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Facultad de Economía

INVESTMENT IN TRANSPORT CAPACITY AND REGULATION OF REGIONAL MONOPOLIES IN NATURAL GAS COMMODITY MARKETS

Farid Gasmi
Juan Daniel Oviedo

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F. GASMI
Toulouse School of Economics (ARQADE & IDEI)
farid.gasmi@tse-fr.eu

and

J.D. OVIEDO†
Universidad del Rosario
juan.oviedo@urosario.edu.co

Abstract

This paper develops a model of the regulator-regulated firm relationship in a regional natural gas commodity market which can be linked to a competitive market by a pipeline. We characterize normative policies under which the regulator, in addition to setting the level of the capacity of the pipeline, regulates the price of gas, under asymmetric information on the firm's technology, and may (or may not) operate (two-way) transfers between consumers and the firm. We then focus on capacity and investigate how its level responds to the regulator's taking account of the firm's incentive compatibility constraints. The analysis yields some insights on the role that transport capacity investments may play as an instrument to improve the efficiency of geographically isolated markets.

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†Corresponding author.

1 Introduction

This paper explores the issue of how the regulator's objective of mitigating monopoly power, typically emphasized in policy reforms of the natural gas industry, should affect the capacity of transport networks. Such reforms have been first conducted in the United States and the United Kingdom over the last two to three decades and then in the European Union since the late 90s. With the ongoing industry liberalization process, in particular, in the EU, significant investments in the building of pipeline capacity have been engaged. These heavy investments can be justified not only by the need to anticipate growth in demand and to ensure security of supply, but also as safeguards against possible exercise of monopoly power in isolated regional markets.[1] Such "local" monopolies seem, indeed, likely to emerge in the EU, at least in the early stages of the liberalization process, as an inheritance of the history of the structure of the industry.[2]

The purpose of this paper is to analyze the role that investments in transport capacity of networks may play in the effort to mitigate the welfare consequences of monopoly power in isolated regional gas commodity markets. Using an industry configuration presented in Cremer et al (2003), for the case of perfect competition, and Cremer and Laffont (2002) and Gasmi and Oviedo (2012), for the case of imperfect competition under complete information, we develop a model of the regulator-regulated firm relationship in a regional natural gas commodity market which can be linked to a competitive market by a pipeline. First, we characterize normative policies under which the regulator, in addition to setting the level of the capacity of the pipeline, regulates the price of gas, under asymmetric information on the firm's technology, and may operate (two-way) transfers between consumers and the regional monopoly. We then focus on capacity and investigate how its level responds to the regulator's taking account of the firm's incentive compatibility constraints. The analysis yields some insights on the role that

[1] This last point has been made clear by Borenstein et al (2000) for the case of the electricity industry in California.

[2] The EU gas industry has historically been highly concentrated. Following the reforms of the late 90s, an oligopolistic market structure seems to have developed (Chaton et al., 2012).

transport capacity investments may play as an instrument to improve the efficiency of geographically isolated gas markets.

This paper is organized as follows. The next section presents the basic market configuration considered in the paper, describes the cost structures of the gas transport and supply activities, and outlines the information structures and timing of events assumed in the analysis. We assume that the regulator first sets the level of transport capacity, a long term decision, and then the level of price and transfers (if appropriate), a short-term decision, but that at the time of making this latter decision, the regulator faces adverse selection due to the fact that the marginal cost of the firm is private information. While, as is standard in the theory of incentive regulation, the level of the regulatory variables (price and transfers) will be marginal cost-dependent, we assume that for capacity this is not the case. Next, given the purpose of this paper, which is to analyze the response of capacity to incentive compatibility constraints, we take as a benchmark a situation in which, at the time of determining the capacity level, the regulator makes a decision under uncertainty about the firm's marginal cost.

Sections 3 and 4 are organized in a similar manner, but in section 3 we assume that the regulator may use transfers whereas in section 4 transfers are not permitted. In each of those two sections, first the optimal regulatory mechanism under asymmetric information and the control scheme under uncertainty are characterized. Then the levels of capacity achieved under the regulatory mechanism, which accounts for the firm's incentive compatibility constraints, and the control scheme under uncertainty, which doesn't, are compared. Section 5 summarizes our main results and contributions to the literature of gas markets regulation and the appendix gives the formal proofs of the results.

2 Industry configuration, information structures, and timings of events

Consider a regional natural gas commodity market, market M, covered by a single firm, firm m, producing with a technology represented by a cost function $C_m(q_m) = \widetilde{\theta} q_m + F_m$, where q_m is output, $\widetilde{\theta}$ is marginal cost such that $\widetilde{\theta} \in \{c, \theta\}$ with $c < \theta$, and F_m is fixed cost.[3] We assume that there may well be an alternative source of gas at a price precisely equal to c, the lower of the two possible values of firm m's marginal cost. This gas would come from a competitive market, market C_p, which is geographically distinct from market M but may be linked to it by a pipeline of capacity K built at cost $C(K)$, with $C(\cdot)$ being increasing and convex, $C'(0) = 0$,and $C''(0) > 0$.[4] The regional monopoly's marginal cost is thus at least as large as the level at which the gas shipped from the competitive market is produced.

This firm is regulated and, following standard practices in regulatory economics, when it has a low (high) marginal cost c (θ), it will be referred to as the good- (bad-) "type" firm or the more (less) efficient firm. Hence, we may think, and in fact will in this paper, of $(\theta - c)$ as representing the productive inefficiency due to monopoly power when the firm is of the bad type and will hereafter refer to this cost difference as the "cost gap." Gas produced under competitive conditions in market C_p and shipped into the regional market M should help the regulator to counter the exercise of market power by the monopoly. Figure 1 below illustrates this industry configuration.

[3] The financing of this fixed cost F_m is always accounted for in the policies considered in this paper. However, we assume that it is bounded. This point will be further discussed later in the paper.

[4] In this paper, we assume that the cost of building the pipeline (if any) is supported by the social planner/regulator, and hence there is no need to be more specific about the cost structure of this activity. In particular, adding a fixed cost in our framework does not affect the results. In some ongoing piece of work, we assume that the pipeline is built by a regulated private firm.

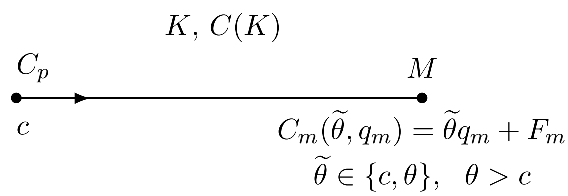


Figure 1: Industry configuration

We take the view that the fundamental reason for society to support an investment in the building of a pipeline of a certain capacity is to allow imports of gas into the regional market that would bring consumers the benefits of competition.[5] However, those benefits should be balanced against, among other things, the firm's fixed costs which need to be financed from costly public funds. Letting $Q_M(\cdot)$ represent the regional market demand which is assumed to be linear, if a volume of gas corresponding to full capacity of the pipeline is shipped from the competitive market into the regional market, the firm remains a monopoly on the residual demand $Q_M(p_M) - K$ where K is the capacity of the pipeline and p_M is market price.

In addition to controlling the building and the capacity of the pipeline, we assume that the regulator has potentially two regulatory instruments, namely, transfers between consumers and the firm (T) and pricing of the gas commodity (p_M). However, in this paper we assume that capacity is not contingent upon the firm's type.[6] We consider the cases where the regulator uses the two regulatory instruments and where pricing is the only available regulatory instrument. Regulation is carried out under asymmetric information on the firm's marginal cost and the way we introduce asymmetric information follows the standard approach in regulatory economics.[7] More specifically, we assume that at the time the regulator makes the decision on the level of the regulatory instrument(s), the regional firm privately knows the value of its marginal cost $\widetilde{\theta}$, whereas the regulator has only some prior beliefs represented by the probabilities α and $1 - \alpha$ that this marginal cost respectively takes on the values θ and c. Figure 2 below shows the timing of events.

[5] Market C_p assumed to be efficient, we focus on consumption in market M where market power is an issue.

[6] In the vocabulary of contract theory, one may say that capacity is "not contractible."

[7] See Laffont and Martimort (2002).

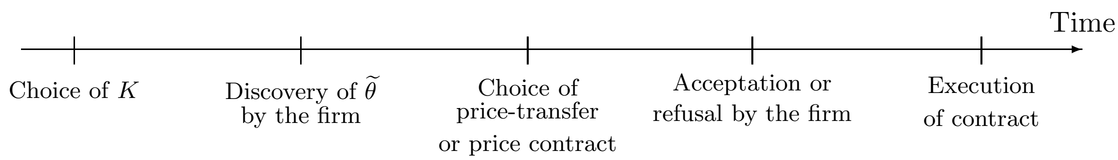


Figure 2: Timing of events under asymmetric information

Given the purpose of this paper, which is to analyze the response of the level of transport capacity to asymmetric information, we take as a benchmark a control scheme in which the regulator determines this level under uncertainty. The sequencing of events of such a scheme is as follows. First, the regulator chooses the capacity of the pipeline. Then, nature draws the marginal cost of the firm $\widetilde{\theta}$ which is simultaneously discovered by the firm and the regulator. Finally, the regulator sets the level of the regulatory instruments, price and transfers or price only. Hence, when determining the transport capacity level, the regulator, being uncertain about the value of the firm's marginal cost $\widetilde{\theta}$, sets this level based on the expected value of marginal cost. Figure 3 below exhibits this timing of events.

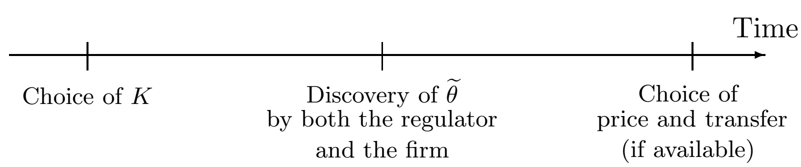


Figure 3: Timing of events under uncertainty (benchmark)

The optimal policies when this control scheme under uncertainty is used are derived by backward induction. First, at the price-(transfer-, if available) setting stage, the regulator maximizes ex-post social welfare under the ex-post constraints associated with the regulatory scheme for a given level of capacity. This yields the optimal price (and transfer) and the Lagrange multipliers associated with the constraints as functions of firm's type and network capacity. Second, at the capacity-setting stage, the regulator maximizes ex-ante welfare under the ex-post constraints and taking into account the optimal price, transfer (if available), and Lagrange multipliers functions obtained in the first stage. However, since capacity is always controlled by the regulator, the solution of this sequential constrained welfare maximization program is the same as that obtained by maximizing ex-ante welfare with respect to the available regulatory instruments, under the ex-post constraints associated with the regulatory scheme.

In the same vein, the optimal policies, when the regulatory mechanism under asymmetric information is used, are obtained by maximizing ex-ante social welfare under the ex-post constraints. However, there is an important difference which is that since at the time of setting the regulatory instruments, price and transfers (if available), the firm has private information on its marginal cost, the regulator has to offer it an incentive compatible contract. Hence, the set of ex-post constraints in which the regulator maximizes ex-ante social welfare now should incorporate those that guarantee that the solution is compatible with the firm's incentives.

As indicated, our main objective is to analyze within this normative framework the impact of firm's incentives on the capacity of the transport network. For a a fixed set of available regulatory instruments, we characterize both the the asymmetric information regulatory mechanism and the control scheme under uncertainty and compare the achieved optimal levels of pipeline capacity. This is carried out in the next two sections on the basis of an analysis of the regulatory mechanism scheme A and the control scheme B under which, in addition to controlling K, the regulator sets p_M and T, under A, and only p_M, under B. The comparison of the levels of capacity achieved under uncertainty and under asymmetric information allows us to characterize the conditions under which incentive regulation calls for "over-" ("under-") sizing of the pipeline that links the regional market to the competitive market.

3 Transport capacity and compatibility with firm's incentives when transfers are allowed

In this section, we consider control scheme A in which, in addition to controlling the transport capacity K, the regulator sets the gas commodity price p_M and may use public funds raised through taxation to make monetary transfers between consumers and the firm. Since taxation generates a deadweight loss, transferring T monetary units to the firm costs taxpayers $(1+\lambda)T$ where λ is the social cost of public funds. Letting $S(\cdot)$ denote the gross surplus of consumers in market M and $U(\widetilde{\theta})$ the utility of the $\widetilde{\theta}$-type firm is given by

$$U(\widetilde{\theta}) = (p_M(\widetilde{\theta}) - \widetilde{\theta})[Q_M(p_M(\widetilde{\theta})) - K] - F_m + T(\widetilde{\theta}) \tag{1}$$

and ex post social welfare is expressed as

$$\begin{aligned} W(\widetilde{\theta}) = & \left\{ S(Q_M(p_M(\widetilde{\theta}))) + \lambda p_M(\widetilde{\theta}) Q_M(p_M(\widetilde{\theta})) \right\} \\ & - \left\{ (1+\lambda) \left[\widetilde{\theta}(Q_M(p_M(\widetilde{\theta})) - K) + cK + C(K) + F_m \right] \right\} - \lambda U(\widetilde{\theta}) \end{aligned} \tag{2}$$

This expression says that social welfare is equal to the social value of total supply of gas (gross consumer surplus plus fiscal value of revenues from gas supply), minus the social cost of gas supply, minus the social opportunity cost of the firm's rent.[8]

[8] Total supply of gas $Q_M(p_M(\widetilde{\theta}))$ in the market, composed of K units imported from the competitive market and $q_m(\widetilde{\theta})$ units produced locally by the firm $\widetilde{\theta}$, brings taxpayers an aggregate (net) welfare $V(\widetilde{\theta})$ given by

$$\begin{aligned} V(\widetilde{\theta}) = \quad & \{ S(Q_M(p_M(\widetilde{\theta}))) - p_M(\widetilde{\theta}) Q_M(p_M(\widetilde{\theta})) \} \\ & + \{ (1+\lambda) \left[(p_M(\widetilde{\theta}) - c)K - C(K) \right] \} - \{ (1+\lambda) T(\widetilde{\theta}) \} \end{aligned}$$

This taxpayers' welfare comprises the net surplus of consumers in the regional market, the social valuation of profits generated by the K units of gas imported from the competitive market, and the social cost of the transfer T made to the firm. The utilitarian social welfare function W is then given by the sum of this taxpayers' welfare and the firm's utility. Substituting for V given above and T from (1) yields expression (2). We then see that reducing the monopoly's utility is socially desirable for this utility includes a transfer of public funds raised through distortionary taxes. We also see that the social valuation of total production explicitly includes the fiscal value of the revenues that it generates. Indeed, given that transfers are allowed, these revenues allow the government to rely less on public funds collected through taxation that generates a deadweight loss.

The firm's participation and output nonnegativity constraints that will be taking into account in the social planner's/regulator's optimization programs are given by

$$U(\widetilde{\theta}) \geq 0 \tag{3}$$

$$q_m(\widetilde{\theta}) = Q_M(p_M(\widetilde{\theta})) - K \geq 0 \tag{4}$$

Under the scheme A, given the timings described in Figures 2 and 3, optimal regulation under uncertainty and asymmetric information both entail maximizing expected or ex ante social welfare

$$\mathrm{E}_{\widetilde{\theta}}[W(\widetilde{\theta})] = \alpha W(\theta) + (1-\alpha)W(c) \tag{5}$$

with respect to $p_M(\theta)$, $p_M(c)$, $U(\theta)$, $U(c)$, and K, subject to the ex post constraints

$$U(\theta) \geq 0 \quad (\overline{\phi}) \tag{6}$$

$$U(c) \geq 0 \quad (\underline{\phi}) \tag{7}$$

$$q_m(\theta) \geq 0 \quad (\overline{\nu}) \tag{8}$$

$$q_m(c) \geq 0 \quad (\underline{\nu}) \tag{9}$$

where the corresponding Lagrange multipliers are shown in parentheses. However, for scheme A under asymmetric information, as we will see below, incentive compatibility constraints need to be added to this set of constraints. For ease of exposition, hereafter we simplify the notation by letting $\overline{p}_M \equiv p_M(\theta)$, $\underline{p}_M \equiv p_M(c)$, $\overline{U} \equiv U(\theta)$, $\underline{U} \equiv U(c)$, $\overline{q}_m \equiv q_m(\theta)$, $\underline{q}_m \equiv q_m(c)$, $\overline{Q}_M \equiv Q_M(p_M(\theta))$, $\underline{Q}_M \equiv Q_M(p_M(c))$, and $Q'_M \equiv Q'_M(p_M(\theta))$ $(= Q'_M(p_M(c))$.

3.1 Scheme A under uncertainty

To solve for the optimal policies when scheme A under uncertainty is used, one maximizes ex ante social welfare (5) with respect to $p_M(\theta)$, $p_M(c)$, $U(\theta)$, $U(c)$, and K, subject to the constraints (6)-(9). The corresponding first-order conditions are:[9]

$$\alpha\lambda\overline{Q}_M + [\alpha(1+\lambda)(\overline{p}_M - \theta) + \overline{\nu}]Q'_M = 0 \tag{10}$$

$$(1-\alpha)\lambda\underline{Q}_M + [(1-\alpha)(1+\lambda)(\underline{p}_M - c) + \underline{\nu}]Q'_M = 0 \tag{11}$$

$$(1+\lambda)\left[\alpha(\theta - c) - C'(K)\right] - (\overline{\nu} + \underline{\nu}) = 0 \tag{12}$$

$$-(\alpha\lambda - \overline{\phi}) = -((1-\alpha)\lambda - \underline{\phi}) = 0 \tag{13}$$

$$\overline{\phi U} = \underline{\phi}\underline{U} = 0 \tag{14}$$

$$\overline{\nu}\ \overline{q}_m = 0 \tag{15}$$

$$\underline{\nu}\ \underline{q}_m = 0 \tag{16}$$

From (14) it is straightforward to see that the participation constraint is binding for both types of firm, i.e., $\overline{U} = \underline{U} = 0$. Some further useful properties implied by this system of first-order conditions are stated in the lemma that follows.

Lemma 1 *Under scheme A with uncertainty, optimal prices and shadow costs of the firm's output nonnegativity constraints satisfy* $\underline{p}_M \leq \overline{p}_M$ *and* $\underline{\nu} \leq \overline{\nu}$.

This lemma says that optimal price is nondecreasing in the firm's marginal cost. Moreover, regarding the values of the shadow costs of the firm's output nonnegativity constraint, $(\overline{\nu}, \underline{\nu})$, out of the four possible combinations $(\overline{\nu} = 0, \underline{\nu} = 0)$, $(\overline{\nu} > 0, \underline{\nu} = 0)$, $(\overline{\nu} > 0, \underline{\nu} > 0)$, and $(\overline{\nu} = 0, \underline{\nu} > 0)$, the lemma rules out the latter combination as a solution. Hence, the decision to shut down the firm, if it is of the more efficient type, and let it active, if it is of the less efficient one, is never socially optimal. Moreover, it can be shown that a solution with $\overline{\nu} > 0$ and $\underline{\nu} > 0$ cannot arise either, i.e., the decision to always shut down the firm, independently of its type, is also never optimal.[10] Hence, one can ignore the nonnegativity constraint (9) and write

[9] Given that $C''(K) > 0$ for any $K \geq 0$, the demand schedule is concave and downward-sloping, and that $(p_M - \widetilde{\theta}) \geq 0$, the condition $(1+\lambda)C''(K)\left[(1+2\lambda)Q'_M + (1+\lambda)(p_M - \widetilde{\theta}))Q''_M\right] < 0$ holds, and hence the ex post welfare function (2) and the ex ante expected social welfare function (5) are strictly concave. These conditions are thus necessary and sufficient and the solution of this system is not only a local but also a global interior welfare maximizers.

[10] To see this assume that $\overline{\nu} > 0$ and $\underline{\nu} > 0$. Then, (15) and (16) imply $\overline{q}_m = \underline{q}_m = 0$, which says that the market M is fully covered by gas which is shipped from the competitive

that $\underline{\nu} = 0$, which says that the more efficient firm is always active, in which case, from the proof of the lemma in the appendix, we obtain $\underline{p}_M < \overline{p}_M$.

Letting $\varepsilon(\overline{Q}_M) \equiv -Q'_M \overline{p}_M / \overline{Q}_M$, $\varepsilon(\underline{Q}_M) \equiv -Q'_M \underline{p}_M / \underline{Q}_M$ and rewriting the first-order conditions (10)-(16) yields Proposition 1 below that describes the solutions corresponding to the two remaining combinations on the ν's, namely, $(\overline{\nu} = 0, \underline{\nu} = 0)$ and $(\overline{\nu} > 0, \underline{\nu} = 0)$.

