Energy Efficiency and Price Regulation*

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Abstract

This paper examines the incentives embedded across different regulatory regimes – price cap, rate of return and mandated target regulation – for investment in energy efficiency programs at the supplier's end of the network. In our model, a monopolist chooses whether or not to undertake an investment in energy efficiency, which is not observable by the regulator. We explore how the monopolist's choice of effort changes under different regulatory regimes. We show that, in equilibrium, the monopolist chooses to exert positive effort more often under price cap regulation than under no regulation or mandated target regulation and that she exerts no effort under rate of return regulation. In terms of expected welfare, however, the results are ambiguous and complex. In particular, we provide a full characterisation of the optimal effort, optimal prices (regulated or unregulated) and expected welfare for the different regimes and show the trade-offs between rent extraction and incentives.

1 Introduction

Energy efficiency programs have returned to the forefront of public policy. Such public interest in energy efficiency programs had not been seen since their introduction in

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the 1970s as a response to the oil shocks. Energy efficiency is seen today as a cost-effective approach to sustainable energy use and greenhouse gas emissions reductions. For instance, Metz (2001) argues that energy efficiency improvement could potentially contribute to half of greenhouse emission reduction by 2020.

Despite their high profile, energy efficiency opportunities have by and large not been materialised (Interlaboratory Working Group, 2000). This is particularly the case in the electricity sector where between 20 and 60 per cent of total electricity used could be conserved by cost effective initiatives (Greenstone & Allcott, 2012). Although there are demand side management (DSM) programs[1] that reduce consumption by a kilowatt-hour at a cost lower than the cost of supplying that electricity, they are not widely used (Freeman *et al.* , 2010). There are several reasons why this may be the case. First, electricity suppliers (especially network service providers) need to invest in a range of infrastructure that is required to integrate distributed energy resources, including energy storage technologies, the digital hardware and software for improving transmission and distribution system reliability and security, and the supply-side and customer-side systems needed for full customer connectivity (Lester & Hart, 2012). Second, these firms operate in a regulated environment where prices are usually set by a regulatory agency or government department that may not reward such investments by not considering them prudent or efficient. Finally, investment in energy efficiency may not be recouped if demand for electricity falls in the future or if the regulatory regime changes.

It follows then that electricity suppliers need to be incentivised to undertake energy efficiency investment. Key policies promoting energy efficiency in the electricity sector include taxes, cap-and-trade systems and direct regulation of the firms' operation. Creating incentives for suppliers/distributors to undertake energy efficiency initiatives can be complex as these incentives interact with the form of price regulation. For example, in a context where firms are allowed to recover, via prices, all the costs of supplying electricity to consumers, regulated firms may have little incentive to undertake energy efficiency investment. The interaction between price regulation and incentives for energy efficiency is the subject of this paper.

In particular, we analyse the incentives for energy efficiency embedded across different regulatory regime – rate of return, price cap and mandated target regulation.

[1] DSM programs aim at both reducing consumers' absolute electricity usage and shifting it from peak to off peak periods. Examples include enticements for consumers to acquire more energy efficient electrical appliances and real time pricing of electricity consumption.

The interaction between price regulation and incentives for energy efficiency is an important public policy issue and the subject of this paper. We pursue this by building a theoretical model of a monopolist who can choose whether or not to undertake an investment in energy efficiency. The investment is not observable by the regulator who can only determine whether the investment has been successful in terms of the level of energy efficiency achieved. More specifically, the firm's choice of effort affects the probability of a successful outcome with a higher effort resulting in a higher probability of achieving a better energy efficiency outcome.

In this setting, regulatory regimes cannot explicitly compensate the firm for the effort it has put into energy efficiency. We explore how different existing regulatory regimes perform in terms of expected amount of energy efficiency and total welfare. In particular, we show, not surprisingly, that the monopolist chooses to exert effort more often under price cap regulation than under no regulation and that she exerts no effort under rate of return regulation. While we can show that price cap regulation dominates an unregulated monopolist in terms of expected welfare, the comparison between price cap and rate of return regulation, and between rate of return regulation and an unregulated monopolist, is ambiguous and complex. For example, when choosing low effort is optimal regardless of the form of regulation, then price cap regulation always dominates an unregulated monopolist – both set prices ex-ante (that is, prior to the realisation of the energy efficiency outcome) and prices are lower under price cap regulation.

The comparison between rate of return regulation and price cap regulation and that between rate of return regulation and no regulation are subtler. Rate of return regulation sets prices ex-post, conditional on the realisation of the energy efficiency outcome, so that profits are ex-post zero. This means that rate of return regulated prices can be either higher or lower than those under price cap regulation or no regulation. It follows that the regime which will yield the highest expected welfare will depend on demand, costs and the weight assigned by the regulator to the monopolist's profits in total surplus. We show, however, that mandated target regulation is always dominated by both price cap and rate of return regulation in terms of expected welfare although it can do better than an unregulated monopolist. The key reason is that mandated target regulation is too coarse and the trade off between providing incentives to invest in energy efficiency and rent extraction is less pronounced than under existing regulatory regimes such as price cap and rate of return regulation. More generally, we provide a full characterisation of the optimal effort, optimal prices (regulated or unregulated) and expected welfare for the different regimes and show the trade-offs between rent extraction and incentives.

This paper is organised as follows. Section 2 describes the key elements of the model. Section 3 develops the benchmark case of an unregulated monopolist's choice of optimal effort and profit-maximising quantity and price. In Section 4, we characterise outcomes under three distinct regulatory regimes, namely, rate of return, price cap and mandated target regulations. Section 5 compares the welfare under the different regulatory regimes, while Section 6 concludes.

1.1 Related Literature

Wirl (1995) examines the impact of regulation on DSM programs in a setting where electricity demand depends on service demand – the product of electricity usage and the energy efficiency of the appliances. The regulated firm aims to maximise profits which are equal to the electricity sales revenue minus the electricity supply cost and investment in incremental energy efficiency. Wirl (1995) shows that rate of return regulation fails to provide incentives for the firm to undertake DSM. This is a direct result of the incentives that firms regulated under rate of return regulation face to maximise total quantity sold (as the regulated price is greater than their incremental cost). Nevertheless, when combined with a shared savings mechanism, where the firm is allowed to share some of the benefits accruing to consumers, rate of return regulation can lead to incentives for provision of DSM programs. The type of energy efficiency program offered by the regulated firm, however, would favour high consumption rather than energy conservation. For example, the regulated firm would favour programs with high rebound effect – which refers to consumers' response to more efficient appliances with more rather than less electricity consumption – such as providing more efficient lighting and air conditioning. Doing so would result in consumers using more lighting in their gardens or setting lower temperatures in their living rooms.

In contrast, Wirl (1995) shows that, under price cap regulation, the regulated firm may choose to invest in energy efficiency at the consumer's premises to mitigate the losses when consumers are sold electricity at below cost prices. Otherwise, the same issue as in rate of return regulation arises – a regulated firm has an incentive to maximise quantity of electricity sold as long as the regulated price cap is above its incremental cost of supplying electricity. This suggests that to incentivise regulated firms to invest in energy efficiency requires decoupling revenue from quantity (Eto *et al.* , 1997; Brennan, 2010; Sullivan *et al.* , 2011). We also investigate the incentives embedded in different regulatory regimes but focus on energy efficiency at the supplier's end of the network rather than at the consumer's side.

