i}) - C(q_i(1 - h)),$$

with FOC

$$q_iP'(q_i + q_{-i}) + P(q_i + q_{-i}) - C'(q_i(1 - h))(1 - h) = 0. \tag{2}$$

These two first instruments are referred in the literature as command-and-control instruments.

2.3 Taxes

In this part we assume that firms do not abate pollution by using a cleaning technology. Instead, they pay a tax t for every unit of pollution they generate, then, firm i solves

$$\max_{q_i} q_iP(q_i + q_{-i}) - tq_i,$$

with FOC

$$q_iP'(q_i + q_{-i}) + P(q_i + q_{-i}) - t = 0. \tag{3}$$

Taxes are a market-based instrument to internalize externalities, in this case, pollution.

Although emission standards, performance standards and taxes are designed for the same purpose of fighting pollution, equations (1), (2) and (3) reveal that they do not necessarily lead to identical results. Specifically, they do not imply the same production or emissions abated, and thus, the damage and social welfare differ for the instruments.

Along these lines, it is natural to ask which instrument leads to higher social welfare, less emissions or higher production. The following sections answers such kind of questions, starting with the standards.

3 Emission vs. performance standards

3.1 One-stage game

In this part of the study, we consider the situation where the standards are fixed exogenously, without taking into consideration social welfare. This setting is plausible if for instance, the abatement technology of the firms is unknown to the regulator. Similarly, it provides the basis to study the effects of endogenizing the instruments. Since the firms are symmetric, we assume that they all face the same regulation, i.e., the same standard and the same level.

Because $P' < 0$ and $C'' \geq 0$, it exists at least one symmetric equilibrium (and no asymmetric ones); if the inverse demand function P is log-concave, then the equilibrium is unique. This argument is valid for the three instruments under study in this paper; for further discussion on existence of equilibria, see Amir and Lambson (2000).

Let us suppose that under emission standards, $e > 0$ is set as the maximum amount of emissions that the firms can send to the atmosphere. The symmetric equilibrium will be denoted with the super-index e, then, every firm produces q^e and reduces its pollution in $q^e - e$ emissions with a cost of $C(q^e - e)$.

Similarly, the super-index h is used for the equilibrium under the performance standard. In this case, the firms will be allowed to pollute $100h$ percent of their production and will produce q^h units of output. Then, the firms will abate $q^h(1 - h)$ units of contaminants, with $0 < h < 1$.

The following result analyzes how the equilibrium output changes when the regulatory instrument increases; the more the firms are allowed to pollute, the more they will produce, which is not surprising. This and the rest of the proofs are shown in Section 6. Since Lemma 1 relies on fixed-point techniques, and in general we have more than one equilibrium, the result holds for the extremal equilibria; for ease in the notation, we avoid distinguishing between minimal and maximal equilibrium.

Lemma 1 *For every number of firms $n \geq 1$, $e < q^e$ and $0 < h < 1$:*

i) production q^e is increasing in e under emission standards,

ii) production q^h is increasing in h under performance standards.

Recall that a firm regulated through an emission standard will generate e emissions, if the instrument is the performance standard, the emissions will be $q^h h$. From Lemma 1, production increases with e or h and becomes obvious that so do the emissions.

Similarly, with a more relaxed regulation, consumers are better off, given that production increases and the prices go down. These two straightforward results are summarized in Corollary 2, since the results are immediate, we omit its proof.

Corollary 2 *For every number of firms $n \geq 1$, $e < q^e$ and $0 < h < 1$:*

i) individual (and total) emissions are increasing in e and h under emission and performance standards, respectively;

ii) consumer surplus is increasing in e and h under emission and performance standards, respectively.

Now we compare the performance of both regulatory instruments under study, in terms of the equilibrium variables. We analyze their relative performance in production, consumer surplus, profits and social welfare. Such results rely on the magnitude of the instruments, so for now, we assume that the instruments are selected in such a way that the final emissions are the same for both regimes; specifically, e and h are exogenously fixed such that $e = q^h h$.