Proposition 1 *When, in addition to controlling capacity, the social planner determines price, has the ability to make transfers between consumers and the firm, and faces uncertainty about the marginal cost of the regional monopoly at the time of setting capacity, there are two possible exclusive policies $(K, \overline{p}_M, \underline{p}_M, \overline{\phi}, \underline{\phi}, \overline{\nu}, \underline{\nu})$. These policies, denoted by $A1_u$ and $A2_u$, are characterized as follows:*

$A1_u$ - *Under this policy, both types of firms are active ($\overline{\nu} = \underline{\nu} = 0$) and have zero utility ($\overline{\phi} = \alpha\lambda$, $\underline{\phi} = (1-\alpha)\lambda$), market prices follow a Ramsey-type rule, and pipeline capacity is such that the social marginal cost of imports is equal to the expected social marginal cost of local production:*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\overline{Q}_M)} \tag{17}$$

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\underline{Q}_M)} \tag{18}$$

$$(1+\lambda)C'(K) = \alpha(1+\lambda)(\theta - c) \tag{19}$$

$A2_u$ - *Under this policy, the firm of bad type is shut down, the firm of good type is active but gets zero utility ($\overline{\nu} > 0$, $\underline{\nu} = 0$, $\underline{\phi} = (1-\alpha)\lambda$), market price obeys the Ramsey rule (18), capacity is at the level that just shuts down the firm of bad type ($K = \overline{Q}_M$) and is such that the social marginal cost of imports plus the shadow cost of this firm's output nonnegativity constraint (equivalent to the cost of interrupting*

market C_p, i.e., $K > 0$. Solving the first-order conditions (10) and (11) for $\overline{\nu}$ and $\underline{\nu}$ and substituting into (12) yields $\lambda\overline{Q}_M + (1+\lambda)[\overline{p}_M - c - C'(\overline{Q}_M)]Q'_M = 0$. However, $\underline{\nu} > 0$ implies $\lambda\overline{Q}_M + (1+\lambda)(\overline{p}_M - c)Q'_M \geq 0$. Hence, since $C'(\cdot) \geq 0$, we have $\overline{Q}_M = \overline{q}_m + K \leq 0$ which contradicts $K > 0$.

its production) is equal to the expected social marginal cost of local production, i.e.,

$$(1+\lambda)C'(K)+\overline{\nu} \quad =\alpha(1+\lambda)(\theta-c) \qquad (20)$$

Policy $A1_u$ *occurs if and only if the condition* $(0<)(\theta-c)<\frac{C'(\overline{Q}_M)}{\alpha}$*, which says that the cost gap is "sufficiently low," holds. Policy* $A2_u$ *occurs if and only if the reverse of this condition, i.e.,* $(\theta-c)\geq\frac{C'(\overline{Q}_M)}{\alpha}$*, which says that the cost gap is "sufficiently high," is true.*

Under policy $A1_u$, even if the local monopoly does not have the "right" marginal cost (c), it meets part of the market demand with a (Ramsey-type) price markup which allows it to balance its budget. Adding $(1+\lambda)c$ on both sides of (19), we see that, at the optimum, capacity is such that the social marginal cost of imports, $(1+\lambda)[c+C'(K)]$, is equal to the expected social marginal cost of the firm, $(1+\lambda)[\alpha\theta+(1-\alpha)c]$. It is optimal to let even the less efficient firm be active because the expected social marginal cost of local production is smaller than the social marginal cost of imports at the level of these imports at which the less efficient firm is inactive, $(1+\lambda)[c+C'(\overline{Q}_M)]$, a condition given at the end of the proposition.[11]

Under policy $A2_u$, because the expected social marginal cost of having gas supplied locally is greater than the social marginal cost of importing it at the imports level that makes the less efficient firm inactive, indeed, society finds it worthwhile to shut down this bad type firm. However, capacity is now such that the expected social marginal cost of local production is equal to the social marginal cost of imports plus the shadow cost of the less efficient firm's output nonnegativity constraint ($\overline{\nu}$) since this firm's production is now interrupted.[12]

[11] Recall from Lemma 1 and the discussion that follows the lemma that the low-marginal cost firm is always active.

[12] The bad type firm's utility is obviously nil under this policy that interrupts its production (in fact, the optimal value of $\overline{\phi}$ is $\alpha\lambda$). Although we do not provide an explicit form for $\overline{\nu}$, we find that the (shutting) level of price of this firm is such that

$$\frac{\overline{p}_M-\theta}{\overline{p}_M} \quad =\frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\overline{Q}_M)}-\frac{\overline{\nu}}{\alpha(1+\lambda)\overline{p}_M}$$

To illustrate the policies discussed in Proposition 1, let us assume the following functional forms:

$$Q_M(p_M) = \gamma - p_M, \quad C(K) = \frac{\omega}{2}K^2; \quad \gamma, \omega > 0, \quad \gamma > \theta > c \tag{21}$$

Then, if, and only if, the condition

$$(0 <)(\theta - c) < \left[\frac{\omega(1+\lambda)}{\omega(1+\lambda) + \alpha(1+2\lambda)}\right](\gamma - c) \tag{22}$$

which says that the cost gap is "low," holds, policy $(A1_u)$, under which the firm is active independently of its type, occurs and price markups and capacity are given by

$$\overline{p}_M = \theta + \left[\frac{\lambda}{1+2\lambda}\right](\gamma - \theta) \tag{23}$$

$$\underline{p}_M = c + \left[\frac{\lambda}{1+2\lambda}\right](\gamma - c) \tag{24}$$

$$K = \frac{\alpha(\theta - c)}{\omega} \tag{25}$$

The reverse of condition (22), which says that the cost gap is "high," i.e.,

$$\left[\frac{\omega(1+\lambda)}{\omega(1+\lambda) + \alpha(1+2\lambda)}\right](\gamma - c) \leq (\theta - c) < (\gamma - c) \tag{26}$$

where the right-hand-side of this inequality comes from the fact that $\gamma > \theta$, is a necessary and sufficient condition for policy $(A2_u)$, under which only the firm of good type is active, to occur. The market price markup under this policy is given by (24) and transport capacity that makes the firm of bad type shut down satisfies

$$K = \left[\frac{\alpha(1+\lambda)}{\omega(1+\lambda) + \alpha(1+2\lambda)}\right](\gamma - c) \tag{27}$$

3.2 Scheme A under asymmetric information

Under asymmetric information about the value of the firm's marginal cost $\widetilde{\theta}$, after building transport capacity the regulator has to offer *feasible* contracts

yielding $\overline{\nu} = \alpha(1+\lambda)\left[\left(\theta - \frac{\lambda\overline{Q}_M}{(1+\lambda)Q'_M}\right) - \overline{p}_M\right]$. Hence, this shadow cost of the bad type firm's output nonnegativity constraint can also be interpreted as the social marginal valuation of the expected price reduction required to guarantee that this firm is shut down.

to the regional firm. Such contracts need to satisfy, in addition to the firm's participation and output nonnegativity constraints (6)-(9), the firm's incentive compatibility constraints which can be written as:

$$\overline{U} \geq \underline{U} - (\theta - c)\underline{q}_m \quad (\overline{\mu}) \tag{28}$$

$$\underline{U} \geq \overline{U} + (\theta - c)\overline{q}_m \quad (\underline{\mu}) \tag{29}$$

where the corresponding Lagrange multipliers are shown in parentheses.[13] Adding up (28) and (29) yields $\underline{q}_m \geq \overline{q}_m$ which implies the standard result $\underline{p}_M \leq \overline{p}_M$.[14] As a consequence, the Lagrange multiplier associated with the c-type firm's output nonnegativity constraint (9), $\underline{\nu}$, is equal to zero.[15] Moreover, because a more efficient firm can always mimic a less efficient one at a lower level of cost, the participation constraint of the former, i.e., (7), can also be ignored (see (29)).

Maximizing expected social welfare given by (5) subject to the remaining constraints yields the following first-order conditions which are necessary and sufficient:[16]

$$\alpha\lambda\overline{Q}_M + [\alpha(1+\lambda)(\overline{p}_M - \theta) + \overline{\nu} - \underline{\mu}(\theta - c)]Q'_M = 0 \tag{30}$$

$$(1-\alpha)\lambda\underline{Q}_M + [(1-\alpha)(1+\lambda)(\underline{p}_M - c) + \overline{\mu}(\theta - c)]Q'_M = 0 \tag{31}$$

$$(1+\lambda)\left[\alpha(\theta - c) - C'(K)\right] - \overline{\nu} - (\overline{\mu} - \underline{\mu})(\theta - c) = 0 \tag{32}$$

$$-[\alpha\lambda - \overline{\phi} - (\overline{\mu} - \underline{\mu})] = 0 \tag{33}$$

$$-[(1-\alpha)\lambda + (\overline{\mu} - \underline{\mu})] = 0 \tag{34}$$

$$\overline{\mu}[\overline{U} - \underline{U} + (\theta - c)\underline{q}_m] = \underline{\mu}[\underline{U} - \overline{U} - (\theta - c)\overline{q}_m] = 0 \tag{35}$$

$$\overline{\phi U} = 0 \tag{36}$$

$$\overline{\nu}\,\overline{q}_m = 0 \tag{37}$$

[13] These expressions of the firm's incentive compatibility constraints are derived by using (1) and a standard add-and-substract technique.

[14] See, e.g., Baron (1989).

[15] To see why this is true note that, since $\underline{q}_m \geq \overline{q}_m$, clearly the more efficient firm cannot be shut down while the less efficient one is left active, i.e., $\overline{\nu} = 0 \Rightarrow \underline{\nu} = 0$. When the nonnegativity constraints (8) and (9) are both binding, i.e., both firms are shut down $(\overline{\nu}, \underline{\nu} > 0)$, the incentive constraints (28) and (29) are trivially satisfied and we are back to the case with uncertainty analyzed in the previous subsection. But then in this case, we have already shown (see footnote (10)) that such a solution cannot arise at the optimum.

[16] See footnote 9.

From (33) and (34), we see that $\overline{\phi} = \lambda > 0$ and the participation constraint of the less efficient firm is binding, i.e., $\overline{U} = 0$. It is then straightforward to show that the incentive compatibility constraint of the more efficient firm is binding, and hence $\underline{U} = (\theta - c)\overline{q}_m$.[17] This equality and the fact that feasible prices satisfy $\underline{p}_M \leq \overline{p}_M$ imply that the incentive compatibility of the less efficient firm, (28), is not binding, and hence $\overline{\mu} = 0$. Proposition 2 below gives a characterization of the optimal policies described by the above first-order conditions (30) – (37).

Proposition 2 *When, in addition to controlling capacity, the social planner regulates price under asymmetric information about the marginal cost of the regional monopoly and has the ability to make transfers between the consumers and the firm , there are two possible policies $(K, \overline{p}_M, \underline{p}_M, \overline{\phi}, \underline{\phi}, \overline{\nu}, \underline{\nu})$ which are exclusive. These optimal policies denoted by $A1_{ai}$ and $A2_{ai}$ are characterized as follows:*

$A1_{ai}$ - *Under this policy, $\overline{\nu} = \underline{\nu} = 0$ (the firm is always active), $\overline{\mu} = 0$ and $\underline{\mu} = (1-\alpha)\lambda$ (the θ-type firm's incentive constraint is not binding while the c-type firm's is), $\overline{\phi} = \lambda$ and $\underline{\phi} = 0$ (the θ-type firm's informational rent is nil while the c-type firm makes a strictly positive rent), and market price markup and capacity are such*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\overline{Q}_M)} + \frac{\lambda}{1+\lambda}\frac{(1-\alpha)}{\alpha}\frac{(\theta - c)}{\overline{p}_M} \quad (38)$$

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\underline{Q}_M)} \quad (39)$$

$$(1+\lambda)C'(K) = (\alpha + \lambda)(\theta - c) \quad (40)$$

$A2_{ai}$ - *Under this policy, $\overline{\nu} > 0$ and $\underline{\nu} = 0$ (only the more efficient firm is active), $\underline{\mu} = (1-\alpha)\lambda$ (the c-type firm's incentive constraint is binding), $\underline{\phi} = 0$ (the c-type firm makes a strictly positive rent), and market price markup satisfies (39) while capacity K $(= \overline{Q}_M)$ is such that*

$$(1+\lambda)C'(\overline{Q}_M) + \overline{\nu} = (\alpha + \lambda)(\theta - c) \quad (41)$$

[17] These observations on the firm utility are consistent with the fact that the rent of the firm is socially costly as can be seen from (2).

Policy $A1_{ai}$ occurs if and only if the condition $(0 <)(\theta - c) < \frac{C'(\overline{Q}_M)}{\alpha+\lambda}$, *which says that the cost gap is "sufficiently low," holds. Policy $A2_{ai}$ occurs if and only if the reverse of this condition, i.e.,* $(\theta - c) \geq \frac{C'(\overline{Q}_M)}{\alpha+\lambda}$, *which says that the cost gap is "sufficiently high," is true.*

Under policy $A1_{ai}$, even if it is of the less efficient type, the firm meets part of the market demand. While the more efficient firm pricing rule is of a standard Ramsey type, that of the less efficient one shows an "extra" distortion term, $\frac{\lambda}{1+\lambda}\frac{(1-\alpha)}{\alpha}\frac{(\theta-c)}{\overline{p}_M}$. This distortion of the less efficient firm's output is necessary to decrease the information rent of the more efficient firm, $\underline{U} = (\theta - c)\overline{q}_m$. Adding $(1 + \lambda)c$ on both sides of (40), we see that optimal capacity is such that the social cost of importing an additional unit is equal to the expected social cost of having this unit produced by the firm plus the social opportunity cost of the expected information rent that this unit generates, $\lambda(1-\alpha)(\theta-c)$. When this policy arises this aggregate social cost of having the marginal unit produced in the regional market is smaller than the social marginal cost of having it shipped in from the competitive market, at the level of imports where the less efficient firm is shut down, a condition that is stated at the end of Proposition 2.

Under policy $A2_{ai}$, the comparison between aggregate social cost of having an additional unit produced by the firm and the social cost of having it imported at a level of imports such that the θ-type firm is indeed inactive calls for the shutting down of the firm if it is of this less efficient type. Pricing of the active firm (the c-type) follows a standard Ramsey rule and, as can be seen from (41), capacity is such that the aggregate social marginal cost of local production is equal to social marginal cost of imports to which is now added the shadow cost of the θ-type firm's output nonnegativity constraint $\overline{\nu}$ to account for its shutting down.[18]

Using the functional forms given in (21), the solution to the system of first-order conditions (30)-(37) yields two policies. Policy $A1_{ai}$ occurs if, and

[18] The shutting down level of price for the firm θ is given by

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\overline{Q}_M)} + \frac{\lambda}{1+\lambda}\frac{(1-\alpha)(\theta-c)-\overline{\nu}}{\alpha\overline{p}_M}$$

only if, the condition

$$(0 <)(\theta - c) < \frac{\alpha(1+\lambda)}{(\alpha+\lambda)} \left[\frac{\omega(1+\lambda)}{\omega(1+\lambda)+\alpha(1+2\lambda)} \right] (\gamma - c) \qquad (42)$$

saying that the cost gap is "low," holds. Under this policy, both types of firms are active and price markups and capacity are given by

$$\overline{p}_M = \theta + \frac{\lambda\left[(1-2\alpha)(\theta-c)+\alpha(\gamma-c)\right]}{\alpha(1+2\lambda)} \qquad (43)$$

$$\underline{p}_M = c + \left[\frac{\lambda}{1+2\lambda}\right](\gamma - c) \qquad (44)$$

$$K = \frac{(\alpha+\lambda)(\theta-c)}{\omega(1+\lambda)} \qquad (45)$$

The reverse of condition (42), i.e.,

$$\frac{\alpha(1+\lambda)}{(\alpha+\lambda)} \left[\frac{\omega(1+\lambda)}{\omega(1+\lambda)+\alpha(1+2\lambda)} \right] (\gamma - c) \leq (\theta - c) < (\gamma - c) \qquad (46)$$

which says that the cost gap is "high," is a necessary and sufficient condition for policy $A2_{ai}$ to occur. Under this policy, the c-type firm is active and market price markup and transport capacity are respectively given by (24) and (27).

3.3 Scheme A under uncertainty vs. under asymmetric information

By comparing the capacity levels achieved under scheme A under uncertainty (K_u^A) and under asymmetric information (K_{ai}^A), we are now able to assess the impact, on investment in transport capacity, of the firm's incentive compatibility constraints (28) and (29). Since $C'(\cdot)$ is increasing, from (12) and (32), we obtain

$$\begin{aligned} sign[K_{ai}^A - K_u^A] &= sign[(1+\lambda)[C'(K_{ai}^A) - C'(K_u^A)]] \\ &= sign[(1-\alpha)\lambda(\theta - c) - (\overline{\nu}_{ai}^A - \overline{\nu}_u^A)] \end{aligned} \qquad (47)$$

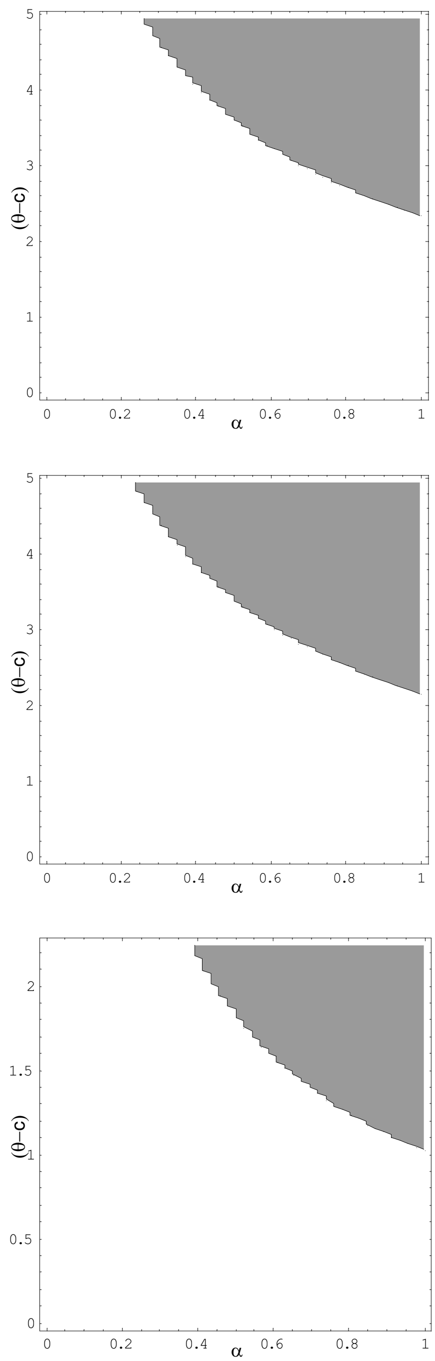
The next proposition gives the sign of this capacity difference.

Proposition 3 *When, in addition to controlling capacity, the social planner regulates the gas commodity price and may operate transfers between the firm* *and the consumers, accounting for the firm's incentive compatibility calls for transport capacity expansion (in the weak sense), i.e.,* $K_{ai}^A \geq K_u^A$.

To illustrate this proposition let us use functional forms given in (21). A first step is to directly compare the capacity levels given in (25), (27), and (45). This is straightforward and left to the reader. However, since the intervals defining the parameter space for each policy are not always compatible, we complete the illustration of this proposition with numerical simulations. Because scheme A doesn't depend on the to the fixed cost, we ran simulations with $F_m = 0$ and focused on the relationship between the capacity gap $(K_{ai}^A - K_u^A)$ and the endogenous variables $\overline{\nu}_{ai}^A$ and $\overline{\nu}_u^A$ in the $\{\alpha, (\theta - c)\}$-space. We used the following grids of parameters:

- Case 1: $\{\gamma, c, \omega, \lambda\} = \{10, 2, 0.50, 0.33\}$, $(\theta - c) \in [0, 4.94]$ and $\alpha \in [0, 1]$
- Case 2: $\{\gamma, c, \omega, \lambda\} = \{10, 2, 0.52, 0.85\}$, $(\theta - c) \in [0, 4.94]$ and $\alpha \in [0, 1]$
- Case 3: $\{\gamma, c, \omega, \lambda\} = \{10, 2, 0.17, 0.25\}$, $(\theta - c) \in [0, 2.24]$ and $\alpha \in [0, 1]$

Figure 4 (a-b) exhibits the results of the simulated values of $(K_{ai}^A - K_u^A)$, $\overline{\nu}_{ai}^A$, and $\overline{\nu}_u^A$. Figure 4a shows in white and gray the regions where respectively $(K_{ai}^A - K_u^A) > 0$ and $(K_{ai}^A - K_u^A) = 0$. Figure 4b exhibits the curves formed by the $(\alpha, (\theta - c))$ pairs such that $\overline{\nu}_{ai}^A = 0$ and $\overline{\nu}_u^A = 0$. A cross-examination of these figures shows that whenever $\overline{\nu}_{ai}^A = 0$, $\overline{\nu}_u^A = 0$, $K_{ai}^A > K_u^A$, as stated in the proof of Proposition 3 given in the appendix. When both $\overline{\nu}_{ai}^A$ and $\overline{\nu}_u^A$ are strictly positive, i.e., when the θ-type firm is shut down under both uncertainty and asymmetric information, $K_{ai}^A = K_u^A$. Finally, we see that when $\overline{\nu}_{ai}^A > 0$ and $\overline{\nu}_u^A = 0$, i.e., when the θ-type firm is shut down under asymmetric information but remains active under uncertainty, $K_{ai}^A > K_u^A$.



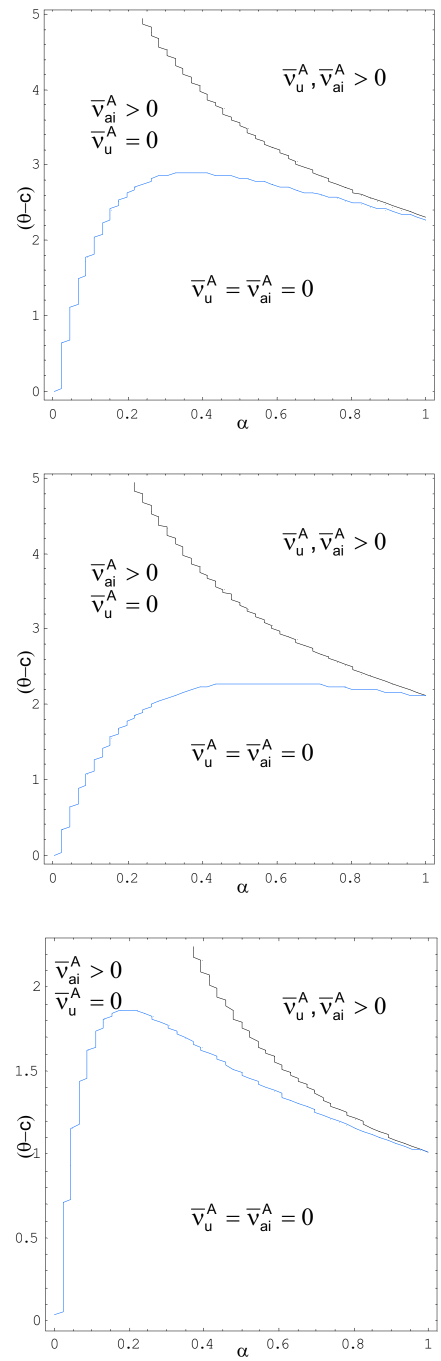


Figure 4a: $K_{ai}^A - K_u^A$

Figure 4b: $\overline{\nu}_{ai}^A$ and $\overline{\nu}_u^A$

4 Transport capacity and compatibility with firm's incentives when transfers are not allowed

Let us now consider scheme B in which the social planner controls capacity, regulates price, but may no longer operate transfers between consumers and the firm. In this case, the $\widetilde{\theta}$-type firm's utility is merely its profits $\Pi(\widetilde{\theta})$ given by

$$\Pi_m(\widetilde{\theta}) = (p_M(\widetilde{\theta}) - \widetilde{\theta})[Q_M(p_M(\widetilde{\theta})) - K] - F_m \tag{48}$$

Ex post social welfare is expressed as

$$\begin{aligned} W(\widetilde{\theta}) = \; & \{S(Q_M(p_M(\widetilde{\theta}))) - p_M(\widetilde{\theta})Q_M(p_M(\widetilde{\theta}))\} \\ & +\{(1+\lambda)\left[(p_M(\widetilde{\theta}) - c)K - C(K)\right]\} \\ & +\{(p_M(\widetilde{\theta}) - \widetilde{\theta})\left[Q_M(p_M(\widetilde{\theta})) - K\right] - F_m\} \end{aligned} \tag{49}$$

This social welfare is the sum of the net consumer surplus, the social value of the profits generated by the K units imported from the competitive market, and the profits of the firm that now cannot be taxed as transfers are not allowed. Gathering terms, we obtain

$$\begin{aligned} W(\widetilde{\theta}) = \; & \left\{S(Q_M(p_M(\widetilde{\theta}))) + \lambda p_M(\widetilde{\theta})K\right\} \\ & -\left\{\widetilde{\theta}(Q_M(p_M(\widetilde{\theta})) - K) + (1+\lambda)\left[cK + C(K)\right] + F_m\right\} \end{aligned} \tag{50}$$

which shows that, as now transfers are not allowed, the regulator assigns a fiscal value $\lambda p_M(\widetilde{\theta})K$ only to the revenues generated by the K units shipped from the competitive market C_p into the regional market M. The firm's participation and output nonnegativity constraints are respectively given by

$$\Pi_m(\widetilde{\theta}) \geq 0 \tag{51}$$

$$q_m(\widetilde{\theta}) = Q_M(p_M(\widetilde{\theta})) - K \geq 0 \tag{52}$$

Scheme B under uncertainty and asymmetric information both call for taking into account the ex-post participation and output nonnegativity constraints

$$\overline{\Pi}_m = (\overline{p}_M - \theta)\overline{q}_m - F_m \geq 0 \quad (\overline{\phi}) \tag{53}$$

$$\underline{\Pi}_m = (\underline{p}_M - c)\underline{q}_m - F_m \geq 0 \quad (\underline{\phi}) \tag{54}$$

$$\overline{q}_m = \overline{Q}_M - K \geq 0 \quad (\overline{\nu}) \tag{55}$$

$$\underline{q}_m = \underline{Q}_M - K \geq 0 \quad (\underline{\nu}) \tag{56}$$

where the corresponding Lagrange multipliers are shown in parentheses, when maximizing ex ante social welfare

$$\mathrm{E}[W(\widetilde{\theta})] = \alpha W(\theta) + (1-\alpha)W(c) \tag{57}$$

with respect to $\overline{p}_M$, $\underline{p}_M$, and K. A property of the set defined by the above constraints that turns out to be very useful for analyzing the optimization program is described in the lemma that follows.

