The informational value of environmental taxes*

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Abstract

We propose informational spillovers as a new rationale for the use of multiple policy instruments to mitigate a single externality. We investigate the design of a pollution standard when the firms' abatement costs are unknown and emissions are taxed. A firm might abate pollution beyond what is required by the standard by equalizing its marginal abatement costs to the tax rate, thereby revealing information about its abatement cost. We analyze how a regulator can take advantage of this information to design the standard. In a dynamic setting, the regulator relaxes the initial standard in order to induce more information revelation, which would allow her to set a standard closer to the first best in the future. Updating standards, though, generates a ratchet effect since a low-cost firm might strategically hide its cost by abating no more than required by the standard. We characterize the optimal standard and its update across time depending on the firm's abatement strategy. We illustrate our theoretical results with the case of NO_x regulation in Sweden. We find evidence that the firms that pay the NO_x tax experience more frequent standard updates and more stringent revisions than those who are exempted.

Keywords: pollution, environmental policy, tax, asymmetric information, ratchet effect, multi-governance, policy overlap.

JEL codes: D04, D21, H23, L51, Q48, Q58.

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1 Introduction

The laws pertaining to many major environmental problems, as for instance, clean air, clean water and management of hazardous waste - are typically enacted and managed at all levels of government, implying that many regulations overlap and override each other. This is, for instance, the case of climate policy, where all countries and regions that have implemented climate policies seem to rely on several policy instruments (covering the same emission sources) rather than a single one (see e.g., Fankhauser et al. 2010, Levinson 2011 and Novan 2017).

The multiplicity of policy instruments to address a single pollution problem has been justified on several grounds. For instance, some (additional) market failures, regulatory failures or behavioral failures may reduce the economic efficiency of market-based instruments and justify additional policy instruments (see e.g., Bennear and Stavins 2007, Lehmann 2012, Lecuyer and Quirion 2013, Coria et al. 2021). The aim of this paper is not to discuss these justifications, but to introduce and discuss another rationale: the informational value of the policy overlap. We highlight the informational value of a pollution tax in the design of other environmental regulations when a firm's costs of abating pollution are unknown. We investigate whether and how a tax can help regulators set and update a standard (a cap) on pollutant emissions. Our idea is that the tax rate reveals information about the marginal cost of compliance that can be used to better target the standard to the firm's true cost.

The empirical motivation behind our paper is the overlap between market-based and command and control regulations that occurs in many places around the world. The economic literature traditionally argues for the superiority of market-based regulations over command-and-control, primarily because of the relative cost savings expected with market-based approaches. Even if market-based regulations such as environment taxes and emission trading schemes, are increasingly being used to implement environmental policy, command and control are still the most prevailing regulations in place.[1] Examples of the overlap between market-based and command and control regulations abound. In China, a large number of technological measures to save energy and improve air quality have been adopted in addition to the implementation of emissions trading schemes on carbon dioxide (see e,g., Stavins and Stowe 2020). Moreover, European

[1]For instance, Schmitt and Schulze (2011) document that between 1970 and 2011 command and control were the most prevalent air-pollution control instruments in the European Union. In China and India, most of the environmental legislation also takes the form of command and control (see Greenstone and Hanna 2014).

countries are increasingly using taxes to reduce carbon emissions and pesticide use, which overlap with technical requirements and the issuance of limit values on polluting inputs or emissions.

We develop a theoretical analysis of the design of an emission standard by a welfare-maximizing regulator under asymmetric information about abatement costs, with a tax on emissions set exogenously (i.e. out of the control of the regulator). Using such framework, we investigate how taxing emissions modifies emission standards. Does taxing polluters result in more or less stringent standards? How does the standard evolve over time with and without tax? Our model characterizes the value of the informational spillover that the tax induces on the design of the standard over time. We then move to an empirical analysis for the case of Sweden, where NO_x emissions by stationary pollution sources are regulated through a combination of a nationally determined emission tax and locally negotiated emission standards. We investigate the extent to which the informational spillover generated by the tax has been used in the design of NO_x standards.

To the best of our knowledge, this is the first study investigating the informational value of an economic instrument (a tax) for the design of a command-and-control instrument (a standard). Previous studies have analyzed the effectiveness of multiple instruments when there is uncertainty about abatement costs. Building on Weitzman (1974), Roberts and Spence (1976) show, for instance, that a mixed system, involving taxes and quantity regulations (in the form of marketable tradable permits) is preferable to either instrument used separately because such a mix better approximates the shape of the pollution damage function. A similar argument is developed by Mandell (2008) and Caillaud and Demange (2017), who show that, under some conditions, it is more efficient to regulate a part of emissions by a cap-and-trade program and the rest by an emission tax, rather than using a single instrument. Another strand of the literature has taken a mechanism design approach to analyze environmental regulation when abatement costs are unknown by the regulator, e.g., Kwerel (1977), Dasgupta et al. (1980), Spulber (1988), Lewis (1996), Duggan and Roberts (2002). Those studies rely on the direct revelation mechanism to identify a regulation that induces truthful revelation of abatement costs. They end up recommending complex instruments, such as non-linear pollution taxes. Our approach is different in the sense that we do not look at the design of an individual instrument to induce information revelation. We indeed take it as given: the environmental tax is exogenous to the regulator. The question is rather how the regulator can take advantage of the information revealed by the tax to set correctly another instrument which does not reveal information. We thus show that regulators can make use of the informational properties of a market-based instrument to improve the design of a command-and-control instrument. It is so even if the market-based instrument is exogenous for the regulator because it is controlled by another administration, potentially at higher level, e.g. national or federal.[2]

The methodology we use has been developed in mechanism design and contract theory with the so-called Principal-agent model. A Principal (here the regulator) interacts with an agent (here the firm) under asymmetric information about one of the agent's characteristics (here its abatement cost) called its 'type'. Under adverse selection (as in our paper), types are exogenous to the agent. The agent undertakes an action (here how much pollution to emit) that reveals information about its type. The Principal designs a mechanism that induces the agent to reveal its type. The equilibrium is then called separating because it separate types. Otherwise it is pooling.[3]

The Principal-agent framework under adverse selection leads to the well-known ratchet effect when it is repeated. The ratchet effect arises when the agent correctly anticipates that the future regulation will be updated to be more stringent if it reveals that its type is low-cost. The agent prefers to hide its cost by 'mimicking' a high-cost type. In our framework, it means that the firm prefers not to over-comply with the standard despite its short-term interest in doing so. Thus, the firm hides its type to have a less stringent standard in the future.

The ratchet effect has been studied in contract theory but seldom investigated in the context of environmental policies. Previous theoretical analysis has shown that the ratchet effect precludes information revelation, often leading to pooling and semi-pooling equilibria (Freixas et al., 1985, Laffont and Tirole, 1988). For instance, Laffont and Tirole (1988) deals with a procurement model under asymmetric information on production costs with a continuum of types and two periods. If the contract lasts only one period, the optimal contract reveals all types. However, this is not anymore true when the relationship is repeated. The authors show that some pooling is necessary in the first period due to the ratchet effect.

Our framework differs from mechanism design and contract theory in several dimen-

[2] This assumption is consistent with current practices. See e.g., Segerson (2020), who discusses how market-based regulations such as environmental taxes and emission trading schemes are increasingly being used by national/subnational regulators around the world to implement environmental policy, while local regulators typically use command and control regulations.

[3] We use the terminology of separating or pooling the types of a single agent (firm) following Fundenberg and Tirole (1991) pages 326-327. It is also used by Gerardi and Maestri (2020) who analyze a game with a single firm (the principal) and a single worker (the agent).

sion, notably on the mechanism itself which is not a payment contingent on the agent's decision but rather a limit on the decision itself, i.e. a cap on pollution. Moreover, the revelation of types is not induced by the mechanism but rather by a tax on pollution which is out of the Principal's control. It turns out that some pooling occurs even if the relationship lasts only one period. With multiple periods, the Principal relaxes the standard to reveal (separate) more types when the relationship becomes dynamic. We identify how much information is revealed with and without the ratchet effect.

The mechanism design literature has been applied to the regulation of natural monopolies and network industries when production costs are firm's private information (Laffont and Tirole, 1993). Such studies analyze specific instruments such as rate-of-return or price-cap, while in contrast we look at a cap of polluting emissions.[4]

Similar dynamic contracting under adverse selection arises in the seller-buyer relationships (Hart and Tirole, 1988, Skreta, 2006) or in labor contracts (Kanemoto and MacLeod, 1992). In the former literature, Strulovici (2017) shows that, with an infinite horizon as assumed here, all equilibria converge to a fully separation of types. In contrast, in our paper, some pooling of types remains over time and no more revelation of types occurs after the second period.

In the most recent literature, the paper closest to ours is Gerardi and Maestri (2020), who study the relationship between a worker (privately informed about his productivity) and a firm that can only commit to short-term contracts. In line with our results, they show that the labor contracts can entail full revelation of types in the first period if the discount factor is high enough. Otherwise, the equilibrium is close to a pooling allocation where the rm offers the most protable contract that the high-cost worker is willing to accept.

In contrast to Gerardi and Maestri (2020), who investigate the case of two cost-types, in our framework, there is a continuum of types, and some of them are pooled. More precisely, the standard determines a threshold type such that all types below this threshold are revealed while those above are pooled. We show that learning occurs only during the first period, i.e., no more types are revealed among those types that are pooled after the first period. We also show that the ratchet effect reduces this threshold type, meaning that fewer types are revealed and more are pooled when the firm is forward-looking by anticipating correctly the update of the standard.

The paper is organized as follows. Section 2 introduces the theoretical model.

[4]In the conclusion section, we discuss how our analysis can be useful for the regulation of quality in natural monopolies like in Baron (1985).

We analyze the design of an optimal emission standard by considering successively a myopic firm in Section 3 and a forward-looking firm in Section 4. We characterize the optimal standard and its update over time depending on how the firm responds to both the standard and the tax. Section 5 investigates to what extend our theoretical predictions on the optimal design of the standard are in line with what we observe on NO_x regulation in Sweden. Finally, Section 6 concludes the paper.

2 The model

2.1 A model of pollution control

Let us consider a public authority called 'the regulator' (hereafter referred as 'she') regulating the polluting emissions released by a firm through an emission standard. The regulator is a welfare-maximizer: she cares about environmental damage and the cost of controlling pollution. Uncontrolled emissions denoted e^0 can be abated by the firm at some cost which is unknown by the regulator. Let q denote pollution abatement. The benefit from reducing pollution by q units is $B(q)$ while the cost is $\theta C(q)$. The parameter θ captures the level of abatement costs. It is called the firm's type and it is exogenously given.[5] It belongs to the range $[\underline{\theta}, \bar{\theta}]$ with $\Delta\theta = \bar{\theta} - \underline{\theta} > 0$. The density and cumulative distribution of the *a priori* beliefs on the distribution of θ over the range $[\underline{\theta}, \bar{\theta}]$ are denoted f and F respectively. The benefit function $B(q)$ is increasing and (weakly) concave, reflecting decreasing (or constant) marginal benefit from abating pollution. Similarly, the cost function $C(q)$ is increasing and convex, thereby implying an increasing marginal cost of abatement.

The welfare from having a firm of type θ abating q units of polluting emissions is:

$$W(q, \theta) \equiv B(q) - \theta C(q). \tag{1}$$

The first-best abatement level $q^*(\theta)$ maximizes $W(q, \theta)$ with respect to q. It is defined by the following first-order condition:

$$B'(q^*(\theta)) = \theta C'(q^*(\theta)), \tag{2}$$

for every $\theta \in [\underline{\theta}, \bar{\theta}]$, where $q^*(\theta) \leq e^0$.

[5]The model can easily be extended to endogenize θ via the investment in new technologies at expenses of a fixed cost. The same argument would hold as long as the investment is profitable for the firm. If not, the standard might be strengthened further to induce this investment.