Whenever the equilibrium variable under discussion corresponds to the emission standard, we will superscript such variable with an e. If it corresponds to the performance standard, the superscript will be h.

Proposition 3 *Let e and h such that $e = q^h h < q^e$. Then:*

i) production is higher under performance standard, $q^h > q^e$;

ii) social welfare is higher under performance standard, $W^h > W^e$;

iii) individual (and total) profits are higher under emission standard, $\pi^e > \pi^h$ ($n\pi^e > n\pi^h$).

Proposition 3 states that whenever the damage to the environment coincides for both emission and performance standards, the firms will prefer the former one. Nonetheless, society is better off with the performance standard, and as an immediate consequence, consumers prefer it as well. Another way to see this latter result is that firms produce more when the emissions are regulated as a proportion of the production, hence, the price is lower and the consumers are better off. Corollary 4 summarizes this fact.

Corollary 4 *If $e < q^e$ and $0 < h < 1$ are such that $e = q^h h$, price is lower under performance standard, $p^h < p^e$, and consumer surplus is higher, $CS^h > CS^e$.*

Under a linear demand, linear abatement cost and cuadratic damage function, Example 1 illustrates our previous results for different choices of e and h such that $e = q^h h$. Moreover, the following example serves as a motivation for the next section. The second part of Example 1 computes e and h that maximize social welfare. Such computation suggests that social welfare is higher under performance standards. This result is later generalized in Section 3.2.

Example 1 Consider an industry with n symmetric firms that face a linear inverse demand function $P(Q) = a - bQ$, $a, b > 0$, and have a linear abatement cost $C(y) = cy$, with $a > c > 0$. One unit of production causes one unit of polluting emission that damages the environment by $D(x) = sx^2/2$, $s > 0$. Suppose that the e and h are exogenously set.

The reader can easily verify that, $q^e = \frac{a-c}{b(1+n)}$, $q^h = \frac{a-c(1-h)}{b(1+n)}$, $p^e = \frac{a+nc}{1+n}$, $p^h = \frac{a+nc(1-h)}{1+n}$, $\pi^e = \frac{(a-c)^2}{b(1+n)^2} + ce$ and $\pi^h = \frac{[a-c(1-h)]^2}{b(1+n)^2}$.

It is clear that in this example, the firms have a dominant strategy under emission standards, which coincides with the equilibrium of a standard symmetric Cournot model with linear inverse demand function, linear cost of production and no environmental regulation. On the other hand, production is always higher under performance standards, independently on the relationship between e and h. The comparison between profits depends on the magnitude of the standards and parameters.

Table 1 shows the results for $a = 3$, $b = c = s = 1$, $n = 2$ and three different sets of exogenous e and h that lead to the same pollution. The abbreviation *e.s.* stands por emission standards, and *p.s.*, for performance standards. In particular, notice that the chosen combinations of e and h induce the amount of emissions: 0.20, 0.40 and 0.60. Hence, we can verify all of our results previously provided: production is higher under the performance standard, firms are better off with the emission standard but since damage is the same for both instruments, and social welfare is superior for the performance standard, so is the consumer surplus.

Variable	e.s.	p.s.	e.s.	p.s.	e.s.	p.s.
Exogenous standard	0.20	0.26	0.40	0.48	0.60	0.67
Individual output	0.67	0.75	0.67	0.83	0.67	0.89
Individual profit	0.64	0.57	0.84	0.68	1.04	0.79
Social Welfare	2.10	2.19	2.26	2.42	2.26	2.46
Final emissions per firm	0.20	0.20	0.40	0.40	0.60	0.60
Emissions abated per firm	0.47	0.55	0.27	0.43	0.07	0.29

Table 1: Solution to the one-stage-game for $a = 3$, $b = c = 1$, $n = 2$ and chosen values of e and h such that $e = q^h h$.