Eom (2009) and Chu & Sappington (2012) analyse a shared-savings incentive mechanism for energy efficiency programs with an energy saving target and investigate the design of a plan that maximises net social welfare. Chu & Sappington (2013) extend the analysis by considering a nonlinear reward structure. All the studies assume that effort to provide energy efficiency is unobservable by the regulator and take into account of impact of asymmetric information between the regulator and the regulated firm in the provision of energy efficiency programs. They suppose there is a positive relationship between effort and the resulting energy efficiency, and show that there is no simple, standard financial reward structure that will always induce the desired level of energy efficiency effort in all settings, as many factors may impact on the incentive mechanism, for instance, energy price, magnitude of rebound effect and extent of observable energy efficiency investment. In contrast, we examine the case where there is a probabilistic relationship between effort and the actual amount of energy efficiency achieved. This results in moral hazard and we investigate its impact on existing regulatory regimes rather than focus on the design of an optimal incentive scheme.

Finally, the existing literature on mandated targets focuses on standards for household appliances (Daniel, 1980; Einhorn, 1982) and on the mandated quantitative targets for reducing energy use (Satchwell & Cappers, 2011; Brennan & Palmer, 2013; Palmer *et al.* , 2013). There are, however, very few analytical studies. Exceptions include Satchwell & Cappers (2011) and Brennan & Palmer (2013). Satchwell & Cappers (2011) analyse the financial impacts of the US Energy Efficiency Resource Standards (EERS) program on a specific regulated firm, while Brennan & Palmer (2013) examine the economics of EERS by comparing with alternative measures such as energy taxes and cap-and-trade systems[2]. In contrast, we compare the power (and efficiency) of the incentives for energy efficiency embedded in mandated target regulation with that of price cap and rate of return regulation.

[2]The study by Brennan & Palmer (2013) found that EERS is not an optimal option when the policy goal is reducing energy use rather than reducing emissions. What's more, an EERS could be optimal when marginal external harm falls with greater energy use.

2 The Model

We consider a monopolist that supplies electricity to final consumers. For simplicity, the demand function for electricity in the market is assumed to be linear, and the inverse demand function is given by:

$$P(Q) = a - bQ, \text{ with } a > 0,\, b > 0,$$

where Q denotes the amount of electricity that could be consumed by end users, and P is unit retail price of electricity. The monopolist can purchase wholesale electricity at a fixed price $c > 0$ and faces no fixed costs. In order to supply Q units of electricity to consumers the monopolist needs to purchase Q_s units in the wholesale market. In general, due to network losses, $Q < Q_s$. By exerting effort $E = \{0, e\}$ the monopolist can improve energy efficiency by optimising the operation of the network[3]. In particular, we denote by $\Phi(E) = \frac{Q}{Q_s}$ the energy efficiency parameter, which is a function of effort and can take two values $0 < \underline{\Phi} < \overline{\Phi} < 1$. We assume that positive effort implies a higher probability of achieving high energy efficiency as detailed below.

We also assume that the cost of exerting effort E is equal to E. Thus, the total cost of acquiring Q_s units in the wholesale market and exerting effort E is given by:

$$C(Q_s,\, E) = cQ_s + E.$$

It follows that the monopolist's profit from selling Q units to final consumers is equal to

$$\pi(Q,\, E) = P(Q)Q - \frac{cQ}{\Phi(E)} - E. \tag{1}$$

Energy efficiency is not a deterministic function of effort and instead is determined according to the probabilities defined in Table 1.

Table 1: Relationship between effort level and energy efficiency

	$\underline{\Phi}$	$\overline{\Phi}$
$E = 0$	ν	$1 - \nu$
$E = e$	$1 - \nu$	ν

We assume that $\nu > \frac{1}{2}$ so that as it is standard in moral hazard models the high level of effort is more likely to lead to higher energy efficiency than low level of effort. Note

[3]For example, upgrading or optimising the network.

that the assumption that high energy efficiency can eventuate even under zero effort is a normalisation to simplify the characterisation of equilibrium behaviour. Without loss of generality, we assume a symmetric probability for energy efficiency under the two the levels of effort.

Given Table 1, the quantity of electricity the monopolist needs to purchase from the wholesale market is an expected value determined by the electricity price P and the effort devoted to energy efficiency E, which could be denoted as

$$Q_s = \begin{cases} Q_{sl} = \frac{\nu Q}{\underline{\Phi}} + \frac{(1-\nu)Q}{\overline{\Phi}}, & E = 0 \\ Q_{sh} = \frac{(1-\nu)Q}{\underline{\Phi}} + \frac{\nu Q}{\overline{\Phi}}, & E = e \end{cases} . \tag{2}$$

According to (2), the expected level of energy efficiency is defined as

$$\Phi(E) = \begin{cases} \Phi_l = \frac{\underline{\Phi}\overline{\Phi}}{(1-\nu)\underline{\Phi}+\nu\overline{\Phi}}, \text{ if } E = 0 \\ \Phi_h = \frac{\underline{\Phi}\overline{\Phi}}{\nu\underline{\Phi}+(1-\nu)\overline{\Phi}}, \text{ if } E = e \end{cases} , \tag{3}$$

with $\Phi_h > \Phi_l$ by assumption. To insure an interior solution, we assume that:

$$a\Phi_l - c \geqslant 0, \tag{4}$$

Consumer's surplus is denoted by $S(Q)$ and overall surplus by $W(Q, E) = S(Q) + \gamma\pi(P, E)$, where $0 < \gamma < 1$ is the weight assigned by the regulator to the monopolist's expected profit. The objective of the regulator is to maximise expected total surplus. As noted before, the regulator can observe the realisation of the level of energy efficiency – for example, by monitoring both demand and the amount the electricity purchased by the supplier from the wholesale market, but not the level of effort.

3 The Unregulated Monopolist

From 1, the unregulated monopolist's expected profit can be rewritten as $\overline{\pi}(Q_s, E) = [a\Phi(E) - c]Q_s - b[\Phi(E)]^2 Q_s^2 - E$. We can then calculate it by using (2) and (3):

$$\overline{\pi}(Q_s, E) = \begin{cases} \overline{\pi}_l = (a\Phi_l - c)Q_{sl} - b\Phi_l^2 Q_{sl}^2, & E = 0 \\ \overline{\pi}_h = (a\Phi_h - c)Q_{sh} - b\Phi_h^2 Q_{sh}^2 - e, & E = e \end{cases} . \tag{5}$$

The first-order conditions (FOCs) are respectively

$$\frac{\partial \overline{\pi}_l}{\partial Q_{sl}} = a\Phi_l - c - 2b\Phi_l^2 Q_{sl} = 0, \qquad E = 0$$
$$\frac{\partial \overline{\pi}_h}{\partial Q_{sh}} = a\Phi_h - c - 2b\Phi_h^2 Q_{sh} = 0, \quad E = e$$

These FOCs yield that the optimal amount of electricity the monopolist purchases in the wholesale market is a function of effort:

$$Q_s^* = \begin{cases} Q_{sl}^* = \frac{a\Phi_l - c}{2b\Phi_l^2}, & E = 0 \\ Q_{sh}^* = \frac{a\Phi_h - c}{2b\Phi_h^2}, & E = e \end{cases}. \tag{6}$$

The profit-maximising prices are then:

$$P^* = \begin{cases} P_l^* = a - b\Phi_l Q_{sl}^* = \frac{a\Phi_l + c}{2\Phi_l}, & E = 0 \\ P_h^* = a - b\Phi_h Q_{sh}^* = \frac{a\Phi_h + c}{2\Phi_h}, & E = e \end{cases}. \tag{7}$$

One can readily check that second-order conditions are satisfied. We can replace (6) into (5) to obtain the maximised expected profits as a function of effort:

$$\overline{\pi}^* = \begin{cases} \overline{\pi}_l^* = \frac{[a\Phi_l - c]^2}{4b\Phi_l^2}, & E = 0 \\ \overline{\pi}_h^* = \frac{[a\Phi_h - c]^2}{4b\Phi_h^2} - e, & E = e \end{cases}. \tag{8}$$

We stress that the monopolist chooses a single price prior to the realisation of the energy efficiency. Although the energy efficiency outcome will be known by the time the electricity is used by consumers, we assume that the monopolist sells the electricity retail at a fixed price determined prior to the delivery of electricity.

