Credence Bad and Informed Government

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Abstract

This article analyzes the choice of environmental policy when the government has more information than a polluting industry on the magnitude of the environmental damage. Environmental policy is modelled as a contract contingent on the environment being clean or dirty, that ties the output to an environmental tax paid by firms. The menu of contracts proposed by the government potentially has a signaling role to play in addition to the Pigovian task of internalizing the environmental externality. The analysis characterizes the alloca-

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tive distortions created either by the cost of disclosing information, or by the impossibility of such a disclosure.

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1 Introduction

When the output of an industry generates polluting emissions, firms may find it difficult to have an accurate perception of the actual damage imposed by their production on the environment. This paper focuses attention on situations in which the government is better informed than polluting firms about the magnitude of their environmental externality. Assessing the true social costs of pollution often requires analytical skills and technical background that the industry does not possess. In contrast, one can expect that some governments would have better knowledge of the environmental damage than would the polluting firms because of the significant resources these governments devote to monitoring polluting emissions. The governments of industrialized countries, for instance, have recently launched expensive satellites into space[1], that are dedicated to improving estimates of greenhouse gas emissions. These heavy expenditures provide the governments who can afford them with superior information about the polluting damage of their industry. Like climate change, most of the transboundary pollutions such as

[1]These satellites are Ibuki for the Japan, Orbiting Carbon Observatory for the U. S. and Environmental Satellite for the E. U..

acid deposition, pollutions of the North Sea and the Black Sea, or damage to the stratospheric ozone layer, are examples of "credence" bad: it is prohibitively costly or impossible for each individual firm or consumer to directly observe the damage from pollution. In such circumstances, government are likely to become heavily involved in making it practicable for individuals to assess the actual degradation of the environment.

The purpose of the article is to examine how private information affects the government's design of environmental policy. Such a context of asymmetric information has been largely overlooked in the literature of environmental regulation which has rather focused on the assumption that the industry is better informed than the government about the costs and benefits that firms incur (see Baron, 1985, Spulber, 1988, Laffont, 1994 and Lewis, 1996). This well-known context of asymmetric information raises classic self-selection problems that can be solved with the help of screening games in which the first-mover is the uninformed government. A general result emerging from this literature is that environmental taxes should be used by the regulator as means of providing polluters with the correct incentives for fully reporting their information. Most studies along this line, such as Laffont (1994) or Boyer and Laffont (1999), examine to what extent public policies for environmental protection must be distorted in order to reduce the polluter's rent of asymmetric information.

However, the results obtained in screening games cannot directly apply to situations where firms cannot perfectly observe their polluting emissions, whereas the government is privately informed about the pollution damage. To address this issue, we investigate a signaling game in which the government designs a menu of contracts contingent upon the environment being clean or dirty. The menu is proposed to the polluting industry on a take-it-or-leave-it basis, and so may be used to signal the magnitude of the environmental damage to firms. Contracts are tying the output quantity to an environmental tax paid by firms. The government makes her contract proposal before firms enter the market. If they accept the offer, the contract is executed, otherwise firms get their reservation profits. In this setting, the contract faces the dual task of inducing firms to internalize the environmental externality and disclosing information about the actual state of the environment. As the government's private information is an argument of the firms profits – in the dirty environment, more polluting firms incur lower production costs –, the situation pertains to the "common-values" category of principal-agent relationship in the terminology of Maskin and Tirole (1992).

The analysis characterizes Perfect Bayesian Equilibrium contracts that can be separating or pooling depending on the prior information available to firms before contracting, i. e., their degree of optimism if the environment turns dirty, or their degree of pessimism if the environment turns clean.

First, if uninformed firms are far too optimistic when the environment happens to be dirty, then the unique equilibrium menu of contracts achieves separation of the two states of the environment. This separating equilibrium contract is costly in that it signals the dirty environment with a social loss compared to the full information benchmark. Nevertheless, this is the least costly distortion needed for revealing full information to firms. The signaling distortion is another instance of that recognized by Spence (1974) to make the signal credible in his education model.

Second, if firms prior beliefs attach a very high probability to the environment being dirty – in other terms, firms are slightly too optimistic when the environment happens to be dirty –, only pooling equilibrium contracts prevail. In this case, the government is worse off revealing to firms that the environment is dirty because the signaling cost entailed by the information disclosure would exceed the social loss of concealing information. This is a rather disturbing result since it points out that the government, albeit benevolent, finds it more desirable from the social standpoint to hide information.

These results provide novel insight on why environmental policies under asymmetric information might deviate from standard levels implied by the Pigovian principle under full information. The logic of transmitting information to firms at work in the signaling model clearly departs from that of extracting information from firms which prevails in the screening approach. On the one hand, the allocative distortions in screening models arise from the provision of incentives to induce uninformed firms to self-select, thereby revealing their underlying characteristics. On the other hand, the signaling process sheds light on two different reasons for the emergence of allocative distortions, which are inherent to separation and pooling respectively. The first reason is the provision of incentives to prevent uninformed firms from mistaking the dirty environment for the clean one in the separating equilibrium menu of contracts. The second reason for allocative distortion stems from the failure of information disclosure when the government has far too weak incentives to signal the true state of the environment.

The paper is organized as follows. Section 2 sets out the structure of the model and characterizes the Perfect Bayesian Equilibrium contracts. Section 3 offers conclusions.

2 The model

Let us consider an economy in which the output of competitive firms has some negative impact on the environment due to polluting emissions e. The relation between output x and emissions is assumed to be fixed and the release of pollutants per unit of output is measured by ε, i. e., $e = \varepsilon x$. For ease of presentation, the damage from pollution is represented by the linear function $D(e) = \varepsilon x$.

Firms have cost determined by some function $c(x, \varepsilon)$ with the following properties (subscripts denote partial derivatives here and throughout): $c(0, \varepsilon) = 0$, $c_x(x, \varepsilon) > 0, c_{xx}(x, \varepsilon) \geq 0$, that is, marginal production costs are nondecreasing; moreover, $c_\varepsilon(x,\varepsilon) < 0$ and $c_{x\varepsilon}(x,\varepsilon) > 0$, meaning respectively that there is a trade-off between environmental cleanness and firms efficiency[2] and output and pollution are cost complements. If the firm sells x units at a market price p, its profit is $px - c(x,\varepsilon)$. The maximizing output is denoted by $x(p,\varepsilon)$ and satisfies $p = c_x(x(p,\varepsilon),\varepsilon)$.