Now suppose that e and h are not arbitrarily picked; instead, the regulator sets them by maximizing social welfare. In the first stage, the regulator chooses the optimal level of regulation and in the second one, the firms compete in quantity. Then, if emissions standards are going to be the regime, the environmental authority will solve:

$$\max_{e} \int_{0}^{nq^e} P(t)dt - nC(q^e - e) - D(ne); \tag{4}$$

otherwise, if performance standard is the policy adopted, h will be the solution to the following problem

$$\max_h \int_0^{nq^h} P(t)dt - nC(q^h(1-h)) - D(nq^h h). \tag{5}$$

Given the primitives in this example, the level of emissions that maximize social welfare under the emission standard is $e^* = \frac{c}{ns}$; it is also possible to find an explicit solution for h^*, but since it is algebraically complicated, we illustrate the results for the parameters $a = 3$, $b = c = s = 1$ and $n = 2$ in Table 2. Throughout the paper, as in this example, we use the super-index * for the policies that maximize social welfare.

Variable	e.s.	p.s.
Optimal standard	0.50	0.62
Individual output	0.67	0.87
Individual profit	0.94	0.76
Social Welfare	2.28	2.46
Final emissions per firm	0.50	0.54
Emissions abated per firm	0.17	0.33

Table 2: Solution to the two-stage game for $a = 3$, $b = c = s = 1$, $n = 2$ and e^* and h^* that maximize social welfare.

Table 2 shows that production and social welfare are still higher under the performance standard and the firms still prefer the emission standard. But how robust are these results? Do they rely on the primitives of Example 1 or they can be generalized? Fortunately, the comparison of social welfare is robust to any specification of the model that satisfies our general assumptions in Section 2, which are usual in the economic literature, i.e., optimal social welfare is always higher under performance standards. The ranking among the rest of the variables will depend on the primitives of the model.

3.2 Two-stage game

Suppose that there is a regulator or environmental authority that chooses the efficient level of emission or performance standards; all the firms are subject to the same regulation. This is, in the first stage, the regulator chooses the instrument and its level by maximizing social welfare, in the second stage, the firms compete à la Cournot. As detailed in Example 1, if the policy instrument is the emission standard, the regulator will solve problem (4), otherwise, it will solve problem (5).

It turns out that the regulator prefers the performance standard because it induces a higher social welfare, which is a very powerful result in terms of environmental policy. Recall that the super-index * indicates that the standard is chosen such that it maximizes social welfare.

Theorem 5 *In the two-stage game, social welfare is higher under performance standard, $W^{h^*} > W^{e^*}$.*

In what follows we compare the rest of the equilibrium variables. We cannot establish which regulation leads to less emissions, that will depend on the primitives of the market. For example, Table 2 shows that the performance standard induces a higher level of emissions (0.54 vs 0.50 of the emission standard). In contrast, an opposite result is illustrated in Table 3, when the cost of abatement is cuadratic; more on this example will be discussed below.

From Proposition 3, we know what happens when either regulation end up in the same number of emissions: firms prefer the emission standard because they make more profit by producing less; the consumers are better off with more production, i.e., with the performance standard. On the other hand, if emissions under the performance standard are at least as high as with the emission standard, the firms will produce more under performance standards, leading to a higher consumer surplus. We cannot predict what the firms prefer, but given Theorem 5 and Proposition 6 part ii) (below), they might prefer any of the policy instruments, it will depend on the shape of the inverse demand function and abatement costs.

Proposition 6 *If $q^{h^*}h^* \geq e^*$, then*

i) $q^{h^*} > q^{e^*}$, and

ii) $CS^{h^*} > CS^{e^*}$.

As mentioned before, the hypothesis in Proposition 6 is not the general case. For instance, if the demand is linear, and the abatement cost and damage functions are cuadratic, pollution might be higher under emission standards. Example 2 illustrates this result, i.e., no clear-cut conclusions can be stated.

