Bocconi

IEFE
Centre for Research on Energy and Environmental Economics and Policy

Working Paper Series - ISSN 1973-0381

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Working Paper n. 65

March 2014

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Laura Abrardi†, Carlo Cambini‡

March 2014

Abstract

We study the optimal tariff structure that could induce a regulated utility to adopt energy efficiency activities given that it is privately informed about the effectiveness of its effort on demand reduction. The regulator should optimally offer a menu of incentive compatible two-part tariffs. If the firm's energy efficiency activities have a high impact on demand reduction, the consumer should pay a high fixed fee but a low per unit price, approximating the tariff structure to a decoupling policy, which strenghtens the firm's incentives to pursue energy conservation. Instead, if the firm's effort to adopt energy efficiency actions is scarcely effective, the tariff is characterized by a low fixed fee but a high price per unit of energy consumed, thus shifting the incentives for energy conservation on consumers. The optimal tariff structure also depends on the cost of the consumer's effort (in case the consumer can also adopt energy efficiency measures) and on the degree of substitutability between the consumer's and the firm's efforts.

Keywords: Energy efficiency, demand-side regulation, decoupling, price-cap.
JEL codes: L51

*We would like to thank Timothy Brennan, Massimo Filippini and David E.M. Sappington for useful discussion and comments to previous version of the paper.

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1 Introduction

In recent years, energy conservation has risen to the attention of the public and policymakers due to the increased sensibility toward environmental issues and investment-oriented considerations, suggesting the opportunity of demand-side management in the energy industry and a revision of the current regulatory framework.

Traditional regulation methods such as rate of return regulation as well as incentive regulation methods (Armstrong and Sappington, 2006; Joskow, 2008), are not designed to provide incentive to utilities for promoting energy conservation and energy efficiency projects. However, energy conservation and the improvement of the level of efficiency in the use of energy are important energy policy goals. Indeed, alternative policy instruments to pursue energy conservation, such as the adoption of white certificates[1], have been only partially successful in promoting energy efficiency, meaning that some additional regulatory interventions are needed.[2]

The addition of energy efficiency goals to the social planner's objectives calls for a revision of the standard regulatory schemes. Indeed, incentive-based regulation performs badly in promoting energy conservation, as the reduced sales (ultimate goal of the energy efficiency programs) and the consequent reduction in revenues and profits actually constitute a disincentive for the adoption of the energy efficiency measures by the utilities (Gillingham, Newell and Palmer, 2009; Brennan, 2010a, 2010b; Carter, 2011). A regulatory intervention that compensates the utility for the costs of demand reducing activities by raising prices has an ambivalent effect: on one hand, it creates a distortion in the utility's optimal decisions by raising the opportunity cost of lost sales. On the other hand, on the demand side, higher prices increase the consumers' incentive to ration their consumption. Any policy intervention directed to incentivize energy efficiency should then reconsider the price structure of traditional models, in reason on the different leverages and more articulated effects that an intervention on prices could have over the goal of reducing energy demand. Our contribution aims to analyse the interplay between tariff regulation and energy efficiency goals and provide guidance to regulators with respect to policy design.

Regulators have answered to the need of new, more adequate, regulatory schemes

[1] White cerificates are tradable permits representing a certain amount of energy saving to achieve a quantified target of energy reduction.

[2] The implementation of white certificates is sensitive to the specific market structure and regulatory framework of the national context of application, thus requiring country-specific adaptations. Moreover, white certificates target energy efficiency, and only a few measures target behavioural change of consumption patterns, thus representing only a partial response to energy conservation objectives. For more details, see Mundaca and Neij (2009), Bertoldi et al. (2010) and Giraudet et al. (2012).

in a number of ways. A widely adopted solution is that of decoupling policies[3], which guarantee to utilities constant revenues and profits regardless of how much energy they deliver (Brennan, 2013). An obvious flaw of decoupling policies is that, while they do not disincentivize utilities to adopt energy conservation programs, they neither provide incentives to their efficient realization. This weakness becomes particularly critical in presence of information asymmetries in the costs or effectiveness of the programs. An alternative to decoupling policies consists of monetary incentives based on the utilities' performance with respect to the energy efficiency pre-determined objectives. However, incentive schemes have downsides as well. First, they present a not negligible implementation complexity and require significant regulatory capabilities, both in the design on the incentive measures and in the monitoring of the utilities' performance. An even more fundamental problem is related to the scarcity of formal guidance at the theoretical level, which can results in suboptimal and overlapping energy-efficiency incentives, possibly conflicting with the incentives toward productive efficiency intrinsic in different tariff mechanisms.

Although several authors have provided useful policy discussion (e.g., Moskovitz, 1989; Stoft and Gilbert, 1994; Eto et al., 1998, Brennan, 2010a), rigourous theoretical work in the field is recent and sparse, which could explain the notable variety of the measures adopted by regulators at the implementation level (see Dixon et al., 2010, for a survey of energy conservation policies in the United States and Tanaka, 2011, for other countries).

The few existing theoretical studies range from moral hazard models (Eom and Sweeney, 2009; Chu and Sappington, 2013), that assume an unobservable effort in demand-reducing activities, to adverse selection studies (Chu and Sappington, 2012), which instead assume the utility's superior information on effectiveness and cost of energy conservation activities, to models in which the consumers' preferences cannot be perfectly observed by the regulator (Lewis and Sappington, 1992). Moreover, a quite substantial literature can be found on gain sharing plans (Eom, 2009; Chu and Sappington, 2012). Gain sharing plans provide to energy firms incentives toward energy conservation by specifying in advance how the realized benefits of the programs will be divided between the utility and consumers.

One important limit of all these works is that, by studying how to promote energy efficiency (EE hereafter) activities by the utilities, they restrict the attention to the supply side of the market. However, by doing this, they overlook an important instrument

[3]Decoupling has been effectively implemented in the US in the states of Oregon and California and, on a more limited basis, in Maryland, New Jersey, North Carolina, Utah and Ohio (Kushler, York, Witte, 2006).

of demand side management, namely the price. As a matter of fact, the firm's effort in promoting EE activities has certainly an important effect on consumers' demand, but we cannot disregard the primary role of the energy price on demand management. In practice, utilities are usually regulated through a tariff, whose function is twofold: it not only provides the necessary revenues to the firm, but it also configures itself as an instrument of demand management. A complete analysis cannot discount the latter, and should thus include the price in the set of incentives toward energy conservation.

Actually, the need to formally include the consumers' response to policy adopted has already been suggested (Chu and Sappington, 2012[4]) but little work has been done on the subject.

The optimal use of price as an incentive to energy conservation is the aim of the present work.

In our model, an energy utility can exert effort to promote energy conservation by consumers and induce them to reduce their demand. These activities may be highly effective, and allow consumers to maintain the same level of comfort[5] with significantly lower consumptions, or have lower effectiveness. For example, the installation on consumers' premises of energy-saving devices allows consumers to save energy and yet benefit from the same levels of usage of the appliances. The firm is privately informed about the effectiveness of energy conservation activities. The regulator can merely observe the results of the firm's effort, namely the consumer's comfort obtained from a given level of quantity of energy consumed[6]. In this environment, the regulator must motivate the utility to deliver the effort by providing explicit financial rewards for observed levels of consumers' comfort. The firm's revenues come from a two-part tariff, with a unit price on the energy consumed and a fixed fee. In this setting, a firm that knows that its EE activities are highly effective gains a rent by underexerting the effort and explaining its low performance in terms on demand reduction with an unresponsive demand. Our objective is to find the optimal menu of tariffs, which induces the firms to correctly self-select and at the same time allows the optimal trade-off be-

[4] The authors claim that "in settings where consumers can undertake energy conservation activities, energy prices might also be structured to influence these activities".