An emission standard defines a minimal abatement effort denoted s.[6] Assume, for now, that pollution is regulated solely through the standard. Under uncertainty about θ, the regulator imposes a standard that maximizes the expected welfare given her beliefs about the firm's type. Let $\hat{\theta} \equiv E_\theta[\theta]$ be the firm's expected type given the regulator's beliefs. The abatement standard without tax $\hat{q}^*$ maximizes the expected welfare

$$E_\theta[W(q, \theta)] = W(q, \hat{\theta}) = B(q) - \hat{\theta}C(q),$$

with respect to q. The first-order condition that defines $q^*(\hat{\theta})$ equalizes the marginal benefit from abatement to the expected marginal cost:

$$B'(q^*(\hat{\theta})) = \hat{\theta}C'(q^*(\hat{\theta})). \tag{3}$$

As we will explained later on, the standard $s = q^*(\hat{\theta})$ is called *pooling*.

Consider now a tax per unit of pollution denoted τ. It makes abatement profitable for the firm even in the absence of an emission standard because the firm saves τ each time it reduces emissions by one unit. Therefore, in absence of a standard, the firm chooses the abatement level that minimizes its cost net of the tax bill saved, formally $\theta C(q) - \tau q$.[7] Let us denote as $q^\tau(\theta)$ the abatement effort carried out by the firm of type θ. It is defined by the first-order condition that equalizes the marginal abatement cost to the tax rate:

$$\theta C'(q^\tau(\theta)) = \tau. \tag{4}$$

Therefore $q^\tau(\theta) = C'^{-1}\left(\frac{\tau}{\theta}\right)$ for every θ. It is increasing with the tax rate τ and decreasing with the type θ. We assume that the tax does not fully reflect the marginal benefit of abatement. This is to say, the abatement level induced by the tax is sub-optimal regardless of the type: $q^\tau(\theta) < q^*(\theta)$ for every θ.[8]

The *regulation game* is the non-cooperative game aiming at modeling the relation-

[6]Given uncontrolled emissions e^0 and pollution abatement q, the emissions released to the environment are given by $e^0 - q$. Such emissions should not exceed an emission standard denoted by $\bar{e}$. Thus, $e^0 - q \leq \bar{e}$, or equivalently, $q \geq \bar{e} - e^0$. Thus, we can say that an emission standard defines a minimal abatement effort that we denote by $s \equiv \bar{e} - e^0$.

[7]Note that it is equivalent to minimizing costs including the fiscal cost $\theta C(q) + \tau[e^0 - q]$, where the fixed term τe^0 will not affect first order conditions.

[8]This assumption implies that standards are set for all of the firm's types. It avoids considering the case of over-abatement with tax compared to the optimal level. This can easily be justified empirically since most environmental taxes are set below the Pigouvian rate.

ship between the regulator setting the standard and the firm. The tax τ and the firm's type θ are *exogenous* to both players. They are determined before the regulator chooses the standard. The tax is common knowledge while the type is firm's private information. After the type θ has been privately observed by the firm, the regulator and the firm interact into an infinity of stage games. During each of them, the regulator sets a standard and the firm chooses how much pollution to abate. The sequence of moves is as follow:

0 The firm observes its type θ and the tax rate τ is common-knowledge.

t Stage game in period $t \geq 1$:

- t.1 The regulator chooses the standard s_t.
- t.2 The firm chooses its abatement strategy $q_t \geq s_t$.
- t.3 The welfare and costs are realized.

The firm's type does not change over time.[9] Both players discount payoffs (welfare and costs) with the same factor $\beta > 0$. We first analyze the design of the standard in a static framework where the game lasts only one period as a benchmark before investigating equilibrium solutions of the regulation game.

2.2 The static standard

Suppose the regulation game is played only in period 1. Given the standard s, the firm chooses its abatement effort that minimizes its cost subject to complying with the standard. The firm of type θ chooses q that minimizes $\theta C(q) - \tau q$ subject to $q \geq s$. If the constraint is not binding, the tax rate drives the firm's abatement effort and the firm equalizes marginal abatement cost to the tax rate by choosing the abatement level $q^\tau(\theta)$, defined in (4). Otherwise, the firm's abatement effort matches the standard s. Thus, firm θ's best reply to the standard s defines an *incentive-compatibility* (IC) constraint:

$$q(\theta) = \max\{s, q^\tau(\theta)\}. \tag{5}$$

The regulator chooses the standard s that maximizes the expected welfare $E[W(q(\theta), \theta)] = E[B(q(\theta)) - \theta C(q(\theta))]$ subject to the firm's IC constraint (5). For low tax rates, the

[9]We discuss how relaxing this assumption by assuming that θ changes overtime changes our result at the end of Section 3.

abatement level induced by the tax $q^\tau(\theta)$ is so low that the IC constraint simplifies to $q(\theta) = s$ for every θ. The standard is set at $s = q^*(\hat{\theta})$. The firm reduces pollution to meet the standard but not more regardless of its type. The solution is *pooling* in the sense that the firm's abatement effort does not reveal information about its type.

For higher tax rates, the IC constraint defines a threshold $\tilde{\theta}$ such that $q(\theta) = q^\tau(\theta)$ if $\theta \leq \tilde{\theta}$ and $q(\theta) = s$ if $\theta \geq \tilde{\theta}$. This is to say, if the firm's type θ is below the threshold, the firm abates a level determined by the tax while it abates what is required by the standard if its type is above the threshold. The threshold is defined by $q^\tau(\tilde{\theta}) = s$ or, equivalently, by $\tilde{\theta} = \frac{\tau}{C'(s)}$. Hence, the regulator chooses the standard s to maximize:

$$\max_s \int_{\underline{\theta}}^{\tilde{\theta}} W(q^\tau(\theta), \theta) dF(\theta) + \int_{\tilde{\theta}}^{\bar{\theta}} W(s, \theta) dF(\theta) \text{ subject to } q^\tau(\tilde{\theta}) = s.$$

Let us denote the standard that solves this problem as s^s (with an upper-script 's' for static). The first-order condition yields:

$$B'(s^s)[1 - F(\tilde{\theta})] = \int_{\tilde{\theta}}^{\bar{\theta}} \theta dF(\theta) C'(s^s).$$

Using $f(\theta|\theta \geq \tilde{\theta}) = \frac{f(\theta)}{1 - F(\tilde{\theta})}$ leads to

$$B'(s^s) = E[\theta|\theta \geq \tilde{\theta}] C'(s^s), \tag{6}$$

The standard is chosen such that the marginal benefit of abatement equals the marginal cost in expectation for all types for which the standard is binding, i.e, with a θ higher than $\tilde{\theta}$.[10]

3 Information revelation with a myopic firm

3.1 Regulation update

We assume that the firm is myopic or short-term in its thinking, as it considers only the current abatement costs when picking its abatement strategy. This assumption is relaxed in the next section. We use the concept of Perfect Bayesian Equilibrium (PBE). We construct a PBE in which the regulator updates the standard based on the

[10]Note that our assumption $q^*(\theta) > q^\tau(\theta)$ implies that the standard is binding for some types.

firm's past abatement strategy. The equilibrium strategies are formally described in Appendix A.1. Let us consider the first standard update in period 2. Given the first-period standard s_1, after having observed the firm's abatement strategy in period 1, the regulator designs a new standard s_2. The regulator takes advantage of the information revealed by the firm's abatement decision during the first period to update its beliefs on the firm's type. Given the information obtained, she tailors the standard closer to the firm's expected type. If the firm over-complies by abating $q^\tau(\theta) > s_1$, the regulator can perfectly infer that its type is θ. She updates the standard to the first-best abatement level $s_2 = q^*(\theta)$. We say that the regulator has *revealed the firm's type* θ (its private information) with the standard s_1. All types below a threshold type denoted $\tilde{\theta}_1$ are revealed. The threshold type is such that the firm's abatement induced by the tax equals to the standard, i.e. $q^\tau(\tilde{\theta}_1) = s_1$, which, given (4), leads to:

$$\tilde{\theta}_1 = \frac{\tau}{C'(s_1)}, \tag{7}$$

A firm with type $\theta < \tilde{\theta}_1$ over-complies and, therefore, experiences a standard update $s_2 = q^*(\theta)$. Hence the standard reveals all information about types in the range $[\underline{\theta}, \tilde{\theta}_1]$. Note that an increase of the threshold type $\tilde{\theta}_1$ would lead to revelation of more types as the range $[\underline{\theta}, \tilde{\theta}_1]$ expands.

If the firm abates the level required by the standard s_1, some uncertainty about its type remains. Nevertheless the information on the firm's type becomes more precise because types lower than $\tilde{\theta}_1$ can be excluded. The firm's type should therefore belong to the range $[\tilde{\theta}_1, \bar{\theta}]$. It is distributed according to the conditional cumulative $F(\theta|\theta \geq \tilde{\theta}_1)$. In the beginning of period 2, the regulator and the firm are thus starting a regulation game with the updated distribution of types. This sequence of regulation update is represented in Figure 1 below.

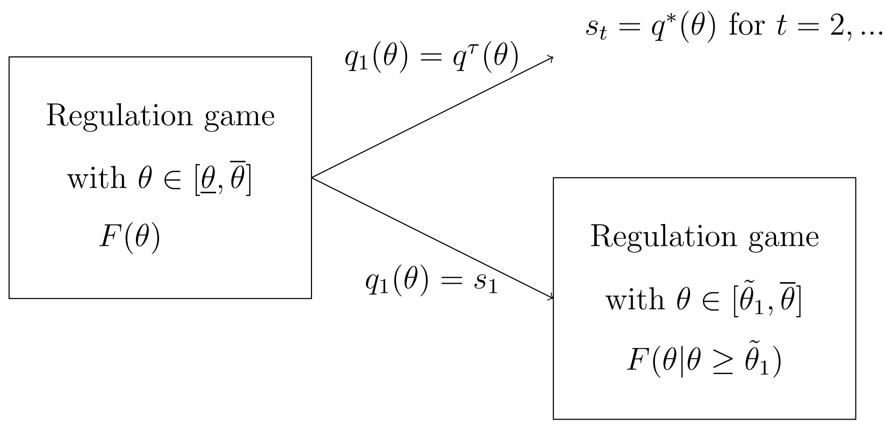

Figure 1: Regulation update

If in period 2 the regulator would want to reveal some types in the range $[\tilde{\theta}_1, \bar{\theta}]$. Hence, she should relax the standard so that firm over-complies with the standard if its type is within this range. The second period standard s_2 should then be such that $s_2 < s_1$ to obtain a threshold $\tilde{\theta}_2 > \tilde{\theta}_1$ so that all types in the range $[\tilde{\theta}_1, \tilde{\theta}_2]$ are revealed. As shown in Appendix A.2., this is not optimal. This allows us to establish the following Lemma.

Lemma 1 $\tilde{\theta}_2 = \tilde{\theta}_1$ *such that no more information is revealed after period 1.*

The proof is by contradiction. We show that, if the standard is relaxed to $s_2 < s_1$, the expected discounted welfare in period 1 would have been higher with s_2 instead of s_1, which contradicts that s_1 would have been optimal. Hence, starting from date $t = 2$, the standard s_t pools at types in the range $[\tilde{\theta}_1, \bar{\theta}]$ by setting $s_t = s_2 > s_1$ for every $t > 1$. Thus, if the firm's type in the range $[\tilde{\theta}_1, \bar{\theta}]$, the IC constraint (5) bowls down to $q_t = s_t$. The updated standard s_2 maximizes the expected welfare given the updated beliefs:

$$E[W(s_2, \theta)|\theta \geq \tilde{\theta}_1] \tag{8}$$

The first-order condition that defines the solution s_2^d to (8) is:

$$B'(s_2^d) = E[\theta|\theta \geq \tilde{\theta}_1]C'(s_2^d). \tag{9}$$

It is similar to the one of the standard without tax in (3) with the expected type $E[\theta|\theta \geq \tilde{\theta}_1]$.

