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On the Social Value of Disclosed Information and Environmental Regulation

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Abstract

This paper presents an analysis of environmental policy in imperfectly competitive market with private information. We examine how environmental taxes should be optimally levied when the regulator faces asymmetric information about production and abatement costs in an irreversible observable policy commitment game. Under our setting, the paper investigates how information disclosure can improve the efficiency of the tax setting process and may offer an efficient complement to conventional regulatory approaches. From a policy perspective, our findings suggest that access to publicly disclosed information improves the ability of the regulator to levy firms' specific environmental taxes. Despite its advantages, however, informational disclosure may harm the environmental policy it purports to enhance since it facilitates collusive behavior. We show that information sharing may occur and thus leads to a superior outcome in terms of industry output and emissions. Disclosure may undermine market performance and environmental policy.

JEL Classification Numbers: D81, D82, H23, L51, Q58.

Keywords: Environmental Regulation, Emissions Taxes, Collusion, Disclosed Information, Private Information, Information Sharing.

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1 Introduction

Environmental taxation is part of mainstream environmental thought and policy. Emissions taxes are the most widely used and historically experienced market-based instruments in addressing environmental policies. Their design aims to accomplish deep and structural changes in the economic and ecological behavior of individuals, households, and firms by adjusting price signals in an environmentally positive manner. Environmental taxes have many advantages when compared to other instruments and policies. Their role is not limited to correcting the externality. They allow least-cost abatement, raise governmental revenues[1], provide incentives to polluters to internalize the negative external effects of their activities. Public authorities may also use environmental taxes in order to finance public goods. For instance, many OECD countries impose emissions taxes on several industries to fund the cleanup of highly polluted old activities such as inactive hazards and to partially subsidize social programs[2] or the development of renewable energies. In addition, recycling revenues from environmental taxes may lead to a double dividend, according to Goulder's definition (Goulder (1995)), by improving the environmental quality and achieving a less distortionary tax system. Furthermore, recycling environmental taxes may find positive impacts on fiscal re-balancing in many countries: in the current economic circumstances, these taxes can be a significant source of fiscal revenue and thus can contribute to reduce major fiscal deficits in many European countries[3].

More recently, the idea of an internationally harmonized Carbon tax commands some intellectual respect to reduce the global effects of greenhouse gas emissions and meet a certain target level of Climate change. It is true today that we do not know yet the type of regulatory institutions, including policy instruments and participants, that will succeed the post-2012 Kyoto Protocol in the multinational efforts to stabilize Carbon emissions and concentrations in the atmosphere in order to slow global warming. Therefore, the plausible architecture may include an industry-specific Global Carbon Tax. According to Nordhaus (Nordhaus (2007, 2015)), an internationally harmonized but nationally retained Carbon tax may be proposed as an instrument to achieve some strategic aspects of international environmental agreements including those focused on Climate change. Furthermore, recycling revenues from Carbon

[1] According to EUROSTAT (Environmental Statistics and Accounts in Europe 332, 2010), environmentally related taxes range from a few percent and up to 12 percent of total taxes and social contributions in European countries. For instance, many EU Member States have used different energy taxes on the road transport sector, mainly for revenue-raising purposes.

[2] In the United States, a regulatory fee on lead paint manufacturers imposed by the State of California was used in part to fund government programs that addressed the health risks of children exposed to such emissions.

[3] As noted by the OECD (2012), environmental taxation provides potentially a win-win option by protecting the environment and reducing greenhhouse gases, and addressing fiscal consolidation.

tax may reduce distortive taxes, e.g. taxes on labor or capital (ILO (2009))[4]. Finally, such Carbon tax is more easily administrated and more transparent then a cap-and-trade system (Weitzman (2014)).

As market-based instruments, emissions taxes are today much better understood and are widely accepted by both the public and policy makers. The structure and the efficiency properties of pollution taxes have been analyzed under different market structures (Katsoulacos and Xepapadeas (1995); Requate (2005)). Since Weitzman's seminal work "Prices vs. Quantities" (Weitzman (1978, 1974)), there has been a growing interest in the analysis of environmental taxes under informational uncertainties (Lee (1999); Stavins (1996); Ulph (1996)). Under asymmetric information, for many real world externalities, emissions taxes set at the level that appears to be optimal ex ante fail to attain the optimal solution (Shrestha (2001)). Thus, the proper design of environmental taxes largely depends on the regulatory context and other informational distortions (Antelo and Loureiro (2009); Carlsson (2000); Chavez and Stranlund (2009); Hoel and Karp (2001); Long and Soubeyran (2005); Malueg and Yates (2009); McKitrick (1999)). In order to provide recommendations with respect to environmental policy, it is important to understand and acknowledge the potential impacts and limitations of such taxes in very heterogeneous informational environments. Research continues to refine our understanding of emissions taxes and their performance, implementation and relative role under different informational uncertainties.

In this paper, we highlight a way in which the design and implementation of environmental regulation can be improved by focusing on the potential for effective emissions taxes through disclosure. In our setting, publicly disclosed information is intended to enhance environmental efficiency by addressing problems of information asymmetry: in general information is misleading, or is simply difficult to obtain or to evaluate, or cannot be used because of behavioral bias. Thus, disclosure can be used to influence the flow of information in a specific market, which will reduce risks and costs to the regulator in decision-making, monitoring and enforcement[5]. Despite its advantages, however, informational disclosure may harm the environmental policy it purports to enhance since it gives incentives to players to collude. Questions examined in this paper include: Under what conditions publicly disclosed information enhances the environmental tax setting process? Does it induce changes in the behavior of players in the marketplace and lead to a reduction in emissions? Our aim is also to understand the motivation and possible barriers to share information between firms

[4] The International Labour Organization reports that a global price on CO_2 would rise global employment by cutting labour taxes.

[5] Information disclosure may also offer an efficient complement to conventional regulatory approaches in improving the efficiency of the tax setting process, e.g. reducing information asymmetries and improving transparency.

which is important for designing effective environmental policy. In other words, is there any incentive for a firm to share information and coordinate its actions with others' actions?

To this end, since public authorities often lack information they need for efficient regulation of the commons, we consider a tractable model in which a regulatory agency seeks to control emissions from players producing homogenous commodity under costs uncertainties. A Stackelberg-Cournot setting is developed: the regulator who usually possesses sovereign authority, occupies the position of the leader and commits ex ante to a decision and announces it to the followers. This implies that the regulatory decision once made remains in force for an extended period of time while rivals respond in the marketplace. Then, the model analyzes the situation where the regulator designs environmental taxes based on the presence of publicly disclosed information and private signals, avoiding the need to specify the nature of the probability distributions of costs uncertainties[6]. We show that access to more detailed information improves the ability of the regulator to set efficiently emissions taxes. Therefore, requiring agents to reveal some information may lead to behavior intended to conceal or distort this information. Thus, it is important to analyze the impact of policy commitment on information transmission by allowing firms to share information. In other words, we examine whether environmental regulation could reverse some well-known results about the effects of information sharing. We show that, by facilitating collusion, making information publicly available can undermine market performance and environmental policy.

Public authorities often lack of the information they need in setting environmental policy. They can neither foresee nor control the uncertainties at the time they design environmental policy. Under costs uncertainties, policy design requires a complete information about the probability distributions of the uncertainties which is rarely available to the social planner a priori.[7] Even in the absence of such information, the regulator can make some assumptions about the probability distributions and try to design a better emissions tax. However, if such ex ante assumptions turn out to be wrong, the designed policy may turn out to be even worse than the one that completely ignores the presence of costs uncertainties.

Furthermore, at the time when policy decisions are made, it is uncertain which state of the world will emerge. Hence, environmental policy cannot be revised and subsequently

[6] The information structure adopted in this paper is different from that adopted in the respective literature, especially the mechanism design literature which provides approaches to elicit the private information of firms. These usually induce higher administrative costs than those of the conventional instruments such as emissions taxes. To our knowledge the revelation approach has not had a great influence on environmental policy debates and has not been employed in real pollution control situation.

[7] For example, Karp and Yohe (1979) and Weitzman (1978) presented an optimal environmental instrument in a situation where the social planner can correctly characterize the probability of the uncertainties a priori. Both papers considered the second order Taylor approximation of costs and make some regulatory assumptions about the probability distributions of the uncertainties (Shrestha (2001)).

be adjusted in the light of actual circumstances. If it is possible to periodically adjust the levels of regulatory variables in response to the realized and observed levels of costs at each period, then the regulator may approximate the optimal solution. Unfortunately, in many environmental problems and in most policy contexts, adjustments request long administrative and legal procedures, i.e., the regulator cannot change its policy decision periodically but must enforce it for a fixed period of time. Thus, in order to accomplish their mission in protecting the environment, policy makers may welcome any available information, even though it is incomplete, which helps them to overcome the burden of uncertainty about the state of the world and the likely actions of polluters. Such valuable information could come from mandatory reporting or simply from empirical studies of how observables like production and pollution control technologies and input and output levels determine firms' abatement costs. For example, suppose in a particular emission control setting that the regulator has some information about how production and abatement costs vary with input and output levels. If fuel is substituted by other green inputs and the regulator knows something about how green inputs affect abatement costs, then this information can be optimally used in setting differentiated green taxes as policy instruments for environmental protection.

Today, reporting and information disclosure by public agencies, World Environmental Organizations, NGOs or watchdog groups may be an interesting complement for traditional forms of regulation in protecting the environment and may have a significant effect on the environmental performance of firms and future compliance and emissions. In addition, disclosure programs may cost the government far less than drafting and implementing industry-specific complex regulations, and allow regulators to spend their time where it will have the most bang for its buck. For instance, the US Toxic Release Inventory (TRI) Programs require certain industries to annually report their toxic emissions. Between 1988 and 1999, these programs led to a significant voluntary decrease in the total amount of TRI chemicals released in the United States, beyond any mandated levels or legal requirement. Similar programs have been instituted in other countries and contexts, including the Canadian National Pollutant Release Inventory or the European Pollutant Emission Register. More recently, in response to public concerns about the known and unknown risks of drilling and slick-water fracturing[8], the US environmental laws[9] require information disclosure of the chemicals associated with such activities. Therefore, the more meaningful efforts toward disclosing chemicals

[8] A now-common technique that consists of injecting water and chemicals down wells at high pressure.

[9] For example, the Occupational Safety and Health Act and Emergency Planning and Community Right-to-know Act require operators in the United States to keep material safety data sheets for chemicals on their sites.

have occurred at the State and industry levels. A growing number of states[10] have required post-fracturing disclosure of the identity of chemicals used at well sites, a description of the quantity of each chemical used, and, often, a description of the quantity of water used. The knowledge of chemical-based inputs in the US fracturing industry may be considered as an important component of addressing environmental regulation. Thus, disclosed information might be used strategically as an efficient complement to existing regulatory requirement and induces the regulator to set non-uniform taxes across firms.