Example 2 As in Example 1, we work with a linear inverse demand function, $P(Q) = a - bQ$, $a, b > 0$, and a quadratic damage function, $D(x) = sx^2/2$, $s > 0$. But now, instead of linear, the abatement cost is quadratic, $C(y) = cy^2$, with $c > 0$. The reader can easily verify that in the second stage, the firms choose to produce $q^e = \frac{a+2ce}{2c+b(n+1)}$ and $q^h = \frac{a}{2c(1-h)^2+b(n+1)}$ under emission and performance standards respectively.

In the first stage, the regulator finds the optimal standards e^* and h^* by solving equations 4 and 5 respectively, leading to the rest of the equilibrium variables. The equilibrium can be explicitly obtained, but to avoid long algebraic expressions, we directly illustrate our main purpose in Table 3. Specifically, we show that it is possible to find parameters that make economic sense and generates more emissions under the emission standard, for example, when $a = 5$, $b = 2$, $c = s = 1$ and $n = 2$.

Variable	e.s.	p.s.
Optimal standard	0.4630	0.5858
Individual output	0.7407	0.7883
Individual profit	1.4318	1.3493
Social Welfare	4.6296	4.7575
Final emissions per firm	0.4630	0.4617
Emissions abated per firm	0.2777	0.3266

Table 3: Solution to the two-stage game for $a = 5$, $b = 2$, $c = s = 1$, $n = 2$ and e^* and h^* that maximize social welfare.

Recall that in Example 1, specifically in Table 2, the performance standard leads to more pollution, in contrast to Example 2, Table 3. Nonetheless, contrary to the consumers, in both cases the firms are better off under emission standards, where their production is lower. Unfortunately, a clear-cut comparison for profits cannot be established in a general way. Similarly, this is the case for output when emissions are greater for the emission standard.

So far, we have compared two command-and-control regulatory instruments for pollution control: the emission and the performance standards, and we have shown that the performance standard is welfare superior. Such superiority is robust no matter if the standards are i) exogenously set to generate the same amount of pollution or ii) optimally chosen in order to maximize social welfare.

The previous result is very powerful in terms of public policy and thus, we now compare the performance standard versus a tax, which is a natural way to internalize a negative externality such as pollution.

4 Standards vs. taxes

As well as emission and performance standards, emission taxes have been widely used by governments to reduce the pollution that results from production, and studied in the literature. Hence, we introduce a comparison of taxes and standards.

Since Pigouvian taxes were born as a way to internalize externalities and maximize social welfare, we only consider the two-stage game for the standards. Ebert (1992) shows that in the absence of abatement technologies, the tax induces the optimal allocation, i.e., the production that maximizes social welfare. On the other hand, if the firms can reduce pollution by means of a cleaning technology, a tax is not enough to achieve the first-best. In other words, maximum welfare is higher in the absence of abatement. Because the main purpose of this work is to find the instruments that induce a higher welfare, we refrain from allowing abatement technologies when analyzing the tax. From Ebert (1992)'s results, it is straightforward that if the firms can clean their emissions, social welfare suffers a loss.

Section 2.3 describes the optimal behavior of the firms that are subject to the payment of tax t per unit of pollution. The optimal per firm output q^* that maximizes social welfare is the solution to the problem

$$\max_q \int_0^{nq} P(z)dz - D(nq), \tag{6}$$

i.e., q^* satisfies the FOC

$$P(nq^*) - D'(nq^*) = 0. \tag{7}$$

Equations (3) and (7) imply that the optimal tax is

$$t^* = D'(nq^*) + q^* P'(nq^*).$$

The next result states that standards are preferable to taxes in terms of maximizing social welfare. In particular, Theorem 7 shows that emission standards are welfare superior than taxes; by Theorem 5, it is immediate that performance standards are also more desirable than taxes.

Theorem 7 *Social welfare is higher under standards than under taxes, specifically,* $W^{h^*} > W^{e^*} > W^{t^*}$.