Explicit example:

For instance, the cost function can be given by $c(x,\varepsilon) = (c-\varepsilon)\,x^2/2$*, where* $c > \varepsilon$ *to assure convexity; then,* $x(p,\varepsilon) = \frac{p}{c-\varepsilon}$.

Let $P(x,\varepsilon)$ denote the inverse demand function with the following restrictions: (i) For all ε, $P(x,\varepsilon)$ is nonincreasing in q and nonnegative, and there exists $x^e(\varepsilon) \geq 0$ such that $P(x,\varepsilon)$ is decreasing in x for $x \leq x^e(\varepsilon)$, and $P(x,\varepsilon) \geq c_x(x,\varepsilon) + \varepsilon$ if and only if $x \leq x^e(\varepsilon)$; (ii) $P(x,\varepsilon)$ is twice continuously differentiable for $x \leq x^e(\varepsilon)$; (iii) $P(x,\varepsilon)$ is strictly decreasing in ε whenever $P(x,\varepsilon)$ is positive. Condition (ii) guarantees the existence of a consumption level $x^e(\varepsilon)$ that is efficient from the social standpoint. By condition (iii), consumers' willingness to pay for the product is higher with a lower environmental damage. The assumption that consumers may have some degree of environmental consciousness is consistent with recent works in environmental economics that recognize the existence of feedbacks between economic activity and environmental externalities (see, for instance,

[2] The statement that there is a trade-off between environmental cleanness and firms efficiency is consistent with the conclusions of Palmer, Oates and Portney (1995) or Jorgenson and Wilcoxen (1990) for the U. S. economy.

Carbone and Smith (2008)). Ignoring income effects, the total value $v(x,\varepsilon)$ to consumers of the product is given by

$$v(x,\varepsilon) = \int_0^x P(a,\varepsilon)\, da. \tag{1}$$

The surplus enjoyed by consumers is then $v(x,\varepsilon) - px$. Taking pollution into account, the social welfare generated by the output is $SW(x,\varepsilon) = v(x,\varepsilon) - \varepsilon x - c(x,\varepsilon)$. Note that, under our assumptions, $SW_{x\varepsilon}(x,\varepsilon) = P_\varepsilon(x,\varepsilon) - 1 - c_{x\varepsilon}(x,\varepsilon) < 0$, that is, quantity and pollution are net substitutes from the social standpoint since an increase in the pollution rate lowers the net marginal social welfare generated by the output.

Explicit example:

A simple example is $v(x,\varepsilon) = vx - \varepsilon x^2/2$, *for which* $P(x,\varepsilon) = v - \varepsilon x$. *Microeconomic foundations for this are as follows. Consumers do not attach the same value to the polluting product. They are uniformly distributed with a unit density on the interval* $[0, v]$ *according to an increasing valuation indexed by* θ. *Each consumer buys at most one unit of the product. The surplus of consumer* θ *is given by* $\frac{\theta - p}{\varepsilon}$, *which yields the demand function* $X(p,\varepsilon) = \frac{v-p}{\varepsilon}$ *corresponding to* $P(x,\varepsilon) = v - \varepsilon x$.

The environmental damage is a credence attribute of the product in the sense that it is too expensive to be observed neither by consumers, nor by firms themselves. In contrast, the government has private information about the actual value of ε. *Ex ante*, firms believe that the environment is either clean or dirty with some probability. Denoting the set of potential states of the environment by $I = \{c, d\}$, firms think that pollution intensity is ε^i with the probability $\mu_0^i \in (0,1), i \in I, \varepsilon^c < \varepsilon^d$ and $\mu_0^c + \mu_0^d = 1$. Simply stated, uninformed firms are too optimistic when the environment happens to be dirty, and too pessimistic when the environment is clean.

The government is endowed with the power to propose an environmental contract to the industry on a take-it-or-leave-it basis. The contract designed by the government specifies an environmental policy $\alpha^i = (x^i, t^i)$ in each state of the environment, where an output quantity x^i is tied to a tax t^i paid by firms. Following the Pigovian principle, the tax amount is transferred from firms to consumers. To enter the market, a firm must accept α^i, in which case it produces x^i and pays a total of t^i for the resulting emissions.

We consider the following three-stage game between the government and firms.

Stage 1: The government learns the actual state of the environment and proposes an environmental contract tying the output to the environmental tax $\{\alpha^i = (x^i, t^i)\}_{i \in I}$.

Stage 2: Using Bayes' rule, firms update their beliefs about ε^i on the basis of the government's proposal and form interim beliefs $\mu(\alpha) = \{\mu^i(\alpha^i)\}_{i \in I}$, where $\mu^i(\alpha^i)$ is firms assessment of the probability that pollution intensity is ε^i. Given interim beliefs, firms choose whether to accept or to reject the environmental contract. If the firms refuse the contract, the game ends and the payoffs to firms are zero, these payoffs being the expected reservation profit computed using interim beliefs. If the firms accept the contract, the play continues to the third stage.

Stage 3: The contract is executed and the outcome is implemented according to its terms: firms enter the market, choose the output quantity specified by the contract and pay the corresponding tax. The beliefs held by firms about the state of the environment are the same as the interim beliefs formed at the previous stage. The expected profit at this stage is necessarily higher than the expected reservation profit.

The government-industry relationship is analyzed here as a signaling game: the contracts offered by the informed government may signal to firms how polluting their product is. Nevertheless, all the variables are contractually set in the screening way (see Rothschild and Stiglitz, 1976) rather than in the signaling tradition of Spence (1974)[3]. Moreover, a particular feature of the model is that the government's private information ε^i is an argument of the firms profit through costs, which closely relates the model to the common-values category of principal-agent relationships (see Maskin and Tirole, 1992).

As a benchmark, we consider first the case of complete information in

[3] The signal t would be chosen before contracting if the signaling game were designed in the spirit of Spence (1974).

which the realization of ε^i is publicly observed. In state i of the environment, the government chooses the output quantity so as to maximize the social welfare function $SW(x^i, \varepsilon^i) = v(x^i, \varepsilon^i) - \varepsilon^i x^i - c(x^i, \varepsilon^i)$ and the profit to the firm is $\pi^i(\alpha^i) = px^i - c(x^i, \varepsilon^i) - t^i$. As free entry of firms will drive their profit to zero, we have $t^i = px^i - c(x^i, \varepsilon^i)$. Combining this to $SW(x^i, \varepsilon^i)$, social welfare in state i can be rewritten as $W^i(\alpha^i) = v(x^i, \varepsilon^i) - \varepsilon^i x^i - px^i + t^i$. The government therefore chooses x^i to solve

$$\begin{aligned} & \max_{x^i} W^i(\alpha^i) \\ \text{subject to } \pi^i(\alpha^i) &= 0 \end{aligned} \tag{2}$$

Denoting the solution by x^{i*} and $t^{i*} = px^{i*} - c(x^{i*}, \varepsilon^i)$, the first-order conditions for welfare maximization (2) yields

$$P\left(x^{i*}, \varepsilon^i\right) - \varepsilon^i = p = c_x(x^{i*}, \varepsilon^i) \tag{3}$$

When ε^i is observable, the output quantity specified by the equilibrium contract requires that the marginal social value of the polluting product exactly offsets the sum of the marginal environmental damage and the marginal production cost. The first-best contracts $\alpha^{i*} = (x^{i*}, t^{i*})$ are depicted in Figure 1. Quantity x^{i*} is the point of tangency between the government's indifference curve $W^i(\alpha)$ and the isoprofit dashed curve $\pi^i(\alpha) = 0$. Let W^{i*}

denote the welfare associated with x^{i*}.