[5] The idea that the firm's effort affects the consumer's comfort is borrowed from Chu and Sappington (2013).

[6] The focus on consumer's comfort as an incentive to utilities to energy conservation was first suggested by Sant (1908) as part of the Energy Savings Model, according to which utilities should sell customers the actual services for which they use energy, such as light and heat, rather than the quantity of energy consumed. For example, consumers could be charged for hours of service (such as lumen-hours of light or heating-degree hours) rather than watts of power consumed. While this approach could be difficult to implement in practice, Fox-Penner (2010) notices that the adoption of smart meters may eventually facilitate an accurate measure of comfort.

tween rent extraction and inefficiency. In this regard, our approach differs substantially from Chu and Sappington (2013), who study policies that allow the first best outcome, abstracting from the goal of rent reduction.

We find that the tariff structure is indeed an instrument for energy conservation. When demand is less responsive to EE activities, the most efficient tariff has a strong variable component, with a high price paid per unit consumed covering all the firm's costs: due to the low effect of EE effort on demand, it is more cost-effective trying to reduce demand through a higher price rather than through EE activities. When instead EE activities are highly effective, the regulator should base its tariff structure to a larger extent on the fixed fee, so as to replicate a decoupling policy and incentivize the utility to exert the effort; the energy price in this case is low so as to reduce the marginal loss from any unsold quantity, thus minimizing the disincentives to invest in EE activities. The presence of information asymmetries only strenghtens this result, with the regulator offering a menu of tariffs where the one designed for the firm in the highly effective environment is polarized toward a fixed revenue solution, while the contract designed for the other type of firm is polarized toward a standard price regulation policy.

We then extend our setting assuming that not only firms but also consumers can exert an effort in energy conservation activities. In this case, the regulator should decide how to incentivize efforts from both parties and which tariff structure is preferable to allocate efforts between consumers and firms. The main problem in this framework is that the price qualifies at the same time as the loss of the firm for any lost sale and the gain for the consumer for any reduction of demand. It follows that a high price is both a disincentive to the firm to exert effort, and an incentive for the consumer. The regulator should then find the optimal trade-off between the firm's and the consumer's incentives. This optimal allocation of incentives obviously depends on the relative costs of the firm's and consumer's effort, but also on the degree of substitutability between them. When efforts are complement, meaning that the effort of say the firm generates a positive effects also on the consumers' effort, then the regulator may prefer to reduce the optimal regulated price and to increase the fixed component, hence moving towards a decoupling policy, to promote energy efficiency activities. On the contrary, when efforts are substitute, hence the increase in effort by one party negatively affects the other, the regulator may prefer to increase the regulated price and decrease the fixed component in order to reduce overall consumption given that efforts in energy conservation activities are reduced.

Our analysis proceeds as follows. Section 2 describes the core elements of the model. Section 3 finds the socially optimal solution in the perfect information benchmark.

Section 4 provides the optimal policy under imperfect information. Section 5 presents an extension where, in a perfect information setting, also consumers can make own efforts in promoting energy savings. Section 6 concludes. All longer proofs are reported in the Appendix.

2 The model

An energy-selling firm can devote some effort e to promote energy efficiency (EE) programs by its customers. The energy efficiency programs could be, for instance, the installation of energy-efficient appliances at the customers' premises or the promotion of energy-saving behaviour that does not sacrifice consumers' comfort.

In choosing their level of consumption, customers seek to maximize their utility $V(x)$, that is a function of the comfort[7] x, such that $V(0) = 0$, $V_x > 0$, $V_{xx} < 0$. The customer's comfort is a function of the quantity q of energy consumed and of the effort e devoted by the firm to energy efficiency activities: $x = q + \theta e$, where $\theta > 0$ is the marginal impact of EE effort on comfort[8]. The parameter θ can be interpreted as the responsiveness of the demand to the EE effort, or alternatively as the effectiveness of EE activities. We assume that θ can take on two possible values, i.e. $\theta \in \{\theta_H, \theta_L\}$, with $\theta_H > \theta_L$. If $\theta = \theta_H$, the demand is highly responsive (we denote this framework with the H subscript) to EE activities and one unit of effort by the firm allows customers to significantly increase their comfort given the same level of consumption or, similarly, to strongly reduce their consumption and yet mantain the same levels of comfort. Viceversa, if $\theta = \theta_L$, EE activities have lower marginal impact on consumers' comfort (we will refer to this state as L).

The production of quantity q entails for the firm a total production cost $C(q)$, with $C' > 0$ and $C'' > 0$, which includes fixed costs that do not depend on the scale of the production. Moreover, the production of q entails a social cost (e.g., the environmental loss) equal to $D(q)$, with $D' > 0$ and $D' > 0$. The firm incurs also in the cost $\psi(e)$ for delivering effort e, with $\psi(0) = 0$, $\psi' > 0$ and $\psi'' > 0$.

The regulator recognises to the firm a constant price p on the sales and a fixed transfer F. The firm chooses the level of effort in order to maximize its profits $\pi(q, e) = pq + F - C(q) - \psi(e)$. Note that a tariff structure in which the firm's revenues are

[7] For a similar approach, see also Chu and Sappington (2013).

[8] Similarly to Chu and Sappington (2013), we assume that the level of comfort is positively correlated with the quantity consumed q, i.e., $\partial x/\partial q > 0$ for all e. Moreover, given a level of consumption q, the energy efficiency effort e is assumed to be comfort-enhancing, i.e., $\partial x/\partial e = \theta > 0$ for all q. Note that we assume a linear relationship to simplify the analysis and provide a clear intuition of the results. The outcome remains unaffected if we generalize the comfort function as $x = f(q, \theta, e)$ with $\partial x/\partial(\cdot) > 0$.

entirely made up by the fixed fee and are thus uncorrelated with the quantity sold is, in our framework, equivalent to a decoupling policy[9]. Conversely, a fixed fee equal to zero defines a standard price-cap or rate of return policy, in which revenues are entirely proportional to sales.

The regulator seeks to maximize the welfare W, defined as consumer's net surplus minus the social cost of the production plus a share $\alpha < 1$ of the firm's profits: $W = V(x) - pq - F - D(q) + \alpha\pi(q, e)$. The introduction of the firm's profits into the regulator's objective function replicates Baron and Myerson's (1982) approach and constitutes a generalization of the situation analyzed by Chu and Sappington (2012, 2013), in which the regulator's objective is focused only on the consumer's surplus. Given that $\pi(q, e) = pq + F - C(q) - \psi(e)$, the welfare can be rewritten as

$$W = V(x) - D(q) - \alpha\left(C(q) + \psi(e)\right) - (1 - \alpha)\left(pq + F\right). \tag{1}$$

Notice that, from the definition of the welfare in (1), the firm's revenues have a social cost equal to $(1 - \alpha)$.

Consumers' demand is given by the solution to the following problem:

$$\max_q V(x) - pq - F, \tag{2}$$

that is

$$V_x = p. \tag{3}$$

V_x, on the left-handside of (3), is a function of both q and θe. For a given level of $e\theta$, $\frac{\partial V_x}{\partial q} = \frac{\partial V_x}{\partial x}\frac{\partial x}{\partial q} = V_{xx} \cdot 1 < 0$: from (3), the quantity demanded is a decreasing function of the price.