Our setting may characterize many types of oligopolistic markets where policy changes require long administrative and legal procedures. This is true under complex international negotiations which cannot be readily changed in response to players' actions. This policy setting is also relevant in industries where players generate a negative externality for an extensive region or country and where the regulator as well as competitors accumulate some accurate information about operating and production costs of complying with the environmental regulation since polluters interact recurrently with the regulator in order to fulfill the requirements imposed by environmental policy. This is obviously the case of energy companies using fossil fuels and the chemicals industry. Thus, one possible practical interpretation of our model is that it represents the type of policy decision that has to be made about pollution in the utility industries. Such policy instrument could be potentially adjusted to deal with greenhouse gases in the U.S. energy sector, where electricity is produced by firms engaged in a competition à la Cournot (SO_2/CO_2 emissions market). It also can be adjusted to deal with chemicals in the fracturing industry. The model may also be applied to the European wholesale energy market where the European Commission is requesting market participants to report part of the private information on their activities publicly available. The data relating to generation units, transportation and consumption of electricity which need to be made available to market participants are very detailed[11].

Before turning to the analysis of environmental policy, a few words regarding our model setup and linearity assumptions are needed. First, the model is flexible, relevant in the management of the commons, and admits several interpretations in terms of firms competing in a homogeneous product market such as wholesale electricity. The model is also relevant in the management of the commons, e.g. the fishery industry. Second, the paper follows the tradition of the literature on environmental taxation and considers linear-Bayesian

[10]From 2010 through 2012, Arkansas, Colorado, Louisiana, Michigan, Mississippi, Montana, New Mexico, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, West Virginia, and Wyoming all updated, released, or proposed new statutes, agency directives, or regulations to require basic chemical disclosure.

[11]See EU regulation No 1227/2011 of the European Parliament and the Council of 25 October 2011 on wholesale energy market integrity and transparency, Official Journal of the European Union, L 361, 8, December 2011. See also Commission Regulation (EU) No 543/2013 of 14 June 2013 on submission and publication of data in electricity markets.

equilibrium. Our modeling setup assumes linear-quadratic payoffs coupled with an affine information structure which admits two components, common and private values, that yields a unique linear Bayesian equilibrium of the game. The first component represents publicly disclosed information and the second component is private information which obeys a linear conditional expectation property. Third, linear equilibrium is tractable, particularly in the presence of noisy private information, and has proved to be very useful as a basis for empirical analysis. Fourth, our model covers the case in which firms in the marketplace cannot exclude the possibility of collusion. Since information exchange and coordination within an industry is important for designing effective environmental policy, our purpose is to understand under what conditions information sharing is beneficial.

The remainder of the paper is structured as follows. In Section 2, we explore the model setup that provides the basis for environmental regulation under two informational regimes. We analyze the optimal tax rule under complete and asymmetric information settings in Section 3. Comparative statics and special cases are performed and examined in the same section. In Section 4 we analyze whether firms in the marketplace have incentive to share valuable information about their marginal costs when they are private to the firms. Conclusions are in Section 5. Technical proofs are relegated in the Appendices.

2 Model

The modelling framework for the analysis of environmental tax under costs' uncertainties aims to place our results in relation to the respective literature. Specifically, this requires a presumption of linear marginal costs as well as linear demand function, which demands caution in the interpretation of our findings. Therefore, the results can be a quite good approximation for more general functions, provided that the feasible value range of the random variable is sufficiently small (Weitzman (1974)).

We consider a single polluting industry with $I = \{1, 2\}$ non-identical firms producing a homogeneous final good and generating emissions. We might think of this commodity as the energy but other interpretations are possible. Consumers' preferences are described by a quasi-linear function:

$$\nu\left(Q, Y\right) = \alpha\ Q - \left(\frac{\beta}{2}\right)\ Q^2 + Y;\ \alpha, \beta \geq 0,$$

where $Y \geq 0$ represents the aggregate amount of a numéraire commodity (residual income), is produced in an exogenous market and thus can be neglected throughout the further analysis. The consumers' utility maximization program gives rise to the following inverse demand function:

$$p(Q) = \alpha - \beta Q, \tag{1}$$

where p denotes the unit price of the good and $Q = \sum_{i=1}^{2} q_i$ is the total output of the industry. We assume that emissions by firm i, e_i, are proportional to firm output q_i:

$$e_i = \phi\ q_i;\ \forall i \in I,\ 0 < \phi < 1. \tag{2}$$

Emissions depend on the technology of production used by each firm and can be reduced through the choice of an abatement technology, and also by varying the level of output produced. For instance, a power utility which adopts an environmental friendly abatement technology (renewable energy or Carbon capture and storage) will face an increase in the subsequent cost of producing each unit of output and might be able to reduce emissions more effectively than a dirty power station that has selected initially a relatively cheap technology involving low operating and production unit costs (coal). For instance, in the electricity sector, installation of Selective Catalytic Reduction, which incurs high costs, reduces greenhouse gases (NO_x) by up to 99%. In contrast, Selective Non-Catalytic Reduction has lower costs but only reduces NO_x emissions up to 35%. Thus, the initial abatement technology decision, made before future regulation, will have implications for the costs of reducing emissions during future operations.

We consider a tax per unit emissions: firm i must pay τ_i for each unit of emissions. This tax rate must be set optimally by the regulator. The environmental damage in each period, generated by the production activity is given by the following quadratic convex function:

$$D = \frac{1}{2}\ \delta\ \mathcal{E}^2;\ \delta > 0 \tag{3}$$

where $\mathcal{E} = \sum_{i \in I} e_i$ represents the aggregate level of emissions or total pollution level. A marginal increase in output, entails a positive and increasing environmental damage (i.e. pollution is convex in output). The positive parameter δ is an exogenous variable that captures the regulator's valuation of the environment.[12] This type of damage function is commonly used in the literature and assumes that this damage is exogenous for consumers: they do not take into account the effect of their consumption decisions on the environment.

[12] The parameter δ can also represent the steepness of marginal damages or equivalently the degree of convexity of the damage function.

2.1 Information Structure

Following the pertinent literature, we introduce incomplete information by assuming that agents observe noisy private and public signals about marginal costs. We assume that the technology used by each firm is stochastic but it exhibits constant returns to scale[13], namely for a given state of the nature the marginal production and abatement cost is constant and is equal to $\widetilde{x}_i$. Before choosing its strategy, each firm observes the following random variable[14]:

$$\widetilde{x}_i = \widetilde{u}_i + \widetilde{c}_i. \tag{4}$$

The first component, $\widetilde{u}_i$, is related to the publicly disclosed information and is observed by all players, the regulator as well as both firms. We suppose that all $\widetilde{u}_{i,i\in I}$ are independent and identically distributed with mean μ_{u_i} and variance $\sigma^2_{u_i}$. The second component, $\widetilde{c}_i$, is the private information of firm i and is not observable by the others. This is the sense in which the signals are private. Prior to producing, each firm receives a noisy estimate of its uncertain private marginal cost given by:

$$\widetilde{c}_i = \widetilde{s} + \widetilde{\varepsilon}_i \tag{5}$$

The first term on the right-hand side $\widetilde{s}$ is the common cost component that is the same for all firms and represents the industry-wide shocks that affects the firms. The second term $\widetilde{\varepsilon}_i$ is a firm-specific noise term, which can be viewed as the remaining uncertainties or random shocks that are not correlated across firms.

Assumption 1. *Let $\widetilde{s}$ be a positive random variable and distributed according to some prior density with mean μ_c and finite variance σ^2_c (i.e. $\widetilde{s} \sim (\mu_c, \sigma^2_c)$). Also, let $\widetilde{\varepsilon}_i$ have mean zero and variance σ^2_ε.*[15] *In addition, $\widetilde{\varepsilon}_i$ is uncorrelated with $\widetilde{s}$ and the noise terms of other firms $\widetilde{\varepsilon}_j$, $j \neq i$.*

A firm can make inferences about the marginal cost of its rivals based upon its private

[13] This assumption is routinely made in the literature on environmental taxes for the sake of simplification, but it does not restrict the generality of results.

[14] Most models in the respective literature are based on a non-separable cost function. This way of modelling is necessarily associated with non-linear marginal costs and is thus incompatible with the framework adopted in our paper. Hence, due to the need for linear marginal costs, we consider that the firms'cost function is additively separable. This insight is helpful for analyzing the presence of public and private information in setting emission taxes. Therefore, our analysis can be extended to reflect the case of non-constant marginal costs. Note that this would not change the qualitative results of our paper.

[15] This implies that, in setting the tax rates, the regulator cannot observe the exact marginal costs, but its expectation about the marginal costs functions turns out to be correct on the average.

information[16]*:*

$$\mathbb{E}[\tilde{c}_i|\tilde{c}_j] = \gamma\ \tilde{c}_j + \lambda,\ \gamma = \frac{\sigma_c^2}{(\sigma_c^2 + \sigma_\varepsilon^2)},\ \lambda = (1-\gamma)\,\mu_c;\ \forall i, j = 1, 2,\ i \neq j.$$

This assumption states that the assumption that the signals are conditionally independent can be replaced by the assumption that for each i and j, $i \neq j$, $\mathbb{E}\left[\widetilde{c}_i \mid \widetilde{c}_j\right]$ is linear in $\widetilde{c}_j$.

While in the related literature the signals are supposed in general to be binomial or normally distributed[17], our assumption assume that the expectation of the true state conditional on the signals is linear in the signals and thus is general enough to include some interesting distributions. The linearity setting (about demand, costs and conditional expectations) is analytically convenient and conceptually satisfactory because we do not need to specify the distributions. Furthermore, we do not need to impose nonnegativity constraints on the quantities of output and prices selected by the firms.

This information structure allows us to analyze how the different components of the marginal costs contribute to the optimal environmental taxes. For example, if σ_ε^2 equals zero, then both firms can perfectly observe their rival's marginal costs, as there is no private component. Similarly, if σ_ε^2 and σ_c^2 both equal zero, then the marginal cost for firm i equals the public component $\widetilde{u}_i + \mu_c$, so the regulator can perfectly observe each firm's marginal cost. Finally, if $\sigma_{u_i}^2$ equals zero, then there is no public information about the marginal costs, and the two firms are ex-ante symmetric for the regulator. Therefore, the information available to agents can have important implications on the resulting optimal environmental taxes and market outcomes.

In the following we suppose that all players, including the regulator, are perfectly informed about the realizations of the public component. This assumption is made to simplify the analysis. Our results hold in the case where players observe imperfectly the public information.

Having described the information structure, we now explain the timing of the model:

1. Before agents move, nature draws randomly the public component of the marginal cost $\{\widetilde{u}_i\}_{i\in I}$. The realization of $\{\widetilde{u}_i\}_{i\in I}$ is perfectly observed by all players.

2. The risk neutral regulator sets the environmental taxes $\{\tau_i\}_{i\in I}$ optimally to maximize the expected welfare.

[16]For more details, see Basar and Ho (1974); Ericson (1969); Gal-Or (1986); Li (1985); Shapiro (1986); Vives (2002, 2001).

[17]The assumption of normality is very convenient analytically but has the drawback that prices and quantities may take negative values.

3. The common component of the marginal cost $\widetilde{s}$ is drawn randomly and observed by both firms, but not by the regulator.

4. The private component of the marginal cost $\{\widetilde{\varepsilon}_i\}_{i\in I}$ is drawn randomly and observed by the corresponding firm, but not by the regulator or the other firm.

5. Given the marginal costs and the environmental taxes, each risk neutral firm determines its output and emission abatement levels.