Lemma 1 indicates that the tax is used to reveal types only during the first period. In that period, types in the range $[\underline{\theta}, \tilde{\theta}_1]$ are revealed. No more types are revealed after period 1. Hence, the tax does not impact the abatement strategy of the firm if its type belong to the range $[\tilde{\theta}_1, \bar{\theta}]$. We now move to the choice of the first period's standard s_1.[11]

3.2 First period's standard

In the first period, the regulator chooses the standard s_1 that maximizes the discounted expected welfare given that the standard will be updated to $s_2 = q^*(\theta)$ if the firm abates $q^\tau(\theta) > s_1$ and to the standard $s_2 = s_2^d$ if the firm abates s_1. As shown by Lemma 1, the standard remains unchanged after period 2. Hence the per-period expected welfare is $W(q^*(\theta), \theta)$ if abatement is $q^\tau(\theta) > s_1$ and $E[W(s_2^d, \theta)|\theta \geq \tilde{\theta}_1]$ if abatement is s_1. Let us denote by $\rho \equiv \sum_{j=1}^{\infty} \beta^j = \dfrac{\beta}{1-\beta}$ the current value of a constant future flow of welfare. The regulator thus maximizes:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} W(q^\tau(\theta), \theta) dF(\theta) + \int_{\tilde{\theta}_1}^{\bar{\theta}} W(s_1, \theta) dF(\theta) + \rho \left[\int_{\underline{\theta}}^{\tilde{\theta}_1} W(q^*(\theta), \theta) dF(\theta) + V(s_2^d, \tilde{\theta}_1) \right] \tag{10}$$

where $\tilde{\theta}_1$ is defined in (7) with $\underline{\theta} < \tilde{\theta}_1 < \bar{\theta}$. The last term in the brackets in (10) is the per-period welfare in expectation from period 2 onward. It includes two terms: (i) the first-best welfare $W(q^*(\theta), \theta)$ when the firm is of type $\theta \leq \tilde{\theta}_1$ and it reveals its type by over-complying, and (ii) the maximal value of the expected welfare with the revised standard s_2 given the updated beliefs that the firm's type is $\theta \geq \tilde{\theta}_1$.

The solution to the problem in equation (10) is denoted s_1^d and satisfies the following first-order condition:

$$B'(s_1^d) = E[\theta|\theta \geq \tilde{\theta}_1] C'(s_1^d) - \rho \underbrace{\left[W(q^*(\tilde{\theta}_1), \tilde{\theta}_1) - W(s_2^d, \tilde{\theta}_1) \right]}_{\text{Welfare gain from revealing } \tilde{\theta}_1} f(\tilde{\theta}_1 | \theta \geq \tilde{\theta}_1) \frac{d\tilde{\theta}_1}{ds_1}, \tag{11}$$

where $\dfrac{d\tilde{\theta}_1}{ds_1} = -\tilde{\theta}_1 \dfrac{C''(s_1^d)}{C'(s_1^d)} < 0$ is found by differentiating (7) and $q_2(\tilde{\theta}_1)$ is the firm $\tilde{\theta}_1$'s abatement level during the second period. The standard s_1^d is such that the marginal benefit of a more stringent standard on the left-hand side of (11) equals the marginal cost on the right-hand side. Likewise for the first-order condition of the static prob-

[11] If we restrict our case to two types of cost, as in Gerardi and Maestri (2020), the standard entails full revelation of types in the first period when the tax is high enough. The analysis of the two types case is available on request.

lem in (6), the marginal cost is computed in expectation over all types for which the standard is binding, i.e., all θ higher than $\tilde{\theta}_1$. What is new compared to (6) is the second term on the right-hand side that accounts for the marginal value of the information revealed by the tax. This value is the marginal loss of welfare from not revealing types with a more stringent standard. It is decomposed into three terms. First, $\frac{d\tilde{\theta}_1}{ds_1} < 0$ captures the fact that increasing s_1 decreases the threshold type $\tilde{\theta}_1$, which means that fewer firm's types are revealed. Second, the difference in the brackets $W\left(q^*(\tilde{\theta}_1), \tilde{\theta}_1\right) - W\left(s_2^d, \tilde{\theta}_1\right)$ is the welfare gain of revealing the marginal type θ_1 (or the welfare loss of not revealing it). Indeed, if $\tilde{\theta}_1$ had been revealed, the standard could be set at the efficient level $q^*(\tilde{\theta}_1)$ for the rest of the game, thereby achieving the maximal welfare $W\left(q^*(\tilde{\theta}_1), \tilde{\theta}_1\right)$ each period. Instead, the welfare level achieved is $W\left(s_2^d, \tilde{\theta}_1\right)$ each period (where s_2^d is defined by (9)). Third, this loss is weighted by the regulator's updated beliefs about the share of threshold types $f(\tilde{\theta}_1|\theta \geq \tilde{\theta}_1)$ and discounted with $\rho = \frac{\beta}{1-\beta}$.

Since the welfare gain from revealing $\tilde{\theta}_1$ in (11) is strictly positive, the right-hand side of (11) is higher than the right-hand side of (6) for a given standard.[12] Since the left-hand side of both conditions (6) and (11) are the same function of the standard, we have $s_1^d < s^s$. This is to say, the standard is relaxed to acquire information that is used the next period. Thus, in a dynamic setting in which a firm is regulated by a standard and a tax, the tax is used to reveal information about the marginal cost of abatement that can be used when revising the standard. The way in which the regulator can modify the first-period standard to increase information revelation is summarized in the proposition below.

Proposition 1 *The first-period standard is lower than in the static game to induce more revelation of types, i.e., $s_1^d < s^s$. It is then strengthened to the first-best abatement level if the firm reveals its type by over-complying, i.e., if $q_1(\theta) = q^\tau(\theta) > s_1^d$ then $s_2 = q^*(\theta) > s_1^d$. It is also strengthened if the firm does not over-comply with the standard since the tax is used to reveal types only during the first period, i.e., $s_2 = s_2^d > s_1^d$ if $q_1(\theta) = s_1^d$.*

Proposition 1 explains how the regulator takes advantage of the tax to better design the standard. Compared to the case without tax or with only one period, the standard is less stringent in the first period to induce more information revelation in the sense

[12]Consistently, the first-order (11) boils down to the one of the static model (6) when $\beta = 0$.

that more types are revealed through over-compliance. In the second period, the standard is strengthened regardless the firm's abatement strategy. It is set at the first-best abatement level if the firm reveals its type by over-complying. If not, it is also strengthened because the tax is not used anymore to reveal types.

Before moving to the analysis of a strategic firm, we briefly discuss how our results would change if the firm's type changes over time. Although this extension would require a full analysis, we outline how having a new draw of type θ at the beginning of period 2 would modify the design of the standard in period 1 and its update in period 2. By assuming perfect correlation of type across the two periods, we assign a maximal value to the information revealed by the environmental tax about the abatement costs in the second period. Full information is revealed if the firm over-complies during the first period, which leads the regulator to implement the first-best. Furthermore, the regulator can exclude a full range of potential types if the firm does not over-comply. In reality, a firm's abatement costs evolve over time due to technological progress and the business environment, which means in our model that the first-period cost type is only partly correlated to the second-period one. Nevertheless, as long as the types are correlated over time, the information revealed in the first period has some value in the second period. Even though the first-best might not be achieved if the firm over-complies, welfare is improved as long as the information about the first-period type allows the regulator to reduce the variance of her beliefs about the second-period type. The standard is probably strengthened but not as much as it would be with perfect correlation. Similarly, when the firm's abatement does not exceed the standard, the full range of potential types excluded in the first period cannot be excluded in the second period. Yet the regulator has more precise information about the firm's type in the second period than she had initially in the first period, which allows her to modify the standard in the second period. Hence, the informational spillovers between policy instruments would remain even under imperfect but positive correlation among the firm's abatement costs across time. However, in contrast to the case of perfect correlation, the standard might change after period 2 to induce the revelation of new types.

4 Information revelation with a forward-looking firm

Let us assume now that the firm is forward-looking and strategic. It takes into account the impact of its abatement strategy in the first period on the second period standard.

The revision of the standard leads to the well-known *ratchet effect* in mechanism design: the firm behaves strategically to avoid more demanding regulations in the future.[13] In our framework, the firm might not pick its per-period cost-minimizing abatement strategy $q^\tau(\theta)$ if its type is $\theta < \tilde{\theta}_1$ to avoid a more stringent standard in the future. Doing so, the firm does not reveal its type θ. It is at a cost now but the future reward might offset this cost. We investigate to what extend the regulator can still take advantage of the tax to reveal types and update the standard accordingly.

Two behaviors might prevent the revelation of the firm's type. First, the firm might hide its cost by abating at the level of the standard s_1 instead of its cost-minimizing abatement level $q^\tau(\theta) > s_1$. Doing so, the firm increases its cost in the first period. However, this extra cost can be more than offset by the future gain from a lower standard updating, as the firm will then be required to abate s_2 instead of $q^*(\theta)$. Second, the firm θ might mimic a higher-cost type θ' such that $\tilde{\theta}_1 > \theta' > \theta$ by picking the abatement strategy $q^\tau(\theta') > s_1$ to avoid a more stringent standard update in the future, i.e. $s_2 = q^*(\theta')$ instead of $s_2 = q^*(\theta)$ with $q^*(\theta') < q^*(\theta)$. We examine these two opportunistic behaviors separately.[14] They define two dynamic incentive-compatibility (DIC) constraints ensuring truthful revelation of types with a strategic firm. We examine each of these constraints before characterizing the solution.

4.1 The hiding dynamic incentive-compatibility constraint

The firm of type θ does not hide its type by abating $q^\tau(\theta)$ instead of s_1, if the following *hiding DIC constraint* holds:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \rho[\theta C(q^*(\theta)) - \tau q^*(\theta)] \leq \theta C(s_1) - \tau s_1 + \rho[\theta C(s_2) - \tau s_2]. \quad (12)$$

The discounted cost if the type is revealed on the left-hand side of (12) should not be higher than if it is hidden on the right-hand side of (12). The firm has to balance the current extra cost of abating s_1 instead of its cost-minimization level $q^\tau(\theta)$ (first two terms on each side of the inequality), with the discounted future benefit of having a laxer updated standard s_2 instead of $q^*(\theta)$ (terms in brackets on the two sides of the inequality).

It turns out that the hiding DIC constraint is more stringent than the IC constraint

[13] See Freixas et al. (1985) for a formal characterization of the ratchet effect in mechanism design.

[14] Note that a firm would never mimic a lower type because it would imply abating more both periods.

in (5). Substituting $s_1 = q^\tau(\tilde{\theta}_1)$ into (12) shows that this inequality does not hold for $\theta = \tilde{\theta}$ as long as $\rho > 0$ for any future standard s_2 less stringent than $q^*(\tilde{\theta})$. By continuity, it does not hold either for types close to $\tilde{\theta}_1$. Hence, the standard $s_1 = q^\tau(\tilde{\theta}_1)$ does not satisfy the hiding DIC constraint for types close to $\tilde{\theta}_1$ as well as for higher types.