It also seems important to point out the role of $e\theta$ in determining the consumer's demand function. For a given level of q, $\frac{\partial V_x}{\partial(e\theta)} = \frac{\partial V_x}{\partial x}\frac{\partial x}{\partial(e\theta)} = V_{xx} \cdot 1 < 0$. Hence, V_x is a decreasing function of θe. In other words, an increase of θe shifts of the demand function: consumers reduce their demand for all p when θe increases, as the effort exerted by the firm allows customers to achieve the same level of comfort with lower consumptions.

We first find the optimal policy under perfect information. Then, we will assume that θ and e are private information of the firm and the regulator can only observe the level of comfort achieved.

[9] For an analysis of decoupling policies, see, e.g., Brennan (2013).

3 Perfect information benchmark

In perfect information, the regulator contracts over the tariff (p, F) and the effort e. It is worth noting that setting a price equal to p and an effort e, indirectly determines a consumer's demand q through the demand function defined by (3). It follows that the regulator can equivalently contract over the price or the quantity.

The regulator solves

$$\max_{q_i, e_i} V(x_j) - p_j q_j - F_j - D(q_j) + \alpha \pi_j(q_j, e_j)$$

$s.t.$

$$\pi_j(q_j, e_j) = p_j q_j + F_j - C(q_j) - \psi(e_j) \geq 0 \quad (4)$$

$$V_x = p_j. \quad (5)$$

for all $j \in \{H, L\}$. Constraint (4) represents the firm's participation constraint of at least zero profits, while constraint (5) is the consumer's demand function expressed in (3),$V_x = p$. As rents are costly for the regulator, in the optimal solution constraint (4) is binding. The first best solution is defined by the following proposition.

Proposition 1 *Under perfect information, the regulator offers to the firm a contract* $\left(p_j^*, F_j^*, e_j^*\right)$ *if* $\theta = \theta_j$*, with the following characteristics:*

$$q_j^* : V_x(q) = C'(q) + D'(q) \quad (6)$$

$$e_j^* : V_x(e) = \psi'(e)/\theta_j \quad (7)$$

$$p_j^* = V_x(q_j^*, e_j^*) \quad (8)$$

$$F_j^* = C(q_j^*) + \psi(e_j^*) - p_j^* q_j^* \quad (9)$$

for all $j \in \{H, L\}$.

From equation (6) of Proposition 1, the optimal quantity is such that the marginal benefit of one additional unit of consumption (V_x) is equal to its marginal cost, namely the marginal production cost C' and the social cost D'. Moreover, from (5), the regulator sets the price equal to the sum of marginal production and social costs, thus leading consumers to choose the first best level of consumption. From equation (7), the optimal level of the firm's effort is such that the marginal utility of effort (namely, the increase of the consumer's surplus by $V_x \theta_j$) is equal to its marginal cost, ψ'. Finally, the fixed trasfer is such that the firm's profit are zero.

Before analyzing the first best levels of x, e and p, let us study the demand function, defined by the value of θe. The following Lemma defines the contribution of the firm's effort in determining the consumer's comfort in the two frameworks, H and L.

Lemma 1 *In perfect information, it holds* $e_H^*\theta_H > e_L^*\theta_L$*, implying a lower demand function when EE activities are highly effective.*

Lemma 1 implies that, for a given price p, the demand for energy is lower when the consumers' comfort is strongly affected by the firm's EE activities. From another perspective, the consumers' comfort depends on the combined effect of firm's effort e and the effectiveness θ of EE activities. Given the same quantity, consumers are able to achieve a higher comfort when EE activities are highly effective (i.e., $\theta = \theta_H$), though Lemma 1 doesn't elaborate whether this is true only because of the higher θ or also because of higher e. Proposition 2 will provide further clarification.

The pair of contracts (p_H^*, F_H^*, e_H^*) and (p_L^*, F_L^*, e_L^*) satisfying conditions (6), (7), (8) and (9) is characterized by the following proposition.

Proposition 2 *In perfect information,* $q_H^* < q_L^*$*,* $e_H^* > e_L^*$*,* $p_H^* < p_L^*$*,* $x_H^* > x_L^*$*,* $F_H^* > F_L^*$*.*

The graphical representation of the results of Proposition 2 in perfect information is provided by Figure 1. On the left, the figure represents condition (6) defining the optimal quantity. Given that $e_H^*\theta_H > e_L^*\theta_L$ from Lemma 1, it follows that $V_x(q; e_H^*\theta_H) < V_x(q; e_L^*\theta_L)$ for all q, as shown in Figure 1.a with the function $V_x(q; e_H^*\theta_H)$ on the left of $V_x(q; e_L^*\theta_L)$. From (6), it follows that $q_H^* < q_L^*$. The vertical axis shows the price, as provided by the optimality condition (8) that defines the demand function. Given that $V_x(q_H^*; e_H^*\theta_H) < V_x(q_L^*; e_L^*\theta_L)$, we obtain $p_H^* < p_L^*$. In Figure 1.b we derive the optimal value of e by exploiting condition (7). As $q_H^* < q_L^*$, it must be that $V_x(e; q_H^*) > V_x(e; q_L^*)$ for all e. Moreover, as $p_H^* < p_L^*$, the only possible solution is the one showed in the figure, with $e_H^* > e_L^*$. Indirectly, the figure also gives information about the final level of comfort achieved by the customer. Indeed, since $p_H^* < p_L^*$ and given that $V_x = p$ by (5), $V_{x_H} < V_{x_L}$, implying that $x_H^* > x_L^*$.

The results of Proposition 2 have a straightforward interpretation. As consumption is socially costly, it is in the regulator's interest trying to realize the customers' comfort by investing in EE activities rather than through consumption. Indeed, an additional unit of effort in EE activities entails a marginal reduction of the consumers' demand equal to θ. This implies that the marginal effect of effort on demand reduction is stronger when $\theta = \theta_H$ rather than when $\theta = \theta_L$. Given the higher effectiveness of EE activities in the H framework, the optimal solution must entail $e_H^* > e_L^*$ and $q_H^* < q_L^*$. In other words, when EE activities are highly effective, the optimal regulatory policy is to spur the EE effort, keeping consumption low, as opposed to the situation in which EE activities have low effectiveness. Incentives for exerting high effort can be provided

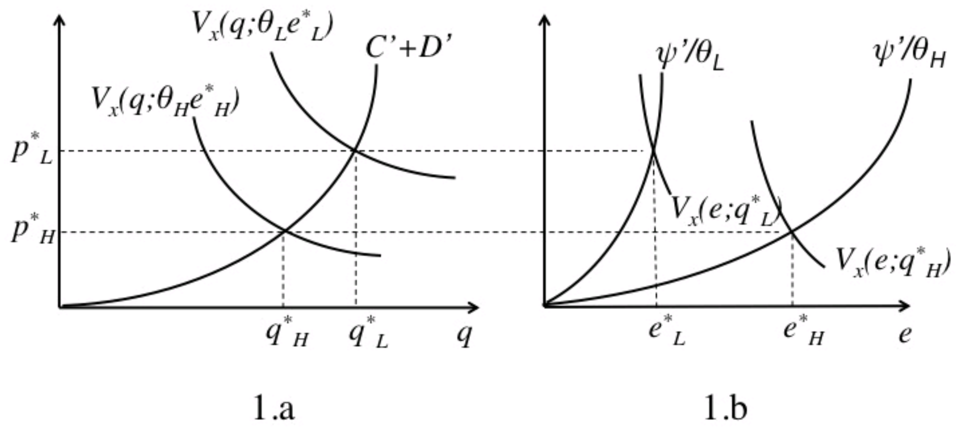

Figure 1: First best outcome

by reducing the marginal loss from any unsold quantity, that is the price. Indeed, $p^*_H < p^*_L$. To compensate the firm in the H environment for the lower revenues and higher effort cost, a larger fixed component must be included in the tariff, i.e., $F^*_H > F^*_L$.