The characterization of a linear equilibrium when there is market power and private information needs some careful analysis to be able to model the capacity of a player in the marketplace to influence the optimal environmental policy. Our pollution-tax game can be described as a Stackelberg game where the regulator is the *leader* and firms are the *followers*. At an initial stage of the game, each firm makes a decision about information production and disclosure. Importantly, information production and revelation decisions are taken prior to the arrival of private information, so issues of incentives to reveal information are ignored.[18] The revelation may result from direct regulatory oversight, or through other mechanisms such as internal whistle-blowers, disclosures by the media or environmental watchdog groups, or simply due to random events that bring information into the public domain.

Then at a subsequent stage, having observed the public component of the marginal costs, the regulator sets $\{\tau_i\}_{i\in I}$ to maximize $\mathbb{E}(W)$. Recall that the regulator can neither foresee nor control the uncertainties at the time it makes the regulatory decision which remains in force for an extended period of time so that there is no possibility of adjusting periodically the levels of regulatory variables in response to the observed levels of costs. Finally, given the taxes and the observed common and private values of the marginal costs, firms compete as Cournot rivals and decide their output levels to $\max_{q_i} \mathbb{E}(\pi_i)$, for $i \in I$. Each firm's production generates pollution e_i, which affects the environmental quality.

We solve this asymmetric information game by backward induction. First, we focus on the firms' profit-maximization problem. Second, having derived the equilibrium output levels and the price given the taxes, we return our attention to the regulator's welfare maximization problem and solve for the optimal firm-specific taxes per unit of emissions that maximizes the expected welfare.

[18] In this case, there is no need to get into the details of information acquisition and how a certain rate of decrease in individual information precision is achieved. One may just starts with a given rate and explores the implication. Incorporating the details of information acquisition and the construction of the particular acquisition function, although being interesting, require substantial effort and analysis that does not add to the insights we aim to present in this paper.

2.2 Firms

In this section we characterize the behavior of producers, who are subject to a tax per unit of emissions, set irrevocably by the regulator prior to the time at which firms commit to their initial production decisions. We assume that the two firms are risk-neutral and act as Cournot competitors in this duopoly market.[19] Taking the tax rates as given, each firm chooses its production level so as to maximize its expected profits conditional on its own marginal cost:

$$\max_{\widetilde{q}_i} \ \mathbb{E}_{\widetilde{c}_j} \ [(\widetilde{p} - \widetilde{u}_i - \widetilde{c}_i - \phi \ \tau_i) \ \ \widetilde{q}_i \mid \widetilde{c}_i, \widetilde{u}_i, \widetilde{u}_j] \, ; \ \forall i, j = 1, 2, i \neq j \tag{6}$$

where the market price depends on both firms' production level (i.e. $\widetilde{p} = \alpha - \beta \ (\widetilde{q}_1 + \widetilde{q}_2)$). Note that each firm predicts the other firm's marginal conditional on its own marginal cost, so the market price also depends on the marginal costs. Since we consider a linear demand and constant marginal costs, we restrict our search to a linear equilibrium. Furthermore, under our assumptions, the model satisfies the linear conditional expectation property. In other words, the affine information structure of the model ensures that conditional expectations are linear. Thus, the equilibrium strategies are affine in the observed signals.

Given the profit maximization problem in (6), we can solve for the linear equilibrium in the usual way by identifying coefficients with the candidate linear strategy:

$$\widetilde{q}_i = \theta_{i1} + \theta_{i2} \ \widetilde{c}_i + \theta_{i3} \ \widetilde{u}_i + \theta_{i4} \ \widetilde{u}_j ; \ \forall i, j \in I, \ i \neq j \tag{7}$$

$$\theta_{i1} = \rho_{i0} + \rho_{i1} \ \tau_i + \rho_{i2} \ \tau_j . \tag{8}$$

2.3 Regulator

Given the information structure and firms' optimal behavior, the regulator sets an environmental tax based on emissions. To do so optimally, the regulator maximizes the expected social welfare function which includes the expected consumer surplus, $\mathbb{E}(CS)$, the firms' expected profits, $\sum_{i \in I} \mathbb{E}(\pi_i)$, and the government total expected revenue generated by pollution taxes, $\mathbb{E}(R)$, minus the expected value of environmental damage due to firms' production

[19] Market entry is not allowed in this setup. The regulator can be politically held responsible for forcing firms out of the market or into bankruptcy. Furthermore, it may even be optimal for the regulator not to induce bankruptcy, as bankruptcy will result in a lower total contribution by firms toward remediation costs, leaving the regulator a larger "orphan share" of the costs to fund itself.

process, $\mathbb{E}(D)$:

$$\mathbb{E}(W) = \mathbb{E}\left(CS - D\right) + \sum_{i=1}^{2} \mathbb{E}(\pi_i) + \ell\ \mathbb{E}(R) \tag{9}$$

where ℓ is a positive parameter which represents the relative importance of the indirect social benefit of environmental taxation, commonly called the "second dividend" that is used to diminish the tax burden that weights on the rest of society.

Before we proceed, we have to make the following assumption about the parameter ℓ:

Assumption 2. *We assume that the parameter $\ell' = (\ell - 1)$ is strictly positive where ℓ represents the weight on the revenue from emissions taxes.*

Assumption 2 ensures that the regulator's objective function is concave, so the optimal tax rates can be analytically derived by taking the first-order conditions of the objective function. Furthermore, it leads to positive quantities for both firms in equilibrium, and implies that both firms pay a non-negative emissions tax.[20]

3 Analysis

3.1 The Full Information Case

It is useful to consider first the complete information benchmark. Thus, in this section we assume that all the uncertainty due to private or public information are perfectly observable to all players in the game (i.e., firms and the regulator). The equilibrium with full information can then give us a comparison regarding how uncertainty affects the equilibrium output and price. The full information equilibrium is characterized as follows.

Proposition 1. *With full information, the regulator sets the following optimal taxes:*

$$\tau_i^F = \frac{\alpha\left(2\omega + \ell' - 1\right)}{2\phi\left(\ell' + \omega\right)} - \frac{\omega\ \left(\ell' + 1\right)\ \left(x_i + x_j\right)}{4\phi\ \ell'\left(\ell' + \omega\right)} + \frac{x_i(1 - \ell')}{2\phi\ell'};\ \forall i, j = 1, 2,\ i \neq j, \tag{10}$$

where $\omega = \left(\frac{\beta + \delta\phi^2}{3\beta}\right)$.

[20] ℓ can also be seen as the marginal cost of public funds. Different empirical research studies (see Long and Soubeyran (2005)) found that $1 < \ell < 2$. In what follows, we restrict our analysis to this empirically relevant range which means that $0 < \ell' < 1$.

Given the optimal taxes in (10)*, the equilibrium output and price are as follows:*

$$Q^F = \frac{(\ell' + 1)\ (2\alpha - (x_1 + x_2))}{6\beta\ (\ell' + \omega)} \tag{11}$$

$$p^F = \frac{2\alpha\,(2\ell' + \omega + 1) + (\ell' + 1)\,(x_1 + x_2)}{6\ (\ell' + \omega)} \tag{12}$$

Proof. See Appendix A. □

Note that in equilibrium, environmental taxes and the resulting output levels and price are positive as long as the choke price α is high enough. Additionally, we can verify that, as ℓ' tends towards one, $\forall i, j = 1, 2,\ i \neq j,\ \tau_i^F = \tau_j^F$. In this case, the regulator sets the same tax rate for both firms.

3.2 The Asymmetric Information Case

Similar to the full information case, we first analyze each firm's profit maximization problem, which is the second stage of the game. Given the public disclosed information and their own private costs, firm i maximizes its own expected profits as a function of the tax rates, set by the regulator. Note that the expectation operator in the firm's problem is defined over the other firm's private marginal costs. Under our setting, firms use strategies that are affine in their signals, then verify these strategies to form an equilibrium.

Each firm maximizes its expected profits. We show in Lemma 1 that the equilibrium output for both firms are linear in the marginal cost components and the tax rates.

Lemma 1. *Under asymmetric information, the parameter vector θ can be calculated as follows:*

$$\theta_{i1} = \underbrace{\frac{\alpha(2+\gamma) + \lambda}{3\beta(2+\gamma)}}_{\rho_{i0}} + \underbrace{\frac{-2\phi}{3\beta}}_{\rho_{i1}}\,\tau_i + \underbrace{\frac{\phi}{3\beta}}_{\rho_{i2}}\,\tau_j;\ \forall i, j = 1, 2, i \neq j \tag{13}$$

$$\theta_{12} = \theta_{22} = -\frac{1}{\beta\,(2+\gamma)} \tag{14}$$

$$\theta_{13} = \theta_{23} = -\frac{2}{3\beta} \tag{15}$$

$$\theta_{14} = \theta_{24} = \frac{1}{3\beta}. \tag{16}$$

Proof. See Appendix B. □

This Lemma has a simple interpretation. It establishes that there exists a unique linear solution to the optimization problem in the asymmetric information case. In fact, because the best response of a firm is linear in its expectations, and because we assumed linear demand and costs functions, it is easy to verify that there do not exist solutions to firms' maximization problem other than the linear one.

Substituting the expressions of θ in Lemma 1 into the expressions of $\widetilde{q}_1$ and $\widetilde{q}_2$, we solve for the linear equilibrium for the firm outputs:

$$\widetilde{q}_i = \frac{\alpha + \phi\,(\tau_j - 2\tau_i)}{3\beta} + \frac{\lambda}{3\beta\,(2+\gamma)} - \frac{\widetilde{c}_i}{\beta\,(2+\gamma)} - \frac{2\widetilde{u}_i}{3\beta} + \frac{\widetilde{u}_j}{3\beta};\ \forall i,j = 1,2, i \neq j. \tag{17}$$

Note that $\widetilde{q}_1$ and $\widetilde{q}_2$ still depend on τ_1 and τ_2 only through θ_{11} and θ_{21} respectively. As is evident from the last equation, the sensitivity of the equilibrium to private and public information depends not only on the precision captured by γ, but also on the public and private values of marginal costs. Given the industry output, we can then compute the market price:

$$\begin{aligned}\widetilde{p} =& \alpha - \beta[\widetilde{q}_1 + \widetilde{q}_2] = \alpha - \beta\,(\theta_{11} + \theta_{21}) + \frac{\widetilde{u}_1 + \widetilde{u}_2}{3} + \frac{\widetilde{c}_1 + \widetilde{c}_2}{(2+\gamma)} \\ =& \frac{\alpha + \phi\,(\tau_1 + \tau_2)}{3} - \frac{2\lambda}{3\,(2+\gamma)} + \frac{\widetilde{u}_1 + \widetilde{u}_2}{3} + \frac{\widetilde{c}_1 + \widetilde{c}_2}{(2+\gamma)}\end{aligned} \tag{18}$$

Similar to the associated literature, we focus in our analysis on the interior solution. Given the best response function for both firms, the regulator maximizes the expected welfare to set the optimal taxes in the first stage of the game:

$$\max_{\tau_1,\tau_2} \mathbb{E}_{\widetilde{c}_1,\widetilde{c}_2} \left[\widetilde{W}\,(\tau_1,\tau_2) \,\middle|\, \widetilde{u}_1, \widetilde{u}_2 \right] \tag{19}$$

$$\ni \widetilde{W}\,(\tau_1,\tau_2) \equiv -\left(\frac{\beta + \delta\phi^2}{2}\right)\widetilde{Q}^2 + \sum_{i=1}^{2} \left[(\alpha - \widetilde{u}_i - \widetilde{c}_i)\,\widetilde{q}_i + \phi\,\ell'\,\tau_i\,\widetilde{q}_i\right] \tag{20}$$

where $\ell' = \ell - 1 > 0$ and the parameter $\ell > 1$ represents the relative weight the regulator defines on the revenue from emissions taxation: a higher value of ℓ implies the regulator puts a higher value on its revenue component.