3.1 Optimal Choice of Effort

In order to ensure that the monopolist remains in the industry the following participation constraint needs to be satisfied:

$$\overline{\pi}(Q_s^*, E) \geqslant 0.$$

For a positive choice of effort to be optimal, the following incentive compatibility constraint, obtained directly from (8), needs to be satisfied:

$$\overline{\pi}_h^* - \overline{\pi}_l^* > 0.$$

Combining the participation and incentive compatibility constraints, we can now determine the unregulated monopolist's optimal choice of effort in Table 2:

Table 2: Optimal Effort Decision of the Unregulted Monopolist

Effort Cost	Profit Comparison	Optimal Effort
$\widetilde{e}_1 \leqslant e$	$\overline{\pi}_l^* \geqslant \overline{\pi}_h^*$	$E = 0$
$0 < e < \widetilde{e}_1$	$\overline{\pi}_h^* > \overline{\pi}_l^* \geqslant 0$	$E = e$

where

$$\begin{aligned}\widetilde{e}_1 &= \frac{(a\Phi_h - c)^2}{4b\Phi_h^2} - \frac{(a\Phi_l - c)^2}{4b\Phi_l^2} \\ &= \frac{c(2\nu - 1)(\overline{\Phi} - \underline{\Phi})[2a\underline{\Phi}\overline{\Phi} - c(\underline{\Phi} + \overline{\Phi})]}{4b\underline{\Phi}^2\overline{\Phi}^2}.\end{aligned}$$

Note that $\overline{\pi}_l^* \geqslant 0$ given (8) and, therefore, the participation constraint is automatically satisfied for both choices of effort. That is, if the cost of positive effort, e, is greater than the benefit of the effort (as measured by the difference in expected profits under the two efforts), then a zero effort is optimal. Otherwise, the unregulated monopolist chooses to exert positive effort. This is summarised in the following result. The proof is straightforward and, therefore, omitted.

Lemma 1 *The unregulated monopolist chooses a positive level of effort whenever $0 \leqslant e < \widetilde{e}_1$. Otherwise she chooses zero effort. The threshold value $\widetilde{e}_1$ increases when the demand shifts outward (i.e., a increases), or it becomes flatter/ less steep (i.e., b decreases). The value of $\widetilde{e}_1$ increases with c for sufficiently low values of c and decreases with c for sufficient high values of c. Explicitly, $\widetilde{e}_1$ decreases in c for $c > \frac{a\underline{\Phi}\overline{\Phi}}{\underline{\Phi}+\overline{\Phi}}$.*

The effort level chosen by the monopolist depends on expected values of energy efficiency, shape of demand function (here it refers to the parameters a and b) and the wholesale price as well.

We now compute the social welfare in the absence of regulation:

$$W(Q^*, E) = \frac{bQ^{*2}}{2} + \gamma[P^*Q^* - \frac{cQ^*}{\Phi(E)} - E] \tag{9}$$
$$= \begin{cases} \frac{bQ_l^{*2}}{2} + \gamma\overline{\pi}_l^*, & E = 0 \\ \frac{bQ_h^{*2}}{2} + \gamma\overline{\pi}_h^*, & E = e \end{cases}.$$

Given equations (6) and (8), we can rewrite the expected total social welfare under an unregulated monopoly for different levels of effort as follows:

$$W^* = \begin{cases} W_l^* = \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2}, & E = 0 \\ W_h^* = \frac{(2\gamma+1)(a\Phi_h - c)^2}{8b\Phi_h^2} - \gamma e, & E = e \end{cases}. \tag{10}$$

In the next section we investigate whether a welfare-maximising regulator may be able to improve upon (10) under different regulatory regimes.

4 Regulation and Energy Efficiency

This section investigates the incentives for energy efficiency across three different types of regulatory regimes commonly observed around the world.

4.1 Rate of Return Regulation (ROR)

Under rate of return regulation, the regulator determines prices to cover the actual costs (including the cost of capital) incurred by the monopolist to supply electricity.[4] In this paper, we consider a stylised, pure form of rate of return regulation where the regulator observes both the actual electricity consumed (Q) and the electricity purchased by the monopolist (Q_s). Therefore, the regulator can infer the level of energy efficiency that has eventuated although she cannot observe the effort exerted by the monopolist. Note that this contrasts with how we model the unregulated monopolist who can only set prices ex-ante, prior to the realisation of the energy efficiency outcome.

Prices then can take two values depending on the realised value of energy efficiency, namely $\underline{P}^{ROR}$ if $\Phi = \underline{\Phi}$ and $\overline{P}^{ROR}$ if $\Phi = \overline{\Phi}$. These values are calculated below but under such prices, the electricity purchased from the wholesale market is given by

[4] In practice, however, regulators typically attempt to ensure that incurred costs are efficient. See, for example, Joskow (1974) and Joskow *et al.* (1989).

either $\underline{Q_s}^{ROR} = \frac{a-\underline{P}^{ROR}}{b\underline{\Phi}}$ if $\Phi = \underline{\Phi}$ or $\overline{Q_s}^{ROR} = \frac{a-\overline{P}^{ROR}}{b\overline{\Phi}}$ if $\Phi = \overline{\Phi}$. As $\underline{P}^{ROR}$ and $\overline{P}^{ROR}$ are fixed ex-post and do not depend on the monopolist's effort level, it can be easily checked that $\overline{\pi}^{ROR}(Q,\, e) - \overline{\pi}^{ROR}(Q,\, 0) = -e < 0$ for both realisations of Φ and, therefore, we have established:

Lemma 2 *The monopolist always chooses to exert zero effort under rate of return regulation.*

We now turn our attention to determining the optimal ex-post regulated prices under rate of return regulation. As the weight given to the profits of the monopolist is less than one, the regulator will set P^{ROR} so that profits are zero. That is:

$$P^{ROR*} = \begin{cases} \underline{P}^{ROR*} = \frac{c}{\underline{\Phi}},\ \Phi = \underline{\Phi} \\ \overline{P}^{ROR*} = \frac{c}{\overline{\Phi}},\ \ \Phi = \overline{\Phi} \end{cases} . \tag{11}$$

The next proposition summarises the outcomes under rate of return regulation including social welfare which is equal to expected consumer's surplus given that the monopolist earns zero profits.

Proposition 1 *Under rate of return regulation, the monopolist chooses $E = 0$, and regulated prices are given by (11), and expected social welfare is given by:*

$$W^{ror*} = \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2}.$$

4.2 Price Cap Regulation

Under our stylised form of price cap regulation, the regulator sets an ex-ante price – that is, a fixed price that is not conditional on the realised quantum of energy efficiency – in order to maximise expected social surplus. In doing so, the regulator faces a trade-off between providing incentives for energy efficiency and reducing the monopolist's rent. In particular, the regulator solves the following problem

$$Max_{(P^{pc})} W^{pc} = S^{pc} + \gamma\overline{\pi}(P^{pc}, E)$$

$$s.t.\ \ \overline{\pi}(P^{pc}, E) \geqslant 0.$$

This problem is solved in several steps. First, we identify the optimal price cap as a function of effort. We then determine the socially optimal level of effort under the optimally determined price cap. Finally, we combine these two steps to fully specify the solution to the problem above, that is, an ex-ante fixed price and the optimal level of effort, as a function of various parameters including the cost of effort. The first step is completed in the following Lemma. The proof is in Appendix A.