Note that, when EE activities are highly effective, the two-part tariff offered to the firm ensures a larger fixed component and a lower price than in case EE activities are less effective. We can thus conclude that, even in the first best situation, the contract offered to the firm is closer to a decoupling policy in case EE activities are highly effective, while it is more similar to a standard per unit regulated tariff if EE activities have lower effectiveness.

4 Asymmetric information

Assume that the value of the parameter θ is the firm's private information, although its probability distribution is common knowledge. Let us denote with λ the probability that $\theta = \theta_H$, and with $1 - \lambda$ the probability that $\theta = \theta_L$. While the effort e and the effectiveness of EE activities θ are unobservable by the regulator, the quantity consumed q and the level of comfort x achieved by the consumer can be observed and verified. For example, the comfort may be measured by the level of temperature in the consumer's homes or their hours of use of the appliances.

In the previous section, we showed that perfect information allows the full rent extraction from firms. However, if the same first best contracts are offered under asymmetric information, firm H can earn a positive profit by choosing the contract designed in perfect information for firm L. This result is a direct consequence of the fact that, being EE activities highly effective, the H firm can achieve the L level of comfort with lower effort cost than the L firm.

When firms have an informative advantage on the value of θ, the regulator offers a menu of incentive compatible contracts. Each contract includes the specifications of the tariff in terms of price p and fixed component F, and the level of observable comfort x that the firm must guarantee to the consumer. Formally, the regulator offers the menu of contracts (p_H, F_H, x_H) and (p_L, F_L, x_L) . In the optimal solution, the firm will self-select and choose contract (p_H, F_H, x_H) if $\theta = \theta_H$, or (p_L, F_L, x_L) if $\theta = \theta_L$. The correct self-selection of firms is ensured by the incentive compatibility of the menu of contracts. To this aim, let us consider the effort exerted by firm H. If it chooses the contract designed for firm L, the effort exerted to achieve a level x_L of comfort is

$$e_{HL} = \frac{x_L - q_L}{\theta_H}, \tag{10}$$

where the subscript HL indicates the effort that a firm of type H needs to exert to achieve a level of comfort x_L. Given that $x_L = q_L + \theta_L e_L$, espression (10) becomes:

$$e_{HL} = \frac{\theta_L}{\theta_H} e_L.$$

Indeed, as $\theta_L < \theta_H$ firm H needs to exert a lower effort than firm L to achieve the same levels of comfort x_L.

Similarly, the effort exerted by firm L to achieve a level x_H of comfort is:

$$e_{LH} = \frac{x_H - q_H}{\theta_L} = \frac{\theta_H}{\theta_L} e_H.$$

The regulator solves

$$\begin{aligned}
&\max_{q_H, e_H, q_L, e_L} \lambda[V(x_H) - D(q_H) - \alpha(C(q_H) + \psi(e_H)) - (1-\alpha)(p_H q_H + F_H)] + \\
&+(1-\lambda)[V(x_L) - D(q_L) - \alpha(C(q_L) + \psi(e_L)) - (1-\alpha)(p_L q_L + F_L)] \qquad (11) \\
&s.t. \\
&V_{x_i} = p_i \;\; \forall i \qquad (12) \\
&p_H q_H + F_H - C(q_H) - \psi(e_H) \geq 0 \qquad (13) \\
&p_L q_L + F_L - C(q_L) - \psi(e_L) \geq 0 \qquad (14) \\
&p_H q_H + F_H - C(q_H) - \psi(e_H) \geq p_L q_L + F_L - C(q_L) - \psi(e_{HL}) \qquad (15) \\
&p_L q_L + F_L - C(q_L) - \psi(e_L) \geq p_H q_H + F_H - C(q_H) - \psi(e_{LH}) \qquad (16)
\end{aligned}$$

Constraint (12) represents the demand function from (5). Constraints (13) and (14) constitute the participation constraints of firms H and L respectively. Finally, constraints (15) and (16) ensure the incentive compatibility of the contracts.

Let us focus on the incentive compatibility constraint for the H firm. Using (14), (15) becomes:

$$p_H q_H + F_H - C(q_H) - \psi(e_H) \geq p_L q_L + F_L - C(q_L) - \psi(e_L) + \psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L),$$

that is

$$p_H q_H + F_H - C(q_H) - \psi(e_H) \geq \psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L). \tag{17}$$

Given that, by assumption, $\psi' > 0$ and $e_L > \frac{\theta_L}{\theta_H} e_L$, the left hand-side of condition (17) is always strictly positive. It follows that condition (13) is not binding. It is also worth noting that equation (17) expresses the rents that must be paid to firm H to ensure the incentive compatiiblity of the menu of contracts. In particular, equation (17) implies that the informational rent paid to firm H is a decreasing function of firm L's effort.

The solution of the regulator's problem is defined in Proposition 3.

Proposition 3 *Optimal regulation under imperfect information is caracterized by the offer of the menu of contracts* (p_H, F_H, x_H) *and* (p_L, F_L, x_L) *such that*

$$\begin{aligned}
V_x(q_H) &= C'(q_H) + D'(q_H), \;\; \textit{or } q_H = q_H^* &\quad (18)\\
V_x(q_L) &= C'(q_L) + D'(q_L) &\quad (19)\\
V_x(e_H) &= \frac{\psi'(e_H)}{\theta_H}, \;\; \textit{or } e_H = e_H^* &\quad (20)\\
V_x(e_L) &= \frac{\psi'(e_L)}{\theta_L}\left(1 + \frac{\lambda}{1-\lambda}(1-\alpha)\left(1 - \frac{\theta_L}{\theta_H}\right)\right) &\quad (21)
\end{aligned}$$

Comparing the results of Proposition 3 with the ones of Proposition 1 in perfect information, we observe that in an asymmetric information setting, the regulator imposes first best effort and quantities (and consequently prices) to the H firm (no distortion at the top), so that $e_H = e_H^*$, $q_H = q_H^*$ and $p_H = p_H^*$. The L firm's effort is distorted downward by the coefficient $1 + \frac{\lambda}{1-\lambda}(1-\alpha)\left(1 - \frac{\theta_L}{\theta_H}\right) > 1$ in (21), implying $e_L < e_L^*$. Theundereffort of the L firm with respect to the first best increases the demand function in the L setting: $V_x(q_L; e_L\theta_L) < V_x(q_L; e_L^*\theta_L)$. This in turn increases the quantity consumed when the environment is L: $q_L > q_L^*$. Moreover, from (12) and (19), the price in the L environment is higher than in the first best: $p_L > p_L^*$. Finally, since rents are costly to the regulator, the L firm obtains no rent (constraint (14) is binding in the optimum), i.e. $F_L = C(q_L) + \psi(e_L) - p_L q_L < F_L^*$. Conversely, the H firm obtains a rent equal to $\psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L)$, so that the H firm's fixed transfer is higher than the one in first best: $F_H = C(q_H^*) + \psi(e_H^*) - p_H^* q_H^* + \psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L) > F_H^*$.