We describe the equilibrium taxes in proposition 2.

Proposition 2. *Under asymmetric information and in the presence of publicly disclosed information, a risk neutral regulator sets differentiated tax rules given by:*

$$\tau_i^* = \frac{(\alpha - \mu_c)\,(2\omega + \ell' - 1)}{2\phi(\ell' + \omega)} - \frac{(\widetilde{u}_i + \widetilde{u}_j)}{4\phi}\,\frac{(\ell' + 1)\,\omega}{\ell'\,(\ell' + \omega)} + \frac{\widetilde{u}_i}{2\phi}\,\frac{(1 - \ell')}{\ell'};\ \forall i,j = 1,2,\ i \neq j. \tag{21}$$

Proof. See Appendix C. □

Note that, the only difference between the two tax rates in equation (21) is the last term in both equations, which results from the difference in publicly disclosed costs $\{u_1, u_2\}$.

Under our assumptions, the second-best solution will vary across polluters if the social planner can use some observable firm-specific characteristics to gain some information about the firms' marginal costs. With this available information, even though it is incomplete, the optimal emissions taxes may be differentiated between polluters. Thus, all players internalize the social value of information.

It is easy to show that under the asymmetric case, the informational rent conceded to firms is defined by:

$$\Delta\tau_i = \tau_i^F - \tau_i^* = \frac{\omega\left(c_i - c_j\right)\left(\ell' + 1\right) - 2\ell'\left(\mu_c + c_i\right)\left(2\omega + \ell' - 1\right)}{4\phi\ell'(\ell' + \omega)};\ \forall i, j = 1, 2,\ i \neq j. \quad (22)$$

$\Delta\tau_i$ is positive if and only if:

$$c_i > \frac{\omega c_j(\ell' + 1) + 2\ell'\mu_c(2\omega + \ell' - 1)}{\omega(1 - 3\ell') + 2\ell'(1 - \ell')}$$

In addition, we can show that $\Delta\tau_i$ is increasing in γ for any $\delta \geq \frac{3\beta(1-\ell')}{2\phi^2}$:

$$\frac{\partial\Delta\tau_i}{\partial\gamma} = \frac{\lambda(2\omega + \ell' - 1)}{2\phi\left(1 - \gamma\right)^2\left(\ell' + \omega\right)} > 0 \quad (23)$$

This means that $\Delta\tau_i$ is strictly decreasing in σ_ε^2 which is not surprising since $\gamma = \frac{\sigma_c^2}{(\sigma_c^2 + \sigma_\varepsilon^2)}$. Thus, the informational rent is decreasing with respect to the precision of the private noise.

Proposition 3. *Given the equilibrium tax rates in equation* (21)*, the equilibrium output for each firm, the industry output, and the price can be calculated as follows:*

$$q_i^* = \left(\frac{\ell' + 1}{3\beta}\right)\left[\frac{2\ \ell'\ (\alpha - \mu_c - \widetilde{u}_i) - (\widetilde{u}_i - \widetilde{u}_j)\ (3\omega + 2\ell')}{12\ \beta\ \ell'\ (\omega + \ell')}\right];\ \forall i, j = 1, 2, i \neq j \quad (24)$$

$$Q^* = \frac{(\ell' + 1)\left[2\left(\alpha - \mu_c\right) - \left(\widetilde{u}_1 + \widetilde{u}_2\right)\right]}{6\beta(\omega + \ell')} \quad (25)$$

$$p^* = \frac{2\alpha\left(3\omega + 2\ell' - 1\right) + \left(\ell' + 1\right)\ \left(\widetilde{u}_1 + \widetilde{u}_2 + 2\mu_c\right)}{6(\omega + \ell')}. \quad (26)$$

Proof. Straightforward using Proposition 2. □

Once again, we suppose that α is large enough, thus shutdown will not arise. Given that we calculate the market output and price, we can check how the environmental parameters and the weight on revenue affect the industry output:

$$\frac{\partial Q^*}{\partial \ell'} = -\frac{\left[2\left(\alpha-\mu_c\right)-\left(\widetilde{u}_1+\widetilde{u}_2\right)\right]\left(1-\omega\right)}{6\beta(\omega+\ell')^2} \leq 0, \text{ if } \omega < 1 \tag{27}$$

$$\frac{\partial Q^*}{\partial \omega} = -\frac{\left(\ell'+1\right)\left[2\left(\alpha-\mu_c\right)-\left(\widetilde{u}_1+\widetilde{u}_2\right)\right]}{6\beta\left(\omega+\ell'\right)^2} \leq 0. \tag{28}$$

The first relation shows that if $\omega < 1$, then an increase in ℓ' decreases the industry output. In other words, as the regulator values the tax revenue more, the tax rates increase. Consequently, competitors in the marketplace react by reducing the industry output in order to avoid the burden of higher taxes. Thus, the regulator cannot ignore the impact of ℓ' on the industry production efficiency. However, when $\omega > 1$ (i.e. for higher value of δ), the partial derivative of Q^* with respect to ℓ' is positive. This means that polluters react aggressively in the product market to any increase in ℓ' and competition between players is exacerbated. Meanwhile, industry output is decreasing in ω. Since ω is increasing in both δ and ϕ, an increase in the damage parameter δ or pollution parameter ϕ discourages market production.

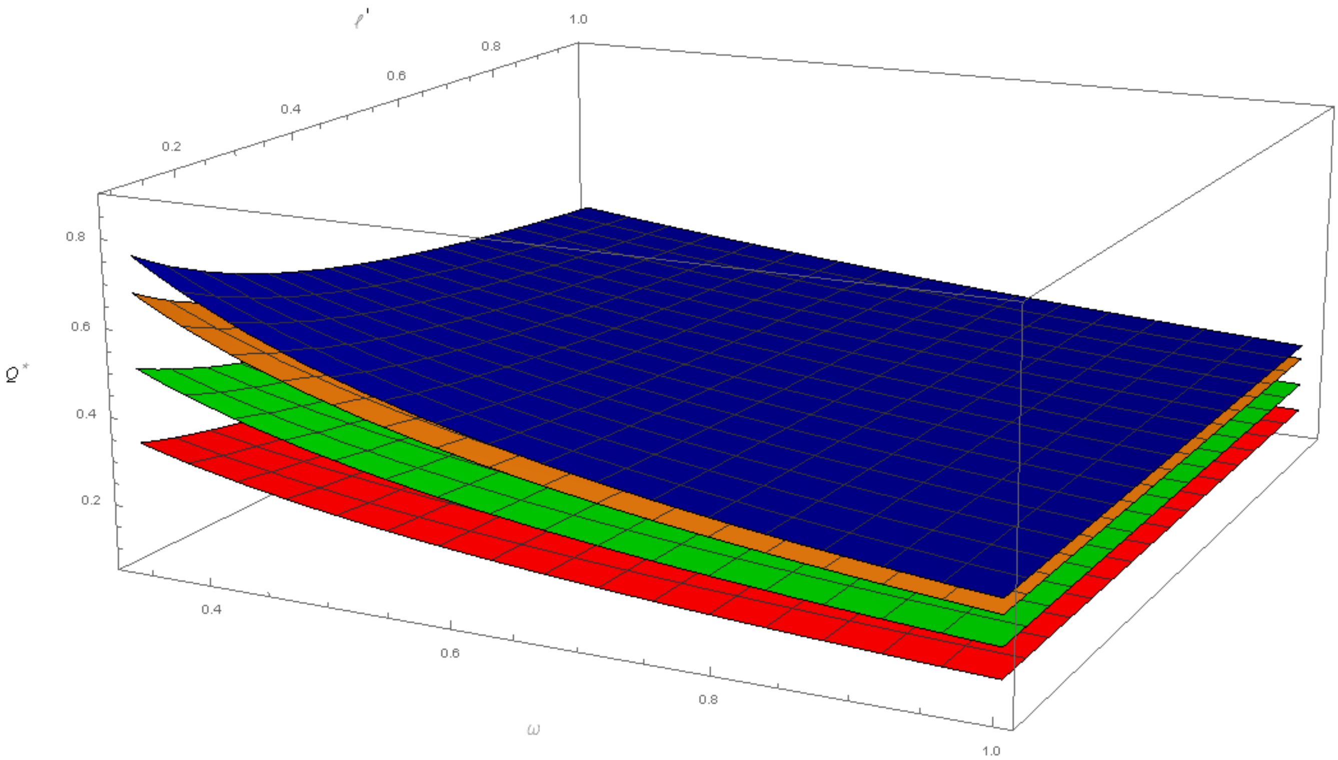

Figure 1: The equilibrium industry output for admissable parameter values.

Figure 1 shows these effects of ℓ' and ω on the optimal industry output in the asymmetric information case. In this figure, we assume that $(\widetilde{u}_1 + \widetilde{u}_2) = \alpha = 2$ and $\beta = \phi = 1$. We consider different μ_c values: $\mu_c = 0.6$ (red curve), $\mu_c = 0.4$ (green curve), $\mu_c = 0.2$ (yellow curve), and $\mu_c = 0.1$ (blue curve). Finally, if μ_c increases, then Q^* decreases $\left(\frac{\partial Q^*}{\partial \mu_c} < 0\right)$ which implies that an increase in the mean of the distribution of the private marginal cost increases the firms' total marginal costs. While the regulator sets the tax rates lower due to higher expected total marginal costs, the end result is lower industry output.

3.3 Asymmetric Information without Publicly Disclosed Information

We consider the case where there is no public component in firms' marginal costs (i.e. $\widetilde{u}_1 = \widetilde{u}_2 = 0$). In this case, firms' marginal costs are composed of only private information (i.e. $\widetilde{c}_i = \widetilde{s} + \widetilde{\varepsilon}_i$). Since the regulator cannot observe either $\widetilde{s}$ or $\widetilde{\varepsilon}_i$, the firms are ex ante symmetric according to the regulator when it sets the optimal tax rates. Consequently, the tax rates are the same for both firms:

$$\tau_i^{**} = \frac{(\alpha - \mu_c)\ (2\omega + \ell' - 1)}{2\phi(\ell' + \omega)};\ \forall i = 1, 2. \tag{29}$$

Intuitively, the only piece of information for the regulator to distinguish the two firms is the publicly disclosed cost for each firm. In the absence of this information, the regulator finds it optimal to apply the same tax rate for both firms, even though the firms may have different private costs. The publicly disclosed information will be of value to decision makers and serves as a differentiation device. The environmental effectiveness and economic efficiency of environmental taxes are improved further because the regulator can distinguish the competitors and sets firm-specific environmental tax.