Lemma 3 *The optimal price cap, as a function of effort, is given by:*

$$P^{pc*} = \begin{cases} \frac{c}{\Phi_l}, & E = 0 \\ \frac{a\Phi_h + c - \sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{2\Phi_h}, & E = e \end{cases}.$$

We now turn our attention to determine the optimal effort from a monopolist who, in equilibrium, will face one of the two fixed prices above. If the price cap is set at $\frac{c}{\Phi_l}$, the monopolist's expected profit is equal to:

$$\begin{aligned} \pi^{pc} &= P^{pc*}Q - \frac{cQ}{\Phi(E)} - E = \frac{P^{pc*}(a - P^{pc*})}{b} - \frac{c(a - P^{pc*})}{b\Phi(E)} - E \\ &= \begin{cases} \pi_l^{pc} = \frac{\frac{c}{\Phi_l}(a - \frac{c}{\Phi_l})}{b} - \frac{c(a - \frac{c}{\Phi_l})}{b\Phi_l} = 0, & E = 0 \\ \pi_h^{pc} = \frac{\frac{c}{\Phi_l}(a - \frac{c}{\Phi_l})}{b} - \frac{c(a - \frac{c}{\Phi_l})}{b\Phi_h} - e, & E = e \end{cases}, \end{aligned}$$

and, therefore, the incentive compatibility constraint can be written as:

$$\pi_h^{pc} - \pi_l^{pc} = \frac{c(a\Phi_l - c)(\Phi_h - \Phi_l)}{b\Phi_h\Phi_l^2} - e.$$

Similarly, if the price cap is set at $\frac{a\Phi_h + c - \sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{2\Phi_h}$, the monopolist's expected profit is equal to:

$$\pi^{pc} = P^{pc*}Q - \frac{cQ}{\Phi(E)} - E = \begin{cases} \pi_l^{pc} < 0, & E = 0 \\ \pi_h^{pc} = 0, & E = e \end{cases},$$

which implies that the incentive compatibility constraint, $\pi_h^{pc} - \pi_l^{pc} > 0$, is always satisfied and the monopolist chooses to exert positive effort at this ex-ante price.

Proposition 2 *The optimal price cap, level of efforts and expected social welfare are fully characterised in Table 3:*

where

$$\widetilde{e}_2 = \frac{c(a\Phi_l - c)(\Phi_h - \Phi_l)}{b\Phi_h\Phi_l^2}.$$

Table 3: Characteristics of Price-cap Regulation

Effort Cost	Effort Level	Optimal Price Cap	Expected Social Welfare
$e \geqslant \widetilde{e}_2$	$E = 0$	$\frac{c}{\Phi_l}$	$\frac{(a\Phi_l - c)^2}{2b\Phi_l^2}$
$0 < e < \widetilde{e}_2$	$E = e$	$\frac{a\Phi_h + c - \sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{2\Phi_h}$	$\frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e)}}{4b\Phi_h^2} - \frac{e}{2}$

Note that the threshold value under price cap regulation is higher than that in the absence of regulation, i.e.,

$$\widetilde{e}_2 - \widetilde{e}_1 = \frac{c(\Phi_h - \Phi_l)[2a\Phi_l(2 - \Phi_h) + c(\Phi_h + \Phi_l - 4)]}{4b\Phi_l^2\Phi_h} > 0$$

Hence, the regulated firm exert high effort more often than under no regulation. The intuition for this is that under price cap regulation, the regulator sets a price ex-ante so that expected profits are zero. The regulator anticipates the optimal effort for the value of the cost of effort and ensures that the monopolist is incentivised to put in positive effort in situations where an unregulated monopolist would choose zero effort. Thus, the range of values of the cost of effort for which is worthwhile from a society's perspective to engage in positive effort is larger under price cap regulation than under unregulated monopoly.

In the same vein as $\widetilde{e}_1$, it can be checked that $\widetilde{e}_2$ is also increasing in a, decreasing in b and either increasing or decreasing in c depending on its value.

It is worth noting that in our setting there is no meaningful distinction between price cap and revenue cap regulation. The optimal revenue cap can be implemented by the optimal price cap, which will result in the same expected revenue and welfare given that the demand function is deterministic. For completion, we spell out in the next Lemma what that optimal revenue cap is with associated calculations provided in Appendix A.

Lemma 4 *The optimal revenue cap, as a function of effort, is given by:*

$$R^{rc*} = \begin{cases} \frac{(a\Phi_l - c)c}{b\Phi_l^2}, & E = 0 \\ \frac{(a\Phi_h - c)c + 2b\Phi_h^2 e + c\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{2b\Phi_h^2}, & E = e \end{cases}.$$

4.3 Mandated Target Regulation

Mandated targets for achieving energy efficiency have become widespread. For example, in the European Union there is a target of 20% improvement in energy efficiency (as well as a 20% share of energy consumption from renewable resources) to be achieved by 2020[5]. Under this approach, the regulator sets a minimum percentage of the energy needs that have to be met through energy efficiency programs. In our model we capture this regulatory approach by assuming that the regulator sets a target, Φ^{mt}, that needs to achieve in order to avoid a penalty $\delta \geqslant 0$ for not meeting the target.

In this setting, the objective of the regulator is to set the target in order to maximise expected welfare subject to the firm's participation constraint:

$$Max_{(\Phi^{mt})} W^{mt} = S^{mt} + \gamma\overline{\pi}(\Phi^{mt}, E)$$

$$s.t. \quad \overline{\pi}(\Phi^{mt}, E) \geqslant 0.$$

In our setting there are only two possible meaningful targets, namely $\overline{\Phi}$ or $\underline{\Phi}$. If the mandated target is set at $\Phi^{mt} = \underline{\Phi}$, it is of course not binding and the monopolist's expected profit is identical to the case of an unregulated monopolist and given by:

$$\begin{aligned} \overline{\pi}^{mt}(\Phi^{mt}, E) &= \begin{cases} P(Q)Q - \frac{cQ}{\Phi_l}, & E = 0 \\ P(Q)Q - \frac{cQ}{\Phi_h} - e, & E = e \end{cases} \\ &= P(Q)Q - \frac{cQ}{\Phi(E)} - E, \end{aligned}$$

and the expected social welfare is

$$W^{mt}(\Phi^{mt} = \underline{\Phi}) = \frac{bQ^2}{2} + \gamma P(Q)Q - \frac{\gamma cQ}{\Phi(E)} - \gamma E.$$

With $\Phi^{mt} = \overline{\Phi}$ as a target, the monopolist's expected profit is

$$\begin{aligned} \overline{\pi}^{mt} &= \begin{cases} P(Q)Q - \frac{cQ}{\Phi_l} - \nu\delta, & E = 0 \\ P(Q)Q - \frac{cQ}{\Phi_h} - e - (1-\nu)\delta, & E = e \end{cases} \\ &= \begin{cases} \overline{\pi}_l^{mt} = (a\Phi_l - c)Q_{sl} - b\Phi_l^2 Q_{sl}^2 - \nu\delta, & E = 0 \\ \overline{\pi}_h^{mt} = (a\Phi_h - c)Q_{sh} - b\Phi_h^2 Q_{sh}^2 - e - (1-\nu)\delta, & E = e \end{cases}. \end{aligned}$$