Proposition 1: *In any equilibrium of the game with observable pollution, firms accept contract α^{i*} in state i of the environment, such that $\pi^i(\alpha^{i*}) = 0$ and $P(x^{i*}, \varepsilon^i) = \varepsilon^i + c_x(x^{i*}, \varepsilon^i)$.*

Note that if the environmental tax is the standard per-unit tax considered by the literature, $t(x) = \tau x$, then $\pi^i(\alpha^i) = px^i - c(x^i, \varepsilon^i) - \tau^i x^i = 0$ and $W^i(\alpha^i) = v(x^i, \varepsilon^i) - \varepsilon^i x^i - px^i + \tau^i x^i$. Thus, the condition for the first-best allocation (3) yields $P(x^{i*}, \varepsilon^i) - \varepsilon^i = p - \tau^{i*} = c_x(x^{i*}, \varepsilon^i)$. As market equilibrium for the polluting product is such that $P(x^{i*}, \varepsilon^i) = p = c_x(x^{i*}, \varepsilon^i) + \tau^{i*}$, the tax must be set at $\tau^{i*} = \varepsilon^i$, that is, the level that fully internalizes the marginal damage from pollution, in accordance with the Pigovian principle.

Corollary 1: *When ε^i is publicly observed, the government can implement the first-best allocation x^{i*} by announcing the per-unit tax $\tau^{i*} = \varepsilon^i$ on the output quantity.*

From now on, we will refer to the first-best contract α^{i*} as the Pigovian contract and the associated per-unit tax $\tau^{i*} = \varepsilon^i$ as the Pigovian tax..

Explicit example:

The cost function is $c(x, \varepsilon) = (c - \varepsilon) x^2/2$, where $c > \varepsilon$, and consumer surplus is $v(x, \varepsilon) = vx - \varepsilon x^2/2$, for which $P(x, \varepsilon) = v - \varepsilon x$. Condition (3) can be rewritten as

$$v - \varepsilon^i x^{i*} - \varepsilon^i = \left(c - \varepsilon^i\right) x^{i*}. \quad (4)$$

Thus, the output is $x^{i*} = \frac{v-\varepsilon^i}{c}$*, the associated welfare level is* $W^{i*} = \frac{\left(v-\varepsilon^i\right)^2}{2c}$ *and the tax is* $t^{i*} = \left(c - \varepsilon^i\right)\frac{\left(v-\varepsilon^i\right)^2}{2c}$.

Let us now solve for the backward-induction outcome of the three-stage game when ε^i is not observable to firms but the government is privately informed about the intensity of pollution. For this, we need to define the expected profit $E_\mu \pi\left(\alpha^i\right) = \sum_{i \in I} \mu^i \pi^i(\alpha^i)$ when firms believe that the pollution intensity is ε^i with probability μ^i. A perfect Bayesian equilibrium (PBE) of this game is a menu of contracts $\widehat{\alpha} = (\widehat{\alpha}^i)_{i\in I}$ and a probability distribution $\widehat{\mu} = \left\{\widehat{\mu}^i(\alpha^i)\right\}_{i\in I}$ such that the following conditions should be satisfied for all $i \in I$:

Condition 1: optimality condition for the government.

$$\widehat{\alpha}^i \in \arg\max_{\alpha} W^i(\alpha) \tag{5}$$

Condition 2: incentive compatibility for the government.

$$W^c(\widehat{\alpha}^c) \geq W^c(\widehat{\alpha}^d) \tag{6}$$

$$\text{and } W^d(\widehat{\alpha}^d) \geq W^d(\widehat{\alpha}^c) \tag{7}$$

Condition 3: break-even condition for firms (firms earn zero profit on each contract).

$$E_{\widehat{\mu}}\pi\left(\widehat{\alpha}^i\right) = 0 \text{ for all } i \in I \tag{8}$$

Condition 4: Bayes' consistency of beliefs.

$$\text{If } \widehat{\alpha}^c \neq \widehat{\alpha}^d, \text{ then } \widehat{\mu}^i(\widehat{\alpha}^i) = 1 \text{ for all } i \in I \tag{9}$$

$$\text{If } \widehat{\alpha}^c = \widehat{\alpha}^d, \text{ then } \widehat{\mu}^c(\widehat{\alpha}^c) = \mu_0^c = 1 - \widehat{\mu}^d(\widehat{\alpha}^d) \tag{10}$$

To determine the equilibrium outcome, we will follow a graphical procedure similar to that initiated by Rothschild and Stiglitz (1976). The complete information outcome identified in Proposition 1 cannot arise: as shown in Figure 1, when the environment is clean, the government could deviate and benefit from offering the contract α^{d*} instead of α^{c*}. Ignoring mixed strategies, we can in principle have two types of pure strategy equilibria: separating equilibria, in which firms accept different contracts in different states of the environment, and pooling equilibria, in which firms sign the same contract in both states of the environment.

We first examine separating equilibrium contracts $\left\{\widehat{\alpha}^i = \left(\widehat{x}^i, \widehat{t}^i\right)\right\}_{i\in I}$, in which $\widehat{\alpha}^c \neq \widehat{\alpha}^d$ and $\widehat{\mu}^i(\widehat{\alpha}^i) = 1$ for all $i \in I$. Such contracts signal the true state of the environment to uninformed firms. Moreover, firms use interim beliefs $\widehat{\mu}^i(\widehat{\alpha}^i) = 1$ to compute their expected reservation profit which is therefore the same as the profit distributed in stage 3 according to the terms of the contract. The break-even conditions can simply be rewritten as

$$\pi^c(\widehat{\alpha}^c) = 0 \text{ and } \pi^d(\widehat{\alpha}^d) = 0. \tag{11}$$

The next lemma states that the separating contract intended to signal the clean environment is the same as when pollution is observable.