The result of Proposition 3 presents two typical characteristics of the literature on regulation under imperfect information. They can be summarized as follows: optimal regulation under imperfect information entails

- an efficient level of effort and positive rents for type H;
- undereffort and no rents for type L.

The incentive compatibility of the menu of contracts is ensured by the provision to the H firm of informational rents. These rents are increasing with the effort exerted by the L firm. As a consequence, the reduction of rents passes through the downward distortion of e_L. The optimal trade off between rent extraction and efficiency can be intuitively derived as follows. Reducing e_L by one unit has three effects. First, the marginal benefit on the consumer's comfort in the L environment is reduced by $\theta_L V_x$. Second, the effort cost of the L firm is reduced by ψ'. Third, type H's rent decreases by $\psi' - \frac{\theta_L}{\theta_H}\psi'$. The unit social cost of the firm's rents is $(1-\alpha)$, as they reduce the consumers' surplus, whose weight in the welfare function 1, but increase the firm's profits, which instead weight α. The probability of type H is λ, so that the expected social gain in rent reduction rents is $\lambda(1-\alpha)\left(\psi' - \frac{\theta_L}{\theta_H}\psi'\right)$. Similarly, the expected reduction of consumer comfort is $(1-\lambda)\theta_L V_x$ and the expected reduction of effort costs is $(1-\lambda)\ \psi'$. The marginal cost in terms of reduction of consumer's utility is equal to the marginal benefit iin terms of rent reduction and decrease of effort cost when

$$(1-\lambda)\theta_L V_x = (1-\lambda)\psi' + \lambda(1-\alpha)\left(\psi' - \frac{\theta_L}{\theta_H}\psi'\right),$$

which leads to the optimal condition (21).

The introduction of the firm's profit into the regulator's objective function reduces the distortion of the effort of the inefficient firm. In the limit case in which the firm's profits have the same weight than the consumer's suprlus (i.e., $\alpha = 1$), the optimal result with asymmetric information replicates the first best outcome in terms of effort. Indeed, the distortion of the firm's effort is necessary to reduce its rents. However, if the rents increase the welfare, the need to reduce them is less pressing. Conversely, the effort e_L is subjected to the highest downward distortion when the firm's profits have no consequence on the social welfare, i.e. $\alpha = 0$.

The tariff structure under imperfect information has important policy implications. Given that $F_H > F_H^* > F_L^* > F_L$ and that $p_L > p_L^* > p_H^* = p_H$, asymmetric information, compared to the perfect information setting, strenghtens the pressure toward a decoupling policy for the H firm and toward the standard regulation for the L firm. In perfect information, the effort e_L^* of the L firm is already lower than e_H^* due to its lower maginal benefit in terms of demand reduction. When asymmetric information issues are introduced, the effort of the L firm must be further distorted downward with the objective of rent reduction. This further polarizes the menu offered toward the extreme policies of a standard per unit regulated tariff and decoupling.

This result contributes to the debate of whether decoupling or standard policies are to be adopted in order to induce energy efficiency. A decoupling policy is socially preferable if EE activities are highly effective. In contrast, standard regulation is to be preferred if EE activities have a small impact on demand.

5 Extension: the consumer's effort

When energy conservation issues are considered, the firm has certainly an important role, as it can for example promote a more energy-conscious behaviour by customers or adopt initiatives that go in that direction. However, the customer's responsibility cannot be discounted. Up until now, we examined how the customer can be induced to energy conservation simply through the instrument of the price. This kind of approach overlooks the fact that EE actions can be undertaken not only by firms, but by customers themselves. For example, a customer may decide to purchase energy saving appliances or shift as much as possible of her consumption during off-peak hours. If not only firms, but also customers can exert effort in energy conservation activities, the regulator's problem becomes that of allocating in the most efficient way the right amount of effort on the two parties. Ideally, a EE initiative should be adopted by the one for whom it is less costly. In this framework, the price has an additional role, as it can help the regulator to induce customers to exert energy-saving effort. Indeed, it is a common occurrence for a customer to trade-off the extra-expenditure of investing in energy-efficiency with a higher expenditure on the energy bill.

To best analyze this case, we abstract from asymmetric information issues, so as to focus on the optimal allocation of EE activities between customers and firms and the tariff that can achieve that allocation.

Suppose that the consumer's comfort x is defined as $x = q + \theta(e_f + e_c + \beta e_f e_c)$, where e_f and e_c are the efforts exerted by the firm an the consumer respectively and q is the quantity consumed. The parameter β indicates the degree of substitutability between the activities undertaken by firms and customers: the activities are substitutes (negative externality) for $\beta < 0$, as the effort exerted by the consumer's reduces the firm's incentive to do the same because of the negative component $\beta e_f e_c$, or can be complement (positive externality) for $\beta > 0$. The effort for the consumer has a cost $K(e_c)$, with $K(0) = 0$, $K' > 0$, $K'' > 0$.

Consumers choose the quantity q and the effort e_c that maximixe their net surplus $V(x) - pq - F - K(e_c)$. It follows that the effort exerted by the consumers is such that $V_x\theta(1 + \beta e_f) = K'(e_c)$.

In the first best situation we are studying, the regulator solves

$$\max_{q,e} V(x) - pq - F - K(e_c) - D(q) + \alpha\pi(q, e_f)$$

$$s.t.$$

$$\pi(q, e) = pq + F - C(q) - \psi(e_f) \geq 0 \tag{22}$$

$$V_x = p \tag{23}$$

$$V_x = \frac{K'(e_c)}{\theta(1 + \beta e_f)} \tag{24}$$

Equation (22) represents the firm's participation constraint, equation (23) is the demand function and equation (24) describes the consumer's choice of effort e_c. The first best quantity q^* and efforts e_f^* and e_c^* are defined as follows:

$$q^* : V_x(q) = C'(q) + D'(q) \tag{25}$$

$$e_f^* : V_x(e_f) = \frac{\psi'(e_f)}{\theta(1 + \beta e_c)} \tag{26}$$

$$e_c^* : V_x(e_c) = \frac{K'(e_c)}{\theta(1 + \beta e_f)} \tag{27}$$

$$p^* = V_x(q^*, e_f^*, e_c^*) \tag{28}$$

$$F^* = C(q^*) + \psi(e_f^*) - p^*q^* \tag{29}$$

Notice that the regulator's preferred level of effort e_c^* coincides with the consumer's autonomous choice of effort. This result is no coincidence, and it follows directly from primary weight that the consumer's surplus has into the the regulator's objective, which fully aligns the objectives between regulator and consumers.

A first immediate result from the optimal conditions from (25) to (29) is that, if $K(\cdot) = \psi(\cdot)$, from (26) and (27) we obtain that $e_f^* = e_c^*$. The reason for this result is straighforward. Given that the weight of the firm's profit is lower than that of the consumer's surplus in the regulator's objective, the first best outcome implies zero profits for the firm, and the welfare function can be rewritten as $V(x) - K(e_c) - C(q) - \psi(e_f) - D(q)$. The same weight of the consumer's and firm's effort cost in the welfare function explains why, if these cost functions are identical, the first best outcome entails the same effort by both consumers and the firm.

To fully understand the implications of the first best outcome, we now present some comparative statics, whose results are summarized in the following proposition for the case characterized by the absence of externalities ($\beta = 0$).