[5] http://ec.europa.eu/clima/policies/package/

The first-order conditions (FOCs) are respectively

$$\frac{\partial \overline{\pi}_l^{mt}}{\partial Q_{sl}} = a\Phi_l - c - 2b\Phi_l^2 Q_{sl} = 0, \quad E = 0$$
$$\frac{\partial \overline{\pi}_h^{mt}}{\partial Q_{sh}} = a\Phi_h - c - 2b\Phi_h^2 Q_{sh} = 0, \quad E = e$$

It follows that optimal electricity supply chosen by the monopolist and the related electricity price are identical with the associated levels under unregulated situation. Given this, the mandated target regulated monopolist's expected profit is calculated as:

$$\overline{\pi}^{mt*} = \begin{cases} \overline{\pi}_l^{mt*} = \frac{(a\Phi_l - c)^2}{4b\Phi_l^2} - \nu\delta, & E = 0 \\ \overline{\pi}_h^{mt*} = \frac{(a\Phi_h - c)^2}{4b\Phi_h^2} - e - (1-\nu)\delta, & E = e \end{cases}.$$

The threshold value of effort cost for energy efficiency is

$$\begin{aligned} \widetilde{e}_4 &= \frac{(a\Phi_h - c)^2}{4b\Phi_h^2} - (1-\nu)\delta - \frac{(a\Phi_l - c)^2}{4b\Phi_l^2} + \nu\delta \\ &= \frac{(a\Phi_h - c)^2}{4b\Phi_h^2} - \frac{(a\Phi_l - c)^2}{4b\Phi_l^2} + (2\nu - 1)\delta \\ &= \widetilde{e}_1 + (2\nu - 1)\delta > \widetilde{e}_1. \end{aligned}$$

That is, the range of effort cost for which the monopolist finds it worthwhile to exert positive effort is larger than that for the unregulated monopolist. This is because by exerting positive effort, the monopolist may avoid paying the penalty for not achieving the target. It is worthwhile to note that to guarantee the monopolist's participation constraint, the penalty should be limited to $\delta \leqslant \frac{[a\Phi_l - c]^2}{4b\nu\Phi_l^2} = \widetilde{\delta}_0$, thus

$$\begin{aligned} &\widetilde{e}_4 - \widetilde{e}_2 \\ &= \frac{[a\Phi_h - c]^2}{4b\Phi_h^2} - \frac{[a\Phi_l - c]^2}{4b\Phi_l^2} + (2\nu - 1)\delta - \frac{c(a\Phi_l - c)(\Phi_h - \Phi_l)}{b\Phi_h\Phi_l^2} \\ &< 0, \end{aligned} \tag{12}$$

which implies that if the fixed penalty is relatively low, the threshold value of effort cost under mandated target regulation is lower than that under price cap regulation.

If the cost of effort is larger than $\widetilde{e}_4$, the monopolist will exert no effort, and the expected social welfare is

$$\begin{aligned} W_l^{mt}(\Phi^{mt} = \overline{\Phi}) &= \frac{bQ_l^{*2}}{2} + \gamma\overline{\pi}_l^* + (1-\gamma)\nu\delta \\ &= \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2} + (1-\gamma)\nu\delta \\ &> W_l^* = W_l^{mt}(\Phi^{mt} = \underline{\Phi}). \end{aligned}$$

This is the same case with a relatively low effort cost where positive effort is chosen by the mandated target regulated firm, i.e., $W_h^{mt}(\Phi^{mt} = \overline{\Phi}) > W_h^{mt}(\Phi^{mt} = \underline{\Phi})$. Therefore, the regulator's optimal choice of mandated target is $\Phi^{mt} = \overline{\Phi}$.

The next proposition summarises the analysis above.

Moreover, compared with the non-regulated circumstance, mandated target regulation contributes to increase expected social welfare, no matter at which level the target is set.

Proposition 3 *The optimal mandated target for energy efficiency is* $\Phi^{mt} = \overline{\Phi}$*. The characterisation of mandated target regulation is summarised in Table 4:*

Table 4: Characterisation of Mandated-target Regulation

Mandated Target	Effort Cost	Effort Level	Expected Social Welfare
$\Phi^{mt} = \overline{\Phi}$	$e \geqslant \widetilde{e}_4$	$E = 0$	$\frac{(2\gamma+1)(a\Phi_l-c)^2}{8b\Phi_l^2} + (1-\gamma)\nu\delta$
	$0 < e < \widetilde{e}_4$	$E = e$	$\frac{(2\gamma+1)(a\Phi_h-c)^2}{8b\Phi_h^2} - \gamma e + (1-\gamma)(1-\nu)\delta$

5 Expected Welfare under Different Regulatory Regimes

This section compares the different regimes from an expected welfare perspective. The comparison is driven by the size of the cost of effort. In particular, for $e \geqslant \widetilde{e}_2$, the monopolist chooses zero effort under all possible scenarios. In this case, price cap regulation always dominates an unregulated monopolist – both set prices ex-ante (that is, prior to the realisation of the energy efficiency outcome) and prices are lower under price cap regulation. This particular ranking is of course true for any cost of effort as a regulator could always choose the unregulated monopolist's price if it were to increase welfare.

Moreover, rate of return regulation performs better than price cap regulation when zero effort is optimal. In this case, it is not necessary to incentivise the firm to exert effort into energy efficiency and rate of return regulation then ensures that profits are ex-post zero whereas under price cap regulation profits are only zero ex-ante so prices are higher to ensure that the firm's participation constraint is satisfied.

At the other extreme, when the cost of effort is sufficiently low (that is, $e < \widetilde{e}_4$), price cap regulation always dominates rate of return regulation as it is socially optimal to set an ex-ante price that whilst ensuring that the firm's participation constraint is satisfied, might result in positive (ex-post) profits for the regulated firm. At this price the firm is incentivised to exert effort in energy efficiency. For intermediate values of the cost of effort, the comparison between rate of return and price cap regulation is more complex as characterised in proposition 4 below.

Finally, we have shown that mandated target regulation is always dominated by both price cap and rate of return regulation in terms of expected welfare although it can do better than an unregulated monopolist. The key reason is that mandated target regulation is too coarse and the trade off between providing incentives to invest in energy efficiency and rent extraction is less pronounced. These results are summarised in the next proposition and its proof is in Appendix B.