Lemma 2: *In any separating PBE, the contract signaling the clean environment is* $\widehat{\alpha}^c = \alpha^{c*}$.

Proof: Suppose that the contract signaling the clean environment is instead some point $\alpha^c = (x^c, t^c)$ that lies to the southwest of α^{c*} on the break-even isoprofit $\pi^c(\alpha) = 0$, so that $W^c(\alpha^c) < W^{c*}$, as in Figure 2. If so, then the government can strictly increase welfare by offering the contract that is shown as an asterisk in the figure, namely $\alpha^c_\delta = (x^c + \delta, t^c + \delta)$ for $\delta > 0$ small enough so that $\pi^c(\alpha^c_\delta) > 0$. Clearly, firms will accept this contract since they can earn strictly positive profits. Moreover, the incentive-compatible conditions (6) and (7) still hold. Indeed, suppose that the dirty environment is truthfully signaled through some contract α^d lying on the break-even isoprofit $\pi^d(\alpha) = 0$, which therefore satisfies both $W^c(\alpha^d) \leq W^c(\alpha^c)$ and $W^d(\alpha^c) \leq W^d(\alpha^d)$. On the one hand, we have $W^c(\alpha^d) < W^c(\alpha^c_\delta)$ since $W^c(\alpha^c) < W^c(\alpha^c_\delta)$. On the other hand, we have $W^d(\alpha^c_\delta) < W^d(\alpha^d)$ since $W^d(\alpha^c_\delta) < W^d(\alpha^c)$. Thus, the government is better off signaling the clean environment with α^c_δ rather than α^c. As the same reasoning holds for all δ, α^{c*} is the only contract that optimally signals the clean environment in a separating PBE.

If there is a PBE, it must specify $\widehat{\alpha}^c = \alpha^{c*}$, thereby yielding an equilibrium welfare level $W^c(\widehat{\alpha}^c) = W^{c*}$. Furthermore, the separating menu $\left\{\widehat{\alpha}^i\right\}_{i \in I}$ must satisfy the incentive-compatibility constraints (6) and (7). Combining these conditions to the break-even ones (11) yields, for all $i \in I$,

$$v(\widehat{x}^i, \varepsilon^i) - \varepsilon^i \widehat{x}^i - c(\widehat{x}^i, \varepsilon^i) \geq v(\widehat{x}^j, \varepsilon^i) - \varepsilon^i \widehat{x}^j - c(\widehat{x}^j, \varepsilon^j) \text{ with } j \neq i \tag{12}$$

Define the contract $\overline{\alpha}^d = \left(\overline{x}^d, \overline{t}^d\right)$ to tie the output quantity to a tax in the following way (see Figure 3): first, $\overline{\alpha}^d$ earns precisely zero profit when the environment is dirty, i. e., $\pi^d(\overline{\alpha}^d) = 0$; and second, the incentive-compatibility constraint above is binding when the environment is clean, i. e.,

$$v(\widehat{x}^c, \varepsilon^c) - \varepsilon^c \widehat{x}^c - c(\widehat{x}^c, \varepsilon^c) = v(\overline{x}^d, \varepsilon^c) - \varepsilon^c \overline{x}^d - c(\overline{x}^d, \varepsilon^d) \tag{13}$$

The next step in solving the government's problem is to show that $\widehat{\alpha}^d = \overline{\alpha}^d$, meaning that the government must always bias the contract intended to signal the dirty environment away from the Pigovian contract prevailing under complete information.

Lemma 3: *In any separating PBE, the contract must signal respectively the clean environment with $\widehat{\alpha}^c = \alpha^{c*}$ and the dirty environment with $\widehat{\alpha}^d = \overline{\alpha}^d$.*

Proof: As required by (11), any contract dedicated to signaling the dirty environment in the separating equilibrium menu must just break even, i. e., $\pi^d(\widehat{\alpha}^d) = 0$. Now suppose that, in addition to signaling the clean environment with α^{c*}, the separating menu signals the dirty environment through some point $\alpha^d = \left(x^d, t^d\right)$ lying on the break-even isoprofit at the southwest side of $\overline{\alpha}^d$ so that both $W^d(\alpha^d) < W^d(\overline{\alpha}^d)$ and the incentive-compatibility requirement $W^d(\alpha^{c*}) < W^d(\alpha^d)$ is met, as illustrated in Figure 3. Then, the government will deviate from α^d by offering the contract depicted as an asterisk in the figure and denoted by α^d_δ, where $\alpha^d_\delta = \left(x^d + \delta, t^d + \delta\right)$ for $\delta > 0$ small enough so that both inequalities $\pi^d(\alpha^d_\delta) > 0$ and $W^c(\alpha^d_\delta) < W^{c*}$ are satisfied. The government is indeed strictly better off signaling the dirty environment with α^d_δ rather than α^d, while leaving the signal of the clean environment α^{c*} unchanged. It can easily be checked that, besides $W^c(\alpha^d_\delta) < W^{c*}$, the other incentive-compatibility constraint, namely $W^d(\alpha^{c*}) < W^d(\alpha^d_\delta)$, is satisfied by the menu $\left\{\alpha^{c*}, \alpha^d_\delta\right\}$. As moreover α^d_δ lies below the break-even isoprofit for the dirty environment, firms will find α^d_δ strictly more profitable than α^d. Since this true for all δ, if there is a separating PBE, it must be the menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$.

Compared to the Pigovian contract α^{d*} that would implement the first-best outcome under complete information, the unique candidate separating equilibrium entails *ex post* a loss in welfare by signaling the dirty environment with the contract $\overline{\alpha}^d$ instead of α^{d*}. Nevertheless, the social loss is the minimum needed for guaranteeing that firms will not mistake the dirty environment for the clean one. In this sense, the menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ is the most efficient way of separating the two states of the environment for the informed government. Moreover, this menu proves to be the unique candidate separating equilibrium because adding the option α^{c*} to $\overline{\alpha}^d$ in the menu prevents firms from mistaking the dirty environment for the clean one upon seeing $\overline{\alpha}^d$. By proposing simultaneously α^{c*} and $\overline{\alpha}^d$, the menu induces firms to correctly revise beliefs after observing $\overline{\alpha}^d$, hence they think that the environment is dirty for certain. This inference process is a noticeable feature of the contractual approach adopted here (on this point, see the "informed principal game with common values" investigated by Maskin and Tirole, 1992). It precludes the multiplicity of separating equilibria that is usually generated by the PBE concept in the standard signaling game designed by Spence (1974), where signaling variables are not contractually set. As a result, the least-cost separating equilibrium outcome singled out with no use of refinement criterion here, is qualitatively similar to that emphasized in the work of Riley (1979) and Cho-Kreps (1987) for traditional signaling games.