Lemma 2 *The constraint set defined by (53)-(56) is convex and satisfies the nondegenerate constraint qualification (NDCQ) condition. In order to satisfy the linear independence constraint qualification (LICQ) condition, when there is no fixed cost, the participation constraints (53) and (54) should be ignored when either (55) or (56) is satisfied with equality, in which case (53) and (54) become liminal constraints, i.e., they are active with* $\overline{\phi} = \underline{\phi} = 0$. *When there is fixed cost, the LICQ condition is always satisfied since the firm is always active, i.e.,* $\overline{\nu} = \underline{\nu} = 0$.

Lemma 2 basically shows that the constraint set faced by the regulator is well behaved and helps to clarify the interpretation of the optimal values of the Lagrange multipliers (the ϕ's and the ν's). Whenever a ν is strictly positive, i.e., the firm is shut down, the interpretation of the ϕ somewhat looses its full significance. For example, take the case of the less efficient firm. If $F_m > 0$, it can be shown by contradiction from (53) that the firm is always active, i.e., $\overline{\nu} = 0$. Hence, for this firm to be inactive, i.e., for $\overline{\nu} > 0$, it must be the case that $F_m = 0$. But then, the participation constraint (53) can be neglected. Technically, this is taken care of by setting $\overline{\phi} = 0$ in the slack complementarity condition, $\overline{\phi}\,\overline{\Pi} = 0$, associated with the firm's participation constraint, which would suggest that the firm is making positive profits.

4.1 Scheme B under uncertainty

With scheme B under uncertainty, the social planner maximizes (57) with respect to $\overline{p}_M$, $\underline{p}_M$, and K, subject to the constraints (53)-(56). The corresponding first-order conditions are given by

$$\alpha[\lambda K + (\overline{p}_M - \theta)Q'_M] + \overline{\phi}[(\overline{p}_M - \theta)Q'_M + \overline{q}_m] + \overline{\nu}Q'_M = 0 \tag{58}$$

$$(1-\alpha)[\lambda K + (\underline{p}_M - c)Q'_M] + \underline{\phi}[(\underline{p}_M - c)Q'_M + \underline{q}_m] + \underline{\nu}Q'_M = 0 \tag{59}$$

$$(1+\lambda)\left[\alpha(\theta - c) - C'(K)\right] + (\alpha\lambda - \overline{\phi})(\overline{p}_M - \theta) + ((1-\alpha)\lambda - \underline{\phi})(\underline{p}_M - c) - \overline{\nu} - \underline{\nu} = 0 \tag{60}$$

$$\overline{\phi}[(\overline{p}_M - \theta)\overline{q}_m - F_m] = 0 \tag{61}$$

$$\underline{\phi}[(\underline{p}_M - c)\underline{q}_m - F_m] = 0 \tag{62}$$

$$\overline{\nu}\ \overline{q}_m = \underline{\nu}\ \underline{q}_m = 0 \tag{63}$$

Some properties implied by (58)-(63) are indicated in the next lemma.

Lemma 3 *With scheme B under uncertainty, provided second-order conditions are satisfied, at the optimum we have* $\underline{p}_M \leq \overline{p}_M$*,* $\underline{\Pi}_m \geq \overline{\Pi}_m$*,* $\underline{\phi} \leq \overline{\phi}$*, and* $\underline{\nu} \leq \overline{\nu}$*.*

Lemma 2 reduces the number of possible combinations of active and inactive constraints (53)-(56), at a candidate solution to the social planner's optimization program, to seven. Lemma 3 further reduces this number to five. Indeed, this lemma rules out solutions with either ($\overline{\phi} = 0, \underline{\phi} = 0, \overline{\nu} = 0, \underline{\nu} > 0$) or ($\overline{\phi} = 0, \underline{\phi} > 0, \overline{\nu} = 0, \underline{\nu} = 0$). Proposition 4 below characterizes the five remaining solutions.

Proposition 4 shows that under policy ($B1_u$) even the relatively less efficient firm is active and capacity is such that the social marginal cost of imports, $(1+\lambda)[c + C'(K)]$, net of the expected marginal fiscal revenue of imported gas, $\lambda[\alpha\overline{p}_M + (1-\alpha)\underline{p}_M]$, is equal to the expected marginal cost of the firm, $\alpha\theta + (1-\alpha)c$.

Under policy ($B2_u$) the less efficient firm just breaks even and capacity is such that the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas is equal to the expected marginal cost of the firm net of the social value of the contribution of the marginal unit of the less efficient firm to the relaxation of its participation constraint, $\overline{\phi}\frac{F_m}{\overline{q}_m}$.

Proposition 4 *When, in addition to controlling capacity, the social planners determines price and faces uncertainty about the regional firm's marginal cost, the optimal policy* $(K, \overline{p}_M, \underline{p}_M, \overline{\phi}, \underline{\phi}, \overline{\nu}, \underline{\nu})$ *is of one of the following types:*

$(B1_u)$ *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} = 0, \underline{\phi} = 0, \overline{\nu} = 0, \underline{\nu} = 0)$ *characterized by the following conditions:*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \frac{\lambda K}{\overline{Q}_M} \frac{1}{\varepsilon(\overline{Q}_M)} \qquad (64)$$

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \frac{\lambda K}{\underline{Q}_M} \frac{1}{\varepsilon(\underline{Q}_M)} \qquad (65)$$

$$(1+\lambda)C'(K) = \alpha(1+\lambda)(\theta - c) + \lambda[\alpha(\overline{p}_M - \theta) + (1-\alpha)(\underline{p}_M - c)] \qquad (66)$$

$(B2_u)$ *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M \geq \theta, \underline{p}_M > c, \overline{\phi} > 0, \underline{\phi} = 0, \overline{\nu} = 0, \underline{\nu} = 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda K + \overline{\phi}\,\overline{q}_m}{(\alpha + \overline{\phi})\overline{Q}_M}\right] \frac{1}{\varepsilon(\overline{Q}_M)} = \frac{F_m}{\overline{p}_M \overline{q}_m}, \qquad (67)$$

(65), and

$$(1+\lambda)C'(K) = \alpha(1+\lambda)(\theta - c) + \lambda\left[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)(\underline{p}_M - c)\right] - \overline{\phi}\frac{F_m}{\overline{q}_m} \qquad (68)$$

$(B3_u)$ *The policy* $(0 < K = \overline{Q}_M < \underline{Q}_M, \overline{p}_M > c, \underline{p}_M > c, \overline{\phi} = 0, \underline{\phi} = 0, \overline{\nu} > 0, \underline{\nu} = 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \frac{\lambda}{\varepsilon(\overline{Q}_M)} - \frac{\overline{\nu}}{\alpha \overline{p}_M}, \qquad (69)$$

(65), and

$$(1+\lambda)C'(\overline{Q}_M) = \alpha(1+\lambda)(\theta - c) + \lambda[\alpha(\overline{p}_M - \theta) + (1-\alpha)(\underline{p}_M - c)] - \overline{\nu} \qquad (70)$$

$(B4_u)$ *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} > 0, \underline{\phi} > 0, \overline{\nu} = 0, \underline{\nu} = 0)$ *characterized by (67),*

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \left[\frac{(1-\alpha)\lambda K + \underline{\phi}\underline{q}_m}{(1-\alpha+\underline{\phi})\underline{Q}_M}\right]\frac{1}{\varepsilon(\underline{Q}_M)} = \frac{F_m}{\underline{p}_M\underline{q}_m}, \tag{71}$$

and

$$\begin{aligned}(1+\lambda)C'(K) &= \alpha(1+\lambda)(\theta - c) \\ &+\lambda\left[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)\frac{F_m}{\underline{q}_m}\right] - \left(\overline{\phi}\frac{F_m}{\overline{q}_m} + \underline{\phi}\frac{F_m}{\underline{q}_m}\right)\end{aligned}\tag{72}$$

$(B5_u)$ *The policy* $(0 < K = \overline{Q}_M = \underline{Q}_M, \overline{p}_M = \underline{p}_M > c, \overline{\phi} = 0, \underline{\phi} = 0, \overline{\nu} > 0, \underline{\nu} > 0)$ *described by (69),*

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \frac{\lambda}{\varepsilon(\underline{Q}_M)} - \frac{\underline{\nu}}{(1-\alpha)\underline{p}_M}, \tag{73}$$

and

$$(1+\lambda)C'(\overline{Q}_M) = (\alpha+\lambda)(\theta - c) + \lambda(\overline{p}_M - \theta) - (\overline{\nu} + \underline{\nu}) \tag{74}$$

When there is no fixed cost $(F_m = 0)$*, only policies* $(B1_u)$*,* $(B3_u)$*, and* $(B5_u)$ *may arise and they are exclusive. Policy* $(B5_u)$ *arises when* $\lambda^2 K + (1+\lambda)Q'_M C'(K) > 0$*. When* $\lambda^2 K + (1+\lambda)Q'_M C'(K) \leq 0$*,* $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$*, and* $(0 <)\alpha(\theta - c) < C'(\overline{Q}_M) + \frac{\lambda^2\overline{Q}_M}{(1+\lambda)Q'_M}$*, policy* $(B1_u)$ *arises, while when* $\lambda^2 K + (1+\lambda)Q'_M C'(K) \leq 0$*,* $\lambda^2 + (1+\lambda)Q'_M C''(K) < \alpha(1+\lambda)^2$*, and* $\alpha(\theta - c) \geq C'(\overline{Q}_M) + \frac{\lambda^2\overline{Q}_M}{(1+\lambda)Q'_M}$*, policy* $(B3_u)$ *arises.*

When there is a fixed cost $(F_m > 0)$*, only policies* $(B1_u)$*,* $(B2_u)$*, and* $(B4_u)$ *may arise and they are exclusive. If* $\lambda^2 K + (1+\lambda)Q'_M C'(K) \leq 0$*,* $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$*,* $0 < \alpha(\theta - c) < C'(K) + \frac{\lambda^2 K}{Q'_M} - \alpha\lambda(\frac{\lambda K\overline{q}_m + Q'_M F_m}{\overline{q}_m Q'_M})$*, and* $\lambda K\overline{q}_m + Q'_M F_m > 0$*, policy* $(B1_u)$ *arises. When* $C'(K) + \frac{\lambda^2 K}{Q'_M} - \alpha\lambda(\frac{\lambda K\overline{q}_m + Q'_M F_m}{\overline{q}_m Q'_M}) \leq \alpha(\theta - c) < C'(K) - \frac{\lambda F_m}{1+\lambda}[\frac{\overline{q}_m + \alpha(\underline{q}_m - \overline{q}_m)}{\overline{q}_m\underline{q}_m}]$*, policy* $(B2_u)$ *arises.*[19] *Finally, when* $\alpha(\theta - c) \geq C'(K) - \frac{\lambda F_m}{1+\lambda}[\frac{\overline{q}_m + \alpha(\underline{q}_m - \overline{q}_m)}{\overline{q}_m\underline{q}_m}]$*, policy* $(B4_u)$ *is optimal and second-order conditions are always satisfied.*

[19] Second-order conditions for this policy are summarized by $\alpha^2\lambda^2(\alpha^2 K + (\overline{q}_m + \lambda K((1-\alpha)\overline{q}_m - K(\lambda - \alpha(2+\lambda))))) - 2\alpha^2\lambda\overline{\phi}\overline{q}_m(\overline{q}_m - (2+\lambda)K) + \alpha\overline{\phi}^2\overline{q}_m(3\overline{q}_m + 2\lambda K) + 2\overline{\phi}^3\overline{q}_m{}^2 - \alpha^2(1+\lambda)(\overline{q}_m - \lambda K)^2 Q'_M C''(K) > 0$.

Under policy $(B3_u)$, the less efficient firm is shut down and capacity is such that the social marginal cost of imports (at the level that makes the less efficient firm inactive) net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm net of the shadow cost of the θ-type firm's output nonnegativity constraint $\overline{\nu}$.[20]

Under policy $(B4_u)$, the firm, independently of its type, just breaks even and capacity is such that the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm, net of the aggregate ex-post social value of the contribution of the marginal unit of the firm to the relaxation of its participation constraint, $\overline{\phi}\frac{F_m}{\overline{q}_m} + \underline{\phi}\frac{F_m}{\underline{q}_m}$.

Finally, under policy $(B5_u)$ the firm, independently of its type, is shut down and capacity is such that the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm net of the aggregate ex-post shadow cost of the firm's output nonnegativity constraint, $\overline{\nu} + \underline{\nu}$.[21] Note that when there is no cost of public funds, i.e., $\lambda = 0$, policy $(B5_u)$ is never optimal.

To illustrate these policy solutions, let us assume that $F_m = 0$ and use the functional forms given by (21). Note that in this particular case the sign of both expressions $\lambda^2 K + (1+\lambda)Q'_M C'(K)$ and $\lambda^2 + (1+\lambda)Q'_M C''(K)$, used as criteria for selecting an optimal policy, is the same as the sign of $-\Psi$, where $\Psi \equiv \omega(1+\lambda) - \lambda^2$. Solving (58)-(63) yields the following policies. If $\Psi \geq 0$, and the condition

$$(0 <)(\theta - c) < \left[\frac{\Psi}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \tag{75}$$

[20] From (69), we see that $\overline{\nu} = \alpha\left[\left(\theta - \frac{\lambda \overline{Q}_M}{Q'_M}\right) - \overline{p}_M\right] > 0$, and hence it can be interpreted as the marginal valuation of the expected price reduction required to guarantee that the less efficient firm is at worse shut down.

[21] We have $(\overline{\nu} + \underline{\nu}) = \left[\left(\alpha\theta + (1-\alpha)c - \frac{\lambda \overline{Q}_M}{Q'_M}\right) - \overline{p}_M\right] > 0$, and hence it can be interpreted as the marginal valuation of the expected price reduction required to guarantee that the firm, independently of its type, is at worse shut down.

holds, policy $(B1_u)$ arises with $\overline{q}_m > 0$ $(\overline{\nu} = 0)$, and

$$K = \left[\frac{\alpha(1+\lambda)}{\Psi}\right](\theta - c) \tag{76}$$

$$\overline{p}_M = \theta + \left[\frac{\alpha\lambda(1+\lambda)}{\Psi}\right](\theta - c) \tag{77}$$

$$\underline{p}_M = c + \left[\frac{\alpha\lambda(1+\lambda)}{\Psi}\right](\theta - c) \tag{78}$$

If $\Psi \geq 0$ but condition (75) does not hold, i.e.,

$$\left[\frac{\Psi}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \leq (\theta - c) < (\gamma - c) \tag{79}$$

we obtain policy $(B3_u)$ with $\overline{q}_m = 0$ $(\overline{\nu} > 0)$, and

$$K = \left[\frac{\alpha(1+\lambda)}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \tag{80}$$

$$\overline{p}_M = c + \left[\frac{\Psi + \alpha\lambda(1+\lambda)}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \tag{81}$$

$$\underline{p}_M = c + \left[\frac{\alpha\lambda(1+\lambda)}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \tag{82}$$

Finally, if $\Psi < 0$ we obtain policy $(B5_u)$ which is characterized by $\overline{q}_m = 0$ $(\overline{\nu} > 0)$, $\underline{q}_m = 0$ $(\underline{\nu} > 0)$, and

$$K = \left[\frac{1+\lambda}{\Psi + (1+\lambda)^2}\right](\gamma - c) \tag{83}$$

$$\overline{p}_M = \underline{p}_M = c + \left[\frac{\Psi + \lambda(1+\lambda)}{\Psi + (1+\lambda)^2}\right](\gamma - c) \tag{84}$$

4.2 Scheme B under asymmetric information

Scheme B under asymmetric information entails maximizing expected social welfare given by (57) under the participation and firm's output non-negativity constraints given by (53)-(56), and the incentive compatibility constraints, with Lagrange multipliers shown in parentheses, given by

$$(\overline{p}_M - \theta)\overline{q}_m \geq (\underline{p}_M - \theta)\underline{q}_m \quad (\overline{\mu}) \tag{85}$$

$$(\underline{p}_M - c)\underline{q}_m \geq (\overline{p}_M - c)\overline{q}_m \quad (\underline{\mu}) \tag{86}$$

and directly derived from the expression of the profit function (48). From (53) and (86), we show that the participation constraint of the c-type firm

(54) can be ignored ($\underline{\phi} = 0$). Furthermore, adding up (85) and (86) yields that price is a nondecreasing function of firm's type and hence $\underline{p}_M \leq \overline{p}_M$.

For the purpose of solving this regulatory program, it is important, for the problem to be concave, that the constraint set defined by (53)-(56) and (85)-(86) be convex, which it turns out not to be. To circumvent this difficulty, we assume that pricing policies are restricted to type-contingent prices. The next lemma shows that, indeed, such a restriction takes care of this problem.

Lemma 4 *When $\underline{p}_M < \overline{p}_M$, the constraint set defined by (53)-(56) and (85)-(86) is convex and "qualified," i.e., it satisfies the NDCQ and LICQ conditions. Moreover, if, at the optimum, $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$, the expected welfare function given in (57) is locally concave.*

In an optimization problem, non-convexity of the constraint set generally leads to multiple solutions. In our case (see the proof of Lemma 4) multiplicity arises in the form of the existence of two solutions, one of which reflects *bunching* in prices, i.e., $\overline{p}_M = \underline{p}_M$. Hence, in essence, Lemma 4 allows us to rule out bunching.

The first-order conditions are then

$$\alpha[\lambda K + (\overline{p}_M - \theta)Q'_M] + (\overline{\phi} + \overline{\mu} - \underline{\mu})[(\overline{p}_M - \theta)Q'_M + \overline{q}_m] - \underline{\mu}(\theta - c)Q'_M + \overline{\nu}Q'_M = 0 \quad (87)$$

$$(1-\alpha)[\lambda K + (\underline{p}_M - c)Q'_M] - (\overline{\mu} - \underline{\mu})[(\underline{p}_M - c)Q'_M + \underline{q}_m] + \overline{\mu}(\theta - c)Q'_M = 0 \quad (88)$$

$$(1+\lambda)\left[\alpha(\theta - c) - C'(K)\right] + (\alpha\lambda - \overline{\phi})(\overline{p}_M - \theta) + (1-\alpha)\lambda(\underline{p}_M - c) - (\overline{\mu} - \underline{\mu})(\overline{p}_M - \underline{p}_M) - \overline{\nu} = 0 \quad (89)$$

$$\overline{\phi}[(\overline{p}_M - \theta)\overline{q}_m - F_m] = 0 \quad (90)$$

$$\overline{\nu}\,\overline{q}_m = 0 \quad (91)$$

$$\overline{\mu}[(\overline{p}_M - \theta)\overline{q}_m - (\underline{p}_M - \theta)\underline{q}_m] = 0 \quad (92)$$

$$\underline{\mu}[(\underline{p}_M - c)\underline{q}_m - (\overline{p}_M - c)\overline{q}_m] = 0 \quad (93)$$

From now on, we make use of the assumption $\underline{p}_M < \overline{p}_M$ which eliminates bunching solutions ($\underline{p}_M = \overline{p}_M$, with either $\underline{\mu} = \overline{\mu} = 0$ or $\underline{\mu}, \overline{\mu} > 0$) and clearly solutions with $\underline{\nu} > 0$. The incentive compatibility constraints (85) and (86) further eliminate solutions with $\underline{\phi} > 0$. The next proposition characterizes the remaining eight possible solutions.