Is it possible to satisfy the hiding DIC constraint for some types? To investigate this question, let us denote by $\dot{\theta}_1$ the type that binds (12) given s_1 and s_2, i.e.,

$$\dot{\theta}_1 C(q^\tau(\dot{\theta}_1)) - \tau q^\tau(\dot{\theta}_1) + \rho[\dot{\theta}_1 C(q^*(\dot{\theta}_1)) - \tau q^*(\dot{\theta}_1)] = \dot{\theta}_1 C(s_1) - \tau s_1 + \rho[\dot{\theta}_1 C(s_2) - \tau s_2]. \quad (13)$$

Let us write the hiding DIC constraint (12) as follow:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \rho[\theta C(q^*(\theta)) - \tau q^*(\theta)] - [\theta C(s_1) - \tau s_1] - \rho[\theta C(s_2) - \tau s_2] \leq 0 \quad (14)$$

Differentiating (14) with respect to θ and substituting $\tau = \theta C'(q^\tau(\theta))$, we obtain:

$$\underbrace{C(q^\tau(\theta)) - C(s_1)}_{\text{(a)}} + \rho \underbrace{[C(q^*(\theta)) - C(s_2)]}_{\text{(b)}} + \underbrace{\rho\,\theta\,[C'(q^*(\theta)) - C'(q^\tau(\theta))]\frac{dq^*(\theta)}{d\theta}}_{\text{(c)}}, \quad (15)$$

where

$$\frac{dq^*(\theta)}{d\theta} = \frac{C'(q^*(\theta))}{B''(q^*(\theta)) - \theta C''(q^*(\theta))} \quad (16)$$

is found by differentiating (2). Condition (15) decomposes the effects of a marginally higher type θ on the hiding DIC constraint into three terms. It includes two direct costs: (a) the current cost of hiding type by abating s_1 instead of $q^\tau(\theta)$, (b) the future benefit from hiding type, which is being allowed to abate s_2 units instead of the standard updated at the first-best level $q^*(\theta)$. Both differences are strictly positive whenever s_1 and s_2 are such that $q^\tau(\theta) > s_1$ and $q^*(\theta) > s_2$, meaning that the direct effect increases (14) with θ. The remaining term (c) is the indirect effect of a marginally higher type θ: it implies a higher first-best abatement level $q^*(\theta)$ due to a more stringent regulation update if the type is revealed. This indirect effect is negative because $\frac{dq^*(\theta)}{d\theta} < 0$. Overall (15) is positive if the direct effect offsets the indirect effect. Let s_2^r denote the equilibrium second-period standard. The following assumption is a sufficient condition for (15) to be positive.

Assumption 1

$$C(q^*(\theta)) - C(s_2^r) + \theta \left[C'(q^*(\theta)) - C'(q^\tau(\theta))\right] \frac{dq^*(\theta)}{d\theta} > 0,$$

for every $\theta \in [\underline{\theta}, \overline{\theta}]$ *where* $q^*(\theta)$*,* s_2^r *and* $\frac{dq^*(\theta)}{d\theta}$ *are defined by (2), (21) and (16) respectively.*

To see under which conditions on the premise of the model Assumption 1 holds, let us focus on the second term on write the right-hand side of the inequality, which can be written as follows:

$$\frac{\left[C'(q^*(\theta)) - C'(q^\tau(\theta))\right] C'(q^*(\theta))}{\frac{B''(q^*(\theta))}{\theta} - C''(q^*(\theta))}. \tag{17}$$

Assumption 1 holds when (17), which is negative, is small compared to $C(q^*(\theta)) - C(q^\tau(\theta)$. That is, (i) when $C(q)$ is not "too convex" because then $C'(q^*(\theta))$ is close to $C'(q^\tau(\theta))$ and $C''(.)$ is low and positive so that the denominator is high, (ii) $B''(.)$ is high, meaning that B is "very concave", (i.e., the marginal damage from pollution is increasing substantially with pollution concentration).

Under Assumption 1, the left-hand side of (14) is increasing with θ which implies that it holds for $\theta \leq \dot{\theta}_1$ but not for $\theta > \dot{\theta}_1$. Furthermore, it also implies $\dot{\theta}_1 < \tilde{\theta}_1$. Thus, under Assumption 1, the hiding DIC constraint holds for every type $\theta \leq \dot{\theta}_1$. Hence, given s_1, the firm reveals its type by over-complying with an abatement effort $q^\tau(\theta) > s_1$ when of type $\theta \geq \dot{\theta}_1$. Otherwise, the firm abates at the standard level s_1. Unlike with a myopic firm, a firm of type θ in the range $[\dot{\theta}_1, \frac{\tau}{C'(s_1)}]$ prefers to hide its type by not over-complying with the standard even if over-compliance is in its short-term interest. Hence, less types are revealed for the same standard.

4.2 The mimicking dynamic incentive-compatibility constraint

The firm of type $\theta < \dot{\theta}_1$ does not mimic another type θ' by abating $q^\tau(\theta') > s_1$ if the following *mimicking DIC constraints* holds for every $\theta < \dot{\theta}_1$:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \rho[\theta C(q^*(\theta)) - \tau q^*(\theta)] \leq \theta C(q^\tau(\theta')) - \tau q^\tau(\theta') + \rho[\theta C(q^*(\theta')) - \tau q^*(\theta')]. \tag{18}$$

The firm of type θ might be tempted to abate less than its cost-minimizing level $q^{\tau}(\theta)$ because, due to the convexity of the cost function $C(q)$, the present extra cost $\theta C(q^{\tau}(\theta')) - \tau q^{\tau}(\theta') - [\theta C(q^{\tau}(\theta)) - \tau q^{\tau}(\theta)]$ is more than offset by the future cost saved $\theta C(q^*(\theta)) - \tau q^*(\theta) - [\theta C(q^*(\theta')) - \tau q^*(\theta')]$. Doing so, the firm of type θ mimics another type θ' which would also over-comply but less, i.e. with $\theta < \theta' < \dot{\theta}$. Let us denote by x the type that minimizes the right-hand side of (18) with respect to $\theta' \in [\underline{\theta}, \dot{\theta}]$:

$$x(\theta) = \arg \min_{\theta' \in [\underline{\theta}, \dot{\theta}_1]} \{\theta C(q^{\tau}(\theta')) - \tau q^{\tau}(\theta') + \rho[\theta C(q^*(\theta')) - \tau q^*(\theta')]\}. \tag{19}$$

We now examine under which conditions the mimicking DIC constraint is binding. First, if $x(\theta) = \dot{\theta}_1$ then the right-hand side of (18) is always strictly lower than the right-hand side of (12). Hence the mimicking DIC constraint holds: the firm of type θ is worse off if it mimics another type by over-complying less than its per-period cost minimizing abatement effort $q^{\tau}(\theta)$. Second, if $x(\theta) < \dot{\theta}_1$ and $x(\theta) \neq \theta$ then $x(\theta) > \theta$ because mimicking a lower type increases the discounting cost so that the firm is better off revealing its type θ. Hence the mimicking DIC constraint might be biding for type θ when $\theta < x(\theta) < \dot{\theta}_1$.

Let $\tilde{\rho}(\theta)$ denote the discount factor for which the mimicking DIC constraint (18) is biding for type θ, where the 'best mimicking strategy' is $x(\theta)$ with $\theta < x(\theta) < \dot{\theta}_1$:

$$\tilde{\rho}(\theta) = \frac{\theta C(q^{\tau}(x(\theta))) - \tau q^{\tau}(x(\theta)) - [\theta C(q^{\tau}(\theta)) - \tau q^{\tau}(\theta)]}{\theta C(q^*(\theta)) - \tau q^*(\theta) - [\theta C(q^*(x(\theta))) - \tau q^*(x(\theta))]}.$$

If $\theta C(q^*(\theta)) - \tau q^*(\theta) - [\theta C(q^*(x(\theta))) - \tau q^*(x(\theta))] > 0$, then $\tilde{\rho}(\theta) > 0$. In this case, $\tilde{\rho}(\theta)$ defines an upper bound on ρ for which the mimicking DIC constraint of type θ holds for every $\theta < \tilde{\theta}_1$. In contrast, if $\theta C(q^*(\theta)) - \tau q^*(\theta) - [\theta C(q^*(x(\theta))) - \tau q^*(x(\theta))] \leq 0$, the mimicking strategy $x(\theta)$ does not pay off because the future cost saved is negative or nil while the current cost is strictly positive. Hence, the mimicking DIC constraint would not be binding for type θ. We thus make the following assumption.

Assumption 2 *$\rho \leq \tilde{\rho}(\theta)$ for every $\theta < \dot{\theta}_1$ whenever $\tilde{\rho}(\theta) > 0$.*

4.3 The equilibrium standards

Under Assumptions 1 and 2, there exists a PBE in which the regulation reveals types below $\dot{\theta}_1$ by making the firm over-complying to the standard if its type is $\theta < \dot{\theta}_1$. The equilibrium strategies are described in Appendix B.1. In this section, we focus exclusively on this equilibrium. Similarly to the case of a myopic firm, the first-period equilibrium standard s_1^r maximizes the below discounted expected welfare where $\dot{\theta}_1$ is defined by (13):

$$\int_{\underline{\theta}}^{\dot{\theta}_1} W(q^\tau(\theta),\theta)dF(\theta)+\int_{\dot{\theta}_1}^{\bar{\theta}} W(s_1,\theta)dF(\theta)+\rho\left[\int_{\underline{\theta}}^{\dot{\theta}_1} W(q^*(\theta),\theta)dF(\theta)+\int_{\dot{\theta}_1}^{\bar{\theta}} W(s_2^r,\theta)dF(\theta)\right] \tag{20}$$

and the second-period equilibrium standard s_2^r is defined by the following first-order condition:

$$B'(s_2^r) = E[\theta|\theta \geq \dot{\theta}_1]C'(s_2^r). \tag{21}$$

The first-period standard s_1^r is characterized by the following first-order condition:

$$\begin{aligned} B'(s_1^r) &= E[\theta|\theta \geq \dot{\theta}_1]C'(s_1^r) \\ &- \left\{W(q^\tau(\dot{\theta}_1),\dot{\theta}_1)+\rho W(q^*(\dot{\theta}_1),\dot{\theta}_1)-\left[W(s_1^r,\dot{\theta}_1)+\rho W(s_2^r,\dot{\theta}_1)\right]\right\} f(\dot{\theta}_1|\theta \geq \dot{\theta}_1)\frac{d\dot{\theta}_1}{ds_1}, \end{aligned} \tag{22}$$

where $\frac{d\dot{\theta}_1}{ds_1} < 0$ is derived in Appendix B.2. Likewise with a myopic firm, the welfare gain from revealing the threshold type $\dot{\theta}$ is the third term in the right-hand side of (22). It is positive because $q^*(\dot{\theta}_1) > q^\tau(\dot{\theta}_1) > s_1^r$ [15] and $q^*(\dot{\theta}_1) > s_2^r$. Hence, as with a myopic firm, the standard is relaxed to induce more of the firm's types to over-comply. Nevertheless, less information is revealed as the firm hides its type if $\theta \in [\dot{\theta}_1, \frac{\tau}{C'(s_1)}]$. Furthermore, since the second line in (22) is strictly positive, comparing (21) and (22) shows that the standard is strengthened in the second period when the firm does not over comply: $s_2^r > s_1^r$.

Proposition 2 *Under Assumptions 1 and 2, the tax is used to reveal types even if the firm anticipates future standard updates. However, for a given standard s_1, less types are revealed as a firm of type $\theta \in [\dot{\theta}_1, \frac{\tau}{C'(s_1)}]$ prefers to hide its type by not abating more than required by the standard even if its short-term interest is to do so.*

Another similarity with the case of the myopic firm is that all information revelation occurs during period 1 in the described PBE. The fact that the standard is strengthened

[15] To see this, recall that we have assumed $q^\tau(\theta) < q^*(\theta)$ for every θ which implies the first inequality for $\theta = \dot{\theta}_1$. Furthermore, $\dot{\theta}_1 < \tilde{\theta}_1$ implies $q^\tau(\dot{\theta}_1) > q^\tau(\tilde{\theta}_1)$ which, combined with $q^\tau(\tilde{\theta}_1) = s_1^r$ by definition of $\tilde{\theta}_1$ in (7), leads to the second inequality.

to $s_2^r > s_1^r$ after the first period implies that if the firm did reveal its type by over-complying in the first period, it continues do so in the future. A firm of any type $\theta > \dot{\theta}$ would never abate $q^\tau(\theta) > s_2^r$ at any period $t > 1$ because the current benefit of doing so is lower than it was in period 1 while the future cost is the same. To be precise, the firm saves $\theta c(s_2^r) - \tau s_2^r - [\theta C(q^\tau(\theta) - \tau q^\tau(\theta)]$ by revealing its type after period 1 which is lower than what it would have saved $\theta c(s_1^r) - \tau s_1^r - [\theta C(q^\tau(\theta) - \tau q^\tau(\theta)]$ in period 1 because $q^\tau(\theta) > s_2^r > s_1^r$ and $\theta C(q) - \tau q$ is convex with a minimum at $q^\tau(\theta)$. Hence, if the firm has to hide its type at some point in time, it should do it in the first period.[16]

Our final result relates the tax rate to informational revelation. In Appendix B.3, we show that $\frac{d\tilde{\rho}(\theta)}{d\tau} > 0$ for every $\theta < \dot{\theta}_1$ such that $\rho(\theta) > 0$.