Furthermore, as demonstrated in equation (30), the optimal environmental tax rate is increasing in ℓ' only if the environmental damage is low enough compared to the slope of the demand curve:

$$\frac{\partial \tau_i^{**}}{\partial \ell'} = \frac{(\alpha - \mu_c)\ (1 - \omega)}{2\ \phi(\omega + \ell')^2} \geq 0;\ \forall i = 1, 2,\ \text{if}\ \omega = \frac{\beta + \delta\phi^2}{3\beta} \leq 1 \tag{30}$$

$$\frac{\partial \tau_i^{**}}{\partial \omega} = \frac{(\ell' + 1)\ (\alpha - \mu_c)}{2\ \phi\ (\omega + \ell')^2} \geq 0;\ \forall i = 1, 2. \tag{31}$$

From equation (31), we conclude that the tax rate is increasing in ω. Since $\omega = \frac{\beta + \delta\ \phi^2}{3\beta}$ is a linear and positive function of δ, the last relation yields that the tax rate is increasing in the environmental valuation. Moreover, since the ω is increasing in ϕ, a higher pollution rate (measured by pollution per output) increases the optimal tax rates.

3.4 Comparative Statics

We now turn to the comparative statics of equilibrium under incomplete information with respect to changes in model parameters. We find useful to explore how marginal changes in model parameters affect the tax rates set by the regulator under public and private information regimes. Without loss of generality, we analyze the comparative statics for τ_i, the tax rate for firm i, and a similar analysis can be carried out for $\tau_{j,}j \neq i$.

3.4.1 Effects of Environmental Valuation and Pollution Rate

We begin our analysis by investigating how the weight on revenue, denoted by ℓ, affects the differential tax rates in the following proposition:

Proposition 4. *Suppose that $\omega < 1$, which implies that the steepness of marginal damages satisfies $\delta \leq \frac{2\beta}{\phi^2}$. For the firm with the lower public cost (i.e. $\widetilde{u}_i \leq \widetilde{u}_j,\ i \neq j$), the tax rate τ_i defined in equation (21) is increasing in ℓ'. Furthermore, for the firm with the higher public cost, the tax rate is decreasing in ℓ' only if:*

$$f = \frac{\widetilde{u}_j - \widetilde{u}_i}{\alpha - \mu_c - \widetilde{u}_j} \geq \frac{2\ (1-\omega)\ (\ell')^2}{\omega\ (\omega + (\ell')^2 + 2\ell')};\ \textit{where}\ \widetilde{u}_j \geq \widetilde{u}_i,\ j \neq i. \tag{32}$$

Proof. First, we calculate the partial derivative of the tax rate given in equation (21):[21]

$$\left.\frac{\partial \tau_i}{\partial \ell'}\right| = \left[\frac{2\ (\alpha - \mu_c - \widetilde{u}_i)\ (1-\omega) + \frac{(\widetilde{u}_j - \widetilde{u}_i)}{(\ell')^2}\ (\omega + (\ell')^2 + 2\ell')\,\omega}{4\ \phi\ (\omega + \ell')^2}\right];\ \forall i, j = 1, 2, i \neq j. \tag{33}$$

Given the assumption on the damage parameter (i.e. $\delta < \frac{2\beta}{\phi^2}$), the first term in the numerator on the right-hand side of equation (33) is positive. The second term in the numerator is also positive for the firm with the lower public cost. As a result, the tax rate for the lower public cost firm is increasing in ℓ'.

Meanwhile, the partial derivative given in equation (33) is negative for the firm with the higher public cost if the numerator on the right-hand side is negative. This is satisfied if the condition in equation (32) holds. □

This proposition states that the tax rate on firm i is increasing in ℓ' if it is more efficient (in terms of the public component of the marginal costs) than its rival j. This means that, in the case of a widely applied Carbon tax or energy tax, we might get large extra revenues. In contrast, if firm i has a higher publicly-known cost, then, for some values of

[21] Note that if the regulator does not value revenue, then it is easy to verify that $\forall i, j, i \neq j, \tau_i = \frac{\alpha - \mu_c - \widetilde{u}_i}{\phi}$.

ℓ' described in equation (32), the second term is negative and dominates the positive effect. This implies that the partial derivative is decreasing in that neighborhood. In other words, an increase in ℓ' entails a negative impact on the tax rate, so on the expected revenue. From a fiscal policy perspective, it is not obvious that environmental taxes have significant revenue-raising potential. Figure 2 shows the importance that the social planner assigns to revenue. It presents the region described in equation (32), where the partial derivative is decreasing in ℓ'.

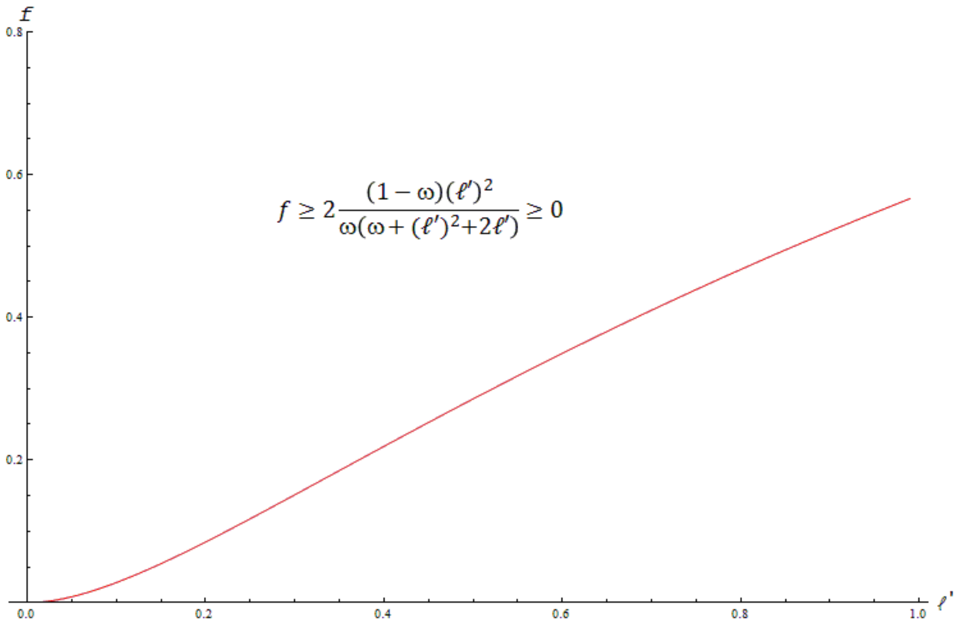

Figure 2: Variations of the tax rules with respect to ℓ' for admissible values of ω.

3.4.2 Effect of Demand Parameters

The effect of the choke price α on the tax rate τ_i for firm i can be derived by taking the partial derivative of equation (21) with respect to α:

$$\frac{\partial \tau_i}{\partial \alpha} = \frac{(2\omega + \ell' - 1)}{2\phi\,(\omega + \ell')} \begin{cases} \geq 0; & \text{if } \ell' \geq 1 - 2\,\omega \\ \leq 0; & \text{otherwise.} \end{cases} \quad ; \ \forall i, j = 1, 2, i \neq j. \tag{34}$$

According to equation (34), given ℓ', if the regulator's weight on the damages, denoted by δ, or the pollution rate, denoted by ϕ, are high enough relative to the slope of the demand, denoted by β, having a higher choke price α increases the tax rate set for firm i. Alternatively, given ω, if the weight on the revenue is high enough, then this would also result in higher tax rates.

Meanwhile, the optimal tax rate is decreasing in the slope of the demand: a higher value for β implies a steeper demand, which leads to less production and pollution, so the regulator decreases the tax rate:

$$\frac{\partial \tau_i}{\partial \beta} = \left(\frac{-\delta\phi^2}{3\beta^2}\right)\left[\frac{(\ell'+1)\ \left[2\ (\alpha-\mu_c)-(\widetilde{u}_i+\widetilde{u}_j)\right]}{4\ \phi(\ell'+\omega)^2}\right] \leq 0;\ \forall i,j=1,2, i\neq j. \tag{35}$$

3.4.3 Effect of Cost Parameters

It is easy to verify that a firm's optimal tax rate is decreasing in the publicly-observed component of its marginal cost. A higher value for $\widetilde{u}_i$ leads to less production and pollution, thus the regulator decreases the tax rate:

$$\frac{\partial \tau_i}{\partial \widetilde{u}_i} = \left[\frac{\omega\ (1-3\ell')+2\ell'\ (1-\ell')}{4\phi\ (\omega+\ell')\ \ell'}\right] \leq 0;\ \forall i,j=1,2, i\neq j,\ \text{if}\ \omega \geq \left(\frac{2\ell'\ (1-\ell')}{3\ell'-1}\right). \tag{36}$$

The effect of the average private cost on the tax rate depends on the weights the regulator has on the revenue and the environmental damage:

$$\frac{\partial \tau_i}{\partial \mu_c} = -\frac{\partial \tau_i}{\partial \alpha} = -\frac{(2\omega+\ell'-1)}{2\phi\,(\omega+\ell')}\begin{cases}\leq 0;\ \text{if}\ \ell' \geq 1-2\ \omega \\ \geq 0;\ \text{otherwise.}\end{cases};\ \forall i,j=1,2, i\neq j. \tag{37}$$

Assuming that this first condition in equation (34) is satisfied, the result shows that when the regulator faces private and public information, a higher mean of the distribution of private costs increases the firm' costs (in expectation) because the signal is more informative, which results in less production and pollution, so the regulator decreases the tax rate. In fact, since the regulator uses emission taxes not only to curb emissions but also to correct the underproduction that emerges in highly concentrated market structures, then an increase of μ_c implies an additional product market inefficiency resulting from underproduction which suggests that the regulator decreases the tax rate in order to offset the decrease in the output industry. However, if $\ell' < 1-2\ \omega$, then the partial derivative is positive: environmental taxes increase with respect to μ_c. In this case, players in the marketplace are less productively efficient. Thus, polluters behave strategically and substantially overproduce, i.e., players are more aggressive and competition is exacerbated. Such overproduction entails an increase in pollution, thereby inducing the regulator to respond with tougher regulation. Finally, the last inequality shows that, if $\ell' \geq 1-2\ \omega$, the optimal tax rate is increasing in the choke price: higher demand results in more production, which entails an increase in pollution. As a result, the regulator sets environmental taxes accordingly making players' overproduction efforts more costly.

If the environmental damage or the regulator's valuation for the damage are high enough, then a regulator who is concerned with the market failure arising from underproduction, avoids over-taxation which entails welfare loss, and sets emissions taxes accordingly. The same optimal tax rate is decreasing in other firm's publicly-observed marginal cost:

$$\frac{\partial \tau_i}{\partial \widetilde{u}_j} = -\frac{(\ell' + 1)\ \omega}{4\phi\ \ell'\ (\omega + \ell')} \leq 0;\ \forall i, j = 1, 2, i \neq j. \tag{38}$$

According to equation (38), a higher value of u_j implies that firm j is getting less efficient, so firm i has a relatively higher market share than before. Therefore, the regulator decreases the tax rate on firm i to encourage the output to be produced by the relatively more efficient firm.

4 Information Sharing

In this section, we analyze the situation where firms get together as a "team", tacitly or cooperatively choose a strategy for how to face environmental policy, and then adhere to this strategy. In the sharing information case, the problem is what the planner could do if firms were to internalize their payoff interdependencies and appropriately adjust their use of available information. Thus, our goal in this section is to know if sharing information about costs is mutually beneficial for firms.