Proposition 5 *When, in addition to determining capacity, the regulator has only price as a regulatory and faces asymmetric information on the firm's marginal cost there are eight types of optimal policies of the form* $(K, \overline{p}_M, \underline{p}_M, \overline{\phi}, \overline{\nu}, \overline{\mu}, \underline{\mu})$ *designated by* $(B1_{ai})$*-*$(B8_{ai})$*. Three of them, namely,* $(B1_{ai})$*-*$(B3_{ai})$*, are identical to policies* $(B1_u)$*-*$(B3_u)$ *obtained with scheme B under uncertainty, and are characterized in Proposition 4. This is so because when the incentive compatibility constraints (85) and (86) are not active* ($\overline{\mu} = \underline{\mu} = 0$)*, we are back to the case under uncertainty. The remaining five policies are characterized as follows:*

$(B4_{ai})$ *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} = 0, \overline{\nu} = 0, \overline{\mu} = 0, \underline{\mu} > 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda K - \underline{\mu}\,\overline{q}_m}{(\alpha - \underline{\mu})\overline{Q}_M}\right]\frac{1}{\varepsilon(\overline{Q}_M)} + \frac{\underline{\mu}(\theta - c)}{(\alpha - \underline{\mu})\overline{p}_M} \tag{94}$$

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \left[\frac{(1-\alpha)\lambda K + \underline{\mu}\,\underline{q}_m}{(1 - \alpha + \underline{\mu})\underline{Q}_M}\right]\frac{1}{\varepsilon(\underline{Q}_M)} \tag{95}$$

$$\begin{aligned}(1+\lambda)C'(K) = [\alpha(1+\lambda) + \underline{\mu}](\theta - c) + \underline{\mu}[(\overline{p}_M - \theta) - (\underline{p}_M - c)] \\ +\lambda[\alpha(\overline{p}_M - \theta) + (1-\alpha)(\underline{p}_M - c)]\end{aligned} \tag{96}$$

$(B5_{ai})$ *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} > 0, \overline{\nu} = 0, \overline{\mu} = 0, \underline{\mu} > 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda K - (\underline{\mu} - \overline{\phi})\overline{q}_m}{(\alpha + \overline{\phi} - \underline{\mu})\overline{Q}_M}\right]\frac{1}{\varepsilon(\overline{Q}_M)} + \frac{\underline{\mu}(\theta - c)}{(\alpha - \underline{\mu})\overline{p}_M} = \frac{F_m}{\overline{p}_M\overline{q}_m} \tag{97}$$

(95), and

$$\begin{aligned}(1+\lambda)C'(K) = [\alpha(1+\lambda) + \underline{\mu}](\theta - c) + \underline{\mu}\left[\frac{F_m}{\overline{q}_m} - (\underline{p}_M - c)\right] \\ +\lambda\left[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)(\underline{p}_M - c)\right] - \overline{\phi}\frac{F_m}{\overline{q}_m}\end{aligned} \tag{98}$$

($B6_{ai}$) *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} = 0, \overline{\nu} = 0, \overline{\mu} > 0, \underline{\mu} = 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda K + \overline{\mu}\ \overline{q}_m}{(\alpha + \overline{\mu})\overline{Q}_M}\right] \frac{1}{\varepsilon(\overline{Q}_M)} \tag{99}$$

$$\frac{\underline{p}_M - c}{\underline{p}_M} = \left[\frac{(1-\alpha)\lambda K - \overline{\mu}\ \underline{q}_m}{(1-\alpha-\overline{\mu})\underline{Q}_M}\right] \frac{1}{\varepsilon(\underline{Q}_M)} + \frac{\overline{\mu}(\theta - c)}{(1-\alpha-\overline{\mu})\underline{p}_M} \tag{100}$$

$$(1+\lambda)C'(K) = [\alpha(1+\lambda) - \overline{\mu}](\theta - c) - \overline{\mu}[(\overline{p}_M - \theta) - (\underline{p}_M - c)] + \lambda[\alpha(\overline{p}_M - \theta) + (1-\alpha)(\underline{p}_M - c)] \tag{101}$$

($B7_{ai}$) *The policy* $(0 < K < \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M > c, \overline{\phi} > 0, \overline{\nu} = 0, \overline{\mu} > 0, \underline{\mu} = 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda K + (\overline{\phi} + \overline{\mu})\overline{q}_m}{(\alpha + \overline{\phi} + \overline{\mu})\overline{Q}_M}\right] \frac{1}{\varepsilon(\overline{Q}_M)} = \frac{F_m}{\overline{p}_M \overline{q}_m} \tag{102}$$

(100), and

$$(1+\lambda)C'(K) = [\alpha(1+\lambda) - \overline{\mu}](\theta - c) - \overline{\mu}\left[\frac{F_m}{\overline{q}_m} - (\underline{p}_M - c)\right] + \lambda\left[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)(\underline{p}_M - c)\right] - \overline{\phi}\frac{F_m}{\overline{q}_m} \tag{103}$$

($B8_{ai}$) *The policy* $(0 < K = \overline{Q}_M < \underline{Q}_M, \overline{p}_M > \theta, \underline{p}_M = \theta, \overline{\phi} = 0, \overline{\nu} > 0, \overline{\mu} > 0, \underline{\mu} = 0)$ *described by*

$$\frac{\overline{p}_M - \theta}{\overline{p}_M} = \left[\frac{\alpha\lambda}{(\alpha + \overline{\mu})}\right] \frac{1}{\varepsilon(\overline{Q}_M)} - \frac{\overline{\nu}}{(\alpha + \overline{\mu})\overline{p}_M}, \tag{104}$$

$\underline{p}_M = \theta$, *and*

$$(1+\lambda)C'(\overline{Q}_M) = (\alpha + \lambda)(\theta - c) + (\alpha\lambda - \overline{\mu})(\overline{p}_M - \theta) - \overline{\nu} \tag{105}$$

When there is no fixed cost ($F_m = 0$)*, only policies* ($B1_{ai}$)*,* ($B3_{ai}$)*,* ($B4_{ai}$)*,* ($B6_{ai}$)*, and* ($B8_{ai}$) *may arise as optimal policies and these policies are exclusive. When there is a fixed cost* ($F_m > 0$)*, only policies* ($B1_{ai}$)*,* ($B2_{ai}$)*,* ($B4_{ai}$)*,* ($B5_{ai}$)*,* ($B6_{ai}$)*, and* ($B7_{ai}$) *may arise as optimal policies and these policies are exclusive.*[22] *From Lemma 4, when* $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$ *second-order conditions of all policies are satisfied.*

[22] The conditions under which these policies may arise cannot be obtained in the general case as $\overline{\phi}$, $\overline{\mu}$, and $\underline{\mu}$ affect the system of first-order conditions in a nonlinear way. However, such conditions will be derived for the particular functional forms given in (21).

Under policy ($B4_{ai}$), even the θ-type firm is active and the social marginal cost of imports, $(1+\lambda)[c+C'(K)]$, net of the expected marginal fiscal revenue of imported gas, $\lambda[\alpha\overline{p}_M+(1-\alpha)\underline{p}_M]$, is equal to the expected marginal cost of the firm, $\alpha\theta+(1-\alpha)c$, plus the social marginal cost associated with the price distortion of both the θ- and c-type firms required to minimize the information rent of the c-type firm, $\underline{\mu}(\overline{p}_M-\underline{p}_M)>0$.

Under policy ($B5_{ai}$), the less efficient firm just breaks even and capacity is such that the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm plus the social marginal cost associated with the price distortion necessary to minimize the information rent of the more efficient firm, net of the ex-post social value of the contribution of the marginal unit of the firm to the relaxation of its participation constraint, $\overline{\phi}\frac{F_m}{\overline{q}_m}$.

Under policy ($B6_{ai}$), even the less efficient firm is active and the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm net of the social marginal cost associated with the price distortion of both the θ- and c-type firms required to minimize the information rent of the less efficient firm, $\overline{\mu}(\overline{p}_M-\underline{p}_M)>0$.

Under policy ($B7_{ai}$), the θ-type firm just breaks even and capacity is such that the social marginal cost of imports net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm, net of the social marginal cost associated with the price distortion necessary to minimize the information rent of the less efficient firm and of the ex-post social value of the contribution of the marginal unit of the firm to the relaxation of its participation constraint, $\overline{\phi}\frac{F_m}{\overline{q}_m}$.

Under policy ($B8_{ai}$), the less efficient firm is shut down and capacity is such that the social marginal cost of imports (at the level they make the less efficient firm inactive) net of the expected marginal fiscal revenue of imported gas, is equal to the expected marginal cost of the firm plus the social marginal cost associated with the price distortions necessary to minimize the information rent of the less efficient firm, net of the shadow cost of the θ-type firm's output nonnegativity constraint $\overline{\nu}$.

Let us illustrate this regulatory scheme assuming that $F_m = 0$ and using the functional forms given by (21). Again, as in the case under uncertainty, the sign of $\lambda^2 + (1+\lambda)Q'_M C''(K)$ (see Lemma 4) is the same as that of $-\Psi$, where $\Psi \equiv \omega(1+\lambda) - \lambda^2$. Solving (87)-(93) under the restriction that $\underline{p}_M < \overline{p}_M$ yields the following policies:[23]

When $\Psi \geq \alpha\lambda(1+\lambda)$ the following group of policies might arise. Policy $(B4_{ai})$ arises when

$$\frac{(1-2\alpha)}{\alpha}\left[\frac{\Psi}{2\Psi + (\alpha+\lambda)(1+2\lambda)}\right](\gamma - c) < (\theta - c) \leq \left[\frac{\Psi}{\Psi + \alpha(1+\lambda)(1+2\lambda)}\right](\gamma - c) \quad (106)$$

with

$$K = \frac{\alpha\left[(1-\alpha)(1+2\lambda)(\gamma-c) - [\lambda - \alpha(1+2\lambda)](\theta - c)\right]}{\Psi + \alpha(1-\alpha)(1+2\lambda)^2} \quad (107)$$

$$\overline{p}_M = \theta + (1-\alpha)\left[\frac{\Psi + \alpha\lambda(1+2\lambda)}{\Psi + \alpha(1-\alpha)(1+2\lambda)^2}\right](\gamma - c) - \left[\frac{(1-\alpha)[\Psi + \alpha(1+2\lambda)^2] - \alpha\lambda(1+\lambda)}{\Psi + \alpha(1-\alpha)(1+2\lambda)^2}\right](\theta - c) \quad (108)$$

$$\underline{p}_M = c + \alpha\left[\frac{\Psi + (1-\alpha)\lambda(1+2\lambda)}{\Psi + \alpha(1-\alpha)(1+2\lambda)^2}\right](\gamma - c) - \alpha\left[\frac{\Psi + \alpha(1+2\lambda) + \lambda^2}{\Psi + \alpha(1-\alpha)(1+2\lambda)^2}\right](\theta - c) \quad (109)$$

Policy $(B1_{ai})$, identical to $(B1_u)$, described by (76)-(78), arises when

$$\left[\frac{\Psi}{\Psi + \alpha(1+\lambda)(1+2\lambda)}\right](\gamma - c) < (\theta - c) \leq \left[\frac{\Psi}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) \quad (110)$$

Policy $(B3_{ai})$, identical to $(B3_u)$, described by (80)-(82), arises when

$$\left[\frac{\Psi}{\Psi + \alpha(1+\lambda)^2}\right](\gamma - c) < (\theta - c) < (\gamma - c) \quad (111)$$

When $0 < \Psi < \alpha\lambda(1+\lambda)$ the following group of policies might arise. Policy $(B4_{ai})$ arises when condition (106) holds. Policy $(B1_{ai})$, identical to

[23] Details about the derivation of these policies are given in the appendix.

$(B1_u)$, described by (76)-(78), arises when

$$\left[\frac{\Psi}{\Psi+\alpha(1+\lambda)(1+2\lambda)}\right](\gamma-c)<(\theta-c)\leq\left[\frac{\Psi}{\alpha(1+\lambda)(1+2\lambda)}\right](\gamma-c) \quad (112)$$

Policy $(B6_{ai})$ arises when

$$\left[\frac{\Psi}{\alpha(1+\lambda)(1+2\lambda)}\right](\gamma-c)<(\theta-c)\leq \left[\frac{\alpha[\Psi+(1-\alpha)\lambda(1+2\lambda)]}{\Psi+\alpha(1-\alpha)\lambda(1+2\lambda)+\alpha(1+\lambda)^2}\right](\gamma-c) \quad (113)$$

with

$$K=\frac{\alpha[(1-\alpha)(1+2\lambda)(\gamma-c)+(1+\lambda)(\theta-c)]}{\Psi+\alpha(1-\alpha)(1+2\lambda)^2} \quad (114)$$

$$\overline{p}_M=\theta+(1-\alpha)\left[\frac{\Psi+\alpha\lambda(1+2\lambda)}{\Psi+\alpha(1-\alpha)(1+2\lambda)^2}\right](\gamma-c) -\alpha(1+\lambda)\left[\frac{(1-\alpha)+(1-2\alpha)\lambda}{\Psi+\alpha(1-\alpha)(1+2\lambda)^2}\right](\theta-c) \quad (115)$$

$$\underline{p}_M=c+\alpha\left[\frac{(1-\alpha)\lambda(1+2\lambda)+\Psi}{\Psi+\alpha(1-\alpha)(1+2\lambda)^2}\right](\gamma-c) +\alpha(1+\lambda)\left[\frac{\lambda-\alpha(1+2\lambda)}{\Psi+\alpha(1-\alpha)(1+2\lambda)^2}\right](\theta-c) \quad (116)$$

Policy $(B8_{ai})$ arises when

$$\left[\frac{\alpha[\Psi+(1-\alpha)\lambda(1+2\lambda)]}{\Psi+\alpha(1-\alpha)\lambda(1+2\lambda)+\alpha(1+\lambda)^2}\right](\gamma-c)<(\theta-c)\leq \left[\frac{\alpha\lambda(1+\lambda)}{\Psi+\alpha(1+\lambda)^2}\right](\gamma-c) \quad (117)$$

with

$$K=\frac{\alpha(1+\lambda)(\gamma-c)+(1-\alpha)\lambda(\theta-c)}{\Psi+\lambda^2+\alpha(1+2\lambda)} \quad (118)$$

$$\overline{p}_M=c+\frac{[\Psi+(\alpha+\lambda)\lambda](\gamma-c)-(1-\alpha)\lambda(\theta-c)}{\Psi+\lambda^2+\alpha(1+2\lambda)} \quad (119)$$

$$\underline{p}_M=\theta \quad (120)$$

Finally, policy $(B3_{ai})$, identical to $(B3_u)$, described by (80)-(82), arises when

$$\left[\frac{\alpha\lambda(1+\lambda)}{\Psi+\alpha(1+\lambda)^2}\right](\gamma-c)<(\theta-c)<(\gamma-c) \quad (121)$$

4.3 Scheme B under uncertainty vs. under a symmetric information

In order to compare the capacity levels achieved by control scheme B under uncertainty (K_u^B) and asymmetric information (K_{ai}^B), it will prove useful to provide alternative expressions, allowed by our linear demand assumption, for the incentive constraints (85) and (86). Indeed, linearity of demand implies $(\overline{q}_m - \underline{q}_m) = (\overline{p}_M - \underline{p}_M)Q'_M$. Hence, the incentives constraints can be rewritten as

$$\left.\begin{array}{l}(\underline{p}_M - \theta)Q'_M + \overline{q}_m \geq 0 \\ (\overline{p}_M - \theta)Q'_M + \underline{q}_m \geq 0\end{array}\right\} \quad (\overline{\mu}) \tag{122}$$

$$\left.\begin{array}{l}(\underline{p}_M - c)Q'_M + \overline{q}_m \leq 0 \\ (\overline{p}_M - c)Q'_M + \underline{q}_m \leq 0\end{array}\right\} \quad (\underline{\mu}) \tag{123}$$

where (122) provides two alternative ways to express (85) while (123) provides two alternative ways to express (86).

Since $C'(K)$ is an increasing function, looking at (60) and (89) yields that when there is no fixed cost,

$$\begin{aligned} sign[K_{ai}^B - K_u^B] &= sign[(1+\lambda)[C'(K_{ai}^B) - C'(K_u^B)]] \\ &= sign[\alpha\lambda(\overline{p}_{M,ai}^B - \overline{p}_{M,u}^B) + (1-\alpha)\lambda(\underline{p}_{M,ai}^B - \underline{p}_{M,u}^B) \\ &\qquad -(\overline{\mu}^B - \underline{\mu}^B)(\overline{p}_{M,ai}^B - \underline{p}_{M,ai}^B) - (\overline{\nu}_{ai}^B - \overline{\nu}_u^B)] \end{aligned} \tag{124}$$

and when there is a fixed cost,

$$\begin{aligned} sign[K_{ai}^B - K_u^B] &= sign[(1+\lambda)[C'(K_{ai}^B) - C'(K_u^B)]] \\ &= sign[\alpha\lambda(\overline{p}_{M,ai}^B - \overline{p}_{M,u}^B) + (1-\alpha)\lambda(\underline{p}_{M,ai}^B - \underline{p}_{M,u}^B) \\ &\qquad +\overline{\phi}_u^B(\overline{p}_{M,u}^B - \theta) + \underline{\phi}_u^B(\underline{p}_{M,u}^B - c) \\ &\qquad -(\overline{\mu}^B - \underline{\mu}^B)(\overline{p}_{M,ai}^B - \underline{p}_{M,ai}^B) - \overline{\phi}_{ai}^B(\overline{p}_{M,ai}^B - \theta)] \end{aligned} \tag{125}$$

Analyzing these signs allows us to state the following proposition:

Proposition 6 *When, in addition to controlling capacity, the social planner regulates the gas commodity price and transfers between the firm and consumers are not allowed, accounting for the firm's incentive compatibility constraints has the following effect on capacity:*

Independently of the existence of a fixed cost, if the regulator does not minimize the informational rents of both types of firms, $\overline{\mu}^B = \underline{\mu}^B = 0$*, there is no effect of incentives on capacity, i.e.,* $K_{ai}^B = K_u^B$*.*

If there is no fixed cost ($F_m = 0$) *and the regulator is constrained to minimize the information rent of the more (less) efficient firm,* $\underline{\mu}^B > 0$ ($\overline{\mu}^B > 0$)*, more (less) transport capacity in the strict sense should arise, i.e.,* $K_{ai}^B > K_u^B$ ($K_{ai}^B < K_u^B$)*.*

If there is a fixed cost ($F_m > 0$)*, three cases need to be considered.*

When the regulator minimizes the information rent of the more efficient firm, $\underline{\mu}^B > 0$*, transport capacity expansion in the strict sense should arise, i.e.,* $K_{ai}^B > K_u^B$*.*

When the regulator minimizes the information rent of the less efficient firm, $\overline{\mu}^B > 0$*, but lets it earn strictly positive profits,* $\overline{\phi}_{ai}^B = 0$*, less capacity in the strict sense should arise, i.e.,* $K_{ai}^B < K_u^B$*.*

When the regulator minimizes the information rent of the less efficient firm, $\overline{\mu}^B > 0$*, but the latter just breaks-even,* $\overline{\phi}_{ai}^B > 0$*,* $\overline{\mu}^B > 0$ *does not allow us to rank* K_{ai}^B *and* K_u^B*.*

Again, let us now illustrate this proposition using the functional forms (21). When $F_m = 0$, we simulate the optimal values of $(K_{ai}^B - K_u^B)$, $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\nu}_{ai}^B$, and $\overline{\nu}_u^B$ in the $\{\alpha, (\theta - c)\}$-space for the parameter grids in Cases 1-3, given in the illustration of Proposition 3. When $F_m > 0$, we simulate the optimal values of $(K_{ai}^B - K_u^B)$, $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\phi}_{ai}^B$, $\overline{\phi}_u^B$, and $\underline{\phi}_u^B$ in the $\{F_m, (\theta - c)\}$-space for the following parameter grids:

- Case 1^+: $\{\gamma, c, \omega, \lambda, \alpha\} = \{10, 2, 0.50, 0.33, 0.43\}$, $(\theta - c) \in [0, 4.94]$, and $F_m \in [0, 2.24]$

- Case 2^+: $\{\gamma, c, \omega, \lambda, \alpha\} = \{10, 2, 0.52, 0.85, 0.43\}$, $(\theta - c) \in [0, 2.24]$, and $F_m \in [0, 5.14]$

- Case 3^+: $\{\gamma, c, \omega, \lambda, \alpha\} = \{10, 2, 0.17, 0.25, 0.68\}$, $(\theta - c) \in [0, 2.24]$, and $F_m \in [0, 2.24]$

Figure 5 (a-b) summarizes the results of the simulated values of $(K_{ai}^B - K_u^B)$, $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\nu}_{ai}^B$, and $\overline{\nu}_u^B$ for Cases 1, 2 and 3, respectively from the top to the bottom. Figure 5a shows in white, gray and black the regions where respectively $(K_{ai}^B - K_u^B) > 0$, $(K_{ai}^B - K_u^B) = 0$, and $(K_{ai}^B - K_u^B) < 0$. The dashed regions in these figure represent the $(\alpha, (\theta - c))$ pairs for which a solution under asymmetric information with $\underline{p}_M < \overline{p}_M$ cannot arise. Figure 5b exhibits the curves formed by the $(\alpha, (\theta - c))$ pairs such that $\overline{\nu}_{ai}^B = 0$, $\overline{\nu}_u^B = 0$, $\overline{\mu}^B = 0$, and $\overline{\mu}^B = 0$.

For the parameter grid of Case 1, we have $\Psi \equiv \omega(1+\lambda) - \lambda^2 > \alpha\lambda(1+\lambda)$ for any $\alpha \in [0, 1]$, and hence no solution with $\overline{\mu}^B > 0$ arises. Cross-examining Figures 5a and 5b, we see that whenever $\underline{\mu}^B > 0$, irrespective of whether or not $\overline{\nu}_{ai}^B$ and $\overline{\nu}_u^B$ are positive, $K_{ai}^B > K_u^B$, as stated in the proposition. For Case 2, $\Psi \equiv \omega(1+\lambda) - \lambda^2 > \alpha\lambda(1+\lambda)$ for any $\alpha \in [0, 0.16]$, and hence solutions with $\overline{\mu}^B > 0$ exclusively arise for $\alpha \in (0.16, 1]$. We observe that whenever $\underline{\mu}^B > 0$ $(\overline{\mu}^B > 0)$, independently of $\overline{\nu}_{ai}^B$ and $\overline{\nu}_u^B$ being equal to zero or positive, $K_{ai}^B > K_u^B$ $(K_{ai}^B < K_u^B)$. For Case 3, $\Psi \equiv \omega(1+\lambda) - \lambda^2 > \alpha\lambda(1+\lambda)$ for any $\alpha \in [0, 0.50]$, and hence solutions with $\overline{\mu}^B > 0$ exclusive arise for $\alpha \in (0.50, 1]$. Cross-examining Figures 5a and 5b, leads to similar conclusions as in Case 2.