Proposition 3 *In the regulation game with a forward-looking strategic firm, a higher tax makes information revelation more likely by increasing the maximal discount factor $\tilde{\rho}(\theta)$ at which the mimicking DIC constraint hold for a given type θ whenever it is binding.*

In the regulation game, the ratchet effect precludes information revelation over time. However, the regulator can still take advantage of the tax to induce over-compliance and information revelation if the firm is of low-cost type. Moreover, compared to the case without tax, the regulator relaxes the standard to induce more over-compliance and, therefore, more types to be revealed. Proposition 3 states that a higher tax makes this information revelation more likely because it relaxes the mimicking DIC constraint (18). A higher tax makes mimicking other types less attractive and, therefore, (18) holds for lower discount rates.

Note that more types can be revealed if the regulator can commit on how the regulation would be updated contingently on the firm's abatement. She would be able to commit to set the standard at a distorted abatement level $q(\theta) < q^*(\theta)$ if the type is revealed by over-compliance. This would relax the hiding DIC constraint and, therefore, increases the threshold $\dot{\theta}_1$ for which it is binding. Hence more types $\theta \leq \dot{\theta}_1$ would be revealed for a given s_1. Similarly, distorting the standard when the type is revealed can help to satisfy the mimicking DIC constraint so it would hold for higher discount factors. Hence, the tax has stronger informational value if the regulator can commit on future regulation updates.

In sum, our theoretical results imply that in a setting where a firm is regulated by a standard and a tax, the revisions of the standard will be more stringent than if

[16] Put differently, the right-hand side of the hiding DIC constraint (12) is the lowest discounted cost from hiding type across time.

the firm was only regulated by the standard. Moreover, the magnitude of the revision of the standard will be larger the larger is the over-compliance with the standard in place. In the next section, we investigate if we observe such outcomes in the case of NO_x regulation in Sweden.

5 Empirical Analysis

For geological reasons, Sweden is particularly vulnerable to acidification, causing negative impacts on lake and forest ecosystems. Consequently, NO_x emissions have been an important environmental policy target. Combustion plants are subject to a heavy NO_x national tax and most (but not all) are also subject to individual NO_x emissions standards issued case-by-case, either by one of the 21 regional County Administrative Boards, or by one of the five Environmental Courts that cover a geographical area of several counties.[17]

NO_x emissions standards were introduced in the 1980s. Standard are boiler-specific so that similar firms might end up with different standards assigned to their boilers within the same juridiction. There is no legal limit for how long a standard is valid, though the common practice seems to be that standards are revised no latter than every tenth year. The standards are specified in the plants' operating licenses, and firms must apply for operating licenses when they start operations and when they make large changes to the operations (e.g. installing a new boiler or retrofitting a boiler to use a different type of fuel). In the application, firms are required to submit information about the operations and can propose emission standards based on evidence. However, each County Administrative Board considers whether the suggested emission standards are reasonable.[18] If a firm violates the standard, it risks criminal charges and could face fines to be determined in court.

Regarding the Swedish tax on NO_x emissions, at the time it was introduced in 1992, close to 25% of the Swedish NO_x emissions came from stationary combustion plants. The installation of measuring equipment was judged too costly for smaller

[17] After the first of June 2012, only 12 County Administrative Boards, instead of 21, are responsible for issuing the operating licenses.

[18] Important legislative frameworks that the County Administrative Boards must consider in the determination of NO_x emission standards are some EU directives and the Swedish Environmental Code. If motivated, the regional decision maker can impose more stringent standards than the minimum requirements specified in these directives. These should be determined in line with the Environmental Code which, for example, states that regulations should be based on what is environmentally desirable, technically possible and economically reasonable.

plants and the charge therefore was only imposed on larger boilers. In order not to distort competition between larger plants and smaller units not subjected to the tax, a scheme was designed to refund the tax revenues back to the regulated plants in proportion to energy output. Energy is measured in terms of so-called useful energy, which can be in the form of electricity or heat depending on end-use. Regulated entities belong to the heat and power sector, the pulp and paper industry, the waste incineration sector and the chemical, wood, food and metal industries. Initially the tax only covered boilers and gas turbines with a yearly production of useful energy of at least 50 GWh, but in 1996 the threshold was lowered to 40 GWh and in 1997 further lowered to 25 GWh per year. From 1992 to 2007, the tax was 40 SEK/kg NOx. In 2008, the charge was raised to 50 SEK/kg NOx. In real terms, the increase to 50 SEK in 2008 was only a restoration of the charge to the real level in 1992.

In this section, we take advantage of the overlap between the locally decided emission standards and the national NO_x tax to investigate two theoretical predictions of our model: (i) boilers that are taxed experience more updating of their standards (more frequent and greater magnitude) compared to boilers that are not, (ii) the standards for the taxed boilers become more stringent for over-complying boilers compared to boilers that emit no more than the standard.

In order to test our predictions, we collected information about boiler specific standards for the period 1980-2012 from county authorities and about boilers subject to the tax system from the Swedish Environmental Protection Agency's NO_x database. Using such information, we compare the stringency of the standards of taxed and untaxed boilers and investigate the determinants of the magnitude of the revision of the standards for taxed boilers.

Preliminary evidence suggests that taxed and untaxed boilers are regulated differently by local authorities. Figure 2 graphs the evolution of the average standard of the boilers already in operations when the tax was implemented over the period 1985-2012. The average standards of the two type of boilers, those that were taxed at some point in time and those that were exempted, follow a similar trend of reduction of the emission standard over time prior to the introduction of the NO_x tax in 1992, 1996 or 1997, depending on the boiler's annual energy use. The two lines diverge just after the tax was introduced, as the standards of taxed boilers become more stringent on average.[19]

[19]Standards often depend on the date of entry, with later entrants facing more stringent regulation (i.e., vintage-differentiated regulation). Figure 2 only plots the standards of boilers already in operations by 1992 to factor out the vintage effect.

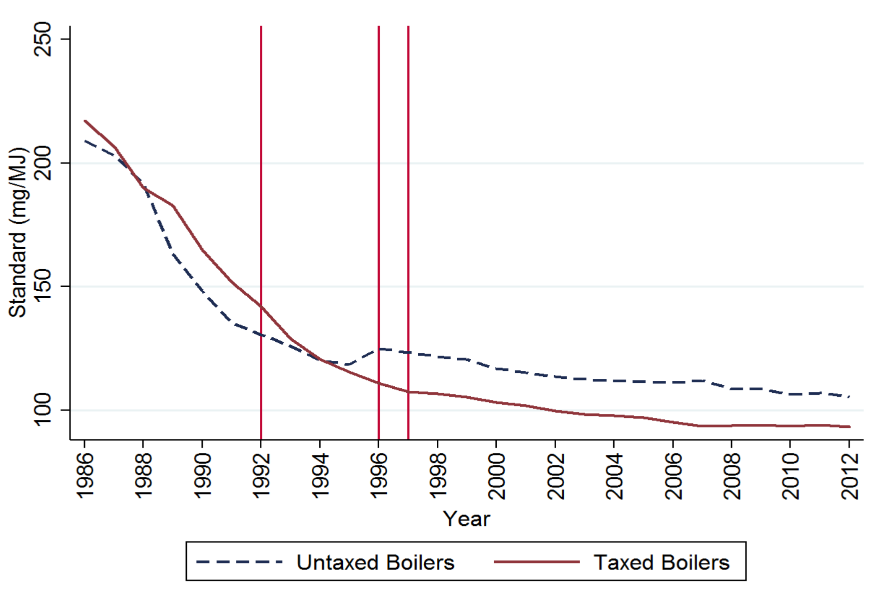

Figure 2: Average Standard by Year

Notes: The figure is based on the revisions of 328 boilers that were already operating when the tax was implemented. The two lines display the yearly average emission standard (mg/MJ) for untaxed and taxed over the period 1985 and 2012. The vertical lines show the years when the tax was first implemented (1992) and when the capacity threshold to be subject to the tax was modified (1996 and 1997).

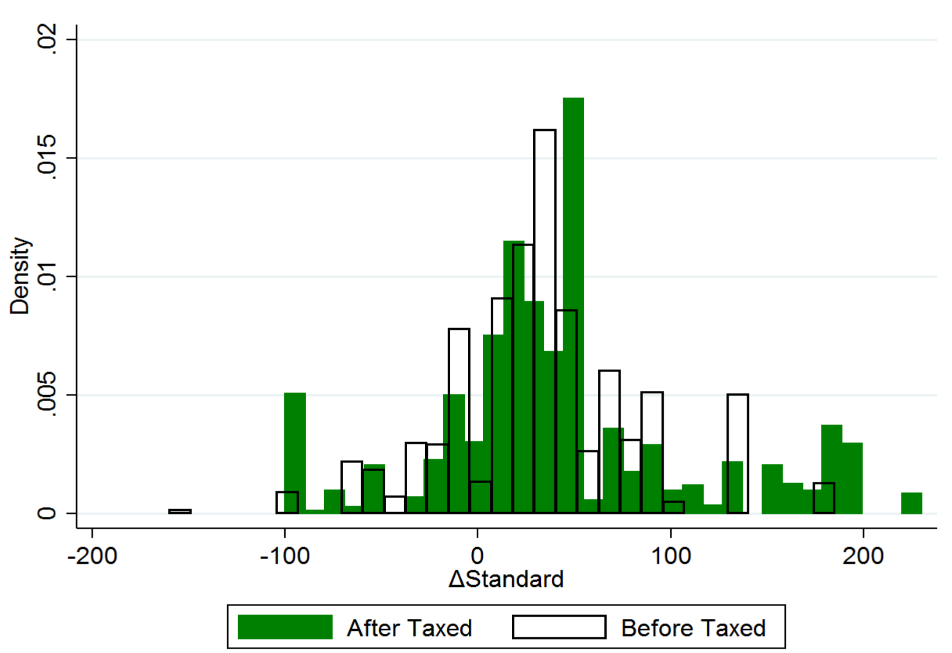

Figure 3: Variations in standard stringency of taxed boilers

Notes: The bars present the distribution of the magnitude of the revisions of the standards of 516 taxed boilers for the revisions that took place before and after the boiler became subject to the tax.

We also examine how standards are revised before and after the tax has been introduced. For a given boiler, we compute the magnitude of the revision $\Delta Standard$ as the difference between the standard that applies to the boiler before and after the revision. The revision strengthens the standard when $\Delta Standard > 0$, while it relaxes it when $\Delta Standard < 0$. In Figure 3, we plot the distribution of the magnitude of the standard revisions for the taxed boilers, separating between those revisions that took place before and after the boilers were taxed. The figure suggests a different distribution before and after the introduction of the tax. A two-sample Kolmogorov-Smirnov test allows us to reject the null hypothesis of equality of the distributions. It seems that there is a greater spread in the magnitude of the revision in absolute values when the boilers are taxed, with a higher share of extreme values on both the positive and negative sides. This evidence is consistent with the idea that the information provided by the tax system is used by the local regulators to better tailor the standard. When updating standards, the regulator might take into account whether the boiler over-complies with current standards, and by how much; this would explain the large variation of the update of stringency of standards for taxed boilers.