We have seen that publicly disclosed information is relevant to regulators in setting efficiently environmental taxes. Therefore, publicly available information may affect the ability and incentive of market participants to coordinate their actions and hence the extent to which market outcomes are characterized by collusion rather than competition[22]. Thus, making information publicly available can undermine market performance and environmental policy by facilitating collusive behavior. Electricity markets may be particularly conductive to collusion since participants meet very frequently (every day in the spot market). Requiring publication of detailed information on power generators output may facilitate collusion and so undermine environmental regulation.

In the following, we compare two cases regarding the mode of competition and compare the effect of an ex ante policy instruments in both cases: non-sharing (NS) and sharing (S) information between competitors in the marketplace.

Note that firms will voluntarily share valuable information if and only if they receive information in return. If there is to be a net gain from information sharing, it must be the

[22] In the 1990's the US Congress passed a legislation concerning railroad freights mandating disclosure of firm-specific information. Transparency requirements led to a significant increase in freight rates which was later proved to be a direct result of collusive behavior.

case that expected profits per "team" member exceed the expected profits when firms behave alone, i.e., there must be an information gathering return to scale or information synergy.

Suppose that some mechanism exists for firms to truthfully share information on their private costs, while the regulator still remains uninformed about the private costs.[23] Thus, the regulator imperfectly foresees firm-specific parameters and the future market conditions, whereas the two firms have perfect information about their rival's marginal costs. In this case, we examine if/when firms are better off sharing their private information.

Proposition 5. *When the regulator sets up emissions taxes to deal with pollution under asymmetric information, if firms cooperatively share information about their costs, then the optimal tax rules do not change.*

Proof. See Mathematical Appendix D. □

In the sharing information game where firms receive perfectly the full vector of costs, this proposition states that, when emissions taxes are the policy instrument in use, then with imperfectly observed marginal costs the regulator sets the same environmental tax rule as in the non-sharing information game.

Let $\left(q_i^S, q_i^{NS}\right)$, $i = 1, 2$, denote the optimal quantities under sharing and non-sharing information. Recall that under non-sharing information, $\forall i, j, i \neq j$, the optimal quantities are given by:

$$q_i^{NS} = \frac{\alpha + \phi\left(\tau_j^{NS} - 2\tau_i^{NS}\right) + \left(\widetilde{u}_j - 2\widetilde{u}_i\right)}{3\beta} + \frac{\lambda}{3\beta\left(2+\gamma\right)} - \frac{c_i}{\beta\left(2+\gamma\right)} \tag{39}$$

We can show that in equilibrium

$$\forall i, j, i \neq j, \mathbb{E}_{c_j}\left[\pi_i^{NS}\middle| c_i\right] = \beta\left(q_i^{NS}\right)^2 \tag{40}$$

In the sharing information case, the optimal quantities are given by:

$$\forall i, j, i \neq j, q_i^S = \frac{\alpha + \phi\left(\tau_j^S - 2\tau_i^S\right) + \left(u_j - 2u_i\right)}{3\beta} + \frac{c_j - 2c_i}{3\beta} \tag{41}$$

and the profits are:

$$\forall i, j, i \neq j, \pi_i^S = \beta\left(q_i^S\right)^2 \tag{42}$$

[23] An outside agency may conduct the transmission of the private information according to the firms' commitments. We assume that the firms can verify each other's report. This assumption has the same effect as the assumption that firms disclose the true value of their realized costs.

We now examine whether or not firms are willing to share information. This depends on a direct comparison of profits in each informational regime.

Proposition 6. *Under emissions taxes, sharing information may occur and is mutually beneficial to firms when private marginal costs are high and the cost differential between the two firms is small. In addition, sharing information yields higher output level and entails an increase in emissions in equilibrium.*

Proof. We focus the analysis on the private part of the marginal costs, i.e. c_i and c_j since $u_{i,i=1,2}$ are common values. Since $\left(\tau_i^S, \tau_j^S\right) = \left(\tau_i^{NS}, \tau_j^{NS}\right), i \neq j$, and given the expression of profits in both cases, then we only need to compare quantities in order to see if firms have incentive to share information about their costs. Let's consider firm i:

$$\Delta q_i = q_i^{NS} - q_i^S = \frac{\lambda - 3c_i}{3\beta\left(2+\gamma\right)} - \frac{c_j - 2c_i}{3\beta} \tag{43}$$

Thus, under our assumptions, the last relation yields:

$$\mathbb{E}\left(\pi_i^{NS}\right) = \pi_i^S \Rightarrow q_i^{NS} = q_i^S \Rightarrow c_j = \frac{c_i\left(1+2\gamma\right)}{\left(2+\gamma\right)} + \frac{\mu_c\left(1-\gamma\right)}{\left(2+\gamma\right)};\ j \neq i. \tag{44}$$

Then if $c_j \leq \frac{c_i(1+2\gamma)}{(2+\gamma)} + \frac{\mu_c(1-\gamma)}{(2+\gamma)} \Rightarrow q_i^{NS} \geq q_i^S$, which means that $\mathbb{E}\left(\pi_i^{NS}\right) \geq \pi_i^S$. Similarly, if $c_i \leq \frac{c_j(1+2\gamma)}{(2+\gamma)} + \frac{\mu_c(1-\gamma)}{(2+\gamma)}$ then $q_j^{NS} \geq q_j^S$ which also means that $\mathbb{E}\left(\pi_j^{NS}\right) \geq \pi_j^S$. As a result, under these conditions, both firms are unwilling to share information about their private costs. □

However, this leaves room for the development of mutual and beneficial sharing information process. This is the case when firms are inefficient and are relatively symmetric in their private costs structure:

$$\left\{\begin{array}{l} c_j \geq \frac{c_i(1+2\gamma)}{(2+\gamma)} + \frac{\mu_c(1-\gamma)}{(2+\gamma)} \\ c_i \geq \frac{c_j(1+2\gamma)}{(2+\gamma)} + \frac{\mu_c(1-\gamma)}{(2+\gamma)} \end{array}\right. \Rightarrow \left\{\begin{array}{l} q_j^S \geq q_j^{NS} \\ q_i^S \geq q_i^{NS} \end{array}\right. \tag{45}$$

The regulator cannot ignore the sharing information issue in this context because pooling information leads to higher output level which entails an increase in emissions[24], thereby making the regulator's task more difficult to induce the desired optimal pollution level.

[24] Higher outputs imply higher consumers' surplus. As a result, environmental damage also increases and offsets completely the increase in surplus $\left(CS - D = -\frac{(\beta+\delta\phi^2)}{2}Q^2\right)$. Thus, the resulting effect on welfare is negative.

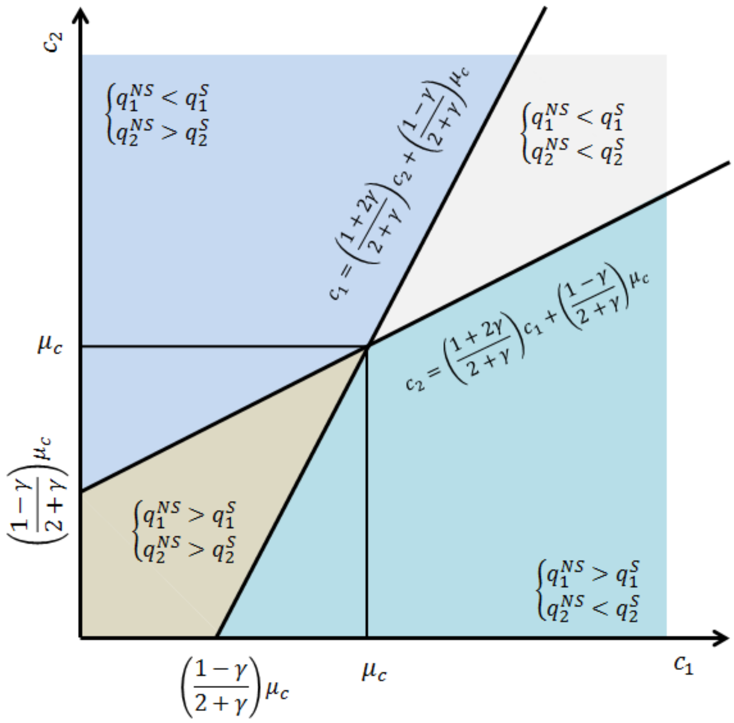

Figure 3: Pooling information between firms. S stands for "sharing information" and NS stands for "non-sharing information".

As we can see on figure 3, both firms have incentives to share information in the North-East region. In other words, if firms have high marginal costs levels, then sharing information is beneficial. Furthermore, it is easy to verify that $\forall i, j, i \neq j$, if $c_i \in \left[0, \frac{\mu_c(1-\gamma)}{(2+\gamma)}\right]$, then both firms do not prefer to share information:

$$\begin{aligned} \text{if } c_i &= 0 \Rightarrow c_j = \frac{\mu_c\,(1-\gamma)}{(2+\gamma)} \leq \mu_c \text{ because } \frac{(1-\gamma)}{(2+\gamma)} < 1 \\ \text{if } c_i &= \mu_c \Rightarrow c_j = \mu_c \end{aligned}$$

This can be shown in the lower west region of Figure 3. Finally, in the last two regions, at least one firm is unwilling to share information while the other prefers to do so. Thus, no information sharing is not the unique equilibrium. Sharing information depends on the value of firms' marginal private costs and can be profitable for firms and detrimental for social welfare.

Since σ_ε^2 has similar qualitative effects on profits as on each firm's output in equilibrium, from the expression defining each firm's output, we can analyze how a variation of the signal error affects expected firm profits when there is no sharing information:

$$\frac{\partial \Delta q_i}{\partial \gamma} = \frac{c_i - \mu_c}{\beta (2 + \gamma)^2} \tag{46}$$

This relation merits some brief discussion to display the intuition behind it in term of practical environmental policy. The sign of the first derivative of firm's i output variation with respect to γ is the sign of the difference between its private marginal costs and the average private marginal costs of the industry:

1. If $c_i \geq \mu_c \Rightarrow \frac{\partial \Delta q_i}{\partial \gamma} \geq 0$. Firm i should benefit from a reduction in σ_ε^2, i.e., higher precision. Higher values of γ means equilibrium outputs have greater correlation. As a result, the less efficient firm becomes more aggressive in the market place and increases its production which should yield higher expected profits. However, the firm's natural response to higher precision could be particularly inappropriate. In fact, since q_i^{NS} is a function of τ_i^{NS}, the net effect depends on the regulator's reaction to an increase in emissions resulting from an increase in production.

2. In contrast, if $c_i < \mu_c \Rightarrow \frac{\partial \Delta q_i}{\partial \gamma} < 0$. An increase in γ should reduce outputs and expected profits. This is true for any $c_i < \mu_c$, i.e., the efficient firm in the market place. Facing higher precision, firm i should benefit from the reduction in σ_ε^2: since the signals of each firm become more correlated, an increase in γ may increase its output and expected profits under environmental regulation.

5 Conclusion

For years now, our attitude towards the environment has become "heads we win, tails future generations lose". Unfortunately, we inhabit a world with serious and severe environmental problems. Mother nature is not a game. Changes that affect those problems have to be undertaken. The point of environmental regulation and of the designing and efficient environmental tax system is to accomplish deep and structural changes in the economic and ecological behavior of individuals, households, and firms in order to curtail environmentally and ecologically undesirable effects. To this end, all prices in a given economy must internalize the social cost of Carbon of all emissions.