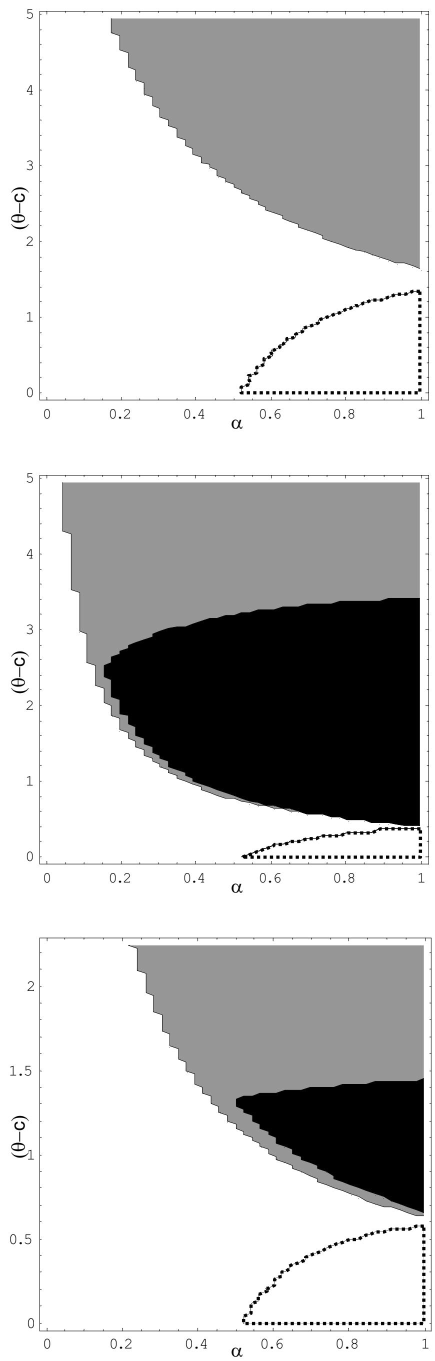


Figure 5a: $K_{ai}^B - K_u^B$

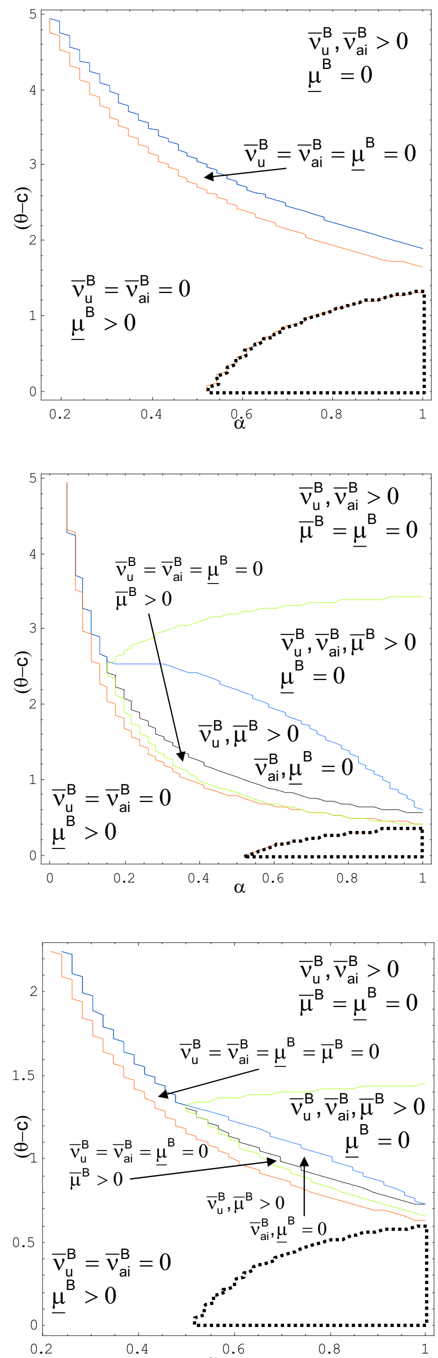


Figure 5b: $\overline{\mu}^B$ and $\underline{\mu}^B$

Figure 6 (a-b) summarizes the results of the simulated values of $(K_{ai}^B - K_u^B)$, $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\phi}_{ai}^B$, $\overline{\phi}_u^B$, and $\underline{\phi}_u^B$ for Cases 1^+-3^+. Figure 6b exhibits the curves formed by the $(\alpha, (\theta - c))$ pairs such that $\overline{\phi}_{ai}^B = 0$, $\overline{\phi}_u^B = 0$, $\underline{\phi}_u^B = 0$, $\overline{\mu}^B = 0$, and $\overline{\mu}^B = 0$.

For Case 1^+, $\Psi \equiv \omega(1 + \lambda) - \lambda^2 > \alpha\lambda(1 + \lambda)$ for any $\alpha \in [0, 1]$, and hence no solution with $\overline{\mu}^B > 0$ arises. From Figures 6a and 6b, we see that whenever $\underline{\mu}^B > 0$, irrespective of whether or not $\overline{\phi}_{ai}^B$, $\overline{\phi}_u^B$, and $\underline{\phi}_u^B$ are equal to zero, $K_{ai}^B > K_u^B$. For Case 2+, $\Psi \equiv \omega(1+\lambda)-\lambda^2 > \alpha\lambda(1+\lambda)$ for any $\alpha \in [0, 0.16]$, and hence solutions with $\overline{\mu}^B > 0$ exclusively arise for $\alpha \in (0.16, 1]$. Since under Case 2^+, $\alpha = 0.43$, solutions with $\overline{\mu}^B > 0$ are possible. Cross-examining Figures 6a and 6b, we see that $\underline{\mu}^B > 0$, irrespective of whether the remaining Lagrange multipliers are positive or equal to zero, $K_{ai}^B > K_u^B$. Moreover, when $\overline{\mu}^B > 0$ and $\overline{\phi}_{ai}^B = 0$, $sign[K_{ai}^B - K_u^B] = -sign[\overline{\mu}^B] < 0$, implying $K_{ai}^B < K_u^B$. However, when $\overline{\phi}_{ai}^B > 0$, this relationship does not hold as can be seen from the white region in Figure 6a which shows cases with $\overline{\mu}^B > 0$ and $K_{ai}^B > K_u^B$. This illustrates the result stated at the end of Proposition 6. Case 3^+ demonstrates similar properties as those obtained under Case 2^+.[24]

[24]For $\Psi \equiv \omega(1 + \lambda) - \lambda^2 > \alpha\lambda(1 + \lambda)$ for any $\alpha \in [0, 0.50]$, and hence solutions with $\overline{\mu}^B > 0$ exclusively arise for $\alpha \in (0.50, 1]$. Since under Case 3^+, $\alpha = 0.68$, it is possible to get solutions with $\overline{\mu}^B > 0$.

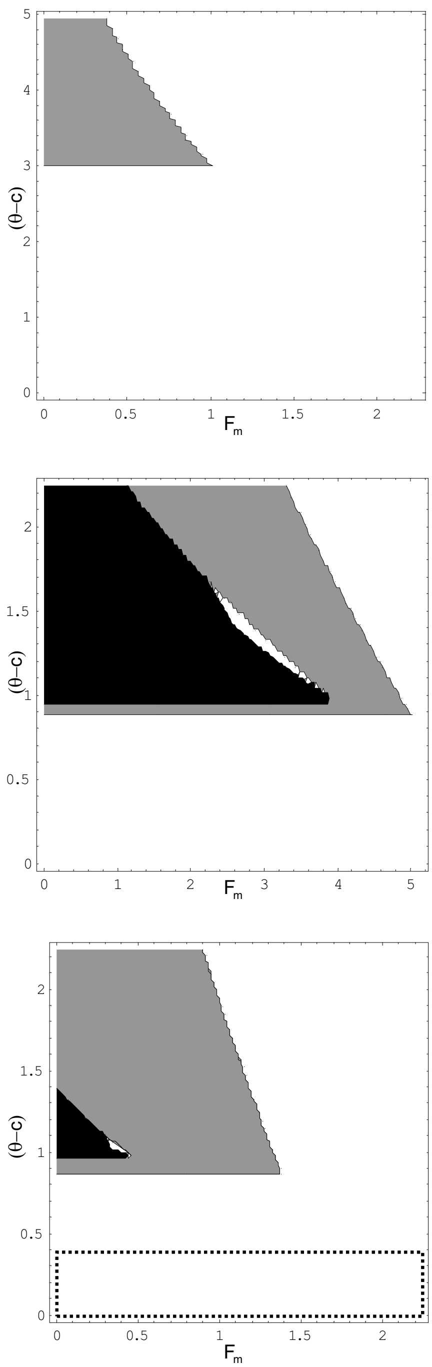


Figure 6a: $K_{ai}^B - K_u^B$

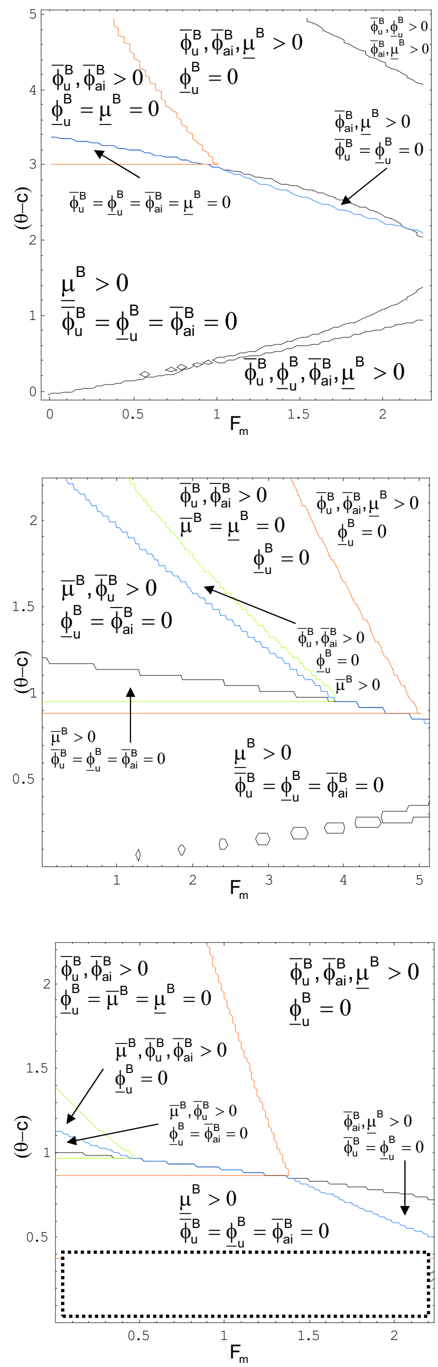


Figure 6b: $\overline{\mu}^B$ and $\underline{\mu}^B$

5 Conclusion

This paper has attempted to contribute to the literature on the regulation of network/infrastructure industries in its application to gas markets along two dimensions. First, we derived, and highlighted the economic properties of, various policies based on two standard regulatory instruments, namely, pricing and taxation, but also, and most importantly, on a third less conventional means of market intervention, namely, investments in the gas transport capacity of the network. As far as this first effort is concerned, although informative, the results obtained are admittedly generally quite intuitive. We nevertheless provide a thorough discussion of the economic interpretation of the conditions that characterize some optimal policies aimed at mitigating the exercise of monopoly power in geographically isolated gas commodity markets. Second, we investigated the impact on network capacity of incorporating in the regulator's objectives the regulated firm's incentives in a context where private information on its technology gives it the opportunity to earn a socially costly information rent. Interestingly enough, we find that this impact is not unambiguous.

When the (less informed) regulator regulates the gas price and may operate transfers between consumers and the firm, we find that investments in transport network expansion may be justified on normative grounds and by the need to give the (better informed) firm proper production incentives and at the same time reduce its information rent. Because in this case the more efficient firm's information rent is positively correlated with the less efficient firm's level of output, building more transport capacity allows shipping competitive gas into the regional market and hence helps putting downward pressure on this level of output and subsequently reducing this firm's information rent.[25]

When the regulator may no longer use transfers, the set of results is much richer. It turns out that in this case the regulator may be concerned about the information rent of either the more efficient firm or the less efficient

[25] Indeed, in this case, information rents are of concern only when the firm happens to be of the more efficient type. When the firm is of the less efficient type, its information rent is nil.

one. We identify and analyze various situations. If incentive constraints are not binding, i.e., the firm behaves truthfully, transport capacity is neutral. When the regulator is concerned about the information rent of the more efficient firm, capacity expansion is beneficial independently of whether or not there is a fixed cost of the regulated firm to be financed . When it is the less efficient firm's rent that negatively affects social welfare, cases where capacity reduction is desirable might arise.

Appendix

Proof of Lemma 1 *Consider the ex-post program under scheme A where the regulator seeks to control market power exercised by a $\widetilde{\theta}$-type firm through the maximization of the social welfare function (2) with respect to $p_M(\widetilde{\theta})$ and $U(\widetilde{\theta})$, for a given level of already installed transport capacity K, under the constraints (3) and (4). Differentiating with respect to $\widetilde{\theta}$ the associated system of first-order conditions yields that when $\nu(\widetilde{\theta}) = 0$, $\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{1+\lambda}{1+2\lambda} > 0$ and clearly $\frac{d\nu(\widetilde{\theta})}{d\widetilde{\theta}} = 0$. When $\nu(\widetilde{\theta}) > 0$, we have $\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} = 0$ and $\frac{d\nu(\widetilde{\theta})}{d\widetilde{\theta}} = (1+\lambda) > 0$.* ■

Proof of Proposition 1 *From (14), we obtain that the participation constraint of the firm is always binding independently of the firm's type, i.e., $\overline{\phi} = \alpha\lambda > 0$ and $\underline{\phi} = (1-\alpha)\lambda > 0$.*

Concerning policy ($A1_u$), the condition $0 < \alpha(\theta - c) < C'(\overline{Q}_M)$ yields $\overline{\nu} = 0$. Substitute into (10) and use the fact that $\varepsilon(\overline{Q}_M) \equiv -Q'_M\overline{p}_M/\overline{Q}_M$ to obtain (17). Rewrite (11) using the fact that $\varepsilon(\underline{Q}_M) \equiv -Q'_M\underline{p}_M/\underline{Q}_M$ to obtain (18). Next, substitute $\overline{\nu} = 0$ into (12) to get (19).

For policy ($A2_u$), when $\alpha(\theta - c) > C'(\overline{Q}_M)$, the first-order condition (12) calls for $\overline{\nu} > 0$. Substitute this result into (10) to obtain (17). Since $\overline{\nu} > 0$ does not appear in (11), rewriting the later still yields (18). Finally, (12) with $\overline{\nu} > 0$ yields (20). ■

Proof of Proposition 2 *In the discussion following the system of first-order conditions (30)-(37), we obtain that in scheme A under asymmetric information $\overline{\phi} = \lambda > 0$ and $\overline{\mu} = 0$. Substituting into (34) yields $\underline{\mu} = (1-\alpha)\lambda$.*

Concerning policy ($A1_{ai}$), the condition $0 < (\alpha + \lambda)(\theta - c) < C'(\overline{Q}_M)$ yields $\overline{\nu} = 0$. Substitute $\underline{\mu} = (1-\alpha)\lambda > 0$ and $\overline{\nu} = 0$ into (30)-(32) to get (38)-(40).

For policy ($A2_{ai}$), when $(\alpha + \lambda)(\theta - c) > C'(\overline{Q}_M)$, the first-order condition (32) calls for $\overline{\nu} > 0$. Substitute $\underline{\mu} = (1-\alpha)\lambda > 0$ and $\overline{\nu} > 0$ into (30)-(32) to get (42)-(41). ■

Proof or Proposition 3 *We know from Propositions 1 and 2 that policy ($A1_u$) arises when $0 < (\theta - c) < \frac{C'(\overline{Q}_M^A)}{\alpha}$ whereas policy ($A1_{ai}$) happens when $0 < (\theta - c) < \frac{C'(\overline{Q}_M^A)}{\alpha+\lambda}$. It is direct then to see that whenever ($A1_{ai}$) is optimal under asymmetric information, so is ($A1_u$) under uncertainty. Thus, from (47) we obtain that asymmetric information induces capacity expansion (in the strong sense), i.e., $K_{ai}^A > K_u^A$ under policy ($A1_{ai}$). When policy ($A2_{ai}$) arises, the benchmark scheme does not necessarily imply shutting down the less efficient firm. When this firm is active under uncertainty, it is easy to see that $K_u^A < \overline{Q}_{M,ai}^A$. When this firm is inactive under uncertainty, no capacity expansion arises. In fact, the two policies are identical and hence $K_u^A = K_{ai}^A$. To see this, solve (20) for $\overline{\nu}$ and substitute into (10) to obtain $\frac{\overline{p}_M - (c + \frac{C'(\overline{Q}_M)}{\alpha})}{\overline{p}_M} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon(\overline{Q}_M)}$. Moreover, solve (41) for $\overline{\nu}$ and plug into (30) to find the same markup expression. Furthermore, since (18) and (39) are identical, we conclude that price and transport capacity under policies ($A2_u$) and ($A2_{ai}$) are the same and consequently $(\overline{\nu}_{ai}^A - \overline{\nu}_u^A) = (1-\alpha)\lambda(\theta - c) > 0$.* ■

Proof of Lemma 2 *To find the conditions which characterize convexity of the set associated to the constraints (53)-(56), a first step is to separately study the properties of the surface levels defined by each constraint when satisfied with equality in the* $\{\overline{p}_M, \underline{p}_M, K\}$*-space.*

When the participation constraint of the less efficient firm (53) is binding, it is represented by the level set $\overline{\Pi}^\star_m(\overline{p}_M, \underline{p}_M, K) = (\overline{p}_M - \theta)\overline{q}_m - F_m = 0$*, with gradient vector* $\nabla\overline{\Pi}^\star_m(\cdot) = ((\overline{p}_M - \theta)Q'_M + \overline{q}_m, 0, -(\overline{p}_M - \theta))$*. Two cases need to be considered depending on whether or not there is a fixed cost. When* $F_m > 0$*, the* θ*-type firm's output nonnegativity constraint (55) must hold with strict inequality,* $\overline{q}_m > 0$*, and consequently* $\overline{p}_M > \theta$*. Since in this case* $\nabla\overline{\Pi}^\star_m(\cdot) \neq 0$*,* $\overline{\Pi}^\star_m(\cdot)$ *is a regular surface in* $\Re^3$*, and from* $\frac{\partial\overline{\Pi}^\star_m(\cdot)}{\partial K} \neq 0$*, the level surface* $\overline{\Pi}^\star_m(\cdot)$ *can be considered as the graph of a function,* $K^\star_{\overline{\Pi}_m}$*, of* K *in terms of* $\overline{p}_M$ *and* $\underline{p}_M$ *in* $\Re^3$*. In such a case we have that* $\frac{\partial K^\star_{\overline{\Pi}_m}}{\partial \overline{p}_M} = \frac{F}{(\overline{p}_M - \theta)^2} + Q'_M$ *and* $\frac{\partial K^\star_{\overline{\Pi}_m}}{\partial \underline{p}_M} = 0$*. The leading principal minors characterizing the Hessian of the function* $K^\star_{\overline{\Pi}_m}$ *are* $\{-\frac{2F_m}{(\overline{p}_M - \theta)^3}, 0\}$*. Consequently, since* $(\overline{p}_M - \theta) > 0$*, when* $F_m > 0$ *the level surface* $\overline{\Pi}^\star_m(\cdot)$ *is concave, i.e., the set below* $\overline{\Pi}^\star_m(\cdot)$ *is convex.*

When $F_m = 0$*, the level set* $\overline{\Pi}^\star_m(\cdot)$ *is not regular everywhere. Indeed, when both* $\overline{p}_M = \theta$ *and* $K = \overline{Q}_M$ *(*$\overline{q}_m = 0$*) the level set* $\overline{\Pi}^\star_m(\cdot)$ *is degenerate as* $\nabla\overline{\Pi}^\star_m(\theta, \underline{p}_M, \overline{Q}_M) = 0$*. However, two regular surfaces can be identified. First, when* $\overline{p}_M \neq \theta$*, the surface* $\overline{\Pi}^\star_m(\overline{p}_M \neq \theta, \underline{p}_M, K = \overline{Q}_M)$ *is regular. In this particular case, the* $K^\star_{\overline{\Pi}_m}$ *function has* $\frac{\partial K^\star_{\overline{\Pi}_m}}{\partial \overline{p}_M} = Q'_M$*,* $\frac{\partial K^\star_{\overline{\Pi}_m}}{\partial \underline{p}_M} = 0$*, and Hessian's leading minors* $\{0, 0\}$*, which define* $\overline{\Pi}^\star_m(\cdot)$ *as a plane with gradient* $\nabla\overline{\Pi}^\star_m(\cdot) = ((\overline{p}_M - \theta)Q'_M, 0, -(\overline{p}_M - \theta)) < 0$*. Second, when* $\overline{p}_M = \theta$*, and since constraint (55) holds,* $\overline{q}_m > 0$*, the level set* $\overline{\Pi}^\star_m(\theta, \underline{p}_M, K < \overline{Q}_M)$ *is regular and is represented by a plane with gradient* $\nabla\overline{\Pi}^\star_m(\cdot) = (\overline{q}_m, 0, 0)$*, perpendicular to the* $\overline{p}_M$*-axis. It is direct to see that these regular surfaces of* $\overline{\Pi}^\star_m(\cdot)$ *define a convex set when* $\overline{p}_M \geq \theta$*.*[26]

Concerning the θ*-type firm's output nonnegativity constraint (55), it can be binding only when* $F_m = 0$*. In such a case, it is represented by the level set* $\overline{q}^\star_m(\overline{p}_M, \underline{p}_M, K) = \overline{Q}_M - K = 0$*, with gradient vector* $\nabla\overline{q}^\star_m(\cdot) = (Q'_M, 0, -1) \neq 0$*. Thus, the level surface* $\overline{q}^\star_m(\cdot)$ *is regular and defines a convex set.*[27] *Note that when* $\overline{p}_M \neq \theta$ *and* $F_m = 0$*,* $\nabla\overline{\Pi}^\star_m(\cdot) = (\overline{p}_M - \theta) \cdot \nabla\overline{q}^\star_m(\cdot)$*, and hence when there is no fixed cost and both (53) and (55) are effective, the gradients of these constraints are not linearly independent, i.e., the Linear Independence Constraint Qualification (LICQ) condition is violated. In order to avoid this, (53) is considered as a liminal constraint, i.e., an active inequality with a Lagrange multiplier equal to zero. See Horsley and Wrobel (2003) for more details.*

[26] A property of standard convex sets says that every two points of a convex set are visible to each other, i.e., the straight segment joining these points is contained in the set. Since $\overline{\Pi}^\star_m(\cdot)$ belongs to the set associated to the participation constraint of the less efficient firm (53), such set will be convex if any point lying to the straight line connecting two points in $\overline{\Pi}^\star_m(\cdot)$, yields positive profits for the θ-type firm. Let us study first the straight line lying the points $(\overline{p}_{M,1} = \theta - \epsilon, \underline{p}_M, K_1 = \overline{Q}_{M,1})$ and $(\overline{p}_{M,2} = \theta, \underline{p}_M, K_2 < \overline{Q}_{M,2} < \overline{Q}_{M,1})$. It is direct to see that $\overline{\Pi}_m(\delta\overline{p}_{M,1} + (1-\delta)\overline{p}_{M,2}, \underline{p}_M, \delta K_1 + (1-\delta)K_2) = -\delta(1-\delta)\epsilon\overline{q}_{m,2} < 0$, which is a contradiction. Let us now check the case where $(\overline{p}_{M,1} = \theta + \epsilon, \underline{p}_M, K_1 = \overline{Q}_{M,1})$ and $(\overline{p}_{M,2} = \theta, \underline{p}_M, K_2 < \overline{Q}_{M,2})$. In this latter case the profit associated to any combination of connecting points is $\overline{\Pi}_m(\cdot) = \delta(1-\delta)\epsilon\overline{q}_{m,2} > 0$, which is consistent with our convexity argument. Therefore, when $F_m = 0$ the level set $\overline{\Pi}^\star_m(\cdot)$ supports a convex set only in cases where $\overline{p}_M \geq \theta$.