Explicit example:

With $c(x,\varepsilon) = (c-\varepsilon)\, x^2/2$ *and* $v(x,\varepsilon) = vx - \varepsilon x^2/2$, *contract* $\overline{\alpha}^d$ *involves the output quantity*

$$\overline{x}^d = \frac{1-\sqrt{\left(\varepsilon^d - \varepsilon^c\right)/c}}{c - \left(\varepsilon^d - \varepsilon^c\right)} \left(v - \varepsilon^c\right). \tag{14}$$

It can be checked that $\overline{x}^d < x^{d*} = \frac{v-\varepsilon^d}{c}$.

So far we have characterized necessary conditions for a separating PBE. We now turn to existence of the unique candidate separating PBE. For

$\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ to be an equilibrium, there must be no defections from this menu that are attractive from the social standpoint. Because $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ is the least-cost separating menu, deviation towards an alternative separating contract is unlikely. We can thus focus on some pooling contract $\beta = (x, t)$ such that $\mu^c(\beta) = \mu_0^c = 1 - \mu^d(\beta)$, and determine conditions under which this contract might be more attractive to the government than the menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$. After observing β, firms beliefs remain unchanged and so the expected reservation profit is $E_{\mu_0}\pi\left(\beta\right) = px - \sum_{i\in I}\mu_0^i c(x, \varepsilon^i) - t$. What are the "best" pooling contracts that could be offered by the government? Due to free entry, firms make zero expected profits, so that $t = px - \sum_{ii\in I}\mu_0^i c(x, \varepsilon^i)$. Given this break-even condition, the welfare level that can be attained at best in state i of the environment is given by the quantity x_0^i that solves

$$\begin{aligned} & \max_x W^i(\beta) \\ \text{subject to } E_{\mu_0}\pi\left(\beta\right) &= 0. \end{aligned} \tag{15}$$

The solutions are depicted in Figure 4 by the interval $\left[x_0^d, x_0^c\right]$. The corresponding pooling contracts are not strictly Pareto-dominated by any other pooling contract. These contracts belong to the set

$\mathcal{P} = \left\{\beta = (x, t) / x \in \left[x_0^d, x_0^c\right] \text{ and } t \text{ such that } E_{\mu_0}\pi\left(\beta\right) = 0\right\}$. Note that given $\beta \in \mathcal{P}$, $W^d(\beta)$ decreases as x increases from x_0^d to x_0^c. Let $\beta^d = \max_{\beta\in\mathcal{P}} W^d(\beta)$ denote the contract that guarantees the highest welfare when the environment is dirty among the pooling contracts inside $\mathcal{P}$.

Explicit example:

With $c(x,\varepsilon) = (c-\varepsilon)\, x^2/2$ *and* $v(x,\varepsilon) = vx - \varepsilon x^2/2$, $E_{\mu_0}\pi(\beta) = 0$ *can be rewritten* $t = px - \left(c - \sum_{i\in I}\mu_0^i\varepsilon^i\right) x^2/2$. *Substituting this expression to* t *in* $W^i(\beta)$ *yields* $x_0^i = \max_x \left[vx - \varepsilon^i x^2/2 - \varepsilon^i x - \left(c - \sum_{i\in I}\mu_0^i\varepsilon^i\right) x^2/2\right]$, *hence*

$$x_0^i = \frac{v - \varepsilon^i}{c + \varepsilon^i - \sum_{i\in I}\mu_0^i\varepsilon^i}. \tag{16}$$

It follows that $W^d(\beta^d) = \frac{\left(v-\varepsilon^d\right)^2}{2\left(c+\varepsilon^d - \sum_{i\in I}\mu_0^i\varepsilon^i\right)}$.

Let us now show that the menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ is an equilibrium only if it is not Pareto-dominated by some pooling contract inside $\mathcal{P}$.

Figure 4 has been drawn for parameter values of μ_0^i so that $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ is Pareto-dominated by at least β^d, therefore $W^d(\overline{\alpha}^d) < W^d(\beta^d)$. Note that this will be the case if and only if the probability that the environment is dirty is sufficiently high (firms are "slightly too optimistic" when the environment is dirty). In this case, it is always possible to devise a pooling contract β inside $\mathcal{P}$ that breaks the separating menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$. It suffices for this to have β lying on the bold part of the break-even isoprofit $E_{\mu_0}\pi(\alpha) = 0$ at the northeast of β^d so that $W^d(\beta) > W^d(\overline{\alpha}^d)$, as shown in the figure. Not only will this contract allow the entry of firms, but the government will also find it more appealing than $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ regardless of the pollution intensity. Thus, separation of the two states of the environment cannot be achieved by offering $\left\{\alpha^{c*}, \overline{\alpha}^{d}\right\}$ unless $W^{d}(\overline{\alpha}^{d}) \geq W^{d}(\beta^{d})$.

We need to define $\overline{\mu}_0^d$ as the solution in μ_0^d of equation $W^d(\overline{\alpha}^d) = W^d(\beta^d)$ so as to establish the existence result for separating PBE. The following proposition establishes that, if firms are sufficiently too optimistic when the environment is dirty, that is, $\mu_0^d \leq \overline{\mu}_0^d$, then the only PBE is the least-cost separating menu $\left\{\alpha^{c*}, \overline{\alpha}^{d}\right\}$.

Proposition 2: *If $\mu_0^d \leq \overline{\mu}_0^d$, then there exists a unique PBE such that $\widehat{\alpha}^c = \alpha^{c*}$ and $\widehat{\alpha}^d = \overline{\alpha}^d$.*

Figure 5 illustrates the parameter configuration such that $\mu_0^d \leq \overline{\mu}_0^d$, or equivalently $W^d(\beta^d) \leq W^d(\overline{\alpha}^d)$. In this case, any pooling contract $\beta = (x, t)$ different from β^d, that just breaks even, i. e., $E_{\mu_0}\pi\left(\beta\right) = 0$, is socially less attractive than $\overline{\alpha}^d$ when the environment is dirty. That is why any sort of pooling contract is inconsistent with equilibrium. One can always find a contract in the neighborhood of $\overline{\alpha}^d$ such as α' in the figure, that is preferred over β by only the government in the dirty environment, and is therefore worthless to the government in the clean environment. If α' is added to β in the menu, it will truthfully signal the dirty environment to firms, while satisfying the incentive-compatibility constraints: $W^d(\beta) < W^d(\alpha')$ and $W^c(\alpha') < W^c(\beta)$. Thus, the government facing the dirty environment will surely choose to add α'. Since moreover α' lies below $\pi^d(\alpha) = 0$, firms knowing that the environment is dirty make strictly positive profits from this contract. Thus, firms will accept α' if it is added to the menu. The existence of α' contradicts that β might be an equilibrium.