Environmental taxation implemented by public authorities to protect the environment has been broadly analyzed in the literature on environmental economics. Choosing the appropriate environmental policy is a key part of successful regulation. The environmental effectiveness and economic efficiency of environmental taxes could be improved further if they are well designed and implemented. The problem is that in any real world environmental regulation scheme, regulators often face imperfect and asymmetric information. Although many authors examined emissions taxes in the presence of asymmetric information, to our knowledge, the role of disclosure has not been analyzed in the previous literature.

This paper deals with the informational problems faced by environmental policy makers in their task of setting emissions taxes. Cost uncertainties have a significant effects on the optimal control instrument adopted in our paper. We explored regulatory strategies in protecting environmental quality under private and common values about marginal costs. The main finding is that a regulator facing private information only can not distinguish the players in the marketplace. Thus, in order to reduce environmental harm, the regulator sets a common tax rule. Therefore, if the regulator has some firms-specific observable information, then differentiated emissions taxes may be optimally implemented. Public disclosed information clearly enhances the efficiency of emissions taxes design, i.e. equilibrium outcomes and the subsequent welfare depend on the available information that agents can observe.

Today, effort to enhance informational access may offer important lessons for environmental regulation moving forward. There are enormous opportunities to make the best use of available information to enhance the quality of the environment. Disclosed information may be used to overcome a serious lack of information on polluted activities, and could have impact on firms' behavior and levels of pollution. Furthermore, by facilitating the dissemination of environmental information in a meaningful way and the fact that information disclosure satisfies the belief that the public has a right to know that they might be affected by third party pollution, our approach is politically more feasible to adopt and thus may not be considered as coercive "new" regulations.

We then examined the situation where players in the marketplace share valuable information. Even if public information enhances the regulatory process, disclosure, however, facilitates information sharing and collusion. Comparing games with and without information pooling, we highlight that, when emission taxes are the policy instrument in use, it is obvious that information sharing may occur and leads to a superior outcome in terms of industry output. Information sharing is mutually beneficial for firms but is not environmentally optimal. Finally, in order to give a better understanding of the impacts of public and private information on the efficiency setting of emission taxes, we presented comparative statics and analyzed some special cases.

In our analysis, we focused on linear equilibria. We assumed linear demand and costs functions coupled with an affine information structure: these assumptions are necessary for tractability and are analytically convenient and conceptually satisfactory in the analysis of environmental regulation with information asymmetry. Importantly, although we believe that the main nature of the results will be sustained for more general functions, our goal in this paper is to demonstrate how disclosure can improve the regulatory process in setting environmental taxes and how this information can give incentives to players to collude. Future work that further explores and extends on these results can help shed more light on emissions taxes in large industrial markets.

A Proof of Proposition 1

We solve for the equilibrium with full information using backward induction. First, we formulate each firm's profit maximization problem, which is the second stage of the game:

$$\max_{q_i} \ \pi_i = [(p - x_i - \phi \ \tau_i) \ \ q_i] \, ; \ \forall i = 1, 2 \tag{A.1}$$

where $p = \alpha - \beta (q_1 + q_2)$. The first order conditions (FOC) of this profit maximization problem leads to the best response function for each firm:

$$\frac{\partial \pi_i (q_i, q_j)}{\partial q_i} = 0 \ \Rightarrow \ q_i = \frac{\alpha - x_i}{2\beta} - \frac{\phi \tau_i}{2\beta} - \frac{q_j}{2}; \ \forall i, j = 1, 2; i \neq j. \tag{A.2}$$

Note that the second order conditions (SOC), which implies $\frac{\partial^2 \pi_i (q_i, q_j)}{\partial q_i^2} = -2 \ \beta; \ \forall i = 1, 2,$ are satisfied since $\beta > 0$. In equilibrium, we obtain:

$$q_i = \frac{\alpha + x_j - 2x_i}{3\beta} + \frac{\phi (\tau_j - 2\tau_i)}{3\beta}; \ \forall i, j = 1, 2; i \neq j. \tag{A.3}$$

Given the best response functions, the equilibrium industry output and price are:

$$Q = \frac{2\alpha - (x_1 + x_2)}{3\beta} - \frac{\phi (\tau_1 + \tau_2)}{3\beta} \tag{A.4}$$

$$p = \frac{\alpha + (x_1 + x_2) + \phi (\tau_1 + \tau_2)}{3} \tag{A.5}$$

The regulator's welfare maximization problem is as follows:

$$\max_{\tau_1, \tau_2} \ W(\tau_1, \tau_2) = (CS - D) + \sum_{i=1}^{2} \pi_i + \ell R \tag{A.6}$$

This leads to the following FOCs:

$$\frac{\partial W}{\partial \tau_1} = \frac{\phi}{3\beta}\left[\left(\beta+\delta\phi^2\right)\ Q-(\alpha+x_2-2\ x_1)+\ell'\ \ (3\beta q_1+\phi\ (\tau_2-2\tau_1))\right] \tag{A.7}$$

$$\frac{\partial W}{\partial \tau_2} = \frac{\phi}{3\beta}\left[\left(\beta+\delta\phi^2\right)\ Q-(\alpha+x_1-2\ x_2)+\ell'\ \ (3\beta q_2+\phi\ (\tau_1-2\tau_2))\right] \tag{A.8}$$

where $\ell' = \ell - 1$. To solve for the optimal tax rates, we add and subtract the two FOCs from each other:

$$\frac{\partial W}{\partial \tau_1} - \frac{\partial W}{\partial \tau_2} = 0 \ \Rightarrow\ (\tau_2-\tau_1) = \frac{(x_1-x_2)(\ell'-1)}{2\phi\ell'} \tag{A.9}$$

$$\frac{\partial W}{\partial \tau_1} + \frac{\partial W}{\partial \tau_2} = 0 \ \Rightarrow\ (\tau_2+\tau_1) = \frac{(2\alpha-(x_1+x_2))\,(2\omega+\ell'-1)}{2\phi\ (\omega+\ell')} \tag{A.10}$$

Combining the last two equations yields the optimal tax rates, the equilibrium output, and price given in equations (10)–(12).

B Proof of Lemma 1

Following the same procedure in appendix A, we first formulate each firm's profit maximization problem:

$$\max_{\widetilde{q}_i}\ \mathbb{E}_{\widetilde{c}_j}\left[\left(\widetilde{p}-\widetilde{u}_i-\widetilde{c}_i-\phi\tau_i\right)\widetilde{q}_i\right];\ \forall i,j=1,2,i\neq j. \tag{B.1}$$

where $\widetilde{p} = \alpha - \beta\left(\widetilde{q}_1+\widetilde{q}_2\right)$ and $\mathbb{E}_{\widetilde{c}_j}$ denotes the common expectation operator taken over $\widetilde{c}_j$. The FOC defining the best response functions for each firm are given below:

$$\frac{\partial \mathbb{E}\widetilde{\pi}_i\left(\widetilde{q}_1,\widetilde{q}_2\right)}{\partial \widetilde{q}_i} = 0 \ \Rightarrow\ \widetilde{q}_i = \frac{\alpha-\widetilde{u}_i-\widetilde{c}_i}{2\beta} - \frac{\phi\tau_i}{2\beta} - \frac{\mathbb{E}[\widetilde{q}_j \mid \widetilde{c}_i]}{2};\ \forall i,j=1,2,i\neq j. \tag{B.2}$$

The SOCs, which implies $\frac{\partial^2\mathbb{E}\widetilde{\pi}_i(q_i,q_j)}{\partial(\widetilde{q}_i)^2} = -2\beta;\ \forall i=1,2$, are satisfied since $\beta>0$. Using assumptions 1 and equation (7), the last two equations can be written as follows:

$$\widetilde{q}_i = \frac{\alpha-\phi\tau_i-\widetilde{u}_i-\widetilde{c}_i}{2\beta} - \frac{(\theta_{j1}+\theta_{j2}\mathbb{E}[\widetilde{c}_j \mid \tilde{c}_i]+\theta_{j3}\widetilde{u}_j+\theta_{j4}\widetilde{u}_i)}{2};\ \forall i,j=1,2,i\neq j. \tag{B.3}$$

We simplify the best response functions to get:

$$\widetilde{q}_1 = \underbrace{\frac{\alpha-\phi\tau_1}{2\beta} - \frac{(\theta_{21}+\lambda\theta_{22})}{2}}_{\theta_{11}} - \widetilde{c}_1 \underbrace{\left(\frac{1}{2\beta}+\frac{\gamma\theta_{22}}{2}\right)}_{-\theta_{12}} - \widetilde{u}_1 \underbrace{\left(\frac{1}{2\beta}+\frac{\theta_{24}}{2}\right)}_{-\theta_{13}} - \widetilde{u}_2 \underbrace{\left(\frac{\theta_{23}}{2}\right)}_{-\theta_{14}} \tag{B.4}$$

$$\widetilde{q}_2 = \underbrace{\frac{\alpha-\phi\tau_2}{2\beta} - \frac{(\theta_{11}+\lambda\theta_{12})}{2}}_{\theta_{21}} - \widetilde{c}_2 \underbrace{\left(\frac{1}{2\beta}+\frac{\gamma\theta_{12}}{2}\right)}_{-\theta_{22}} - \widetilde{u}_2 \underbrace{\left(\frac{1}{2\beta}+\frac{\theta_{14}}{2}\right)}_{-\theta_{23}} - \widetilde{u}_1 \underbrace{\left(\frac{\theta_{13}}{2}\right)}_{-\theta_{24}} \tag{B.5}$$

which lead to the parameter values given in equations (13)–(16).

C Proof of Proposition 2

To set the optimal taxes, the regulator maximizes the expected welfare:

$$\max_{<\tau_1,\tau_2>} \mathbb{E}_{\widetilde{c}_1,\widetilde{c}_2}\left[\widetilde{W}(\tau_1,\tau_2)\middle|\widetilde{u}_1,\widetilde{u}_2\right] \tag{C.1}$$

$$\ni \widetilde{W}(\tau_1,\tau_2) \equiv -\left(\frac{\beta+\delta\phi^2}{2}\right)\widetilde{Q}^2 + \sum_{i=1}^{2}\left[(\alpha-\widetilde{u}_i-\widetilde{c}_i)\,\widetilde{q}_i + \phi\;\ell'\;\tau_i\;\widetilde{q}_i\right] \tag{C.2}$$

where $\widetilde{Q} = \widetilde{q}_1 + \widetilde{q}_2$ denotes the industry output. Using equations (13)–(16), we get:

$$\widetilde{q}_i = \theta_{i1} - \frac{\widetilde{c}_i}{\beta(2+\gamma)} + \frac{\widetilde{u}_j - 2\widetilde{u}_i}{3\beta}; \forall i,j=1,2; i\neq j, \tag{C.3}$$

$$\widetilde{Q} = \widetilde{q}_1+\widetilde{q}_2 = \theta_{11}+\theta_{21} - \frac{\widetilde{c}_1+\widetilde{c}_2}{\beta(2+\gamma)} - \frac{\widetilde{u}_1+\widetilde{u}_2}{3\beta} = A + B\widetilde{C} + F\widetilde{U}, \tag{C.4}$$

$$A = \theta_{11}+\theta_{21},\; B = -\frac{1}{\beta(2+\gamma)},\; \widetilde{C} = \widetilde{c}_1+\widetilde{c}_2,\; F = -\frac{1}{3\beta},\; \widetilde{U} = \widetilde{u}_1+\widetilde{u}_2, \tag{C.5}$$

$$\mathbb{E}\left[\widetilde{Q}^2\right] = A^2 + B^2\mathbb{E}\left[\widetilde{C}^2\right] + F^2\widetilde{U}^2 + 2AB\mathbb{E}\left[\widetilde{C}\right] + 2AF\widetilde{U} + 2BF\widetilde{U}\mathbb{E}\left[\widetilde{C}\right]. \tag{C.6}$$