[27] The output level $\overline{q}^\star_m(\cdot)$ can be considered as the graph of a function, $K^\star_{\overline{q}_m}$, of K in terms of $\overline{p}_M$ and $\underline{p}_M$ in $\Re^3$ with $\frac{\partial K^\star_{\overline{q}_m}}{\partial \overline{p}_M} = Q'_M$ and $\frac{\partial K^\star_{\overline{q}_m}}{\partial \underline{p}_M} = 0$, and the Hessian's leading minors $\{0, 0\}$.

Similar to the analysis performed for the participation constraint of the θ-type firm, when that of the c-type firm, i.e., (54), is binding, it is represented by the level set given by $\underline{\Pi}^\star_m(\overline{p}_M,\underline{p}_M,K) = (\underline{p}_M - c)\underline{q}_m - F_m = 0$, with gradient vector $\nabla\underline{\Pi}^\star_m(\cdot) = (0, (\underline{p}_M - c)Q'_M + \overline{q}_m, -(\underline{p}_M - c))$, and it defines a convex set. Concerning the c-type firm's output nonnegativity constraint (56), it is represented by the level set $\underline{q}^\star_m(\overline{p}_M,\underline{p}_M,K) = \underline{Q}_M - K = 0$, with gradient vector $\nabla\underline{q}^\star_m(\cdot) = (0, Q'_M, -1) \neq 0$, defining a convex set.[28] Therefore, since the intersection of convex sets is convex, the set defined by (53)-(56) is convex.

When there is no fixed cost, $F_m = 0$, and both nonnegativity constraints (55) and (56) are effective they are represented by the level set $\overline{q}^\star_m(\overline{p}_M,\underline{p}_M,K) = \underline{Q}_M - \overline{Q}_M = 0$ with gradient vector $\nabla\overline{q}^\star_m(\cdot) = (-Q'_M, Q'_M, 0) \neq 0$, and then the surface level is a plane perpendicular to the $\overline{p}_M$-axis which coincides with the 45° line between the $\overline{p}_M$- and $\underline{p}_M$-axes. It is then direct to see that the Jacobian $J_{\overline{q}^\star_m,\underline{q}^\star_m} = (\nabla\overline{q}^\star_m, \nabla\underline{q}^\star_m)$ is full rank (the maximum possible number of effective constraints), and hence the Non Degenerate Constraint Qualification (NDCQ) is satisfied.

When $F_m > 0$ and both participation constraints (53) and (54) are binding, they are represented by the level set $\overline{\underline{\Pi}}^\star_m(\overline{p}_M,\underline{p}_M,K) = (\underline{p}_M - c)\underline{q}_m - (\overline{p}_M - \theta)\overline{q}_m = 0$ with gradient vector $\nabla\overline{\underline{\Pi}}^\star_m(\cdot) = (-(\overline{p}_M - \theta)Q'_M - \overline{q}_m, (\underline{p}_M - c)Q'_M + \underline{q}_m, (\overline{p}_M - \underline{p}_M) - (\theta - c)) \neq 0$. Since the Jacobian $J_{\overline{\Pi}^\star_m,\underline{\Pi}^\star_m} = (\nabla\overline{\Pi}^\star_m, \nabla\underline{\Pi}^\star_m)$ is full rank, the (NDCQ) is again satisfied. ■

Proof of Lemma 3 *Consider the ex-post program under scheme B where the regulator seeks to control market power exercised by a $\widetilde{\theta}$-type firm by the maximization, with respect to $p_M(\widetilde{\theta})$, of the social welfare function (50), for a given level of already installed transport capacity K, under the constraints (51) and (52). Differentiating the associated system of first-order conditions with respect to $\widetilde{\theta}$ yields that when the firm is active and makes positive profits, i.e., when $\nu(\widetilde{\theta}) = \phi(\widetilde{\theta}) = 0$, $\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} = 1$, $\frac{d\Pi_m(\widetilde{\theta})}{d\widetilde{\theta}} = [(p_M(\widetilde{\theta}) - \widetilde{\theta})Q'_M + q_m(\widetilde{\theta})]\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} - q_m(\widetilde{\theta}) < 0$, and clearly $\frac{d\nu(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{d\phi(\widetilde{\theta})}{d\widetilde{\theta}} = 0$. In this case, second-order conditions are summarized by $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$.*

When the firm is active and just breaks even, $\nu(\widetilde{\theta}) = 0$ and $\phi(\widetilde{\theta}) > 0$, we obtain $\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{q_m(\widetilde{\theta})}{(p_M(\widetilde{\theta}) - \widetilde{\theta})Q'_M + q_m(\widetilde{\theta})} \gtrless 0$, $\frac{d\Pi_m(\widetilde{\theta})}{d\widetilde{\theta}} = 0$, $\frac{d\nu(\widetilde{\theta})}{d\widetilde{\theta}} = 0$, and $\frac{d\phi(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{[(1+\widetilde{\phi})(p_M(\widetilde{\theta}) - \widetilde{\theta})Q'_M - \widetilde{\phi} q_m(\widetilde{\theta})]Q'_M}{[(p_M(\widetilde{\theta}) - \widetilde{\theta})Q'_M + q_m(\widetilde{\theta})]^2} > 0$. Finally, when the firm is shut down, $\nu(\widetilde{\theta}) > 0$, the participation constraint is trivially satisfied ($F_m = 0$) and hence $\frac{dp_M(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{d\Pi_m(\widetilde{\theta})}{d\widetilde{\theta}} = \frac{d\phi(\widetilde{\theta})}{d\widetilde{\theta}} = 0$, and $\frac{d\nu(\widetilde{\theta})}{d\widetilde{\theta}} = 1$. ■

Proof of Proposition 4 *From the discussion of Lemma 3 in the text we know that only five combinations of Lagrange multipliers are possible.*

Concerning policy $(B1_u)$, replace $\overline{\phi} = \underline{\phi} = \overline{\nu} = \underline{\nu} = 0$ in the system of first-order conditions (58)-(63) to get (64)-(66). Next, solve (58) and (59), respectively, for $\overline{p}_M$ and $\underline{p}_M$ and substitute into (60) to obtain $\lambda^2 K + (1+\lambda)Q'_M C'(K) - \alpha(1+\lambda)Q'_M(\theta - c) = 0$. For this equality to hold, it is required that $\lambda^2 K + (1+\lambda)Q'_M C'(K) < 0$. Moreover, second-order conditions associated with this policy are summarized by $\lambda^2 + (1+\lambda)Q'_M C''(K) < 0$.[29]

[28] The participation constraint (54) is liminal when $F_m = 0$.

[29] Note that when $\frac{C'(K)}{K} - C''(K) \leq 0$, when $\lambda^2 K + (1+\lambda)Q'_M C'(K) < 0$ holds, second-order conditions are always satisfied.

When there is no fixed cost, $F_m = 0$, to insure that this policy yields $\overline{q}_m > 0$, (66) should be satisfied with strict inequality when evaluated at $\overline{q}_m = 0$, i.e., $(1+\lambda)C'(\overline{Q}_M) > \alpha(1+\lambda)(\theta - c) + \lambda[\alpha(\overline{p}_M - \theta) + (1-\alpha)(\underline{p}_M - c)]$. Replacing $\overline{p}_M$ and $\underline{p}_M$ in (58) and (59), evaluated at $\overline{q}_m = 0$, yields $0 < \alpha(\theta - c) < C'(\overline{Q}_M) + \frac{\lambda^2 \overline{Q}_M}{(1+\lambda)Q'_M}$. When there is a fixed cost to finance, $F_m > 0$, we need to guarantee that this solution belongs to the set defined by the participation constraints (53) and (54). From Lemma 3 we restrict ourselves to cases under which policy $(B1_u)$ satisfies $\underline{\Pi}_m > \overline{\Pi}_m$ and then we only need to check the participation constraint of the θ-type firm. First, it is necessary that (66) be satisfied with strict inequality when $(\overline{p}_M - \theta) = \frac{F_m}{\overline{q}_m}$, i.e., $(1+\lambda)C'(K) > \alpha(1+\lambda)(\theta - c) + \lambda[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)(\underline{p}_M - c)]$, which can be rewritten as $0 < \alpha(\theta - c) < C'(K) + \frac{\lambda^2 K}{Q'_M} - \alpha\lambda(\frac{\lambda K \overline{q}_m + Q'_M F_m}{\overline{q}_m Q'_M})$. Second, the pricing rule associated with $(B1_u)$ should satisfy (53), i.e., $\lambda K \overline{q}_m + Q'_M F_m > 0$.

To obtain policy $(B2_u)$, replace $\overline{\nu} = \underline{\nu} = \underline{\phi} = 0$ and $F_m > 0$ in the system of first-order conditions (58)-(63) to get (67), (65), and (68). Since $F_m > 0$, it is necessary that (68) be satisfied with strict inequality when $(\underline{p}_M - c) = \frac{F_m}{\underline{q}_m}$, i.e., $(1+\lambda)C'(K) > \alpha(1+\lambda)(\theta - c) + \lambda[\alpha\frac{F_m}{\overline{q}_m} + (1-\alpha)\frac{F_m}{\underline{q}_m}]$, which can be rewritten as $\alpha(\theta - c) < C'(K) - \frac{\lambda F_m}{1+\lambda}[\frac{\overline{q}_m + \alpha(\underline{q}_m - \overline{q}_m)}{\overline{q}_m \underline{q}_m}]$. Second-order conditions for this policy are summarized by $\alpha^2\lambda^2(\alpha^2 K + (\overline{q}_m + \lambda K((1-\alpha)\overline{q}_m - K(\lambda - \alpha(2+\lambda))))) - 2\alpha^2\lambda\overline{\phi}\overline{q}_m(\overline{q}_m - (2+\lambda)K) + \alpha\overline{\phi}^2\overline{q}_m(3\overline{q}_m + 2\lambda K) + 2\overline{\phi}^3\overline{q}_m{}^2 - \alpha^2(1+\lambda)(\overline{q}_m - \lambda K)^2 Q'_M C''(K) > 0$.

To obtain policy $(B3_u)$, replace $\overline{\phi} = \underline{\phi} = \underline{\nu} = 0$ and $F_m = 0$ in the system of first-order conditions (58)-(63) to get (69), (65), and (70). Next, solve (58) and (59), respectively, for $\overline{p}_M$ and $\underline{p}_M$ and substitute into (60) to obtain $\lambda^2 K + (1+\lambda)Q'_M C'(K) + (1+\lambda)Q'_M[\overline{\nu} - \alpha(\theta - c)] = 0$. We now prove that $[\overline{\nu} - \alpha(\theta - c)] < 0$. Since $\overline{\nu} > 0$ and $\underline{\nu} = 0$, from Lemma 3 we know that $\underline{q}_m > \overline{q}_m = 0$ and hence $\underline{p}_M < \overline{p}_M$. From (58), $\overline{\nu} = \alpha(-(\overline{p}_M - \theta) - \frac{\lambda K}{Q'_M}) > 0$, and from (59), $-\frac{\lambda K}{Q'_M} = (\underline{p}_M - c)$, which results in $\overline{\nu} - \alpha(\theta - c) = -\alpha(\overline{p}_M - \underline{p}_M) < 0$. Consequently, policy $(B3_u)$ arises when $F_m = 0$ and $\lambda^2 K + (1+\lambda)Q'_M C'(K) < 0$. Second-order conditions associated with this policy are summarized by $\lambda^2 + (1+\lambda)Q'_M C''(K) < \alpha(1+\lambda)^2$.[30]

To obtain policy $(B4_u)$, replace $\overline{\nu} = \underline{\nu} = 0$ in the system of first-order conditions (58)-(63) to get (67), (71), and (72). Second-order conditions for this policy are always satisfied.

Finally, to obtain policy $(B5_u)$, replace $\overline{\phi} = \underline{\phi} = 0$ in the system of first-order conditions (58)-(63) to get (69), (73), and (74). Next, solve (58) and (59), respectively, for $\overline{p}_M$ and $\underline{p}_M$ and plug into (60) to obtain $\lambda^2 K + (1+\lambda)Q'_M C'(K) + (1+\lambda)Q'_M[(\overline{\nu} + \underline{\nu}) - \alpha(\theta - c)] = 0$. We next prove that $[(\overline{\nu} + \underline{\nu}) - \alpha(\theta - c)] > 0$. Since $\overline{\nu} > 0$ and $\underline{\nu} > 0$, from Lemma 3 we know that $\underline{p}_M = \overline{p}_M$. From (58), $\overline{\nu} > 0$ necessitates $-\frac{\lambda K}{Q'_M} > (\overline{p}_M - \theta)$, and from (59), $\underline{\nu} > 0$ calls for $-\frac{\lambda K}{Q'_M} > (\overline{p}_M - c)$. Therefore, when $\overline{p}_M - c + \frac{\lambda K}{Q'_M} < 0$, both $\overline{\nu}$ and $\underline{\nu}$ are strictly positive. Now, solve (58) and (59), respectively, for $\overline{\nu}$ and $\underline{\nu}$ and obtain $(\overline{\nu} + \underline{\nu}) - \alpha(\theta - c) = -[\overline{p}_M - c + \frac{\lambda K}{Q'_M}] > 0$. Thus, for $(B5_u)$ to arise as the optimal policy, it is necessary that $F_m = 0$ and $\lambda^2 K + (1+\lambda)Q'_M C'(K) > 0$. Second-order conditions for this policy are always satisfied. ■

[30] Note that this inequality is less stringent than the one summarizing second-order conditions of policy $(B1_u)$. Furthermore, when $\frac{C'(K)}{K} - C''(K) \leq -\frac{\alpha(1+\lambda)}{Q'_M}$, second-order conditions of policy $(B3_u)$ are always satisfied.

Proof of Lemma 4 From Lemma 2, the constraint set defined by (53)-(56) is convex. It then remains to analyze the properties of the sets defined by the incentive constraints (85) and (86).

The incentive constraint of the less efficient firm (85) satisfied with equality is represented by the level set $\overline{\Upsilon}^\star(\overline{p}_M, \underline{p}_M, K) = (\overline{p}_M - \theta)\overline{q}_m - (\underline{p}_M - \theta)\underline{q}_m = 0$, with gradient vector $\nabla\overline{\Upsilon}^\star(\cdot) = ((\overline{p}_M - \theta)Q'_M + \overline{q}_m, -(\underline{p}_M - \theta)Q'_M - \underline{q}_m, -(\overline{p}_M - \underline{p}_M))$. Since adding up the incentive constraints (85) and (86) yields $\underline{p}_M \leq \overline{p}_M$, two cases should be analyzed depending on whether or not this inequality holds in the strict sense. When $\underline{p}_M < \overline{p}_M$ and (85) is satisfied with equality, it can be easily verified that (86) holds with strict inequality. Moreover, linearity of demand implies $(\overline{q}_m - \underline{q}_m) = (\overline{p}_M - \underline{p}_M)Q'_M$, which allows to rewrite $\overline{\Upsilon}^\star(\cdot)$ as $\overline{\Upsilon}^\star(\overline{p}_M, \underline{p}_M, K) = (\overline{p}_M - \theta)Q'_M + \underline{q}_m = 0$. Hence, we obtain that $\nabla\overline{\Upsilon}^\star(\cdot) < 0$, and since $\frac{\partial\overline{\Upsilon}^\star(\cdot)}{\partial K} < 0$, $\overline{\Upsilon}^\star(\cdot)$ can be considered as the graph of a function $K^\star_{\overline{\Upsilon}}$, of K, in terms of $\overline{p}_M$ and $\underline{p}_M$ with $\frac{\partial K^\star_{\overline{\Upsilon}}}{\partial \overline{p}_M} = \frac{\partial K^\star_{\overline{\Upsilon}}}{\partial \underline{p}_M} = Q'_M$.[31] Consequently, when $\underline{p}_M < \overline{p}_M$ the level surface $\overline{\Upsilon}^\star(\cdot)$ is a plane with $\nabla\overline{\Upsilon}^\star(\cdot) < 0$ and hence the set below it is convex. When $\underline{p}_M = \overline{p}_M$, the level set $\overline{\Upsilon}^\star(\cdot)$ cannot be represented through the $K^\star_{\overline{\Upsilon}}$ function since $\frac{\partial\overline{\Upsilon}^\star(\cdot)}{\partial K} = 0$. However, since in this case the gradient vector is $\nabla\overline{\Upsilon}^\star(\overline{p}_M, \overline{p}_M, K) = \frac{\partial\overline{\Pi}_M}{\partial\overline{p}_M} \cdot (1, -1, 0)$, the surface level is a plane perpendicular to the $\overline{p}_M$-axis which coincides with the 45°-line between the $\overline{p}_M$- and $\underline{p}_M$-axes.[32]

Let us now check that $\overline{\Upsilon}^\star(\cdot)$ defines a convex set when both incentive constraints (85) and (86) hold, hence when $\underline{p}_M \leq \overline{p}_M$. To see this, we verify if the points $(\overline{p}_{M,1} = p_M, \underline{p}_{M,1} = p_M, K_1 = K < \overline{Q}_{M,1} = \underline{Q}_{M,1} = Q_M)$ and $(\overline{p}_{M,2} = p_M, \underline{p}_{M,2} = p_M - \epsilon, K_2 = K < \overline{Q}_M = Q_M < \underline{Q}_{M,2})$, each belonging to one of the two regular surfaces defined for the level set $\overline{\Upsilon}^\star(\cdot)$, are "visible" to each other. For the set defined by $\overline{\Upsilon}^\star(\cdot)$ to be convex, it must be the case that any point which lies on the connection between these two points should satisfy the incentive constraint (85). With linear demand, $\underline{q}_{m2} = \underline{q}_{m,1} - \epsilon Q'_M$. Hence, $(\delta\overline{p}_{M,1} + (1-\delta)\overline{p}_{M,2} - \theta)(\delta\overline{q}_{m,1} + (1-\delta)\overline{q}_{m,2}) - (\delta\underline{p}_{M,1} + (1-\delta)\underline{p}_{M,2} - \theta)(\delta\underline{q}_{m,1} + (1-\delta)\underline{q}_{m,2}) = \delta(1-\delta)\epsilon^2 Q'_M < 0$, which violates (85). Thus, to guarantee convexity of the set defined by the level set $\overline{\Upsilon}^\star(\cdot)$, $\underline{p}_M < \overline{p}_M$ should be imposed.

Similarly, when the incentive constraint of the more efficient firm, (86), is binding, it is represented by the level set $\underline{\Upsilon}^\star(\overline{p}_M, \underline{p}_M, K) = (\underline{p}_M - c)\underline{q}_m - (\overline{p}_M - c)\overline{q}_m = 0$ with gradient vector $\nabla\underline{\Upsilon}^\star(\cdot) = (-(\overline{p}_M - c)Q'_M - \overline{q}_m, (\underline{p}_M - c)Q'_M + \underline{q}_m, (\overline{p}_M - \underline{p}_M))$. When $(\underline{p}_M - c)\underline{q}_m - (\overline{p}_M - c)\overline{q}_m = 0$ holds, so does $(\overline{p}_M - c)Q'_M + \underline{q}_m = 0$ and hence $\nabla\underline{\Upsilon}^\star(\cdot) > 0$. Therefore, when $\underline{p}_M < \overline{p}_M$ the level surface $\underline{\Upsilon}^\star(\cdot)$ is a plane and the set above it is convex.[33] Again, as shown for the level set $\overline{\Upsilon}^\star(\cdot)$, to insure convexity of the set defined by $\underline{\Upsilon}^\star(\cdot)$, $\underline{p}_M < \overline{p}_M$ should be imposed.

Summing up, when $F_m > 0$ the relevant level sets defining the constraint set of the regu-

[31] For a general demand function $\frac{\partial K^\star_{\overline{\Upsilon}}}{\partial\overline{p}_M} = \frac{(\overline{p}_M - \underline{p}_M)(\overline{p}_M - \theta)\overline{Q}'_M - (\overline{q}_m - \underline{q}_m)(\underline{p}_M - \theta)}{(\overline{p}_M - \underline{p}_M)^2} \gtreqless 0$ and $\frac{\partial K^\star_{\overline{\Upsilon}}}{\partial\underline{p}_M} = -\frac{(\overline{p}_M - \underline{p}_M)(\underline{p}_M - \theta)\underline{Q}'_M - (\overline{q}_m - \underline{q}_m)(\overline{p}_M - \theta)}{(\overline{p}_M - \underline{p}_M)^2} \gtreqless 0$. The assumption of linearity of market demand helps not only to simplify these expressions but also to sign them.