From the discussion above on Ebert (1992)'s work, it becomes straightforward that using a tax when the firms can abate pollution is the less desirable policy in terms of maximizing social welfare.

From FOC's (1), (2) and (3), one can tell that the ranking of the optimal outputs produced under each environmental policy varies depending on the primitives of the market, in particular, of the demand, abatement cost and damage. The same will happen with the rest of the equilibrium variables of interest. These and the previous results in this section are illustrated in Example 3.

Example 3 Reconsider the industry described in Example 1, with linear inverse demand function, linear abatement cost and cuadratic damage function: $P(Q) = a - bQ$, $C(y) = cy$ and $D(x) = sx^2/2$, with $a, b, s > 0$ and $a > c \geq 0$. The regulator can choose among taxes, emission or performance standards to maximize social welfare. The solution under any of these instruments is shown in Table 4 for $a = 3$, $b = c = s = 1$ and $n = 2$. [3]

Notice that under the previous set of parameters, the firms produce more under performance standards; emission standards minimize the production, $q^{e^*} < q^* < q^{h^*}$. As discussed before, this relationship in optimal production depend on the primitives of the problem. This simple example shows that the ranking for optimal production can differ just by changing the parameters.

Tables 4 and 5 show that under a slight change of the demand (varying the market size, a, and its slope, b) is enough to change the firms behavior, with the abatement technology and damage function remaining the same. When we modify the parameters from Table 4 to Table 5 part (A), only the size of the market changes, a augments from 3 to 6. When we move from Table 5 part (A) to (B), we increase both the size of the market and its slope, a increases by 4 units and b moves from 1 to 1.9.

[3] For optimal taxes, the emissions abated in Tables 4 and 5 are zero because under such regulation, the firms do not have a technology to reduce emissions, they just change their behavior.

Variable	tax	e.s.	p.s.
Optimal Tax/Standard	0.75	0.50	0.62
Individual output	0.75	0.67	0.87
Individual profit	0.56	0.94	0.76
Social Welfare	2.25	2.28	2.46
Final emissions per firm	0.75	0.50	0.54
Emissions abated per firm	0.00	0.17	0.33

Table 4: Solution to the game for $a = 3$, $b = c = s = 1$, $n = 2$ and taxes and standards that maximize social welfare.

	(A)			(B)		
Variable	tax	e.s.	p.s.	tax	e.s.	p.s.
Optimal Tax/Standard	1.50	0.50	0.35	0.17	0.50	0.39
Individual output	1.50	1.67	1.78	1.72	1.58	1.65
Individual profit	2.25	3.28	3.18	5.65	5.24	5.15
Social Welfare	9.00	11.61	11.94	17.24	19.45	19.80
Final emissions per firm	1.50	0.50	0.62	1.72	0.50	0.64
Emissions abated per firm	0.00	1.17	1.16	0.00	1.08	1.01

Table 5: Solution to the game for two different set of parameters, and taxes and standards that maximize social welfare. (A): $a = 6$, $b = c = s = 1$, $n = 2$; (B): $a = 10$, $b = 1.9$, $c = s = 1$, $n = 2$.

We already discussed that in Table 4, the tax leads to a production that lies between those of the standards, $q^{e^*} < q^* < q^{h^*}$. In Table 5 part (A), the optimal tax is the weakest instrument in terms of producing more, $q^* < q^{e^*} < q^{h^*}$; on the other hand, case (B) shows the opposite, i.e., taxes maximize the production of the industry, $q^{e^*} < q^{h^*} < q^*$.

Similarly, the market structure in Table 5 part (A) provides the least profits under taxes $\pi^* < \pi^{h^*} < \pi^{e^*}$; in part (B), taxes are preferred by the firms, $\pi^{h*} < \pi^{e^*} < \pi^*$. In line with Theorem 7, both Tables 4 and 5 show, for the three sets of parameters, that the performance standard is superior in terms of social welfare, followed by the emission standard and finally the tax.