Remark 1. *Since $\widetilde{C}$ and $\widetilde{U}$ are independent under our assumptions, it is easy to verify that:*

$$\mathbb{E}\left[\widetilde{C}\right] = 2\mu_c \tag{C.7}$$

$$\mathbb{E}\left[\widetilde{C}^2\right] = \mathbb{E}\left[\widetilde{c}_1^2\right] + \mathbb{E}\left[\widetilde{c}_2^2\right] + 2\mathbb{E}\left[\widetilde{c}_1\widetilde{c}_2\right] = 4\sigma_c^2 + 4\mu_c^2 - 2\sigma_\varepsilon^2. \tag{C.8}$$

Furthermore, we can compute the other term and the industry output as follows:

$$\mathbb{E}\left[\widetilde{Q}\right] = \mathbb{E}\left[\widetilde{q}_1\right] + \mathbb{E}\left[\widetilde{q}_2\right] = A + 2B\mu_c + F(\widetilde{u}_1 + \widetilde{u}_2), \tag{C.9}$$

$$\mathbb{E}\left[\widetilde{c}_i\widetilde{q}_i\right] = \theta_{i1}\mu_c + \theta_{i2}(\sigma_c^2 + \mu_c^2) + \theta_{i3}\widetilde{u}_i\mu_c + \theta_{i4}\widetilde{u}_j\mu_c;\ \forall i,j = 1,2, i \neq j \tag{C.10}$$

$$\sum_{i=1}^{2} \tau_i \mathbb{E}(\widetilde{q}_i) = \sum_{i=1}^{2} \left[\tau_i(\theta_{i1} + \theta_{i2}\mu_c + \theta_{i3}\widetilde{u}_i + \theta_{i4}\widetilde{u}_j\right];\ \forall i,j = 1,2, i \neq j \tag{C.11}$$

Finally, we obtain the expected welfare:

$$\begin{aligned}\mathbb{E}_{\widetilde{c}_1,\widetilde{c}_2}\left[\widetilde{W}\left(\tau_1,\tau_2\right)\right] = & -\left(\frac{\beta+\delta\phi^2}{2}\right)\overline{Q}^2 + \mu_c\overline{Q} + \sum_{i=1}^{2}\left[\phi\ell'\ \tau_i\ \bar{q}_i + (\alpha - \widetilde{u}_i)\,\bar{q}_i\right] \\ & + \left[\frac{2\left(\sigma_c^2+\sigma_\varepsilon^2\right)}{\beta\left(2+\gamma\right)} - \frac{\left(\beta+\delta\phi^2\right)\left(2\sigma_c^2+\sigma_\varepsilon^2\right)}{\beta^2\left(2+\gamma\right)^2}\right]\end{aligned} \tag{C.12}$$

where $\bar{q}_i = \mathbb{E}(q_i), i = 1,2,\ \overline{Q} = \mathbb{E}(q_i)$. Note that the second line on the right-hand side does not depend on the tax rates, due to risk-neutrality. Given public information $\widetilde{u}_1, \widetilde{u}_2$, maximizing equation (C.12) leads to the following FOCs:

$$\begin{aligned}\frac{\partial\mathbb{E}[\widetilde{W}\left(\tau_1,\tau_2\right)]}{\partial\tau_1} = 0 = & \left(\beta+\delta\phi^2\right)\left(A + 2B\mu_c + D\left(\widetilde{u}_1+\widetilde{u}_2\right)\right) + \mu_c - \alpha + \left(2\widetilde{u}_1 - \widetilde{u}_2\right) \\ & + \phi\ \ell'\ \left(\tau_2 - 2\tau_1\right) + 3\beta\ \ell'\ \bar{q}_1\end{aligned} \tag{C.13}$$

$$\begin{aligned}\frac{\partial\mathbb{E}[\widetilde{W}\left(\tau_1,\tau_2\right)]}{\partial\tau_2} = 0 = & \left(\beta+\delta\phi^2\right)\left(A + 2B\mu_c + D\left(\widetilde{u}_1+\widetilde{u}_2\right)\right) + \mu_c - \alpha + \left(2\widetilde{u}_2 - \widetilde{u}_1\right) \\ & + \phi\ \ell'\ \left(\tau_1 - 2\tau_2\right) - 3\beta\ \ell'\ \bar{q}_2\end{aligned} \tag{C.14}$$

Solving the FOCs for τ_1 and τ_2, we obtain:

$$\frac{\partial\mathbb{E}[\widetilde{W}]}{\partial\tau_1} - \frac{\partial\mathbb{E}[\widetilde{W}]}{\partial\tau_2} = 0 \ \Rightarrow\ \left(\tau_2 - \tau_1\right) = \frac{\left(\widetilde{u}_1 - \widetilde{u}_2\right)\ \left(\ell' - 1\right)}{2\phi\ \ell'} \tag{C.15}$$

$$\frac{\partial\mathbb{E}[\widetilde{W}]}{\partial\tau_1} + \frac{\partial\mathbb{E}[\widetilde{W}]}{\partial\tau_2} = 0 \ \Rightarrow\ \left(\tau_2 + \tau_1\right) = \frac{\left[2(\alpha-\mu_c) - \left(\widetilde{u}_1+\widetilde{u}_2\right)\right]\ \left(2\omega + \ell' - 1\right)}{2\phi\ \left(\omega + \ell'\right)} \tag{C.16}$$

where we make use of Assumption 1. Solving for τ_1 and τ_2, we obtain the optimal tax rates defined in proposition 2.

We also need to check conditions under which the regulator's objective function in (C.12) is concave. Let H denote the Hessian of $\mathbb{E}[\widetilde{W}(\tau_1, \tau_2)]$:

$$H = \begin{pmatrix} H(1,1) = \frac{\partial^2 \mathbb{E}[\widetilde{W}]}{\partial \tau_1^2} & H(1,2) = \frac{\partial^2 \mathbb{E}[\widetilde{W}]}{\partial \tau_2 \tau_1} \\ H(2,1) = \frac{\partial^2 \mathbb{E}[\widetilde{W}]}{\partial \tau_1 \tau_2} & H(2,2) = \frac{\partial^2 \mathbb{E}[\widetilde{W}]}{\partial \tau_2^2} \end{pmatrix} = \begin{pmatrix} (\omega + 4\ell') & (\omega + 2\ell') \\ (\omega + 2\ell') & (\omega + 4\ell') \end{pmatrix} \left(\frac{-\phi^2}{3\beta} \right)$$

The expected welfare in equation (C.12) is concave in τ_1 and τ_2 if and only if the Hessian matrix H is negative definite. In our case, we need to verify whether the naturally ordered principal minors of the matrix alternate in sign:

- the first naturally ordered principal minor is negative:

$$(\omega + 4\ell') \left(\frac{-\phi^2}{3\beta} \right) < 0 \;\Rightarrow\; (\omega + 4\ell') > 0,$$

- the second naturally ordered principal minor is positive, $\det H' > 0$:

$$\left| H \right| = (\omega + 4\ell')^2 - (\omega + 2\ell')^2 > 0 \;\Rightarrow\; (\omega + 3\ell')\,(4\ell') > 0 \;\Rightarrow\; \ell' > 0 \Rightarrow \ell > 1.$$

Since both conditions are satisfied, the tax rates defined in equation (21) maximize the expected welfare.

D Proof of Proposition 5

In the case of merging, let the two firms share their private information on their marginal costs. Therefore, we denote the marginal cost of production by $x_i = u_i + c_i;\ \forall i = 1, 2$. Meanwhile, the information sharing between the firms is to find a more profitable outcome for the firms. Therefore, the firms do not reveal their private costs to the regulator. At the second stage of the game, under the shared information case, a firm i has to

$$\max_{<q_i>} \pi_i = [(p - x_i - \phi\tau_i)\, q_i]\,;\ \forall i = 1, 2. \tag{D.1}$$

where $p = \alpha - \beta(q_1 + q_2)$. The FOCs lead to the following best response functions:

$$\frac{\partial \pi_i(q_i, q_j)}{\partial q_i} = 0 \;\Rightarrow\; q_i = \frac{\alpha - x_i}{2\beta} - \frac{\phi\tau_i}{2\beta} - \frac{q_j}{2};\ \forall i, j = 1, 2, i \neq j. \tag{D.2}$$

Note that the SOCs verify the concave profit function (i.e., $\frac{\partial^2 \pi_i(\cdot)}{\partial (q_i)^2} = -2\beta;\ \forall i = 1, 2$).

Solving the best response function leads to the equilibrium output and price:

$$q_i = \frac{\alpha + (u_j - 2u_i) + (c_j - 2c_i)}{3\beta} + \frac{\phi\,(\tau_j - 2\tau_i)}{3\beta};\ \forall i, j = 1, 2, i \neq j, \tag{D.3}$$

$$Q = \frac{2\alpha - \sum_{i=1}^{2} (u_i + c_i + \phi\ \tau_i)}{3\beta}, \tag{D.4}$$

$$p = \frac{\alpha + \sum_{i=1}^{2} (u_i + c_i + \phi\ \tau_i)}{3}. \tag{D.5}$$

Similar to equation (C.12), the expected welfare in this case equals:

$$\mathbb{E}_{\widetilde{c}_1,\widetilde{c}_2}\left[\widetilde{W}\,(\tau_1, \tau_2)\right] \equiv -\left(\frac{\beta + \delta\phi^2}{2}\right)\widetilde{Q}^2 + \sum_{i=1}^{2}\left[(\alpha - \widetilde{u}_i - \widetilde{c}_i)\,\widetilde{q}_i + \phi\ \ell'\ \tau_i\ \widetilde{q}_i\right] \tag{D.6}$$

where terms that do not depend on the tax rates are suppressed. Given public information $\widetilde{u}_1, \widetilde{u}_2$, maximizing equation (C.12) leads to the following FOCs:

$$\frac{\partial \mathbb{E}[\widetilde{W}]}{\partial \tau_1} - \frac{\partial \mathbb{E}[\widetilde{W}]}{\partial \tau_2} \Rightarrow (\tau_2 - \tau_1) = \frac{(\widetilde{u}_1 - \widetilde{u}_2)\ (\ell' - 1)}{2\phi\ \ell'} \tag{D.7}$$

$$\frac{\partial \mathbb{E}[\widetilde{W}]}{\partial \tau_1} + \frac{\partial \mathbb{E}[\widetilde{W}]}{\partial \tau_2} \Rightarrow (\tau_2 + \tau_1) = \frac{[2(\alpha - \mu_c) - (\widetilde{u}_1 + \widetilde{u}_2)]\,(2\omega + \ell' - 1)}{2\phi\,(\omega + \ell')} \tag{D.8}$$

Note that (D7) and (D8) are similar to (C15) and (C16). As a result, information sharing does not affect the tax rates since the regulator cannot observe marginal costs in either case.

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