Because of asymmetric information, the Pigovian contract α^{d*} is no longer socially optimal when the environment is dirty. It follows that setting the per-unit tax at the Pigovian level in the dirty environment, that is $\tau^{d*} = \varepsilon^d$, fails to implement the socially efficient allocation. However, to restore efficiency, the government can use a two-part tax schedule given by an affine function $t^d(x) = \tau^d x + T^d$ rather than a linear tax schedule. This two-part tax will consist of a Pigovian linear tax $\tau^d = \varepsilon^d$ that helps correct for the environmental externality in the traditional way, combined with the fixed component $T^d = \overline{t}^d - \varepsilon^d \overline{x}^d$ that is adjusted to account for the informational externality. Using the break-even constraint $\pi^d(\overline{\alpha}^d) = p\overline{x}^d - c(\overline{x}^d, \varepsilon^d) - \overline{t}^d = 0$, this fixed component can be rewritten as $T^d = p\overline{x}^d - c(\overline{x}^d, \varepsilon^d) - \varepsilon^d \overline{x}^d$. Using moreover the break-even constraint for the Pigovian tax, i. e., $\pi^d(\alpha^{d*}) = px^{d*} - c(x^{d*}, \varepsilon^d) - \varepsilon^d x^{d*} = 0$, we obtain

$$T^d = \frac{\overline{x}^d}{x^{d*}} c(x^{d*}, \varepsilon^d) - c(\overline{x}^d, \varepsilon^d). \tag{17}$$

Given that $\overline{x}^d < x^{d*}$, (17) shows that T^d is strictly positive provided that $\frac{c(x,\varepsilon^d)}{x}$ is an increasing function of x as in the example $c(x, \varepsilon) = (c - \varepsilon)\, x^2/2$. In this case, T^d can be interpreted as a fee that firms must pay to enter the market only when the environment is dirty. As firms are not required to pay such a fee in the clean environment, T^d actually plays the role of signaling that the environment is dirty rather than clean. The intuitive explanation for the emergence of T^d is then standard. In order to be consistent with equilibrium, the signal must be such that it is socially appealing when the environment is dirty but is not when the environment is clean, while preventing firms from mistaking the dirty environment for the clean one. Such a signal allows the government to prove to firms that the environment is really dirty. Imposing a fee to enter the market is socially more costly when the environment is clean than when it is dirty. Hence, this signal allows firms to discriminate between the two states of the environment.

We next turn to pooling PBE for parameter values such that $\overline{\mu}_0^d < \mu_0^d$. In this case, any pooling contract inside $\mathcal{P}$ that Pareto-dominates the separating menu $\left\{\alpha^{c*}, \overline{\alpha}^d\right\}$ can be supported as a PBE.

Corollary 2: *If $\overline{\mu}_0^d < \mu_0^d$, then the only PBE are the pooling contracts $\beta \in \mathcal{P}$ such that $W^d(\beta) > W^d(\overline{\alpha}^d)$.*

The set of pooling PBE contracts is depicted in Figure 4 as the bold part of the break-even isoprofit $E_{\mu_0}\pi\left(\alpha\right) = 0$ at the northeast of β^d. An intuitive explanation for the non-disclosure of information in this case may be as follows. The information that is revealed by the government's proposal of contract depends on the information publicly available prior to contracting. The more similar are firms prior information and the government's private information in the dirty environment, the less opportune it is to pay the cost of truthfully signaling the dirty environment to firms. When firms are not too optimistic in the dirty environment, revealing information is worthless to the government because the signaling cost exceeds the loss in welfare due to concealing information.

3 Conclusion

This paper has examined how the environmental policy is affected when the government is more informed than a polluting industry about the actual state of the environment. The environmental policy is modelled as a contract contingent on the environment being clean or dirty, that ties the output to an environmental tax paid by firms. The informed government offers a pair of such contracts, which is accepted or rejected by uninformed firms. As firms use the information conveyed by the government's proposal to infer how polluted the environment is, contracts potentially have a signaling role to play in addition to the Pigovian task of internalizing the environmental externality. The analysis characterizes the allocative distortions created either by the cost of disclosing information with separating contracts, or the cost of concealing information with pooling contracts.

When initial beliefs of the firms attach a sufficiently low probability to the environment being dirty, there exists a unique separating equilibrium that minimizes the cost needed for signaling the dirty environment. This unique menu consists of a pair of contracts such that one signals the clean environment via the corresponding Pigovian linear tax, and the other contract dedicated to signaling the dirty environment can take the form of a two-part tax composed of the Pigovian linear tax and a fixed fee that firms must pay to enter the market.

When firms have a high prior belief that the environment is dirty, only pooling equilibrium contracts result and no information is revealed.

It would be worthwhile to examine whether these predictions are robust to more general assumptions. In particular, the signaling framework could be extended into a dynamic setting similar to that in Noldeke and Van Damme (1990), which would allow markets to clear not only before but also after the government has sorted the types of environmental damage. Another dynamic extension in the spirit of Bagwell and Riordan (1991) would be to consider that some firms perfectly observe their polluting emissions and that their number grows as time passes. Then, it would become easier for the government to signal the dirty environment. Finally, one intriguing extension would be to investigate a model in which other decision variables than the environmental tax might be included in the contract proposed by the government, and examine how these variables would interact with the tax and affect signaling costs.