5 Conclusion

This paper ranks three environmental instruments in terms of social welfare: emission standards, performance standards and taxes. We focus in these regimes because they are widely used in practice and studied in the literature. To our end, we consider a two-sage game that involves a welfare-maximizing regulator in the first stage, and n symmetric firms that compete à la Cournot after observing the policy regime set by the environmental authority. For any plausible specification of the model, we find that the performance standard unambiguously dominates in terms of social welfare, and the tax is the less desirable instrument, hence, standards are welfare superior than taxes.

For the rest of the equilibrium variables, the conclusions are not full-fledged, in most of the cases, their comparison depend on the specifics of the model. For instance, we present an example where the firms switch their preferences between standards and taxes with a slight change in the demand. But looking only at standards, the examples suggest that the industry produces more under performance standard but is better off with the emission standard. The first result is robust whenever the optimal performance standard is looser in terms of pollution, i.e., if it results in the same or more pollution that the emission standard. Similarly, if both regimes induce the same number of emissions, the firms are better off with the emission standard.

This work emphasizes the importance of endogenizing the environmental instruments in terms of welfare-maximization. In this sense, one can be sure that with an exogenous abatement technology, the performance standard is the right path to follow to achieve the highest social welfare.

6 Proofs

Lemma 1:

i) Recall that in equilibrium, the FOC (1) holds,

$$q^e P'(nq^e) + P(nq^e) - C'(q^e - e) = 0,$$

in other words, the equilibrium output q^e corresponds to the fixed point of the function

$$f_e(x) = -\frac{P(nx) - C'(x-e)}{P'(nx)}.$$

Notice that $f_e(x)$ is increasing in e given $P' < 0$ and $C'' \geq 0$; then, its extremal fixed points, $\underline{q}^e$ and $\bar{q}^e$, are increasing in e.

ii) This part is proven using a similar argument than part i). Taking the FOC (2), we notice that q^h is a fixed point of the function

$$f_h(x) = -\frac{P(nx) - C'(x(1-h))(1-h)}{P'(nx)},$$

which is increasing in h under our assumptions. Then, the extremal equilibrium outputs, $\underline{q}^h$ and $\bar{q}^h$, are increasing in h. □

Proposition 3:

i) Notice that in equilibrium, the FOC's (1) and (2) hold, i.e.,

$$q^e P'(nq^e) + P(nq^e) - C'(q^e - e) = 0$$

and

$$q^h P'(nq^h) + P(nq^h) - C'(q^h(1-h))(1-h) = 0.$$

Under the assumption $e = q^h h$, the second FOC becomes

$$q^h P'(nq^h) + P(nq^h) - C'(q^h - e)(1-h) = 0.$$

In other words, the (extremal) equilibria q^e and q^h are fixed points of the functions

$$f_e(x) = -\frac{P(nx) - C'(x-e)}{P'(nx)}$$

and

$$f_h(x) = -\frac{P(nx) - C'(x-e)(1-h)}{P'(nx)},$$

respectively. Finally, $C' > 0$, $P' < 0$ and $0 < h < 1$ imply that

$$-\frac{P(nx) - C'(x-e)(1-h)}{P'(nx)} > -\frac{P(nx) - C'(x-e)}{P'(nx)},$$

and hence, $q^h > q^e$.

ii) Now we show that performance standard leads to higher social welfare. To this end, consider the following function:

$$V(x,s) = \int_0^{nx} P(z)dz - nC(x-s).$$

Notice that $\partial V(x,s)/\partial x = n[P(nx) - C'(x-s)]$ and $\partial^2 V(x,s)/\partial x^2 = n[nP'(nx) - C''(x-s)] < 0$, by $P' < 0$ and $C'' \geq 0$. On the other hand:

$W^h - W^e = \left\{\int_0^{nq^h} P(z)dz - nC(q^h(1-h)) - D(nq^h h)\right\} - \left\{\int_0^{nq^e} P(z)dz - nC(q^e - e) - D(ne)\right\}$