[32] Note that the level set $\overline{\Upsilon}^\star(\cdot)$, given that $\underline{p}_M = \overline{p}_M$, is degenerate when $\frac{\partial\overline{\Pi}_M}{\partial\overline{p}_M} = 0$, i.e., when profits of the less efficient firm are maximized.

[33] When $\underline{p}_M = \overline{p}_M$, we have $\underline{\Upsilon}^\star(\overline{p}_M, \overline{p}_M, K) = \overline{\Upsilon}^\star(\overline{p}_M, \overline{p}_M, K)$ and $\nabla\underline{\Upsilon}^\star(\overline{p}_M, \overline{p}_M, K) = -\nabla\overline{\Upsilon}^\star(\overline{p}_M, \overline{p}_M, K)$. Hence, in this case, the two incentive constraints are trivially satisfied.

lator's optimization program under asymmetric information are $\overline{\Pi}_m^\star(\cdot)$, $\overline{\Upsilon}^\star(\cdot)$, *and* $\underline{\Upsilon}^\star(\cdot)$. *Since the intersection of convex sets is convex, the constraint set defined by (53)-(56) and (85)-(86) is convex only when* $\underline{p}_M < \overline{p}_M$. *When* $F_m = 0$ *the relevant level sets defining this constraint set are* $\overline{q}_m^\star(\cdot)$, $\overline{\Upsilon}^\star(\cdot)$, *and* $\underline{\Upsilon}^\star(\cdot)$. *Again, since the intersection of convex sets is convex, we should still impose the restriction* $\underline{p}_M < \overline{p}_M$ *in order to obtain convexity.*

Before proceeding in the proof, let us illustrate our results in the case where $F_m = 0$, $Q_M(p_M(\widetilde{\theta})) = 10 - p_M(\widetilde{\theta})$, $\theta = 4$, *and* $c = 2$. *When* $\underline{p}_M < \overline{p}_M$, *Figure A1a shows that the set defined by (53)-(56) and (85)-(86) is convex in the* $\{\overline{p}_M, \underline{p}_M, K\}$*-space. When* $\underline{p}_M = \overline{p}_M$, *the incentive constraints (85)-(86) are trivially satisfied, and hence the relevant constraint set is defined by (53)-(56). In this case, Figure A1b shows that the constraint set is also convex (see the trapezoidal region defined by bold lines).*

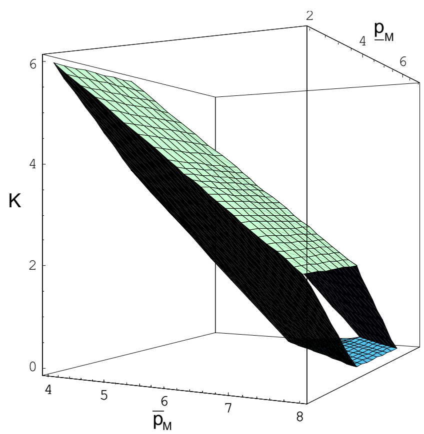


Figure A1a: *Constraint set with* $\underline{p}_M < \overline{p}_M$

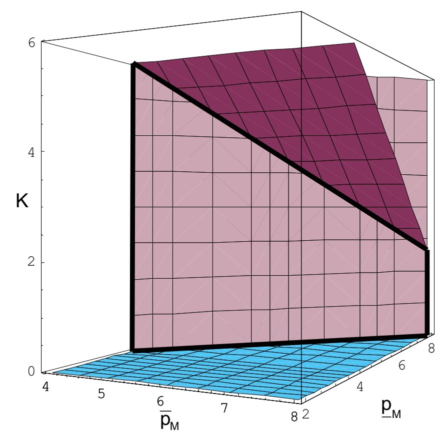


Figure A1b: *Constraint set with* $\underline{p}_M = \overline{p}_M$

However, in the general case where $\underline{p}_M \leq \overline{p}_M$, *the constraint set found by superposing the constraint sets in Figures A1a and A1b is not convex, as shown in Figure A2.*

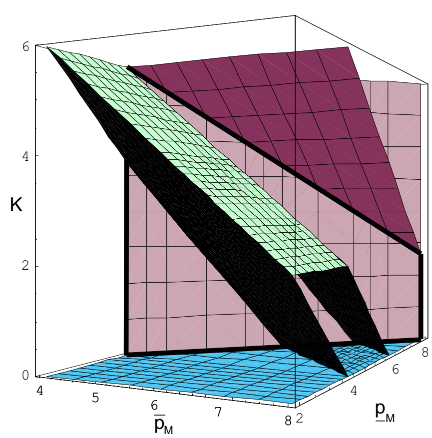


Figure A2: *Constraint set with* $\underline{p}_M \leq \overline{p}_M$

Let us now verify the regularity of the constraint set under asymmetric information. When $F_m = 0$ and both (55) and (85) are binding, they are represented by the level set $\overline{\overline{\Upsilon}}^{\star}(\overline{p}_M, \underline{p}_M, K) = -(\underline{p}_M - \theta)\underline{q}_m = 0$ *with gradient vector* $\nabla\overline{\overline{\Upsilon}}^{\star}(\cdot) = ((\underline{p}_M - \theta)Q'_M, -(\underline{p}_M - \theta) - \underline{q}_m, 0)$ *with* $\underline{p}_M = \theta$, *i.e.,* $\nabla\overline{\overline{\Upsilon}}^{\star}(\cdot) = (0, -\underline{q}_m, 0) \neq 0$ *since* $\underline{q}_m > 0$. *In such a case, the Jacobian* $J_{\overline{\Upsilon}^{\star},\overline{q}^{\star}_m}$ *is full rank. When* $F_m > 0$, *and both (53) and (85) are binding, they are represented by the level set* $\overline{\overline{\Upsilon}}^{\star\star}(\overline{p}_M, \underline{p}_M, K) = F - (\underline{p}_M - \theta)\underline{q}_m = 0$ *with gradient vector* $\nabla\overline{\overline{\Upsilon}}^{\star\star}(\cdot) = (0, -(\underline{p}_M - \theta)Q'_M - \underline{q}_m, (\underline{p}_M - \theta))$ *with* $\underline{p}_M = \theta + \frac{F_m}{\underline{q}_m}$. *Then, the Jacobian* $J_{\overline{\Upsilon}^{\star},\overline{\Pi}^{\star}_m}$ *is again full rank.*[34]

Finally, concerning the local concavity of the welfare function (57), we know that $\frac{\partial^2 E[W]}{\partial \overline{p}_M^2} = \alpha Q'_M < 0$, $\frac{\partial^2 E[W]}{\partial K \partial \overline{p}_M} = \alpha\lambda > 0$, $\frac{\partial^2 E[W]}{\partial \overline{p}_M \partial \underline{p}_M} = 0$, $\frac{\partial^2 E[W]}{\partial K \partial \underline{p}_M} = (1-\alpha)\lambda > 0$, $\frac{\partial^2 E[W]}{\partial \underline{p}_M^2} = (1-\alpha)Q'_M < 0$, *and* $\frac{\partial^2 E[W]}{\partial K^2} = -(1+\lambda)C''(K) < 0$. *The leading principal minors of the Hessian of the welfare function (57) are* $\{\alpha Q'_M, \alpha(1-\alpha){Q'_M}^2, -(1-\alpha)Q'_M[\lambda^2 + (1+\lambda)Q'_M C''(K)]\}$. *Local concavity of the welfare function requires that the last minor be negative, i.e., the condition stated in the lemma.* ■

Proof of Proposition 5 *Let us then start assuming that the incentive constraints (85) and (86) are satisfied with strict inequality. In such a case, we come back to the regulator's optimization program under uncertainty. We should now check which of the five policies* $(B1_u)$*-*$(B5_u)$ *can arise under asymmetric information. When* $F_m = 0$, *since under asymmetric information* $\underline{p}_M < \overline{p}_M$, *only policies* $(B1_u)$ *and* $(B3_u)$ *can arise, renamed as* $(B1_{ai})$ *and* $(B3_{ai})$. *When* $F_m > 0$, *since the less efficient firm cannot be shut down* ($\overline{q}_m > 0$), *from the incentive constraint (86), rewritten as* $\underline{\Pi}_m \geq \overline{\Pi}_m + (\theta - c)\overline{q}_m$, *we obtain* $\underline{\Pi}_m > \overline{\Pi}_m$. *Therefore, from Proposition 4 only policy* $(B2_u)$ *can arise, renamed here as* $(B2_{ai})$.

When the incentive constraint (86) is binding, ($\underline{\mu} > 0$, $\overline{\mu} = 0$), *and there is no fixed cost, only the case where* $\overline{\nu} = 0$ *may arise. Indeed, replace for* $\overline{\nu} > 0$ *into set of constraints (53)-(56) and (85)-(86) to obtain* $\underline{p}_M = c$. *Substituting this into (88) yields* $(1-\alpha)\lambda K + \underline{\mu}\underline{q}_m = 0$. *Since* $\underline{q}_m > 0$, *this equality requires* $\underline{\mu} < 0$, *which is a contradiction. Then, replacing for* $\overline{\phi} = \overline{\nu} = \overline{\mu} = 0$, *and* $\underline{\mu} > 0$ *into (87)-(89), yields (94)-(96) which characterize policy* $(B4_{ai})$.

When there is a fixed cost, in addition to policy $(B4_{ai})$, *there is the possibility to make the less efficient firm just break even,* $\overline{\phi} > 0$. *Replacing* $\overline{\nu} = \overline{\mu} = 0$, $\overline{\phi} > 0$ $\underline{\mu} > 0$ *into (87)-(89), yields (97), (95), and (98) which describe policy* $(B5_{ai})$.

Let us now study the case where the incentive constraint (85) is binding, ($\underline{\mu} = 0$, $\overline{\mu} > 0$) *three cases might arise. First substitute for* $\overline{\nu} = \overline{\phi} = \underline{\mu} = 0$ *into (87)-(89), to obtain (99)-(101) which describe policy* $(B6_{ai})$.

When there is fixed cost, $F_m > 0$, *and replacing for* $\overline{\nu} = \underline{\mu} = 0$ *into (87)-(89), yields (102), (100), and (103) characterizing policy* $(B7_{ai})$. *When there is no fixed cost,* $F_m = 0$, *and replacing for* $\overline{\phi} = \underline{\mu} = 0$ *into the constraint set (53)-(55) and (85)-(86) yields* $\underline{p}_M = \theta$. *Moreover, replacing for* $\underline{\phi} = \underline{\mu} = 0$ *into (87)-(89), we get (104) and (105) describing policy* $(B8_{ai})$. ■

[34] A similar approach can be applied in the two remaining cases, i.e., when both (55) and (86) are binding, and when both (53) and (86) are tight.

Derivation of optimal regulatory policies under asymmetric information assuming (21) *Solving the system of first-order conditions (87)-(93) when we assume* $F_m = 0$ $(\overline{\phi} = \underline{\phi} = \underline{\nu} = 0)$ *with the functional forms (21), yields the following solutions:*

Solution 1: described by $\overline{\nu} = 0$, $\overline{p}_M = \theta + \frac{\alpha(\theta-c)\lambda(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $\underline{p}_M = c + \frac{\alpha(\theta-c)\lambda(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $K = \frac{\alpha(\theta-c)(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $\overline{\mu} = 0$, *and* $\underline{\mu} = 0$. *Second-order conditions are satisfied provided* $\Psi \equiv \omega(1+\lambda)-\lambda^2 > 0$. *In such a case, it is clear to see that* $\underline{p}_M > c$, $\overline{p}_M > \theta$, $K > 0$. *For* $\overline{q}_m > 0$, *it is required that* $\Psi(\gamma-c) > [\Psi+\alpha(1+\lambda)^2](\theta-c)$. *Moreover, this solution makes both incentive constraints (85) and (86) inactive. Hence, we need to check for which values of* $(\theta-c)$ *they are jointly satisfied. As to (85) it requires that* $\Psi(\gamma-c) > \alpha(1+\lambda)(1+2\lambda)(\theta-c)$. *For (86), it is necessary that* $\Psi(\gamma-c) < [\Psi+\alpha(1+\lambda)(1+2\lambda)](\theta-c)$. *It can be seen that this last condition is compatible with those establishing that the incentive constraint (85) holds and* $\overline{q}_m > 0$. *Now, we should check which of these conditions is the more stringent one. After some calculations, we obtain that when the condition* $\Psi \geq \alpha\lambda(1+\lambda)$ *holds, the final interval for this solution is* $[\frac{\Psi}{\Psi+\alpha(1+\lambda)(1+2\lambda)}](\gamma-c) \leq (\theta-c) < [\frac{\Psi}{\Psi+\alpha(1+\lambda)^2}](\gamma-c)$. *Otherwise, when* $0 < \Psi < \alpha\lambda(1+\lambda)$, *the final interval for this solution is* $[\frac{\Psi}{\Psi+\alpha(1+\lambda)(1+2\lambda)}](\gamma-c) < (\theta-c) < [\frac{\Psi}{\alpha(1+\lambda)(1+2\lambda)}](\gamma-c)$. *This solution constitutes policy* $(B1_{ai})$.

Solution 2: described by $\overline{\nu} = 0$, $\overline{p}_M = \underline{p}_M = c+\alpha(\theta-c)+\frac{\alpha(\theta-c)\lambda(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $K = \frac{\alpha(\theta-c)(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $\underline{\mu} = 0$, *and* $\overline{\mu} = \frac{(-1+\alpha)\alpha(\theta-c)(\lambda^2-(1+\lambda)\omega)}{((\gamma-c)+(\theta-c))(\lambda^2-(1+\lambda)\omega)+\alpha(\theta-c)(1+3\lambda+2(1+\lambda)\omega)}$. *In this case, second-order conditions,* $\overline{p}_M = \underline{p}_M > c$, *and* $K > 0$ *necessitate* $\Psi > 0$. *For* $\overline{p}_M \geq \theta$ *it is necessary that* $\Psi \leq \frac{\alpha\lambda(1+\lambda)}{(1-\alpha)}$. $\overline{q}_m$ *requires* $\Psi(\gamma-c) > \alpha[\Psi+(1+\lambda)^2](\theta-c)$. *This solution makes both incentive constraints (85) and (86) binding. To get this result, however, only* $\overline{\mu} > 0$ *which calls for* $\Psi(\gamma-c) < [\alpha(1+\lambda)(1+2\lambda)-(1-2\alpha)\Psi](\theta-c)$. *Hence, the defining interval for this solution, provided* $\Psi \leq \frac{\alpha\lambda(1+\lambda)}{(1-\alpha)}$ *holds, is given by* $[\frac{\Psi}{[\alpha(1+\lambda)(1+2\lambda)-(1-2\alpha)\Psi]}](\gamma-c) \leq (\theta-c) < [\frac{\Psi}{\alpha[\Psi+(1+\lambda)^2]}](\gamma-c)$. *However, from Lemma 4 this solution is neglected.*

Solution 3: described by $\overline{\nu} = 0$, $\overline{p}_M = \underline{p}_M = c+\alpha(\theta-c)+\frac{\alpha(\theta-c)\lambda(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $K = \frac{\alpha(\theta-c)(1+\lambda)}{\omega+\lambda(-\lambda+\omega)}$, $\overline{\mu} = 0$, *and* $\underline{\mu} = -\frac{(-1+\alpha)\alpha(\theta-c)(\lambda^2-(1+\lambda)\omega)}{(\gamma-c)(\lambda^2-(1+\lambda)\omega)+\alpha(\theta-c)(1+3\lambda+2(1+\lambda)\omega)}$. *In this case, second-order conditions,* $\overline{p}_M = \underline{p}_M > c$, *and* $K > 0$ *necessitate* $\Psi > 0$. *For* $\overline{p}_M \geq \theta$, $\Psi \leq \frac{\alpha\lambda(1+\lambda)}{(1-\alpha)}$, *and for* $\overline{q}_m$, $\Psi(\gamma-c) > \alpha[\Psi+(1+\lambda)^2](\theta-c)$. *This solution makes both incentive constraints (85) and (86) binding. To get this result, however, only* $\underline{\mu} > 0$ *which calls for* $\Psi(\gamma-c) > \alpha[(1+\lambda)(1+2\lambda)+2\Psi](\theta-c)$. *Therefore, the defining interval for this solution, provided* $\Psi \leq \frac{\alpha\lambda(1+\lambda)}{(1-\alpha)}$ *holds, is given by* $0 \leq (\theta-c) < [\frac{\Psi}{\alpha[(1+\lambda)(1+2\lambda)+2\Psi]}](\gamma-c)$. *However, from Lemma 4 this solution is neglected.*

Solution 4: described by $\overline{\nu} = 0$, $K = \frac{\alpha((-1+\alpha)(\gamma-c)(1+2\lambda)+(\theta-c)(\lambda-\alpha(1+2\lambda)))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$, $\overline{\mu} = 0$, $\overline{p}_M =$

$$\frac{\lambda((\gamma-c)\lambda+\alpha^2((\gamma-c)+2(\gamma-c)\lambda)-\alpha((\gamma-c)+(\theta-c)+3(\gamma-c)\lambda))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$$

$$+\ \frac{((-1+\alpha)(\gamma-c)-\alpha(\theta-c))(1+\lambda)\omega+c(\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega)}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega},$$

$$\underline{p}_M = \frac{c(-1+\alpha)(\alpha(1+\lambda)(1+2\lambda)+\omega+\lambda(-\lambda+\omega))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$$

$$+\ \frac{\alpha(\alpha(1+2\lambda)((\theta-c)+(c+(\gamma-c))\lambda)-(1+\lambda)(-(\theta-c)\omega+(c+(\gamma-c))(\lambda+\omega)))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega},\ \textit{and}$$

$$\underline{\mu} = \frac{(-1+\alpha)\alpha(\alpha(\theta-c)(1+\lambda)(1+2\lambda)+((\gamma-c)-(\theta-c))(\lambda^2-(1+\lambda)\omega))}{\alpha\lambda((\theta-c)+2(\gamma-c)\lambda)+\alpha^2((\theta-c)+2(\theta-c)\lambda)+2\alpha(-(\gamma-c)+(\theta-c))(1+\lambda)\omega+(\gamma-c)(\omega+\lambda(-\lambda+\omega))}.$$

Second-order conditions are satisfied when $\Psi+\alpha(1-\alpha)(1+2\lambda)^2 > 0$, *which is always true since from Lemma 4, we restrict ourselves to cases where* $\Psi > 0$. *To obtain that* $\overline{q}_m > 0$ *the condition* $[(1-\alpha)\lambda(1+2\lambda)+\Psi](\gamma-c) > [\Psi+\alpha(1+2\lambda)+\lambda^2](\theta-c)$ *should hold. For* $\underline{q}_m > 0$, $-(1-\alpha)[\alpha\lambda(1+2\lambda)+\Psi](\gamma-c) < \alpha[\Psi+\lambda(1+\lambda)](\theta-c)$. *As to the incentive constraint (85), it is satisfied provided that* $(1-2\alpha)\Psi(\gamma-c)+\alpha[(\alpha+\lambda)(1+2\lambda)+2\Psi](\theta-c) > 0$. *Note* *that the denominator of $\underline{\mu}$ is positive whenever the incentive constraint is (85) satisfied. Therefore, $\underline{\mu} > 0$ requires $\Psi(\gamma - c) > [\alpha(1+\lambda)(1+2\lambda) + \Psi](\theta - c)$. Solving the former inequality in Ψ we obtain $\Psi^* > \frac{\alpha(1+\lambda)(1+2\lambda)(\theta-c)}{(\gamma-\theta)} > 0$, and then this solution requires $\Psi > 0$.*[35] *Now we have to check which of the constraints determining that $\overline{q}_m > 0$ and $\underline{\mu} > 0$ is more stringent. After some calculations, we get that the most stringent constraint is that establishing $\underline{\mu} > 0$. This solution illustrates policy $(B4_{ai})$.*

Solution 5: *described by $\overline{\nu} = 0$, $K = \frac{\alpha(-(\theta-c)(1+\lambda)+(-1+\alpha)(\gamma-c)(1+2\lambda))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$, $\underline{\mu} = 0$, $\overline{p}_M = \frac{\lambda(\alpha((-1+\alpha)(\gamma-c)+(-2+\alpha)(\theta-c))+(-1+\alpha)(-1+2\alpha)((\gamma-c)+(\theta-c))\lambda)}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$ $+\frac{((-1+\alpha)(\gamma-c)-(\theta-c))(1+\lambda)\omega+c(\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega)}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$,*
$\underline{p}_M = \frac{c(-1+\alpha)(\alpha(1+\lambda)(1+2\lambda)+\omega+\lambda(-\lambda+\omega))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$ $+\frac{\alpha(\alpha(1+2\lambda)((\theta-c)+(c+(\gamma-c)+(\theta-c))\lambda)-(1+\lambda)((c+(\gamma-c)+(\theta-c))\lambda+(c+(\gamma-c))\omega))}{\lambda^2-\alpha(1+2\lambda)^2+(\alpha+2\alpha\lambda)^2-(1+\lambda)\omega}$, and
$\overline{\mu} = -\frac{(-1+\alpha)\alpha(\alpha(\theta-c)(1+\lambda)(1+2\lambda)+(\gamma-c)(\lambda^2-(1+\lambda)\omega))}{\alpha^2((\theta-c)+2(\theta-c)\lambda)+\alpha\lambda((\theta-c)+2((\gamma-c)+(\theta-c))\lambda)-2\alpha(\gamma-c)(1+\lambda)\omega+((\gamma-c)+(\theta-c))(\omega+\lambda(-\lambda+\omega))}$. Second order conditions are satisfied when $\Psi+\alpha(1-\alpha)(1+2\lambda)^2 > 0$, which is always true. For $\overline{q}_m > 0$, $\alpha[(1-\alpha)\lambda(1+2\lambda)+\Psi](\gamma-c) > [\Psi+\alpha(1-\alpha)\lambda(1+2\lambda)+\alpha(1+\lambda)^2](\theta-c)$. Concerning the incentive constraint (86), it is satisfied when $(1-2\alpha)\Psi(\gamma-c)+[\Psi+\alpha(\alpha+\lambda)(1+2\lambda)](\theta-c) > 0$. When both $\overline{q}_m > 0$ and (86) hold, $\underline{p}_m > c$. Furthermore, for $\overline{\mu} > 0$, both $(1-2\alpha)\Psi(\gamma-c)+[\Psi+\alpha(\alpha+\lambda)(1+2\lambda)](\theta-c) > 0$ and $\Psi(\gamma-c) < \alpha(1+\lambda)(1+2\lambda)(\theta-c)$ should hold.[36]*. After some calculations we obtain that when $\Psi < \alpha\lambda(1+\lambda)$, the incentive constraint (86) is always satisfied and hence the defining interval of this solution is given by those establishing that $\overline{q}_m > 0$ and $\overline{\mu} > 0$. This solution represents policy $(B6_{ai})$.*