Proposition 4 *Ceteris paribus, if $\beta = 0$, both the optimal quantity q^* and the price p^* increase and both optimal level of comfort x^* and the total effort $e^* = e_f^* + e_c^*$ decrease when:*

a. *the consumer's effort costs $K(\cdot)$ increase; in this case, e_f^* increases and e_c^* decreases;*

b. *the firm's effort costs $\psi(\cdot)$ increase; in this case, e_c^* increases and e_f^* decreases;*

c. *the effectiveness θ of EE effort decreases; in this case, both e_c^* and e_f^* decrease.*

Let us focus on the first point of Proposition 4 and denote the initial functions of the effort cost as $\bar{\psi}(\cdot)$ and $\bar{K}(\cdot)$, with $\bar{\psi}(\cdot) = \bar{K}(\cdot)$, and the relative effort and price as, respectively, $\bar{e}^*$ and $\bar{p}^* = V_x(q^*, \bar{e}^*, \bar{e}^*)$.

If $K(\cdot)$ increases (i.e., $K(\cdot) > \bar{\psi}(\cdot)$), then it is optimal to distort both efforts, in such a way that $e_c^* < \bar{e}^* < e_f^*$. The reason for which e_c^* is reduced is obvious, and it is related to the increase of its direct costs. To explain the increase of the firm's effort, we must take into account that, given that the consumer's contribution is now lower in terms of effort, the marginal benefit of an additional unit of the firms' effort is higher. From (26), the optimal level of the firm's effort is when its marginal cost ($\psi'(e_f)$) is equal to its marginal benefit ($\theta V_x(e_f; e_c, q)$); since its marginal benefits have now increased, it is optimal to increase the level e_f^* of the firm's effort with respect to $\bar{e}^*$. In other words, the reduction of e_c^* due to its higher costs is partially compensated by an increase of e_f^*. Moreover, when the cost of the consumer's effort increases, the price is set at a higher level: $p^* > \bar{p}^*$. This occurs because, due to the higher costs of the EE activities, the consumer tends to invest less in them, and rely more on consumption to realize her comfort. This is counter-productive in terms of energy-conservation goals. To induce the consumer to limit the quantity of energy consumed, the regulator increases the price. Notice that in a perfect information framework, the price loses its role of incentive for the firm, as the firm's effort can be perfectly observed. In this case, the increase of the price only reduces the fixed fee, so that the firm's profit remains zero, with no retro-effect on the firm's effort. The increase of the consumer's effort cost also entails a reduction of the optimal level of comfort x^* and the increase of the quantity q^* consumed –from equation (25).

The opposite outcome in terms of efforts can be achieved when $\psi(\cdot)$ increases, as in this case it results $e_f^* < \bar{e}^* < e_c^*$ and $p^* > \bar{p}^*$. The intuition is analogous to the one just provided. Given that $\psi(\cdot) > K(\cdot) = \bar{K}(\cdot)$, the regulator requires less effort from firms. The lower effort by firms raises the marginal benefit of one unit of consumer's effort, so that, even if the cost of the consumer's effort remains unvaried, it is optimal to increase e_c^* above the initial level $\bar{e}^*$. The decrease of the total effort ($e_f^* + e_c^* < 2\bar{e}^*$) increases the consumer's demand. An increase in price is then necessay to induce consumers to reduce their consumption and partially oppose the increase of demand produced by the lower efforts.

Conversely, starting from a situation in which $K(\cdot) = \psi(\cdot)$, a decrease of $K(\cdot)$ entails $e_f^* < \bar{e}^* < e_c^*$ and a decrease of the price $p^* > \bar{p}^*$:

The effort costs are not the only parameters with an impact on the first best outcome. The effectiveness of the EE activities, embodied by the parameter θ, has an influence as well. The higher is θ, the higher is the marginal benefit produced by the efforts – from (26) and (27) – and, consequently, the higher are both e_f^* and e_c^*, so as to best exploit their higher efficacy. Due to the increase of the efforts, the consumer is able to reduce the quantity consumed q^*. The reduction of demand reduces also the social cost of its provision, and this is reflected by the decrease of the price, so that the higher is θ, the lower is the price. Moreover, thanks to the higher effectiveness of EE activities, the consumer is able to increase her comfort despite lower consumptions, because of the higher effort exerted by both herself and the firm and their high effectiveness. This result confirms what we obtained in the previous sections, as the policy with highly effective EE activities entails higher comfort and lower consumption in the H environment.

If $\beta \neq 0$, the optimal policy must take into account the externality generated by the EE activities of consumers and firms. We thus have the following result.

Proposition 5 *Ceteris paribus, if β increases, both the optimal quantity q^* and the price p^* decrease and both optimal level of comfort x^* and the total effort $e^* = e_f^* + e_c^*$ increase.*

The result of Proposition 5 has a straightforward interpretation. If β increases, a positive externality is created and to exploit it, the efforts are increased. The increase of efforts allows consumers to reduce the quantity consumed –more precisely, it reduces the marginal benefit of one additional unit of consumption, which in turn reduces the quantity consumed in the optimum. The reduction of the optimal quantity implies lower marginal social costs ($C'(\cdot)+D'(\cdot)$). The price must then be diminished, so as to reflect the lower social costs and thus induce the consumer to choose the optimal quantity. When efforts are complement, meaning that the effort of say the firm generates a positive effects also on the consumers' effort, then the regulator may prefer to set a lower price and a larger fixed component, hence moving towards a decoupling policy, to promote energy efficiency activities.

On the contrary, when efforts are substitute, the regulator may prefer to increase the regulated price and decrease the fixed component in order to reduce overall consumption given that efforts in energy conservation activities are reduced.

The fact that β is different from zero has interesting implications when a variation of the degree of substitutability is combined with the increase in effort costs, whose effects are described in Proposition 4. In Proposition 4, we showed that, when $\beta = 0$, an increase of $K(\cdot)$ reduces the consumer's effort and increases the firm's. It may no longer be so (or not at the same extent) when $\beta > 0$. Indeed, when $\beta > 0$, the reduction of e_c^* has a negative effect on the total effort $e_f+e_c+\beta e_f e_c$, which is amplified by the shrink of the additional component $\beta e_f e_c$. The fact that the consumer's and the firm's efforts are complement activities implies that the reduction of e_c^* cannot be as pronounced as when $\beta = 0$, so as to exploit the effect of the positive component $\beta e_f e_c$. Moreover, the decrease of e_c^* implies also a lower increase of e_f^*, due to the complementarity between them. The higher is β, the smaller are both the decrease of e_c^* and the increase of e_f^*. Furthermore, if externalities are present, the total effort, after the increase of its cost, is not reduced as much as when externalities are absent. Indeed, the increase of the effort cost would normally induce the regulator to give up pursuing some EE goals, and rely more on consumption to provide the consumer's comfort. However, when EE activities present a positive externality (but the same reasoning is valid when they are highly effective –θ is high), the regulator prefers to continue stimulating the effort in EE activities and keep consumptions low, even when the cost of effort increases. To a smaller decrease of the total effort in turn corresponds a smaller increase of the quantity consumed and consequently a smaller increase of the price, reflecting the smaller increase of the marginal social cost.