In what follows we investigate the impact of the NO_x tax on emission standard updates and the determinants of the magnitude of the update of the standards for taxed boilers.

5.1 Impact of the NO_x tax on emission standard updates

We collected information about 741 boilers subject to emission standards expressed in (mg/MJ). Out of these boilers, 516 boilers have been subject to both the tax and the standards and 225 only subject to the standards. Since standards are revised unevenly across time, we use two statistics to measure the standard update: the frequency and the magnitude of the revisions. Table 1 presents summary statistics of the revisions of stringency of the boilers in our sample[20] On average, there is a statistically larger fraction of revisions for taxed boilers than for untaxed boilers (e.g., 60% vs 41%). Moreover, the magnitude of the revision Δ Standard is statistically larger for taxed boilers. Furthermore, the number of years between revisions is statistically lower for taxed boilers.

	Untaxed	**Taxed**	**p-value**
# Boilers	223	516	—
# Standards	324	901	—
Standards revised (%)	41	60	< 0.001
Δ Standard (mg/MJ)	23.63	38.87	< 0.001
Years between revisions	6.7	6.02	< 0.001

Table 1: Statistics on standards update

We first evaluate the effect of the NO_x tax on the probability of standard revision and on the magnitude of the revision. The outcomes variables correspond to P_{ijt} and $\Delta Standard_{ijt}$, where P_{ijt} takes a value equal to one if the standard that applied to boiler i located at county j was revised at time t, and zero otherwise. As described before, $\Delta Standard_{ijt}$ corresponds to the difference between the standard that applies to boiler i (located at county j) at time $t-1$ and the standard that applies to boiler i at time t.

The outcome variables P_{ijt} and Δ Standard_{ijt} are regressed as a function of the NO_x tax regulation, measured by the dummy variable Tax_{ijt-1} that takes a value equal

[20]We excluded two boilers from the analysis because their emission standards differed significantly from other observations (i.e., outliers). Thus, our analysis is based on 516 boilers subject to both regulations and 223 boilers subject only to emission standards.

to one if boiler i located at county j is subject to the NO_x tax at time $t-1$ and zero otherwise. We should expect the probability of standard revision and the stringency of the revision to depend on the length of time that has elapsed since the previous revision. We proxy for this by the log of the number of years that have elapsed since the boiler was regulated by the last time, denoted as $\Delta \log \text{Years}_{ijt}$. For boilers whose standard has never been revised, the variable corresponds to the log of the number of years that have elapsed since the boiler was assigned the first standard. For those boilers whose standard has been revised, the variable corresponds to the log of the number of years that have elapsed between standard revisions. We use a logarithmic transformation because the number of years that have elapsed since the boiler was last regulated is a highly skewed variable.

Additional controls include a vector Z of L boiler and firm characteristics (for instance, industrial sector and boiler size). Moreover ζ_j are county fixed effects that account for non-observable characteristics of the county that can affect the stringency of the standards, η_t are yearly fixed effects to account for any variation in the outcome that occurs over time and that is not attributed to the other explanatory variables, and ε_{ijt} is the error term.

$$P_{ijt} = \alpha + \beta \text{Tax}_{ijt-1} + \gamma \Delta \log \text{Years}_{ijt} + \sum_{l=1}^{L} \kappa_l Z_{il} + \zeta_j + \eta_t + \varepsilon_{ijt}, \quad (23)$$

$$\Delta \text{Standard}_{ijt} = \alpha + \beta \text{Tax}_{ijt-1} + \delta \Delta \log \text{Years}_{ijt} + \sum_{l=1}^{L} \kappa_l Z_{il} + \zeta_j + \eta_t + \varepsilon_{ijt}, \quad (24)$$

We estimate equations (23) and (24) with robust standard errors clustered at the boiler level to account for the potential correlation of the standards of a given boiler over time.[21]

The data is an unbalanced pooled cross-section over time panel of boilers, where boilers are observed every year from the year when they are assigned the first standard. In our sample, each boiler has received (on average) 1.92 standards, and 427 out of 739 boilers have been assigned only one standard during the whole sampled period. Those boilers that have received more than one standard have received (on average) 2.7 standards, and the average number of years between revisions is 6.1 years.

Regarding the sources of data, information about standards over the period 1980-

[21] Errors are clustered at the boiler level since standards are boiler-specific. By clustering at the boiler level, we control for the potential correlation in the setting of the standards due to the correlation of costs of emissions reductions across periods. Our results are, however, robust to more aggregate clusters, as for instance, clustering at the county level.

2012 specified in the operating licenses of combustion plants was obtained from county authorities. Information on NO_x emissions over the period 1992-2012 comes from the Swedish NO_x database, which is a panel covering all boilers monitored under the tax system. The NO_x database also includes information on boiler capacity, industrial sector, and the availability of NO_x reducing technologies.

See Table 2 for a description of the variables.

Variable	Description	N	Mean	Std.Dev.	Min	Max
Standard	mg NO_x/MJ	11477	110.77	50.22	21.90	300
Tax	1 if subject to NO_x tax; 0 otherwise	11477	0.70	0.45	0	1
# Standards	# of Standards	11477	1.92	1.09	1	7
Standard Revised	(%)	11477	0.54	0.50	0	1
ΔStandard	Current − Previous standard	3757	35.68	60.21	-160	230
logΔYears	log of # years last regulated	10585	1.65	0.84	0	3.33
Boiler/Firm Characteristics						
Waste	1 if waste; 0 otherwise	11477	0.11	0.31	0	1
Food	1 if food; 0 otherwise	11477	0.07	0.25	0	1
Heat and Power	1 if heat and power; 0 otherwise	11477	0.68	0.47	0	1
Pulp and Paper	1 if pulp and paper ; 0 otherwise	11477	0.06	0.24	0	1
Metal	1 if metal; 0 otherwise	11477	0.015	0.12	0	1
Chemicals	1 if chemicals; 0 otherwise	11477	0.025	0.16	0	1
Wood	1 if wood ; 0 otherwise	11477	0.04	0.20	0	1
Boiler Size	Installed boiler effect in MW	10895	55.14	94.51	1.3	825
Over-compliance	1 if over-complies more than mean; 0 otherwise	4617	0.51	0.49	0	1
NO_x technology	1 if technology is intalled; 0 otherwise	11477	0.55	0.59	0	1

Notes: Data about standards was obtained from county authorities. Data on emissions, boiler capacity, industrial sector and availability of abatement technologies was obtained from the Swedish Protection Agency.

Table 2: Summary Statistics

From Table 2, we observe that 70% of the boilers have been taxed at some point in time, and that the majority of the boilers in the data set belong to the heat and power sector. Moreover, there is large variation among standards both in stringency and frequency of revision. Such variation reflects differences in boiler size, technology availability, and industrial sector, among others.

Table 3 presents the results of the regression model specified in equations (23) and (24). The first three columns report the coefficients estimated in the equation on the probability of standard revision under different specifications. In col (1) we control for sectorial fixed effects. In col (2) we control also for county fixed effects, while in col (3) we control for sectorial, county and yearly fixed effects. The last five columns describe the results for the equation on the stringency of the revision. cols (4)-(8) present the results of the regression model specified in equation (24), where - again- in col (4) we only control for sectorial fixed effects, in col (5) we control for sectorial and county fixed effects, and in col (6) we control for sectorial, county and yearly fixed effects. Furthermore, cols (7)-(8) investigate the effects of the NO_x tax on the subsample of first standards' revision and on the subsample of boilers that were in place at the time the tax was first implemented, respectively.

In cols (1)-(3), a negative sign of the coefficient indicates that the determinant reduces the probability of standard revision. We observe that taxed boilers have indeed a statistically significant higher probability of being revised. In the specifications in cols (1) and (2), being taxed increases the probability of standard revision by about 20%. In specification (3), the effect is even larger as the probability of revisions for taxed boilers is about 30% higher than that of untaxed boilers.

The time that has elapsed since the boiler was last regulated also increases the probability of revisions in all specifications. Interestingly, the results in cols (1) and (2) show that the standards of larger boilers are also more likely to be revised.

Regarding cols (4)-(6), the results do not support the hypothesis that the stringency of the standard revisions is larger for boilers that are taxed. The results show, however, that the longer the time that elapses between standard revisions, the greater is the magnitude of the revision. Moreover, in cols (4) and (5) the magnitude of the revisions seem to be larger for larger boilers.

It is possible that any information provided by the tax might have been of use mostly the first time the standards were revised. The results in col (7) suggest so as the positive and statistically significant tax coefficient indicates that the standards of taxed boilers are more stringently revised than untaxed boilers. On average, the first revision of taxed boilers was 14 mg/MJ more stringent than that of untaxed boilers (i.e., about 40% more stringent).

In col (8), we examined whether the effects of the tax were more salient on the subsample of boilers in operations at the time the tax was first implemented (i.e., boilers in operation already in 1992). The results, however, indicate no effect of the tax on the magnitude of the revision for this subsample.

Thus, we can conclude that the results provide empirical support to our hypothesis that the standards of taxed boilers are revised more often, and that the tax might have played a role increasing the stringency of the revisions the first time the standards were revised. The stringency of the revisions, is however, not affected by the tax when analyzing the whole sample of revisions. How can these findings be reconciled? A potential explanation is the existence of spillover effects between taxed and untaxed boilers that took place over time. After increasing the stringency of standards for taxed boilers, the regulator might require boilers that are not taxed to implement similar technologies and management practices for reducing pollution. This argument is consistent with the trends observed in Figure 2, where both taxed and untaxed boilers have reduced their emissions significantly over time. The fact that the standards of taxed boilers are revised more often should also increase the overall stringency of the standards over time, since more frequent increases in the standard stringency for taxed boilers should lead to greater increases in the standard stringency for untaxed boilers when these are revised.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	P_{ijt}			$\Delta Standard_{ijt}$				
NO_x Tax_{t-1}	0.194	0.187	0.286	3.495	-2.104	-0.522	14.217	1.538
	(0.049)	(0.049)	(0.054)	(5.433)	(4.868)	(5.275)	(6.574)	(6.631)
	[<0.001]	[<0.001]	[<0.001]	[0.521]	[0.666]	[0.921]	[0.031]	[0.817]
Log $\Delta Years_t$	0.175	0.195	0.279	4.878	3.783	8.577	7.893	7.838
	(0.031)	(0.031)	(0.036)	(1.804)	(1.695)	(2.715)	(2.939)	(3.364)
	[<0.001]	[<0.001]	[<0.001]	[0.007]	[0.026]	[0.002]	[0.008]	[0.021]
$Size_{ijt}$	0.0006	0.0004	0.0002	0.062	0.063	0.051	0.044	0.036
	(0.0002)	(0.0002)	(0.0002)	(0.036)	(0.031)	(0.031)	(0.038)	(0.034)
	[0.001]	[0.023]	[0.262]	[0.086]	[0.045]	[0.102]	[0.247]	[0.289]
FE Sector	YES	YES	YES	YES	YES	YES	YES	YES
FE County	NO	YES	YES	NO	YES	YES	YES	YES
FE Year	NO	NO	YES	NO	NO	YES	YES	YES
#Obs	9981	9981	9732	3490	3490	3490	2220	2626
#Boilers	681	673	673	301	301	301	280	191
Pseudo R^2/R^2	0.023	0.037	0.068	0.041	0.214	0.240	0.336	0.256

Notes: Cols (1)-(3) of this table present estimates of equation (24). The dependent variable is a binary variable that takes a value equal to one if the standard that applied to boiler i located at county j was revised at time t, and zero otherwise. Cols (4)-(8) of this table present estimates of equation (25). The depend variable corresponds to the difference between the standard that applies to boiler i (located at county j) at time t-1 and the standard that applies to boiler i at time t. Robust standard errors in parentheses, clustered by boiler. p-values in brackets.