Proposition 4 *The comparison of expected social welfare under different regulatory regimes is summarised in Table 5:*

Table 5: The Optimal Regulatlion

Levels of Effort Cost	Effort Level Unreg	ROR	PC	MT	Social Welfare Comparison
$e \geqslant \widetilde{e}_2$	$E=0$	$E=0$	$E=0$	$E=0$	$W^{ror*} > W_l^{pc*} > W_l^{mt*} > W_l^*$
$\widetilde{e}_3 \leqslant e < \widetilde{e}_2$	$E=0$	$E=0$	$E=e$	$E=0$	$W^{ror*} \geqslant W_h^{pc*} > W_l^{mt*} > W_l^*$
$\widetilde{e}_4 \leqslant e < \widetilde{e}_3$	$E=0$	$E=0$	$E=e$	$E=0$	$W_h^{pc*} > W^{ror*} > W_l^{mt*} > W_l^*$
$\widetilde{e}_1 \leqslant e < \widetilde{e}_4$	$E=0$	$E=0$	$E=e$	$E=e$	$W_h^{pc*} > W^{ror*} > W_h^{mt*} > W_l^*$
$0 < e < \widetilde{e}_1$	$E=e$	$E=0$	$E=e$	$E=e$	$W_h^{pc*} > W^{ror*} > W_h^{mt*} > W_h^*$

where $\widetilde{e}_1 = \frac{c(2\nu-1)(\overline{\Phi}-\underline{\Phi})[2a\underline{\Phi}\overline{\Phi}-c(\underline{\Phi}+\overline{\Phi})]}{4b\underline{\Phi}^2\overline{\Phi}^2}$, $\widetilde{e}_2 = \frac{c(a\Phi_l-c)(\Phi_h-\Phi_l)}{b\Phi_h\Phi_l^2}$, $\widetilde{e}_4 = \frac{[a\Phi_h-c]^2}{4b\Phi_h^2} - \frac{[a\Phi_l-c]^2}{4b\Phi_l^2} + (2\nu-1)\delta$, *and* $\widetilde{e}_3$ *denotes the point at which level of effort cost* $W_h^{pc*} = W^{ror*}$.

6 Conclusion

This paper develops a theoretical model to investigate the relationship between a regulated firm's incentive to invest in energy efficiency and the nature of the regulatory regime. In this paper, the reason for the regulated monopolist not to undertake investment in energy efficiency is not due to her desire to maximise quantity but rather due to the inability of a regulator to commit to reimburse the effort costs given that these are not directly observable. This is another channel through which regulatory regimes can disincentivise regulated firms to invest in energy efficiency – in addition to the issue of decoupling that was described in the introductory section. Price cap, rate of return and mandated targets deal with these lack of incentives in different ways. Rate of return provides no incentive to invest in energy efficiency. Even if successful, the ex-post nature of rate of return regulation ensures that the firm earns zero economic profits. Price cap, in contrast, provides incentives for investment in energy efficiency as the firm is able to capture, in the event that the investment is successful, some of the economic rents. Mandate target regulation also provides incentives to invest in energy efficiency by penalising the firm for not achieving its target.

Our analysis suggests two key messages that might be of relevance to policy makers. First, when the cost of effort to undertake energy efficiency investment is low – that is, when there are existing opportunities that can be pursued at low cost and that are likely result in energy savings – a price cap regime is likely to perform better than a rate of return regulatory regime. Conversely, when the cost of effort is too high, rate of return regulation is welfare superior to price regulation as in this instance it is not optimal for the firm to invest in energy efficiency. Second, mandated target regulation is clearly an inferior policy to stimulate investment in energy efficiency. The key reason is that mandated target regulation is too coarse as an instrument to provide the appropriate incentives to the regulated firm.

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Appendix

Appendix A

- Price Cap Regulation

The associated Lagrangian function for price-cap regulation is given by:

$$\begin{aligned} L^{pc} &= \frac{(a-P^{pc})^2}{2b} + (\gamma+\lambda^{pc})[\frac{P^{pc}(a-P^{pc})}{b} - \frac{(a-P^{pc})c}{b\Phi(E)} - E] \\ &= \frac{\Phi(a^2 - 2aP^{pc} + P^{pc2}) + 2(\gamma+\lambda^{pc})[(a\Phi+c)P^{pc} - \Phi P^{pc2} - ac]}{2b\Phi} - (\gamma+\lambda^{pc})E, \end{aligned}$$

where $\lambda^{pc} > 0$ is the Lagrangian multiplier. The Kuhn-Tucker conditions are

$$\frac{\partial L^{pc}}{\partial P^{pc}} = \frac{(P^{pc}-a)\Phi + (\gamma+\lambda)(a\Phi + c - 2\Phi P^{pc})}{b\Phi} \leqslant 0, P^{pc} \geqslant 0, \text{ and } P^{pc}\frac{\partial L^{pc}}{\partial P^{pc}} = 0,$$

$$\frac{\partial L^{pc}}{\partial \lambda} = \frac{(a-P^{pc})(P^{pc}\Phi - c)}{b\Phi} - E \geqslant 0, \lambda^{pc} \geqslant 0 \text{ and } \lambda^{pc}\frac{\partial L^{pc}}{\partial \lambda^{pc}} = 0,$$

from which we identify three possible solutions:

$$\begin{cases} P_1^{pc*} = \frac{a\Phi+c}{2\Phi} - \frac{\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2\Phi} \\ \lambda_1^{pc} = \frac{a\Phi-c}{2\sqrt{(a\Phi-c)^2-4b\Phi^2E}} + \frac{1}{2} - \gamma \end{cases}, \tag{13}$$

$$\begin{cases} P_2^{pc*} = \frac{a\Phi+c}{2\Phi} + \frac{\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2\Phi} \\ \lambda_2^{pc} = -\frac{a\Phi-c}{2\sqrt{(a\Phi-c)^2-4b\Phi^2E}} + \frac{1}{2} - \gamma \end{cases},$$

or

$$\begin{cases} P_3^{pc*} = \frac{(\gamma-1)a\Phi+\gamma c}{(2\gamma-1)\Phi} \\ \lambda_3^{pc} = 0 \end{cases}$$

The participation constraint $\overline{\pi}^{pc}(P^{pc}, E) \geqslant 0$ implies that $P_1^{pc*} \leqslant P^{pc} \leqslant P_2^{pc*}$ with $P_1^{pc*} = \frac{a\Phi+c}{2\Phi} - \frac{\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2\Phi}$ and $P_2^{pc*} = \frac{a\Phi+c}{2\Phi} + \frac{\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2\Phi}$. We can readily check that P_3^{pc*} does not satisfy the participation constraint as:

$$\overline{\pi}^{pc}(\overline{P}_3^{pc*}, E) = \frac{\gamma(\gamma-1)(a\Phi-c)^2}{(1-2\gamma)^2 b\Phi^2} - E < 0.$$

To select between $P_1^{pc*}$and P_2^{pc*}, we compute the expected welfare associated with each price, W_1^{pc} and W_2^{pc}, respectively, as follows:

$$\begin{aligned} & W_1^{pc} - W_2^{pc} \\ &= \frac{(a-P_1^{pc*})[(a-P_1^{pc*})\Phi + 2\gamma(P_1^{pc*}\Phi - c)]}{2b\Phi} - \frac{(a-P_2^{pc*})[(a-P_2^{pc*})\Phi + 2\gamma(P_2^{pc*}\Phi - c)]}{2b\Phi} \\ &= \frac{(2a\Phi\gamma - 2a\Phi + 2\gamma c)(P_1^{pc*} - P_2^{pc*}) - \Phi(2\gamma-1)(P_1^{pc*2} - P_2^{pc*2})}{2b\Phi} \\ &= \frac{(a\Phi - c)\sqrt{(a\Phi-c)^2 - 4b\Phi^2E}}{2b\Phi^2} \geqslant 0 \text{ (from 4)} \end{aligned}$$

It follows that the optimal price cap is $P^{pc*} = \frac{a\Phi+c}{2\Phi} - \frac{\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2\Phi}$.