It is important to remark that the sign of β is relevant for these results. When $\beta < 0$, indicating substitute efforts, the reduction of e_c^* and increase of e_f^* caused by the increase of the consumer's effort costs $K(\cdot)$ is amplified with respect to the case in which $\beta = 0$. Indeed, the two kinds of effort in this situation are substitutes: the decrease of e_c^* strenghtens the increase of e_f^*, and in turn the increase of e_f^* strenghtens the decrease of

e_f^*. This happens because the decrease of the effort exerted by the consumer's reduces the negative component $\beta e_f e_c$, and this increases the firm's incentive to exert its own effort e_f^*.

When $\beta < 0$, an increase of θ does not produce a definite outcome in terms of effort and price. The reason is that a higher effectiveness of the EE effort is a favourable circumstance only if the total effort increases. However, when the negative externality is very strong ($|\beta|$ is sufficiently large), the increase of the individual efforts produces a decrease of the total effort due to the large negative component $\beta e_f e_c$. In this case, to best exploit the higher effectiveness of EE activities, the individual efforts must be reduced. A reduction of the total effort implies in turn higher quantities and higher prices. However, the outcome in this case strongly depends on the extent of the variations of the parameters and on how large is the negative externality.

6 Conclusions

The tariff used to regulate a utility not only accounts for its revenues and profits, but it is also an important instrument of demand regulation. The latter aspect is especially relevant when energy conservation goals are introduced in the regulator's objectives. Quite surprisingly, the role of the price as an incentive to energy conservation has so far received scant attention by the literature, which has rather focused on the incentive schemes to be provided to the firms (decoupling policies or gain sharing plans), thus employing a supply-side perspective. The issue of inducing energy conservation through the price is a delicate matter, as an increase of the energy price on one side induces consumers to reduce their demand, but on the other side it increases the firm's marginal loss for any unit of energy unsold, thus reducing the utility's incentives to further promote energy conservation. The choice of price thus allocates the incentives to energy conservation between consumers and firms.

Energy efficiency activities may have a variable impact on demand. For example, the simple promotion of a more responsible, energy-saving behaviour may be less effective –in terms of demand reduction– than the actual installation of energy-saving devices at the consumers' premises. We find that the higher is the effectiveness of the firm's energy efficiency effort, the more cost-efficient is to have firms bearing most of the responsibility for energy conservation. To this aim, the optimal tariff requires consumers to pay a significant fixed fee, but a relatively low price per unit of energy consumed. This solution, that approximates a decoupling policy, provides strong incentives to the firm to exert energy conservation effort –which is highly effective–, in two ways. First, because of the significant fixed component in the tariff, the frms' revenues are mostly independent from the volume sold. Second, the low price implies low marginal costs for any quantity unsold. When instead the firm's energy efficiency effort has a low impact on demand reduction, consumers should pay a high per unit price but a low fixed fee. The reason, once again, is quite intuitive. As the firm's effort is costly but has a low potential in terms of demand reduction, the energy conservation goal is best achieved by operating directly on consumers, and specifically by reducing their demand through a high price. This high price reduces the incentives for the firm to promote EE activities, but due to their high cost this is consistent with a welfare maximizing solution.

When the firm is privately informed about the effectiveness of the EE activities, the regulator has an additional problem, that is to extract the firm's information, given that a firm in the high effectiveness environment has always an incentive to underperform in effort and explain the high consumptions with a scarcely responsive demand. This hidden information problem can be solved by offering to the firm a menu of contracts, designed in such a way that the firm correctly self-select on the basis of its information. The tariff designed for the high effectiveness environment coincides with the one offered in the perfect information benchmark –thus replicating the no-distortion at the top result of traditional regulation models. Conversely, the tariff designed for the low effectiveness environment distorts downward the firm's effort, further increasing the unit price. With imperfect information, a trade-off emerges between rent reduction and efficiency. The firm in the high effectiveness setting obtains a rent by pretenting a low impact of its effort on demand. This rent is directly proportional to the effort exerted by the firm in low effectiveness environment. To lessen the informational rent of the former, it is necessary to reduce the effort of the latter.

Althought the adoption of smart meters can help regulators to make the consumer's comfort observable, their diffusion - at least in some countries - is still limited. It would then be worthwhile to explore the case in which asymmetric information extends to the consumer's comfort. The impossibility to contract over the consumer's comfort introduces a critical complication, as it eliminates one instrument of regulation. Without a binding target of comfort to achieve, utilities lack the incentive to invest in costly and demand–reducing effort. New regulatory instruments need thus to be introduced. Finally, a comprehensive model should also incorporate all the externalities of energy efficiency activities and should consider a more general setting where more than one policy tools might be available, for example not only regulated tariffs but also tradable permission. We leave these interesting extensions to future analysis.

7 Appendix

Proof of Proposition 1. The lagrangean function is $\mathcal{L}$=$V(x_j) - p_j q_j - F_j - D(q_j) +$

$\alpha\pi_j(q_j, e_j) + \lambda(p_j q_j + F_j - C(q_j) - \psi(e_j))$, where λ is the lagrangean multiplier. As it must be $\pi_j(q_j, e_j) = 0$, the objective function becomes $V(x_j) - C(q_j) - \psi(e_j) - D(q_j)$ which, derived by q_j and e_j, leads to the conditions in Proposition 1. ■

Proof of Lemma 1. The proof will proceed by absurd. Suppose, instead, that $e_H^*\theta_H < e_L^*\theta_L$. Then, given that by assumption $\theta_H > \theta_L$, it must be $e_H^* < e_L^*$. Moreover, $V_x(q)$ is a decreasing function of $e\theta$ for a given level of q: $\frac{\partial V_x}{\partial(e\theta)} = \frac{\partial V_x}{\partial x}\frac{\partial x}{\partial(e\theta)} = V_{xx}\cdot 1 < 0$. Since $e_H^*\theta_H < e_L^*\theta_L$ by hypotesis, $\frac{\partial V_x}{\partial(e\theta)} < 0$ implies that $V_x(q; e_H^*\theta_H) > V_x(q; e_L^*\theta_L)$ for all q. The optimal quantity q_j^* is the solution of condition (6). Since $V_x(q; e_H^*\theta_H) > V_x(q; e_L^*\theta_L)$ for all q, then, from (6), $q_H^* > q_L^*$. Given that we assumed $\frac{d^2(C*D)}{dq^2} > 0$, $q_H^* > q_L^*$ implies $C'(q_H^*) + D'(q_H^*) > C'(q_L^*) + D'(q_L^*)$. From conditions (3) and (6), it follows that $p_H^* > p_L^*$. $V_x(e)$ is a decreasing function of q for a given level of e: $\frac{\partial V_x}{\partial q} = \frac{\partial V_x}{\partial x}\frac{\partial x}{\partial q} = V_{xx}\cdot 1 < 0$. Since $q_H^* > q_L^*$, $\frac{\partial V_x}{\partial q} < 0$ implies that $V_x(e; q_H^*) < V_x(e; q_L^*)$ for all e. Moreover, $\psi'(e)/\theta_H < \psi'(e)/\theta_L$. The optimal effort e_j^* is the solution of condition (7). Since $V_x(e; q_H^*) < V_x(e; q_L^*)$ for all e, and $\psi'(e)/\theta_H < \psi'(e)/\theta_L$ for all e, then (3) and (7) imply that $p_H^* < p_L^*$, which is a contradiction. ■

Proof of Proposition 2. From Lemma 1, $e_H^*\theta_H > e_L^*\theta_L$. Then, $V_x(q; e_H^*\theta_H) < V_x(q; e_L^*\theta_L)$ for all q. It follows that, from (6), $q_H^* < q_L^*$. Moreover, from conditions (3) and (6), $p_H^* < p_L^*$. Given that $q_H^* < q_L^*$, it must be $V_x(e; q_H^*) > V_x(e; q_L^*)$ for all e. Moreover, as $\theta_H > \theta_L$, $\psi'(e)/\theta_H < \psi'(e)/\theta_L$ for all e. It follows that $e_H^* > e_L^*$.