$= \left\{\int_0^{nq^h} P(z)dz - nC(q^h - e) - D(ne)\right\} - \left\{\int_0^{nq^e} P(z)dz - nC(q^e - e) - D(ne)\right\}$

$= V(q^h, e) - V(q^e, e)$

$> \frac{\partial V(q^h,e)}{\partial x}(q^h - q^e) \geq 0.$

The first equality follows by definition; the second one, by the assumption $e = q^h h$, and the third one, by definition of $V(x,s)$. The first inequality is given by strict concavity of $V(x,s)$ with respect to x, and the last one, by $\partial V(q^h, e)/\partial x = n[P(nq^h) - C'(q^h - e)] \geq 0$ and $q^h > q^e$.

iii) To show that profits are higher under emission standards, we follow the next inequalities:

$\pi^e = q^e P[q^e + (n-1)q^e] - C(q^e - e)$

$\geq q^h P[q^h + (n-1)q^e] - C(q^h - e)$

$> q^h P[q^h + (n-1)q^h] - C(q^h - q^h h)$

$= q^h P(nq^h) - C(q^h(1-h)) = \pi^h.$

The first inequality follows by equilibrium and the second one, by $q^h > q^e$, $P' < 0$ and $e = q^h h$. □

Theorem 5:

Let e^* and h^* denote the emission and performance standard that maximize social welfare, respectively, and h such that $q^h h = e^*$, then, we have

$W^{h^*} = \int_0^{nq^{h^*}} P(z)dz - nC(q^{h^*}(1-h^*)) - D(nq^{h^*}h^*)$

$\geq \int_0^{nq^h} P(z)dz - nC[q^h(1-h)] - D(nq^h h)$

$> \int_0^{nq^{e^*}} P(z)dz - nC(q^{e^*} - e^*) - D(ne^*) = W^{e^*}$.

The first equality follows by definition. The first inequality is given by optimality, the second one, by Proposition 3 part ii) and $e^* = x^h h$. Finally, the last equality follows by definition. □

Proposition 6:

i) Let $e = q^{h^*}h^*$, then, by Proposition 3 part i), $q^{h^*} > q^e$. Since we assume that $e^* \leq e$, Proposition 1 part i) implies that $q^{e^*} \leq q^e < q^{h^*}$, which proves the result.

ii) This part follows a similar argument than part i). □

Theorem 7:

Consider $V(x,s) = \int_0^{nx} P(z)dz - nC(x-s)$ defined in Proposition 3, part ii) and notice that by optimality of q^e when the emission standard is e, we have

$$\frac{\partial V(q^e, e)}{\partial x} = n[P(nq^e) - C'(q^e - e)] > 0. \tag{8}$$

On the other hand, let e^* the emission standard that maximizes social welfare and define $e := q^*$, where q^* is the output induced by the optimal tax t^*. By definition of e, it must be the case that $q^e > q^*$, because $q^e > e$ for the problem to be economically interesting. Thus we have

$W^{e^*} = \int_0^{nq^{e^*}} P(z)dz - nC(q^{e^*} - e^*) - D(ne^*)$

$\geq \int_0^{nq^e} P(z)dz - nC(q^e - e) - D(ne)$

$= \int_0^{nq^e} P(z)dz - nC(q^e - q^*) - D(nq^*)$

$> \int_0^{nq^*} P(z)dz - nC(q^* - q^*) - D(nq^*)$

$= \int_0^{nq^*} P(z)dz - D(nq^*) = W^{t^*}$.

The first equality follows by definition of optimal welfare; the first inequality, by optimality of e^*. The second equality follows by the assumption $e = q^*$ and the second inequality, by equation 8 and $q^e > q^*$. The assumption $C(0) = 0$ implies the second last equality, and the last one, is given by definition.

Finally, by Theorem 5, $W^{h^*} > W^{e^*}$, which completes the proof. $\square$

7 References

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