- Revenue Cap Regulation

Under revenue-cap regulation, the Lagrangian function of the welfare maximisation problem could be written as

$$L^{rc} = \frac{(a - \sqrt{a^2 - 4bR^{rc}})^2}{8b} + (\lambda^{rc} + \gamma)(R^{rc} - \frac{c(a - \sqrt{a^2 - 4bR^{rc}})}{2b\Phi(E)} - E),$$

and the Kuhn-Tucker conditions (KTCs) are

$$\frac{\partial L^{rc}}{\partial R^{rc}} \leqslant 0,\ R^{rc} \geqslant 0,\ \text{and } R^{rc}\frac{\partial L^{rc}}{\partial R^{rc}} = 0,$$

$$\frac{\partial L^{rc}}{\partial \lambda^{rc}} = R^{rc} - \frac{c(a-\sqrt{a^2-4bR^{rc}})}{2b\Phi} - E \geqslant 0, \lambda^{rc} \geqslant 0 \text{ and } \lambda^{rc}\,\frac{\partial L^{rc}}{\partial \lambda^{rc}} = 0.$$

From the KTCs we get three sets of solution, i.e.,

$$\begin{cases} R_1^{rc*} = \frac{-c^2+ac\Phi+2b\Phi^2E-c\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2b\Phi^2} \\ \lambda_1^{rc} = \frac{a\Phi-2\gamma c+(2\gamma-1)\Phi\sqrt{a^2-4bR_1^{rc}}}{2(c-\Phi\sqrt{a^2-4bR_1^{rc}})} \end{cases},$$

$$\begin{cases} R_2^{rc*} = \frac{-c^2+ac\Phi+2b\Phi^2E+c\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2b\Phi^2} \\ \lambda_2^{rc} = \frac{a\Phi-2\gamma c+(2\gamma-1)\Phi\sqrt{a^2-4bR_2^{rc}}}{2(c-\Phi\sqrt{a^2-4bR_2^{rc}})} \end{cases},$$

or

$$\begin{cases} R_3^{rc*} = \frac{\gamma(a\Phi-c)(c\gamma+\gamma a\Phi-a\Phi)}{b(1-2\gamma)^2\Phi^2} \\ \lambda_3^{rc} = 0 \end{cases}.$$

Given the above, suppose the monopolist's expected profit with R_3^{rc} is $\overline{\pi}_3^{rc}$, we obtain $\overline{\pi}_3^{rc} < 0$. Hence, the third set of solution dose not satisfy the participation constraint $\pi^{rc} \geqslant 0$, and we just need to consider R_1^{rc} and R_2^{rc} when identifying the socially optimal revenue cap. Denote the social welfare related to R_1^{rc} and R_2^{rc} respectively with W_1^{rc} and W_2^{rc}, then

$$W_1^{rc} = \frac{(a\Phi-c)^2 - 2b\Phi^2E - (a\Phi-c)\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{4b\Phi^2},$$

$$W_2^{rc} = \frac{(a\Phi-c)^2 - 2b\Phi^2E + (a\Phi-c)\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{4b\Phi^2}.$$

As the expected welfare difference between W_1^{rc} and W_2^{rc} is

$$W_2^{rc} - W_1^{rc} = \frac{(a\Phi-c)\sqrt{(a\Phi-c)^2-4b\Phi^2E}]}{2b\Phi^2} > 0,$$

the optimal revenue cap is $R^{rc*} = R_2^{rc} = \frac{-c^2+ac\Phi+2b\Phi^2E+c\sqrt{(a\Phi-c)^2-4b\Phi^2E}}{2b\Phi^2}$.

It is interesting to note that the prerequisite $R^{rc*} < R^*$ is satisfied.

Proof.

$$(a\Phi-c)^2 - 4b\Phi^2E > 0$$

$$\Rightarrow (a\Phi - c)^2 - 4b\Phi^2 E + 2c\sqrt{(a\Phi - c)^2 - 4b\Phi^2 E} > 0$$
$$\Rightarrow -2c^2 + 2ac\Phi + 4b\Phi^2 E - 2c\sqrt{(a\Phi - c)^2 - 4b\Phi^2 E} < a^2\Phi^2 - c^2$$
$$\Rightarrow \frac{-c^2 + ac\Phi + 2b\Phi^2 E + c\sqrt{(a\Phi - c)^2 - 4b\Phi^2 E}}{2b\Phi^2} < \frac{(a\Phi + c)(a\Phi - c)}{4b\Phi^2}$$
$$\Rightarrow R^{rc*} < R^*$$

■

Appendix B

From (12), it could be found that the threshold values of effort cost under different regulatory circumstances satisfy $\widetilde{e}_1 < \widetilde{e}_4 < \widetilde{e}_2$. In the following analysis, we will consider four distinguished situations, i.e., $e \geqslant \widetilde{e}_2$, $\widetilde{e}_4 \leqslant e < \widetilde{e}_2$, $\widetilde{e}_1 \leqslant e < \widetilde{e}_4$ and $0 < e < \widetilde{e}_1$.

- Case 1: In the case where $e \geqslant \widetilde{e}_2$, no positive effort is taken by the monopolist either under the unregulated situation or under any of the three types of regulation analysed above. The resulted expected social welfare under different regulatory circumstances are given as:

$$W_l^* = W^*(E = 0) = \frac{(2\gamma + 1)(a\Phi_l - c)^2}{8b\Phi_l^2},$$
$$W^{ror*} = W^{ror*}(E = 0) = \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1 - \nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2},$$
$$W_l^{pc*} = W^{pc*}(E = 0) = \frac{(a\Phi_l - c)^2}{2b\Phi_l^2},$$
$$W_l^{mt*} = W_l^{mt*}(E = 0) = \frac{(2\gamma + 1)(a\Phi_l - c)^2}{8b\Phi_l^2} + (1 - \gamma)\nu\delta.$$

Then we can obtain the comparison as follows:

$$\begin{aligned} & W_l^{pc*} - W^{ror*} \\ &= \frac{(a\Phi_l - c)^2}{2b\Phi_l^2} - \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} - \frac{(1 - \nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} \\ &= \frac{-cv(1 - \nu)(\overline{\Phi} - \underline{\Phi})^2}{2b\underline{\Phi}^2\overline{\Phi}^2} < 0 \\ & \Rightarrow W_l^{pc*} < W^{ror*}. \end{aligned}$$

It could be found that in this case the expected social welfare under ROR regulation dominates that under price-cap regulation.

Moreover,

$$W_l^{mt*} - W_l^* = (1-\gamma)\nu\delta > 0$$

$$\begin{aligned}
& W_l^{pc*} - W_l^{mt*} \\
&= \frac{(a\Phi_l - c)^2}{2b\Phi_l^2} - \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2} - (1-\gamma)\nu\delta \\
&> \frac{(a\Phi_l - c)^2}{2b\Phi_l^2} - \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2} - \frac{(1-\gamma)\nu(a\Phi_l - c)^2}{4b\nu\Phi_l^2} \\
&= \frac{(a\Phi_l - c)^2}{8b\Phi_l^2} > 0
\end{aligned}$$

To sum up, if the effort cost is so high that no energy efficiency effort is undertaken under any scenario, i.e., when zero effort is the optimal choice for the monopolist, the merit of expected social welfare brought about by these regulatory situations are given as

$$W^{ror*} > W_l^{pc*} > W_l^{mt*} > W_l^*$$

- Case 2: In the case where $\widetilde{e}_4 \leqslant e < \widetilde{e}_2$, only under price-cap regulation does the monopolist have incentive to undertake positive effort for energy efficiency improvement, then under this circumstance the related expected social welfare are respectively:

$$W_l^* = W^*(E=0) = \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2},$$

$$W^{ror*} = W^{ror*}(E=0) = \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2},$$

$$W_h^{pc*} = W^{pc*}(E=e) = \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{4b\Phi_h^2} - \frac{e}{2},$$

$$W_l^{mt*} = W_l^{mt*}(E=0) = \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2} + (1-\gamma)\nu\delta.$$

It could be seen that the comparison between W_l^*, W^{ror*} and W_l^{mt*} is the same with that in the case where $e \geqslant \widetilde{e}_2$, thus we just need to compare W_h^{pc*} to W_l^* , W^{ror*} and W_l^{mt*}.