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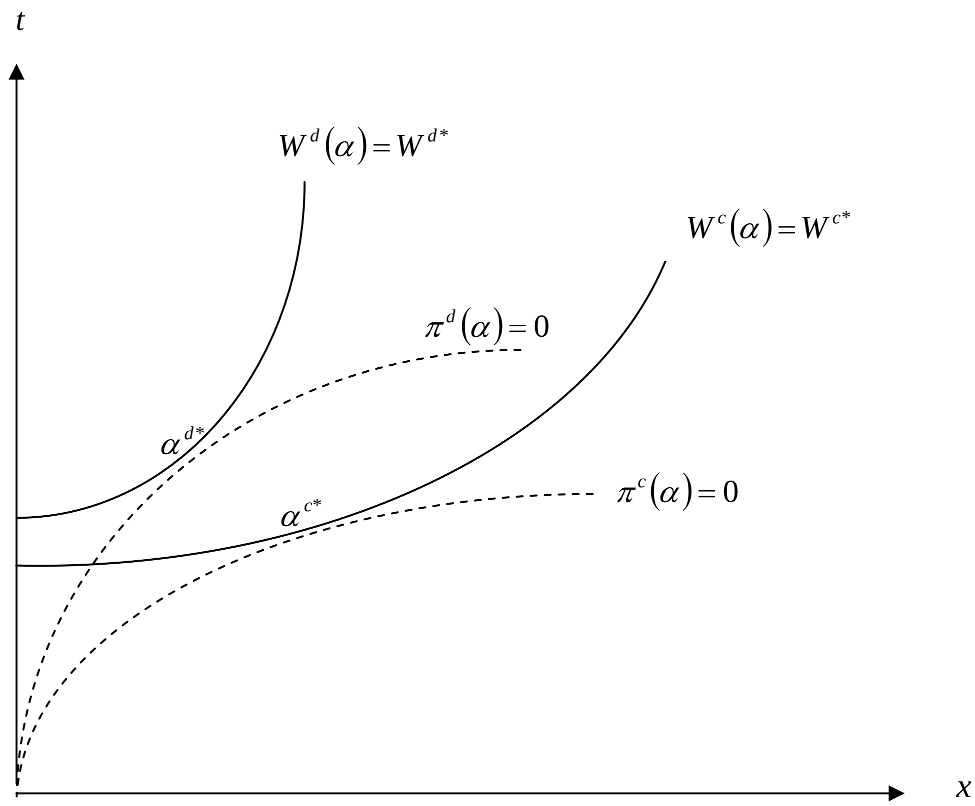

Figure 1
First-best contracts

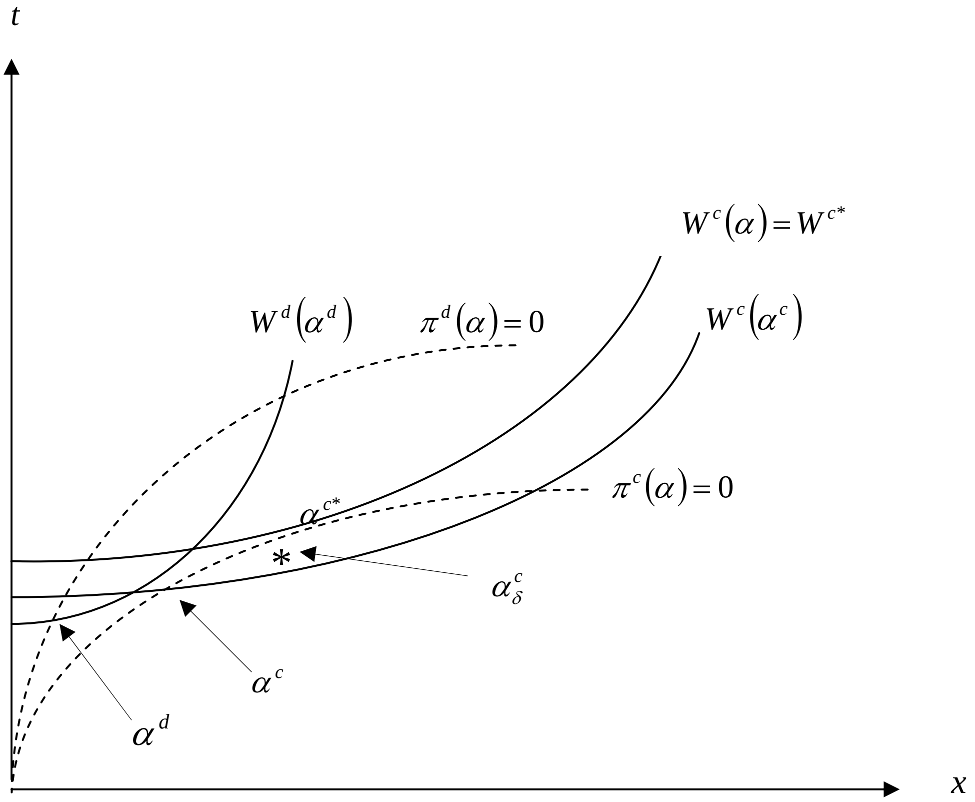

Figure 2
Lemma 2: α^{c*} must signal the clean environment

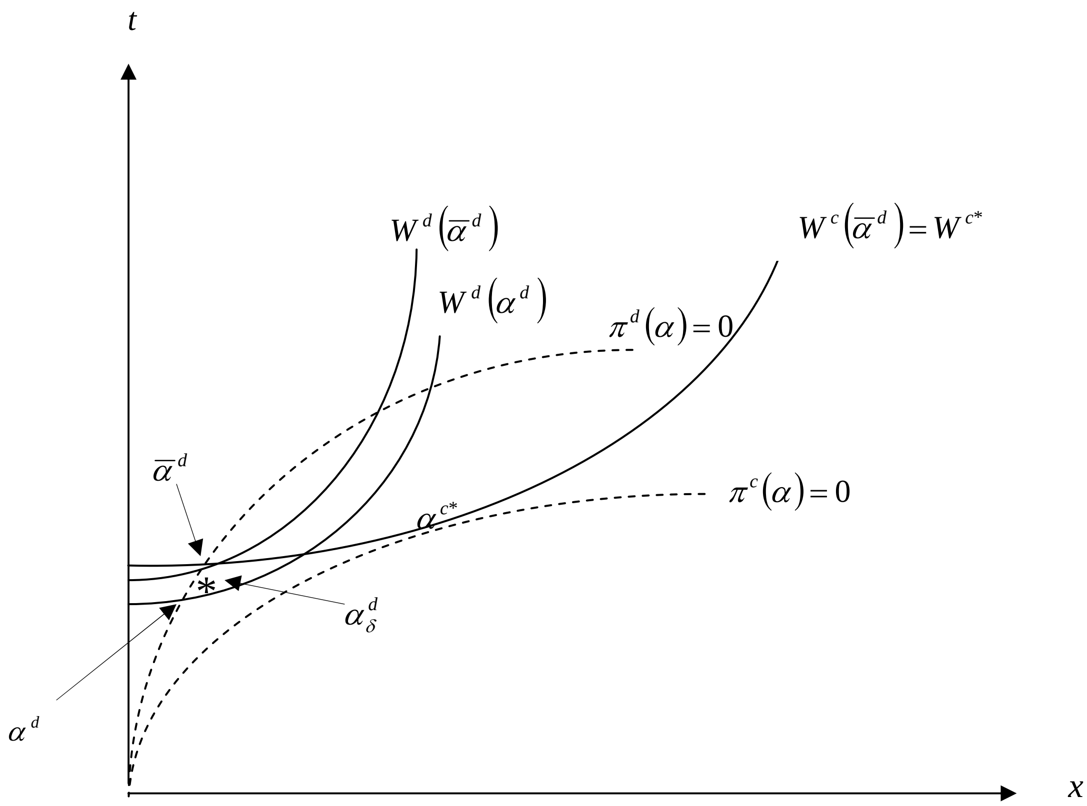

Figure 3

Lemma 3: The unique candidate separating equilibrium menu is $(\alpha^{c*}, \overline{\alpha}^c)$