Table 3: Probability and Stringency of Emission Standard Updates

It is worth to mention that, in contrast to our theoretical analysis, the Swedish standard on NO_x is relative to useful energy (i.e., expressed in mg /MJ). It is therefore a relative rather than an absolute standard. It is well known that relative standards might incentivize firms to increase output to comply with the standards via the so-called dilution effect; see e.g. Phaneuf and Requate (2017, Chapter 5). Nevertheless, we believe that this dilution effect is at least minor as it might play a role only for the heat and power sector because energy is an input for all other sectors and reducing its use is one of the abatement strategies. Furthermore, if it does, this specificity of the heat of power sector is to somehow controlled by means of fixed effects.

Finally, there might be other potential reasons why local regulators would revise the stringency of the standards to different extents (see Segerson 2020 and Shobe 2020 for recent overviews of the literature on environmental federalism). For example, a local regulator might seek to impose regulations that are more stringent than those set at the national level when it feels national regulations are not sufficient for that county. In such case, the national regulation acts as minimum, with counties having the option to go beyond those minimums. Moreover, regulators might update the stringency of the standards in response to technological progress. Our empirical analysis attempts to account for such effects through county fixed effects and yearly fixed effects that should capture heterogeneity across counties and trends on increased standards stringency over time, respectively.

5.2 How taxed boilers standards are updated

To address our second research question, we regress our dependent variables, P_{ijt} and $\Delta Standard_{ijt}$, only for the sample of taxed boilers.[22] The dependent variables are explained as a function of the lagged value of a proxy for "over-compliance" with the standard, measured as the difference between the emissions' concentration specified by the standard and the actual emissions (i.e., $Standard_{ijt} - E_{ijt}$) and as a function of the availability of NO_x reducing technologies at year $t-1$. Our dummy variable over-compliance takes a value equal to one if boiler i over-complies at a level greater than the median over-compliance of all boilers at year $t-1$. It takes a value equal to zero otherwise. Regarding technologies, there is a large scope for NO_x reduction through various technical measures. For example, it is possible to reduce NO_x emissions through investment in post-combustion technologies that clean up NO_x once it has been formed, or through combustion technologies involving the optimal control of combustion parameters to inhibit the formation of thermal and prompt NO_x. Because the adoption of these technologies allows further reductions of NO_x emissions, we expect that their availability increases the probability and stringency of standard revisions. To account for the effect of the availability of NO_x abatement technologies, we include a dummy variable that takes a value equal to one if the boiler had installed NO_x abatement technologies at year time $t-1$, and zero otherwise.

See Table 2 for summary statistics for the over-compliance dummy, and the availability of NO_x reducing technology.

As before, we control for boiler's and firm's characteristics, and sectorial, county and yearly fixed effects. Moreover, we estimate the regressions with robust standard errors clustered at the boiler level. Results are summarized in Table 4 below.

[22] Another reason for restricting the sample to taxed boilers is that we only have information about NO_x emissions if the boiler is taxed, as the untaxed boilers are not required to report their NO_x emissions to the regulator.

	(1)	(2)	(3)	(4)	(5)	(6)
	P_{ijt}		$\Delta Standard_{ijt}$			
Over-compliance$_{ijt-1}$	0.334		7.916		16.663	
	(0.072)		(5.617)		(6.928)	
	[<0.001]		[0.160]		[0.017]	
Technology$_{ijt-1}$		0.166		-8.661		-15.313
		(0.070)		(6.973)		(8.468)
		[0.018]		[0.215]		[0.072]
Log ΔYears$_t$	0.230	0.305	8.969	10.769	7.372	10.575
	(0.056)	(0.004)	(3.549)	(2.918)	(4.272)	(3.407)
	[<0.001]	[<0.001]	[0.012]	[<0.001]	[0.086]	[0.002]
Size$_{ijt}$	0.000	0.000	0.011	0.054	-0.001	0.047
	(0.000)	(0.000)	(0.030)	(0.032)	(0.033)	(0.035)
	[0.778]	[0.624]	[0.712]	[0.087]	[0.986]	[0.183]
FE Sector	YES	YES	YES	YES	YES	YES
FE County	YES	YES	YES	YES	YES	YES
FE Year	YES	YES	YES	YES	YES	YES
#Obs	4178	6715	1954	2728	1549	2155
#Boilers	471	499	220	238	151	161
Pseudo R^2/R^2	0.081	0.072	0.245	0.275	0.263	0.286

Notes: Cols (1)-(2) of this table present estimates of the effects of over-compliance and availability of technology on the probability of standard revisions of taxed boilers. The dependent variable is a binary variable that takes a value equal to one if the standard that applied to a taxed boiler i located at county j was revised at time t, and zero otherwise.
Cols (3)-(6) of this table present estimates of the effects of over-compliance and availability of technology on the magnitude of standards revisions of taxed boilers. The depend variables corresponds to the difference between the standard that applies to taxed boiler i (located at county j) at time t-1 and the standard that applies to taxed boiler i at time t.
Robust standard errors in parentheses, clustered by boiler. p-values in brackets.

Table 4: Probability and Stringency of Revisions on Taxed Boilers

Cols (1)-(2) present the results for the probability of standard revision. In col (1) we observe that belonging to the group of boilers that over-complies with standards more than the median increases the probability of standard revision. Likewise, in col (2) we observe that having adopted NO_x reducing technologies the previous year also increases the probability of revision. As before, the number of years that have elapsed since the boiler was last regulated is an important determinant of the probability of revision.

Cols (3)-(6) present the results for the stringency of the revisions. Cols (3)-(4)

present the results for the whole sample of revisions of taxed boilers. Cols (5)-(6) present the results for the sub-sample of boilers in operations at the time the tax was first implement to investigate if the effects of over-compliance and the availability of NO_x reducing technologies are more salient for the boilers that first became subject to the policy overlap.

The results in cols (3)-(4) show that stringency is not statistically affected by the extent of over-compliance, nor by the availability of NO_x reducing technologies, but it is significantly affected by the number of years that have elapsed between revisions. The results in cols (5)-(6) show that over-compliance by the boilers in place at the time the tax was first implement led to more stringent revisions (almost 24% more stringent given an average standard equal to 68 mg/MJ for taxed boilers in 1992). In constrast, the availability NO_x reducing technologies by these boilers seemed to have led to less stringent standard revisions. A potential explanation to this is that local regulators might have sought to easen the regulatory burden of those boilers to reward their investments and spur the adoption of NO_x reducing technologies. However, such finding should be interpreted with caution since the statistical significant of the coefficient is small.

In sum, we obtain no clear empirical pattern on how standards of taxed boilers are updated depending on over-compliance and technology when we analyze the whole sample of revisions of taxed boilers. We do find some evidence that support our hypothesis that the standards of taxed boilers become more stringent when boilers over-comply with the standards when we analyze the revisions of the boilers that first became subject to the policy overlap.

6 Conclusion

Most major environmental problems are addressed by a series of policy instruments enacted at all levels of government, implying that regulations covering the same emission sources overlap and override each other. This paper investigates the informational value of the policy overlap. When one of the instruments in the mix is a market-based instrument incentivizing firms to abate pollution to the cost-minimizing level, information about the firms' abatement costs is revealed and can be used to improve the design of other regulations implemented by the same or different regulatory authorities. Concretely, observing the abatement induced by the market-based instrument, a regulator can conclude that the cost of reducing emissions is lower than expected and can respond by strengthening the standard in the future, to better balance benefits with costs. We characterize the value of such information. To take advantage of the information revealed by the tax, the regulator can also relax the standard to obtain a more precise distribution of abatement costs. Although the standard is updated based on the firm's abatement strategy, it always strengthened after the learning phase, regardless of whether the firm over-complies with the standards. A firm anticipating the future standard update might hide its abatement cost by distorting its abatement effort. This induces a ratchet effect which undermines information revelation. Nevertheless, the tax can still be used to reveal information about abatement costs when the costs are high enough.

Our analysis of the case of the regulation of NO_x emissions by stationary pollution sources in Sweden provides support to our theoretical predictions. We observe that the standards of taxed boilers are revised more often and that the information provided by the tax seems to have affected the stringency of the first revisions taking place after the tax was implemented. Since regulators often implement similar standards for similar pollution sources, one can expect that over time the increased stringency spills over to untaxed boilers.

Our paper focuses on the case of the overlap between emission taxes and emission standards. However, the rationale for the informational value of the policy overlap could be easily generalized to the case of other environmental policy mixes where a market-based instrument is used (e.g, interaction of tradable emission permits (TEPs) with other instruments, because TEPs reveal the same type of information about abatement costs as taxes). It could also be generalized to other regulatory policy overlaps. An example is the regulation of public utilities, where the regulator often encounters asymmetric information about the cost of production, and the regulation of prices is usually complemented with the regulation of the quality of the products or of pollution, as in Baron (1985). If the costs of improved quality are revealed when the firms make their production decisions, the regulator might be able to infer relevant information about the firms' costs that can be used to better design the quality standards.

A Details and proofs in the regulation game with myopic firm

A.1 Perfect Bayesian Equilibrium with a myopic firm

A Perfect Bayesian Equilibrium (PBE) of the regulation game with a myopic firm is a set of strategies $s_1, s_t(h_t)$ for every $t > 1$, $q_1(s_1, \theta)$, $q_t(s_t, h_t, \theta)$ for every $t > 1$ and every $\theta \in [\underline{\theta}, \overline{\theta}]$, where h_t is the history of past strategies played, and beliefs $f(\theta)$ and $\mu_t(\theta|h_t)$ for $\theta \in [\underline{\theta}, \overline{\theta}]$ for every $t > 1$ such that:

- $q_1(s_1, \theta)$ minimizes the firm's cost in period 1.
- $q_t(s_t, h_t, \theta)$ minimizes the firm's cost in period t.
- s_1 maximizes the expected welfare given the beliefs $f(\theta)$.
- $s_t(h_t)$ maximizes the expected welfare given the beliefs $\mu(\theta|h_t)$.
- $\mu_t(\theta|h_t)$ are updated using Bayes' rule when possible.

Assuming (out-of-equilibrium) passive beliefs, the separating solution is supported by the following strategies and beliefs:

$$q_1(s_1, \theta) = \max\{s_1, q^\tau(\theta)\} \text{ for every } \theta \in [\underline{\theta}, \overline{\theta}],$$

$$q_t(s_t, h_t, \theta) = \max\{s_t, q^\tau(\theta)\} \text{ for every } \theta \in [\underline{\theta}, \overline{\theta}], t > 1$$

$$s_1 = s_1^d$$

$$s_2(h_2) = \begin{cases} q^*(\theta) & \text{if} \quad q_1 = q^\tau(\theta) > s_1^d \\ s_2^d & \text{if} \quad q_1 = s_1^d \\ s^s & \text{otherwise} \end{cases}$$

where $h_1 = (s_1, q_1)$

$$s_t(h_t) = \begin{cases} q^*(\theta) & \text{if} \quad q_{t-1} = q^\tau(\theta) > s_2^d \\ s_2^d & \text{if} \quad q_{t-1} = s_2^d \\ s^s & \text{otherwise} \end{cases}$$

where $h_t = \{(s_1, q_1), ..., (s_{t-1}, q_{t-1})\}$ for every $t > 2$.

$$\mu_2(\theta|h_1) = \begin{cases} 1 & \text{if} \quad q_1 = q^\tau(\theta) > s_1^d \\ f(\theta|\theta \geq \tilde{\theta}_1) & \text{if} \quad q_1 = s_1^d \\ f(\theta) & \text{otherwise} \end{cases}$$

$$\mu_t(\theta|h_t) = \begin{cases} 1 & \text{if} \quad q_{t-1} = q^\tau(\theta) > s_2^d \\ f(\theta|\theta \geq \tilde{\theta}_1) & \text{if} \quad q_{t-1} = s_2^d \\ f(\theta) & \text{otherwise} \end{cases}$$

for $t > 2$, for all $\theta \in [\underline{\theta}, \bar{\theta}]$ with $\tilde{\theta}_1 = \frac{\tau}{C'(s_1)}$.