From (5), x_H^* must be such that $V_x(x) = p_H^*$ and x_L^* must be such that $V_x(x) = p_L^*$. Since $p_H^* < p_L^*$ and $V_{xx} < 0$, then $x_H^* > x_L^*$.

$F_j^* = -p_j^* q_j^* + C(q_j^*) + \psi(e_j^*)$. Since production entails unvariant fixed cost, and $q_H^* < q_L^*$, $p_H^* < p_L^*$, then it must be that $p_H^* q_H^* - C(q_H^*) < p_L^* q_L^* - C(q_L^*)$. Moreover, since $e_H^* > e_L^*$, then $\psi(e_H^*) > \psi(e_L^*)$. Hence, $F_H^* > F_L^*$. ■

Proof of Proposition 3. Assuming that only constraints (14) and (15) –i.e., the participation constraint of the L firm and the incentive compatibility of the H firm– are binding in the optimum, and substituting them into the objective function, the regulator's maximizes:

$$\lambda[V(x_H) - D(q_H) - \alpha(C(q_H) + \psi(e_H)) - (1-\alpha)(C(q_H) + \psi(e_H) + \psi(e_L) - \psi(\frac{\theta_L}{\theta_H}e_L)] +$$
$$+(1-\lambda)[V(x_L) - D(q_L) - \alpha(C(q_L) + \psi(e_L)) - (1-\alpha)(C(q_L) + \psi(e_L))]$$

which, derived by q_H, e_H, q_L and e_L, leads to the conditions in Proposition 3.

We now verify that contraints (13) and (16) are not binding in the optimum. From (17), $p_H q_H + F_H - C(q_H) - \psi(e_H) \geq \psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L) > 0$ as $\frac{\theta_L}{\theta_H} < 1$ and $\psi' > 0$. Moreover, (16) can be rewritten as $p_L q_L + F_L - C(q_L) - \psi(e_L) \geq p_H q_H + F_H - C(q_H) - \psi(e_H) + \psi(e_H) - \psi(e_{LH})$. If (14) and (15) are binding, then it becomes $0 \geq \psi(e_L) - \psi(\frac{\theta_L}{\theta_H} e_L) + \psi(e_H) - \psi(\frac{\theta_H}{\theta_L} e_H)$ which is always satisfied for $e_L < e_H$. It follows that (16) is not binding in the optimal solution. ■

Proof of Proposition 4.

a. The proof will proceed by absurd. Suppose, instead, that e^* increases. Then, given that $V_x(q, e^*)$ is a decreasing function of e^* for a given level of q (as $\frac{\partial V_x}{\partial (e^*)} = \frac{\partial V_x}{\partial x} \frac{\partial x}{\partial (e^*)} = V_{xx} \cdot \theta < 0$), $V_x(q, e^*)$ must decrease for all q. The optimal quantity q^* is the solution of condition (25). Since $V_x(q, e^*)$ decreases for all q, then, from (25), q^* decreases. Given that we assumed $\frac{d^2(C*D)}{dq^2} > 0$, a decrease of q^* implies the decrease of $C'(q^*) + D'(q^*)$. From (25) and (28), it follows that p^* decreases as well. The optimal effort e_c^* is the solution of condition (27). Since p^* decreases and, from (27), $p^* = \frac{K'(e_c)}{\theta}$, then the assumed increase of $K'(e_c)$ implies a lower e_c^*. Moreover, the optimal effort e_f^* is the solution of condition (26). Since p^* decreases and, from (26), $p^* = \frac{\psi'(e_f)}{\theta}$, then e_f^* decreases. But, if both e_c^* and e_f^* decrease, then the assumed increase of e^* is a contradiction.

So, when $K(\cdot)$ increases, e^* decreases. Then, from (25), q^* increases and, from (28), p^* increases. Given that $V' > 0$ and $V'' < 0$, x^* is reduced. Since p^* increases and, from (26), $p^* = \frac{\psi'(e_f)}{\theta}$, then e_f^* increases. Given that $e^* = e_c^* + e_f^*$, and that e^* decreases while e_f^* increases, then e_c^* is reduced.

b. When $\psi(\cdot)$ increases, e^* decreases (see proof by absurd in the previous point). Then, from (25), q^* increases and, from (28), p^* increases. Given that $V' > 0$ and $V'' < 0$, x^* is reduced. Since p^* increases and, from (26), $p^* = \frac{K'(e_c)}{\theta}$, then e_c^* increases. Given that $e^* = e_c^* + e_f^*$, and that e^* decreases while e_c^* increases, then e_f^* is reduced.

c. The proof will proceed by absurd. Suppose, instead, that e^* increases. Then, given that $V_x(q, e^*)$ is a decreasing function of e^* for a given level of q (as $\frac{\partial V_x}{\partial (e^*)} = \frac{\partial V_x}{\partial x} \frac{\partial x}{\partial (e^*)} = V_{xx} \cdot \theta < 0$), $V_x(q, e^*)$ must decrease for all q. The optimal quantity q^* is the solution of condition (25). Since $V_x(q, e^*)$ decreases for all q, then, from (25), q^* decreases. Given that we assumed $\frac{d^2(C*D)}{dq^2} > 0$, a decrease of q^* implies the decrease of $C'(q^*) + D'(q^*)$. From (25) and (28), it follows that p^* decreases as well. The optimal effort e_c^* is the solution of condition (27). Since p^* decreases and, from (27), $p^* = \frac{K'(e_c)}{\theta} = \frac{\psi'(e_f)}{\theta}$, then the assumed decrease of θ implies lower e_c^* and e_f^*, which contradicts the initial hypothesis of the increase of e^*.

So, when θ decreases, e^* decreases. Then, from (25), q^* increases and, from (28), p^* increases. Given that $V' > 0$ and $V'' < 0$, x^* is reduced. Since p^* increases and, from (26), $p^* = \frac{\psi'(e_f)}{\theta} = \frac{K'(e_c)}{\theta}$, then both e_f^* and e_c^* decrease.

■

Proof of Proposition 5. The proof will proceed by absurd. Suppose, instead, that e^* decreases. Then, given that $V_x(q, e^*)$ is a decreasing function of e^* for a given level of q, $V_x(q, e^*)$ must increase for all q. The optimal quantity q^* is the solution of condition (25). Since $V_x(q, e^*)$ increases for all q, then, from (25), q^* increases. Given that we assumed $\frac{d^2(C*D)}{dq^2} > 0$, an increase of q^* implies the increase of $C'(q^*) + D'(q^*)$. From (25) and (28), it follows that p^* increases as well. The optimal efforts e_f^* and e_c^* are the solution of conditions (26) and (27). Since p^* increases and, from (28), $p^* = \frac{K'(e_c)}{\theta(1+\beta e_f)} = \frac{\psi'(e_f)}{\theta(1+\beta e_c)}$, then the assumed increase of β implies higher e_c^* and e_f^*, which contradicts the initial hypothesis of the decrease of e^*. So, when β increases, e^* increases. Then, from (25), q^* decreases and, from (28), p^* decreases. Given that $V' > 0$ and $V'' < 0$, x^* is larger. ■

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