As

$$\frac{\partial W_h^{pc*}}{\partial e} = \frac{(a\Phi_h - c)}{4b\Phi_h^2} \frac{-4b\Phi_h^2}{2\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}} - \frac{1}{2}$$
$$= \frac{-(a\Phi_h - c)}{2\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}} - \frac{1}{2} < 0,$$

we have

$$\begin{aligned}
&W_h^{pc*} - W_l^{pc*} \\
&= \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{4b\Phi_h^2} - \frac{e}{2} - \frac{(a\Phi_l - c)^2}{2b\Phi_l^2} \\
&> \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 \widetilde{e}_2}}{4b\Phi_h^2} - \frac{\widetilde{e}_2}{2} - \frac{(a\Phi_l - c)^2}{2b\Phi_l^2} \\
&\geqslant 0,
\end{aligned}$$

thus it could be found that $W_h^{pc*} > W_l^{pc*} > W_l^{mt*} > W_l^*$.

As $\frac{\partial W_h^{pc*}}{\partial e} < 0$, we can, in the range of $\widetilde{e}_4 \leqslant e < \widetilde{e}_2$, obtain that

$$W_h^{pc*}(e = \widetilde{e}_2) - W^{ror*} < W_h^{pc*} - W^{ror*} < W_h^{pc*}(e = \widetilde{e}_4) - W^{ror*}$$

$$\begin{aligned}
W_h^{pc*} - W^{ror*} &= \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{4b\Phi_h^2} - \frac{e}{2} \\
&\quad - \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} - \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} \\
&\quad \begin{cases} > 0, & \text{if } \widetilde{e}_4 \leqslant e < \widetilde{e}_3 \\ \leqslant 0, & \text{if } \widetilde{e}_3 \leqslant e < \widetilde{e}_2 \end{cases},
\end{aligned}$$

where $W_h^{pc*} = W^{ror*}$ at the point $e = \widetilde{e}_3$. Therefore, in this case the comparison is summarised in the following table.

e	W
$\widetilde{e}_4 \leqslant e < \widetilde{e}_3$	$W_h^{pc*} > W^{ror*} > W_l^{mt*} > W_l^*$
$\widetilde{e}_3 \leqslant e < \widetilde{e}_2$	$W^{ror*} \geqslant W_h^{pc*} > W_l^{mt*} > W_l^*$

- Case 3: In the case where $\widetilde{e}_1 \leqslant e < \widetilde{e}_4$, the monopolist is prone to undertake positive effort for energy efficiency under both price-cap regulation and mandated-target regulation, then under the circumstance the relevant levels of expected social welfare are respectively:

$$W_l^* = W^*(E=0) = \frac{(2\gamma+1)(a\Phi_l - c)^2}{8b\Phi_l^2},$$

$$W^{ror*} = W^{ror*}(E=0) = \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2},$$

$$W_h^{pc*} = W^{pc*}(E=e) = \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{4b\Phi_h^2} - \frac{e}{2},$$

$$W_h^{mt*} = W^{mt*}(E=e) = \frac{(2\gamma+1)(a\Phi_h - c)^2}{8b\Phi_h^2} - \gamma e + (1-\gamma)(1-\nu)\delta.$$

As $e < \widetilde{e}_4 = \frac{[a\Phi_h - c]^2}{4b\Phi_h^2} - \frac{[a\Phi_l - c]^2}{4b\Phi_l^2} + (2\nu - 1)\delta$, it is easy to obtain $W_h^{mt*} > W_l^{mt*}$. From the previous analysis, we know that $W_l^{mt*} > W_l^*$. Therefore, $W_h^{mt*} > W_l^*$.

As

$$\begin{aligned}
&W^{ror*} - W_h^{mt*} \\
&= \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(2\gamma+1)(a\Phi_h - c)^2}{8b\Phi_h^2} + \gamma e - (1-\gamma)(1-\nu)\delta \\
&\geqslant \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(2\gamma+1)(a\Phi_h - c)^2}{8b\Phi_h^2} + \gamma \widetilde{e}_1 - (1-\gamma)(1-\nu)\ \widetilde{\delta}_1 \\
&= \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(2\gamma+1)(a\Phi_h - c)^2}{8b\Phi_h^2} \\
&+ \frac{2\gamma(a\Phi_h - c)^2}{8b\Phi_h^2} - \frac{\gamma(a\Phi_l - c)^2}{4b\Phi_l^2} - \frac{(1-\gamma)(1-\nu)(a\Phi_l - c)^2}{4b\nu\Phi_l^2} \\
&= \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(a\Phi_h - c)^2}{8b\Phi_h^2} - \frac{\gamma\nu(a\Phi_l - c)^2}{4b\nu\Phi_l^2} - \frac{(1-\gamma)(1-\nu)(a\Phi_l - c)^2}{4b\nu\Phi_l^2} \\
&= \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(a\Phi_h - c)^2}{8b\Phi_h^2} - \frac{[1-\nu+(2\nu-1)\gamma](a\Phi_l - c)^2}{4b\nu\Phi_l^2} \\
&\geqslant \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1-\nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2} - \frac{(a\Phi_h - c)^2}{8b\Phi_h^2} - \frac{(a\Phi_l - c)^2}{4b\Phi_l^2} > 0,
\end{aligned}$$

we have $W^{ror*} > W_h^{mt*} > W_l^*$.

From the assumption that $W_h^{pc*} = W^{ror*}$ at the point $e = \widetilde{e}_3 > \widetilde{e}_4$, it could be found that in the case where $e < \widetilde{e}_4$ we have $e < \widetilde{e}_3$. As W_h^{pc*} increases with the decrease in effort cost e, it is safely to conclude that in this case $W_h^{pc*} > W^{ror*}$.

Thus in this case, the comparison is summarised as $W_h^{pc*} > W^{ror*} > W_h^{mt*} > W_l^*$.

- Case 4: in the case where $0 < e < \widetilde{e}_1$, the monopolist is prone to undertake positive effort for energy efficiency except under ROR regulation, then under the circumstance the relevant levels of expected social welfare are respectively:

$$W_h^* = W^*(E = e) = \frac{(2\gamma + 1)(a\Phi_h - c)^2}{8b\Phi_h^2} - \gamma e,$$

$$W^{ror*} = W^{ror*}(E = 0) = \frac{\nu(a\underline{\Phi} - c)^2}{2b\underline{\Phi}^2} + \frac{(1 - \nu)(a\overline{\Phi} - c)^2}{2b\overline{\Phi}^2},$$

$$W_h^{pc*} = W^{pc*}(E = e) = \frac{(a\Phi_h - c)^2 + (a\Phi_h - c)\sqrt{(a\Phi_h - c)^2 - 4b\Phi_h^2 e}}{4b\Phi_h^2} - \frac{e}{2}$$

$$W_h^{mt*} = W^{mt*}(E = e) = \frac{(2\gamma + 1)(a\Phi_h - c)^2}{8b\Phi_h^2} - \gamma e + (1 - \gamma)(1 - \nu)\delta$$

From the analysis in the above three cases, we know $W_h^{mt*} > W_h^*$. Thus in this case, the comparison could be summarised as $W_h^{pc*} > W^{ror*} > W_h^{mt*} > W_h^*$.