A.2 Proof that $\tilde{\theta}_2 = \tilde{\theta}_1$ in the PBE

Let us denote by $V(\tilde{\theta}_t, \theta)$ the expected welfare of the regulation game when the firm's type is θ and the regulator's believes on the distribution of types are $F(\theta|\theta \geq \tilde{\theta}_t)$ on the range $[\tilde{\theta}_t, \overline{\theta}]$.

Suppose the reverse: $\tilde{\theta}_2 \neq \tilde{\theta}_1$. First, we cannot have $\tilde{\theta}_2 < \tilde{\theta}_1$ because $q_2(\theta) = q^\tau(\theta)$ for all $\theta \in [\tilde{\theta}_2, \tilde{\theta}_1]$ and, therefore, the optimal standard is $s_2(q_1) = q^*(\theta)$ for all those types θ, not s_2^d.

Suppose now that $\tilde{\theta}_2 > \tilde{\theta}_1$. It implies $s_2^d < s_1^d$ by definition of $\tilde{\theta}_t = \tau / C'(s_t^d)$ for $t = 1, 2$. Furthermore, if the standard has been revised to s_2^d rather than remained unchanged to s_1^d, it should be that the expected discounted welfare is higher with s_2^d than with s_1^d starting from period 2, that is:

$$\begin{aligned} &\int_{\tilde{\theta}_1}^{\tilde{\theta}_2} W(q^\tau(\theta), \theta) dF(\theta|\theta \geq \tilde{\theta}_1) + \int_{\tilde{\theta}_2}^{\bar{\theta}} W(s_2^d, \theta) dF(\theta|\theta \geq \tilde{\theta}_1) \\ +\beta &\left[\int_{\tilde{\theta}_1}^{\tilde{\theta}_2} W(q^*(\theta), \theta) dF(\theta|\theta \geq \tilde{\theta}_1) + \int_{\tilde{\theta}_2}^{\bar{\theta}} V(\tilde{\theta}_2, \theta) dF(\theta|\theta \geq \tilde{\theta}_1) \right] \\ &> \int_{\tilde{\theta}_1}^{\overline{\theta}} W(s_1^d, \theta) dF(\theta|\theta \geq \tilde{\theta}_1) + \beta \int_{\tilde{\theta}_1}^{\overline{\theta}} V(\tilde{\theta}_1, \theta) dF(\theta|\theta \geq \tilde{\theta}_1). \end{aligned} \tag{25}$$

We show, that if (25) holds, the discounted expected welfare in period 1 is strictly higher with s_2^d rather than with s_1^d. The discounted expected welfare in period 1 with

s_2^d is:

$$\int_{\underline{\theta}}^{\tilde{\theta}_2} [W(q^\tau(\theta), \theta) + \beta W(q^*(\theta), \theta)] \, dF(\theta) + \int_{\tilde{\theta}_2}^{\overline{\theta}} W(s_2^d, \theta) dF(\theta) + \beta \int_{\tilde{\theta}_2}^{\overline{\theta}} V(\tilde{\theta}_2, \theta) dF(\theta). \quad (26)$$

Since $\tilde{\theta}_2 > \tilde{\theta}_1$, (26) can be written as:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} [W(q^\tau(\theta), \theta) + \beta W(q^*(\theta), \theta)] \, dF(\theta) + \int_{\tilde{\theta}_1}^{\tilde{\theta}_2} [W(q^\tau(\theta), \theta) + \beta W(q^*(\theta), \theta) dF(\theta)]$$
$$+ \int_{\tilde{\theta}_2}^{\overline{\theta}} W(s_2^d, \theta) dF(\theta) + \beta \int_{\tilde{\theta}_2}^{\overline{\theta}} V(\tilde{\theta}_2, \theta) dF(\theta). \quad (27)$$

Using (25) multiplied by $1 - F(\tilde{\theta}_1)$, we obtain that (27) is strictly higher than:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} [W(q^\tau(\theta), \theta) + \beta W(q^*(\theta), \theta)] \, dF(\theta) + \int_{\tilde{\theta}_1}^{\overline{\theta}} W(s_1^d, \theta) dF(\theta) + \beta \int_{\tilde{\theta}_1}^{\overline{\theta}} V(\tilde{\theta}_1, \theta) dF(\theta), \quad (28)$$

which is the discounted expected welfare with the standard s_1^d during period 1. We conclude that (26) is strictly higher than (28): the discounted expected welfare is higher if s_2^d rather than s_1^d is implemented during the first stage of the regulation game, which contradicts that s_1^d is the optimal standard in period 1.

B Details and proofs in the regulation game with a forward-looking firm

B.1 Perfect Bayesian Equilibrium with a forward-looking firm

The hiding DIC constraint for periods $t > 1$ is:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \rho[\theta C(q^*(\theta)) - \tau q^*(\theta)] \leq (1 + \rho)[\theta C(s_2) - \tau s_2]. \quad (29)$$

Let us define the following inequalities which compare the right-hand sides of the hiding and mimicking DIC constraints in period 1 and $t > 1$ respectively:

$$\theta C(s_1) - \tau s_1 + \rho[\theta C(s_2) - \tau s_2] \leq \theta C(q^\tau(\theta')) - \tau q^\tau(\theta') + \rho[\theta C(q^*(\theta')) - \tau q^*(\theta')] \quad (30)$$

$$(1+\rho)[\theta C(s_2) - \tau s_2] \leq \theta C(q^\tau(\theta')) - \tau q^\tau(\theta') + \rho[\theta C(q^*(\theta')) - \tau q^*(\theta')] \tag{31}$$

A Perfect Bayesian Equilibrium (PBE) of the regulation game with a forward-looking firm is a set of strategies $s_1, s_t(h_t)$ for every $t > 1$, $q_1(s_1, \theta)$, $q_t(s_t, h_t, \theta)$ for every $t > 1$ and every $\theta \in [\underline{\theta}, \overline{\theta}]$, where h_t is the history of past strategies played, and beliefs $f(\theta)$ and $\mu_t(\theta|h_t)$ for $\theta \in [\underline{\theta}, \overline{\theta}]$ for every $t > 1$ such that:

- $q_1(s_1, \theta)$ minimizes the firm's discounted cost in period 1.
- $q_t(s_t, h_t, \theta)$ minimizes the firm's discounted cost in period t.
- s_1 maximizes the discounted expected welfare given the beliefs $f(\theta)$ in period 1.
- $s_t(h_t)$ maximizes the expected welfare given the beliefs $\mu(\theta|h_t)$ in period t.
- $\mu_t(\theta|h_t)$ are updated using Bayes' rule when possible.

Assuming (out-of-equilibrium) passive beliefs, the separating solution is supported by the following strategies and beliefs:

$$q_1(s_1, \theta) = \begin{cases} q^\tau(\theta) & \text{if (12) and (18) hold for every } \theta' \text{ such that } q^\tau(\theta') > s_1 \\ s_1 & \text{if (12) does not hold and (30) holds for every } \theta' \text{ such that } q^\tau(\theta') > s_1, \\ q^\tau(x(\theta)) & \text{otherwise,} \end{cases}$$

$$q_t(s_t, h_t, \theta) = \begin{cases} q^\tau(\theta) & \text{if (29) and (18) hold for every } \theta' \text{ such that } q^\tau(\theta') > s_2 \\ s_2 & \text{if (29) does not hold and (31) holds for every } \theta' \text{ such that } q^\tau(\theta') > s_2, \\ q^\tau(x(\theta)) & \text{otherwise,} \end{cases}$$

where $x(\theta)$ is defined in (19) for all θ.

$$s_1 = s_1^r$$

$$s_2(h_2) = \begin{cases} q^*(\theta) & \text{if} \quad q_1 = q^\tau(\theta) > s_1^r \\ s_2^r & \text{if} \quad q_1 = s_1^r \\ s^s & \text{otherwise} \end{cases}$$

where $h_2 = (s_1, q_1)$

$$s_t(h_t) = \begin{cases} q^*(\theta) & \text{if} \quad q_{t-1} = q^\tau(\theta) > s_2^r \\ s_2^r & \text{if} \quad q_{t-1} = s_2^r \\ s^s & \text{otherwise} \end{cases}$$

where $h_t = \{(s_1, q_1), ..., (s_{t-1}, q_{t-1})\}$ for every $t > 2$.

$$\mu_2(\theta|h_1) = \begin{cases} 1 & \text{if} \quad q_1 = q^\tau(\theta) > s_1^r \\ f(\theta|\theta \geq \tilde{\theta}_1) & \text{if} \quad q_1 = s_1^r \\ f(\theta) & \text{otherwise} \end{cases}$$

$$\mu_t(\theta|h_t) = \begin{cases} 1 & \text{if} \quad q_{t-1} = q^\tau(\theta) > s_2^r \\ f(\theta|\theta \geq \dot{\theta}_1) & \text{if} \quad q_{t-1} = s_2^r \\ f(\theta) & \text{otherwise} \end{cases}$$

for $t > 2$, for all $\theta \in [\underline{\theta}, \bar{\theta}]$ with $\dot{\theta}_1$ defined in (16) with $s_1 = s_1^r$ and $s_2 = s_2^r$.

B.2 Variation of $\dot{\theta}_1$ with s_1

Differentiating (13) and substituting $\tau = \dot{\theta}_1 C'(q^\tau(\dot{\theta}_1))$ yields:

$$\frac{d\dot{\theta}_1}{ds_1} = \frac{\dot{\theta}_1 C'(s_1^r) - \tau}{C(q^\tau(\dot{\theta}_1)) - C(s_1^r) + \rho\left[C(q^*(\dot{\theta}_1)) - C(s_2)\right] + \rho\dot{\theta}_1\left[C'(q^*(\dot{\theta}_1)) - C'(q^\tau(\dot{\theta}_1))\right]\frac{dq^*(\dot{\theta}_1)}{d\dot{\theta}_1}}$$

The denominator is positive by Assumption 1. We show that the numerator is negative by contradiction. Suppose $\dot{\theta}_1 C'(s_1^r) \geq \tau$. Since $\tau = \dot{\theta}_1 C'(q^\tau(\dot{\theta}_1))$ by definition of $q^\tau(\theta)$ for every θ, $\dot{\theta}_1 C'(s_1^r) \geq \dot{\theta}_1 C'(q^\tau(\dot{\theta}_1))$, which implies $s_1^r \geq q^\tau(\dot{\theta}_1)$. If $s_1^r = q^\tau(\dot{\theta}_1)$, (13) does not hold. As long as $\underline{\theta}$ is sufficiently low, e.g. close to zero, $\exists\theta'$ such that $s_1^r = q^\tau(\theta')$ and, therefore, the hiding DIC constraint (12) is violated for θ'. Hence, the standard s_1^r is not hiding dynamic incentive-compatible, a contradiction.

B.3 Proof of Proposition 3

Let $N(\theta) \equiv \theta C(q^\tau(x(\theta))) - \tau q^\tau(x(\theta)) - [\theta C(q^\tau(\theta)) - \tau q^\tau(\theta)]$ denote the numerator and $D(\theta) \equiv \theta C(q^*(\theta) - \tau q^*(\theta) - [\theta C(q^*(x(\theta))) - \tau q^*(x(\theta))]$ the denominator. Since $x(\theta) > \theta$, we have $\frac{dN(\theta)}{d\tau} = q^\tau(\theta) - q^\tau(x(\theta)) > 0$ and $\frac{dD(\theta)}{d\tau} = q^*(x(\theta)) - q^*(\theta) < 0$. Therefore, since $N(\theta) > 0$ and $D(\theta) > 0$ for all θ, we conclude:

$$\frac{d\tilde{\rho}(\theta)}{d\tau} = \frac{\frac{dN(\theta)}{d\tau}D(\theta) - N(\theta)\frac{dD(\theta)}{d\tau}}{[D(\theta)]^2} > 0.$$

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