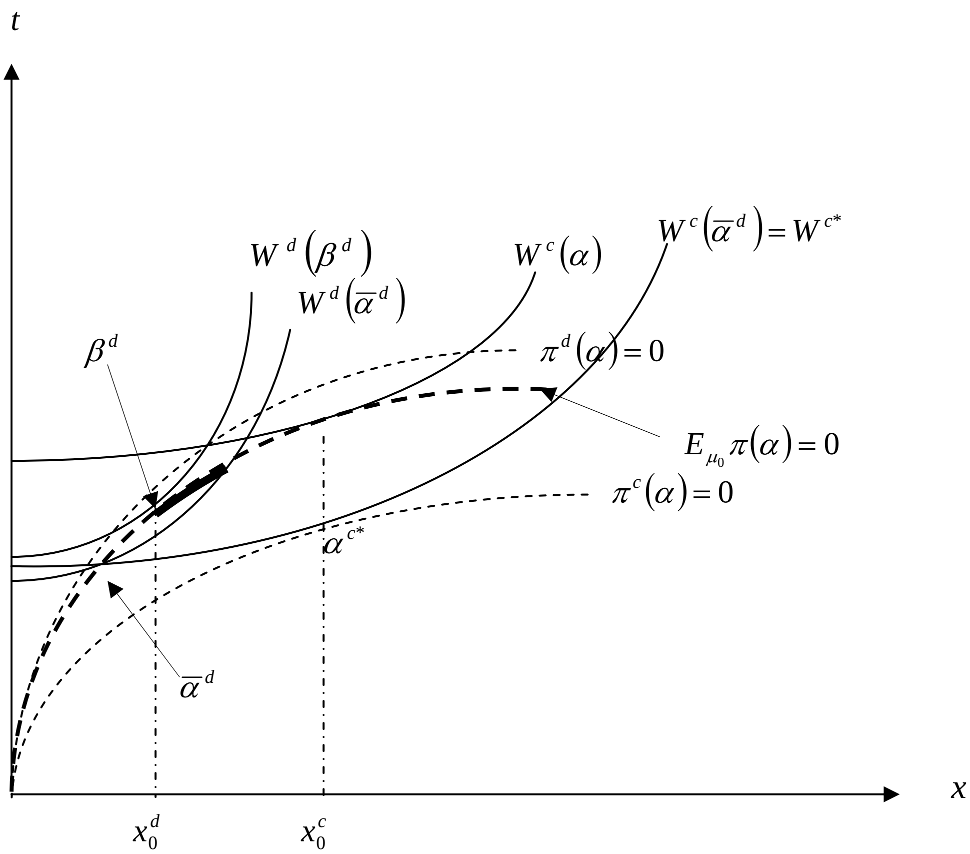

Figure 4
Parameter configuration for pooling equilibrium contracts

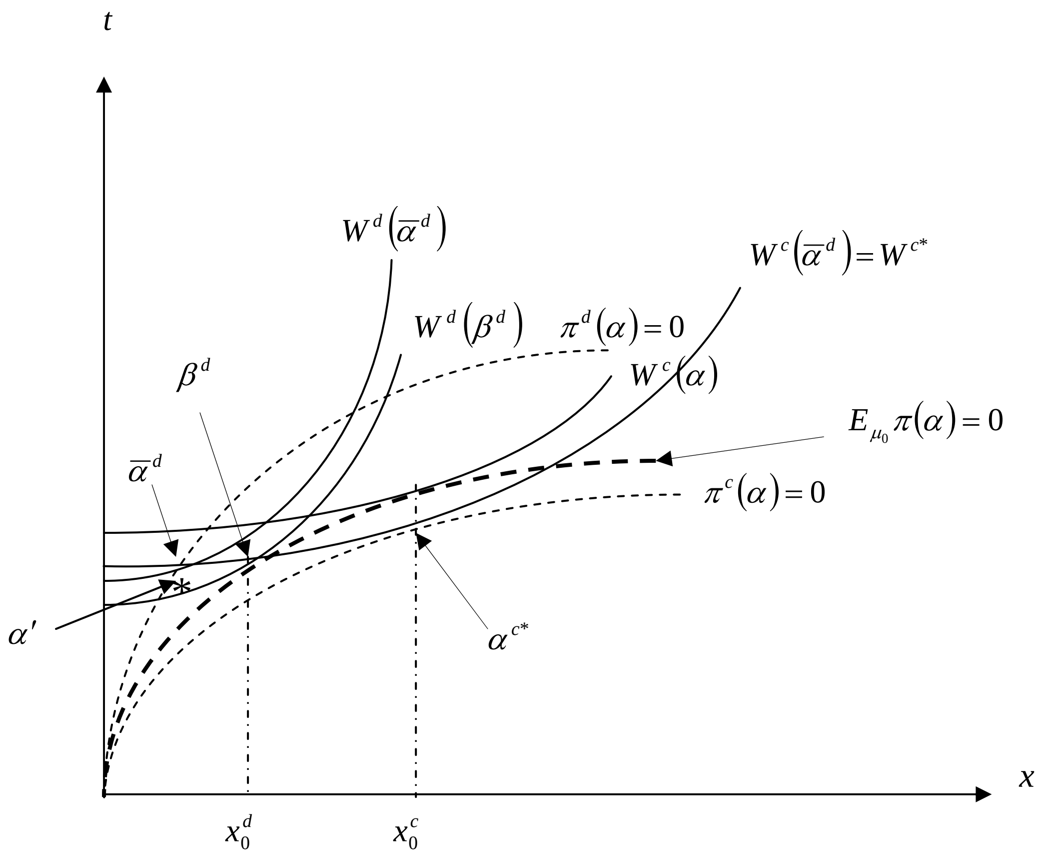

Figure 5
Parameter configuration for a unique separating PBE