Solution 6: *described by $\overline{\nu} = -(\gamma-c)+\alpha(\theta-c)+\frac{(\gamma-c)(1+\lambda)^2}{1+\omega+\lambda(2+\omega)}$, $\overline{p}_M = \underline{p}_M = c+\frac{(\gamma-c)(\lambda+\omega+\lambda\omega)}{1+\omega+\lambda(2+\omega)}$, $\overline{\mu} = \frac{(-1+\alpha)(\gamma-c)(\lambda^2-(1+\lambda)\omega)}{(\gamma-c)(\lambda+\omega+\lambda\omega)-(\theta-c)(1+\omega+\lambda(2+\omega))}$, $K = \frac{(\gamma-c)(1+\lambda)}{1+\omega+\lambda(2+\omega)}$, and $\underline{\mu} = 0$. Second-order conditions are always satisfied. This solution is characterized by $\overline{q}_m = \underline{q}_m = 0$, and makes both incentive constraints (85) and (86) binding by setting $\overline{\mu} > 0$ and $\underline{\mu} = 0$. Shutting down is obtained by setting $\overline{\nu} > 0$, which calls for $0 < \Psi < \frac{\alpha\lambda(1+\lambda)}{(1-\alpha)}$ and $\frac{\Psi}{\alpha}(\gamma-c) < [\Psi+(1+\lambda)^2](\theta-c) < [\Psi+\lambda(1+\lambda)](\gamma-c)$. However, from Lemma 4 this solution is neglected.*

Solution 7: *described by $\overline{\nu} = -(\gamma-c)+\alpha(\theta-c)+\frac{(\gamma-c)(1+\lambda)^2}{1+\omega+\lambda(2+\omega)}$, $\overline{p}_M = \underline{p}_M = c+\frac{(\gamma-c)(\lambda+\omega+\lambda\omega)}{1+\omega+\lambda(2+\omega)}$, $\underline{\mu} = -\frac{(-1+\alpha)(\lambda^2-(1+\lambda)\omega)}{\lambda+\omega+\lambda\omega}$, $K = \frac{(\gamma-c)(1+\lambda)}{1+\omega+\lambda(2+\omega)}$, and $\overline{\mu} = 0$. Second-order conditions are always satisfied. This solution is characterized by $\overline{q}_m = \underline{q}_m = 0$, and makes both incentive constraints (85) and (86) binding by setting $\overline{\mu} = 0$ and $\underline{\mu} > 0$, which requires that $\Psi < 0$. Since, from Lemma 4 we must restrict to cases where $\Psi > 0$ and $\underline{p}_M < \overline{p_M}$, this solution is ignored.*

Solution 8: *described by $\overline{p}_M = c+\frac{-(\theta-c)\lambda+\alpha((\gamma-c)+(\theta-c))\lambda+(\gamma-c)(1+\lambda)\omega}{\alpha+2\alpha\lambda+\omega+\lambda\omega}$, $\underline{p}_M = \theta$, $\overline{\nu} = \frac{\alpha^2((\gamma-c)-(\theta-c))\lambda(1+2\lambda)+(\theta-c)(\omega+\lambda(-\lambda+\omega))+\alpha((\theta-c)(1+3\lambda(1+\lambda))-(\gamma-c)(1+\lambda)(\lambda+\omega))}{\alpha+2\alpha\lambda+\omega+\lambda\omega}$, $\underline{\mu} = 0$, $\overline{\mu} = -\frac{(-1+\alpha)(\alpha(1+\lambda)((\theta-c)-(\gamma-c)\lambda+(\theta-c)\lambda)+(\theta-c)(\omega+\lambda(-\lambda+\omega)))}{(\theta-c)\lambda+\alpha((\theta-c)-(\gamma-c)\lambda+(\theta-c)\lambda)+(-(\gamma-c)+(\theta-c))(1+\lambda)\omega}$, and*
$K = \frac{(\theta-c)\lambda+\alpha((\gamma-c)+(\gamma-c)\lambda-(\theta-c)\lambda)}{\alpha+2\alpha\lambda+\omega+\lambda\omega}$. Second order conditions are always satisfied. This solution is characterized by $\underline{p}_M > c$ and $\overline{q}_m = 0$. For the incentive constraint (86) to hold, $[\Psi+\lambda(\alpha+\lambda)](\gamma-c) > [\Psi+(1+\lambda)(\alpha+\lambda)](\theta-c)$. Provided that this latter condition holds, for $\overline{\mu} > 0$, $\alpha\lambda(1+\lambda)(\gamma-c) > [\Psi+\alpha(1+\lambda)^2](\theta-c)$. Furthermore, $\overline{\nu} > 0$ calls

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[35] Given that $\Psi > 0$, $\underline{q}_m > 0$ and (85) are always satisfied.

[36] Note that the former inequality provides an upper bound for Ψ which allows for the possibility of $\Psi \lesseqgtr 0$. However, from Lemma 4, we restrict to cases with $\Psi > 0$.

for $\alpha[(1-\alpha)\lambda(1+2\lambda)+\Psi](\gamma-c) < [\Psi+\alpha(1-\alpha)\lambda(1+2\lambda)+\alpha(1+\lambda)^2](\theta-c)$. After some calculations, we obtain that when $\Psi < \alpha\lambda(1+\lambda)$, the conditions which define the optimality of this solution are those guaranteeing that $\overline{\nu} > 0$ and $\overline{\mu} > 0$. This solution illustrates policy ($B8_{ai}$).

Solution 9: *described by $\overline{\nu} = \frac{\alpha(\alpha(\theta-c)(1+\lambda)^2+((\gamma-c)-(\theta-c))(\lambda^2-(1+\lambda)\omega))}{\alpha(1+\lambda)^2+\omega+\lambda(-\lambda+\omega)}$, $\overline{p}_M = c+(\gamma-c)-\frac{\alpha(\gamma-c)(1+\lambda)}{\alpha(1+\lambda)^2+\omega+\lambda(-\lambda+\omega)}$, $\underline{p}_M = c+\frac{\alpha(\gamma-c)\lambda(1+\lambda)}{\alpha(1+\lambda)^2+\omega+\lambda(-\lambda+\omega)}$, $\overline{\mu}=0$, $K=\frac{\alpha(\gamma-c)(1+\lambda)}{\alpha(1+\lambda)^2+\omega+\lambda(-\lambda+\omega)}$, and $\underline{\mu}=0$. Second-order conditions are satisfied when $\Psi+\alpha(1+\lambda)^2>0$, which is always true in our case. This solution is characterized by $\overline{q}_m=0$. For the incentive constraint (85) to hold, $\alpha\lambda(1+\lambda)(\gamma-c) < [\alpha(1+\lambda)^2+\Psi](\theta-c)$. Provided that this latter condition holds, for $\overline{\nu}>0$, it is required that $\Psi(\gamma-c) < [\alpha(1+\lambda)^2+\Psi](\theta-c)$. Concluding, two cases might arise: If $\Psi \geq \alpha\lambda(1+\lambda)$, this solution is chosen when $[\frac{\Psi}{\Psi+\alpha(1+\lambda)^2}](\gamma-c) < (\theta-c) < (\gamma-c)$. If $0<\Psi<\alpha\lambda(1+\lambda)$, this solution is chosen when $[\frac{\alpha\lambda(1+\lambda)}{\Psi+\alpha(1+\lambda)^2}](\gamma-c) < (\theta-c) < (\gamma-c)$. This solution illustrates policy ($B3_{ai}$).* ■

Proof of Proposition 6 *The first-order conditions of the regulator's optimization program under uncertainty, (58)-(60), can be expressed as*[37]

$$\frac{\partial E[W^B]}{\partial \overline{p}_M} + \overline{\phi}_u^B \frac{\partial \overline{\Pi}_m^B}{\partial \overline{p}_M} + \overline{\nu}_u^B Q'_M = 0 \tag{A.1}$$

$$\frac{\partial E[W^B]}{\partial \underline{p}_M} + \underline{\phi}_u^B \frac{\partial \underline{\Pi}_m^B}{\partial \underline{p}_M} + \underline{\nu}_u^B Q'_M = 0 \tag{A.2}$$

$$\frac{\partial E[W^B]}{\partial K} - \overline{\phi}_u^B(\overline{p}_M^B-\theta) - \underline{\phi}_u^B(\underline{p}_M-c) - \overline{\nu}_u^B = 0 \tag{A.3}$$

Those of the regulator's optimization program under asymmetric information, (87)-(89), can be written as

$$\frac{\partial E[W^B]}{\partial \overline{p}_M} + (\overline{\phi}_{ai}^B + \overline{\mu}^B - \underline{\mu}^B)\frac{\partial \overline{\Pi}_m^B}{\partial \overline{p}_M} - \underline{\mu}^B(\theta-c)Q'_M + \overline{\nu}_{ai}^B Q'_M = 0 \tag{A.4}$$

$$\frac{\partial E[W^B]}{\partial \underline{p}_M} - (\overline{\mu}^B - \underline{\mu}^B)\frac{\partial \underline{\Pi}_m^B}{\partial \underline{p}_M} + \overline{\mu}^B(\theta-c)Q'_M = 0 \tag{A.5}$$

$$\frac{\partial E[W^B]}{\partial K} - \overline{\phi}_{ai}^B(\overline{p}_M^B-\theta) - (\overline{\mu}^B-\underline{\mu}^B)(\overline{p}_M^B-\underline{p}_M^B) - \overline{\nu}_{ai}^B = 0 \tag{A.6}$$

We know from Propositions 4 and 5 that when there is no fixed cost, $\overline{\phi}_u^B = \underline{\phi}_u^B = 0$ and $\underline{\phi}_{ai}^B = 0$. When there is a positive fixed cost, these propositions yield that $\overline{\nu}_u^B = 0$ and $\underline{\nu}_{ai}^B = 0$. Moreover, from the definition of the firm's profit function (48) and the expected welfare function (57), $\frac{\partial^2\overline{\Pi}_m}{\partial\overline{p}_M^2}, \frac{\partial^2\underline{\Pi}_m}{\partial\underline{p}_M^2} < 0$ and $\frac{\partial^2 E[W^B]}{\partial\overline{p}_M^2}, \frac{\partial^2 E[W^B]}{\partial\underline{p}_M^2}, \frac{\partial^2 E[W^B]}{\partial K^2} < 0$. Let us now separately study two cases according to whether or not there is a fixed cost.

The no-fixed-cost case. *When $F_m=0$, we see from (124) that the effect of accounting for incentives is closely related to the behavior of $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\nu}_{ai}^B$, and $\overline{\nu}_u^B$. As a consequence of Lemma 4 only three cases should be discussed. First, we study the case where $\overline{\mu}^B = \underline{\mu}^B = 0$. Second, we consider the effect of accounting for incentives when the regulator is constrained to minimize the information rent of the more efficient type, i.e., it makes the incentive constraint of the c-type firm binding, $\underline{\mu}^B > 0$. Finally, we analyze the role of incentives*

[37] Note that following Lemma 4 we should exclude the case where both $\overline{\nu}_u^B > 0$ and $\underline{\nu}_u^B > 0$, and hence $\underline{\nu}_u^B = 0$.

when the regulator targets on the information rent of the less efficient firm by setting $\overline{\mu}^B > 0$.

It is direct to see that when the incentive constraints (85) and (86) are satisfied with strict inequality, i.e., $\overline{\mu}^B = \underline{\mu}^B = 0$, the outcome of the regulatory scheme under asymmetric information coincides with that under uncertainty and hence $K^B_{ai} = K^B_u$.

When $\overline{\mu}^B = 0$ and $\underline{\mu}^B > 0$, the only possibility is to have $\overline{\nu}^B_{ai} = 0$.[38] *Since $\underline{\mu}^B > 0$, constraint (86), rewritten as (123), implies that $(\frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} + (\theta - c)Q'_M) < 0$. Then, from (A.4) we obtain $\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} < 0$, while from (A.1) $\frac{\partial E[W]}{\partial \overline{p}_{M,u}} \geq 0$, which implies that $\overline{p}^B_{M,ai} > \overline{p}^B_{M,u}$. Similarly, (123) satisfied with equality yields $\frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} > 0$. Then, from (A.5) we obtain $\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} < 0$, while from (A.2), $\frac{\partial E[W]}{\partial \underline{p}_{M,u}} = 0$ which implies that $\underline{p}^B_{M,ai} > \underline{p}^B_{M,u}$. Plugging all these results into (124) yields that when $F_m = 0$ and $\underline{\mu}^B > 0$, $K^B_{ai} > K^B_u$*

When $\overline{\mu}^B > 0$ and $\underline{\mu}^B = 0$, constraint (85), rewritten as (122), implies $\frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} < 0$ and $(\frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} - (\theta - c)Q'_M) > 0$. Now, two cases should be analyzed depending of whether or not the less efficient firm is shut down under asymmetric information.

> *When $\overline{\nu}^B_{ai} = 0$ we obtain $[\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} - (\frac{\partial E[W]}{\partial \overline{p}_{M,u}} + \overline{\nu}^B_u Q'_M)] = -\overline{\mu}^B \frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} > 0$ and then it is direct to see that $\overline{p}^B_{M,ai} < \overline{p}^B_{M,u}$. From (A.5) we obtain $\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} > 0$, while from (A.2), $\frac{\partial E[W]}{\partial \underline{p}_{M,u}} = 0$ which implies that $\underline{p}^B_{M,ai} < \underline{p}^B_{M,u}$. Now, from conditions (A.3) and (A.6) we obtain $sign[K^B_{ai} - K^B_u] = -sign[\frac{\partial E[W^B]}{\partial K_{ai}} - (\frac{\partial E[W^B]}{\partial K_u} - \overline{\nu}^B_u)] = -sign[\overline{\mu}(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai})] < 0$, i.e., $K^B_{ai} < K^B_u$.*[39]
>
> *When $\overline{\nu}^B_{ai} > 0$ we again obtain that $\overline{p}^B_{M,ai} < \overline{p}^B_{M,u}$ and $\underline{p}^B_{M,ai} < \underline{p}^B_{M,u}$. Two subcases should be analyzed depending of the value of $\overline{\nu}^B_u$. When $\overline{\nu}^B_u = 0$, it is direct to see from (124) that when $\overline{\mu}^B > 0$, $\overline{\nu}^B_{ai} > 0$, and $\overline{\nu}^B_u = 0$, $K^B_{ai} < K^B_u$. When $\overline{\nu}^B_u > 0$, $sign[K^B_{ai} - K^B_u] = -sign[(\frac{\partial E[W^B]}{\partial K_{ai}} - \overline{\nu}^B_{ai})) - (\frac{\partial E[W^B]}{\partial K_u} - \overline{\nu}^B_u)] = -sign[\overline{\mu}(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai})] < 0$, i.e., $K^B_{ai} < K^B_u$*[40]

The with-fixed-cost case. *When $F_m > 0$, we see from (A.1)-(A.6), and (125) that the effect of accounting for incentives is closely related to the behavior of $\overline{\mu}^B$, $\underline{\mu}^B$, $\overline{\phi}^B_{ai}$, $\overline{\phi}^B_u$, and $\underline{\phi}^B_u$. Again, three cases should be studied. First, we study the case where $\overline{\mu}^B = \underline{\mu}^B = 0$. Second, we consider the case where $\overline{\mu}^B = 0$ and $\underline{\mu}^B > 0$. Next, we analyze the role of incentives when $\overline{\mu}^B > 0$ and $\underline{\mu}^B = 0$.*

As in the no-fixed-cost case, we see that when $\overline{\mu}^B = \underline{\mu}^B = 0$, $K^B_{ai} = K^B_u$.

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[38] See the proof of Proposition 5.

[39] If the regulator is allowed to set $\overline{\mu}^B > 0$ without shutting down the firm, $\overline{\nu}^B_{ai} = 0$, when it would have been necessary to do so in the case where incentives are not taken into account, i.e., $\overline{q}_{m,u} = 0$, it should be the case that $\overline{\mu}^B(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai}) > \overline{\nu}^B_u$. Plugging this into (124) yields that when $F_m = 0$, $\overline{\mu}^B > 0$, and $\overline{\nu}^B_{ai} = 0$, $K^B_{ai} < K^B_u$.

[40] Indeed, consistency between (A.3) and (A.6) necessitates that $-(\overline{\nu}^B_{ai} - \overline{\nu}^B_u) < \overline{\mu}^B(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai}) < \overline{\nu}^B_u$. Plugging this result into (124) yields that when $F_m = 0$, $\overline{\mu}^B > 0$, $\overline{\nu}^B_{ai} > 0$, $K^B_{ai} < K^B_u$.

When $\overline{\mu}^B = 0$ *and* $\underline{\mu}^B > 0$, *constraint (86), rewritten as (123), implies that* $(\frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} + (\theta - c)Q'_M) < 0$ *and* $\frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} > 0$. *Two cases should be studied depending of whether or not* $\overline{\phi}^B_{ai} = 0$.

> *When* $\overline{\phi}^B_{ai} = 0$, *from* (A.1) *and* (A.4) *we obtain that* $\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} < 0$, *and* $[\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} - (\frac{\partial E[W]}{\partial \overline{p}_{M,u}} + \overline{\phi}^B_u \frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,u}})] = \underline{\mu}^B(\frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} + (\theta - c)Q'_M) < 0$, *and hence* $\overline{p}^B_{M,ai} > \overline{p}^B_{M,u}$. *Similarly, from* (A.2) *and* (A.5) *we obtain that* $\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} < 0$, *and* $[\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} - (\frac{\partial E[W]}{\partial \underline{p}_{M,u}} + \underline{\phi}^B_u \frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,u}})] = -\underline{\mu}^B \frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} < 0$, *and hence* $\underline{p}^B_{M,ai} > \underline{p}^B_{M,u}$. *Plugging all these results into (125) yields that when* $F_m > 0$, $\underline{\mu}^B > 0$, *and* $\overline{\phi}^B_{ai} = 0$, *disregarding of whether or not* $\overline{\phi}^B_u$ *and/or* $\underline{\phi}^B_u$ *are equal to zero,* $K^B_{ai} > K^B_u$.
>
> *When* $\overline{\phi}^B_{ai} > 0$, *we see that when the regulator is allowed to set* $\underline{\mu}^B > 0$ *and still makes the less efficient firm just break even,* $\overline{\phi}^B_{ai} > 0$, *while would have only been necessary to let it earn zero profits under uncertainty, i.e.,* $\overline{\phi}^B_u, \underline{\phi}^B_u > 0$, *clearly* $\underline{\mu}^B(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai}) > \overline{\phi}^B_{ai}(\overline{p}^B_{M,ai} - \theta) - \overline{\phi}^B_u(\overline{p}^B_{M,u} - \theta) - \underline{\phi}^B_u(\underline{p}^B_{M,u} - c)$. *Plugging all these results into (125) yields that when* $F_m > 0$, $\underline{\mu}^B > 0$, *and* $\overline{\phi}^B_{ai} > 0$, $K^B_{ai} > K^B_u$.

When $\overline{\mu}^B > 0$ *and* $\underline{\mu}^B = 0$, *constraint (85), rewritten as (122), implies* $\frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} < 0$ *and* $(\frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} - (\theta - c)Q'_M) > 0$. *Now, two cases should be analyzed depending of whether or not the less efficient firm is constrained to break even under asymmetric information.*

> *When* $\overline{\phi}^B_{ai} = 0$, *from* (A.1) *and* (A.4) *we obtain that* $\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} > 0$, *and* $[\frac{\partial E[W]}{\partial \overline{p}_{M,ai}} - (\frac{\partial E[W]}{\partial \overline{p}_{M,u}} + \overline{\phi}^B_u \frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,u}})] = -\overline{\mu}^B \frac{\partial \overline{\Pi}_m}{\partial \overline{p}_{M,ai}} > 0$, *and hence* $\overline{p}^B_{M,ai} < \overline{p}^B_{M,u}$. *Similarly, from* (A.2) *and* (A.5) *we obtain that* $\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} > 0$, *and* $[\frac{\partial E[W]}{\partial \underline{p}_{M,ai}} - (\frac{\partial E[W]}{\partial \underline{p}_{M,u}} + \underline{\phi}^B_u \frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,u}})] = \overline{\mu}^B(\frac{\partial \underline{\Pi}_m}{\partial \underline{p}_{M,ai}} - (\theta - c)Q'_M) > 0$, *and hence* $\underline{p}^B_{M,ai} < \underline{p}^B_{M,u}$. *Now, from conditions* (A.3) *and* (A.6) *we see that when the regulator is allowed to set* $\overline{\mu}^B > 0$ *without making binding the participation constraint of the less efficient firm,* $\overline{\phi}^B_{ai} = 0$, *while it would have been necessary to do so in the case where incentives are not taken into account, i.e.,* $\overline{\phi}^B_u > 0$, *it clear that* $\overline{\mu}^B(\overline{p}^B_{M,ai} - \underline{p}^B_{M,ai}) > \overline{\phi}^B_u(\overline{p}^B_{M,u} - \theta) + \underline{\phi}^B_u(\underline{p}^B_{M,u} - c)$. *Hence, substituting into (124) implies that when* $F_m > 0$, $\overline{\mu}^B > 0$, *and* $\overline{\phi}^B_{ai} = 0$, $K^B_{ai} < K^B_u$.
>
> *When* $\overline{\phi}^B_{ai} > 0$ *we again obtain that* $\overline{p}^B_{M,ai} < \overline{p}^B_{M,u}$ *and* $\underline{p}^B_{M,ai} < \underline{p}^B_{M,u}$. *Two subcases should be analyzed depending of the value of* $\overline{\phi}^B_u$ *and/or* $\underline{\phi}^B_u$. *When* $\overline{\phi}^B_u = \underline{\phi}^B_u = 0$, *it is direct to see from (125) that* $K^B_{ai} < K^B_u$. *When either* $\overline{\phi}^B_u > 0$ *or both* $\overline{\phi}^B_u > 0$ *and* $\underline{\phi}^B_u > 0$, $\overline{\mu}^B > 0$ *does not unambiguously imply the sign of* $(K^B_{ai} - K^B_u)$. ■

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