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Cost-Efficiency and Quality Regulation of a Public Utility

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This paper studies the effect of linear cost-efficiency and quality regulation of a public utility on its cost-reducing effort and its provided quality level. The analysis shows that a quality incentive increases both quality and effort, while a cost-efficiency incentive increases effort and decreases quality. Next, introducing uncertainty and asymmetric information, I show that the power of the cost-efficiency and quality incentive should optimally be equal and below one. The incentive powers decrease with increasing uncertainty and increasing dislike for public utility profit. Last, we analyze case studies in electricity, gas and water. As in most cases the power of the quality incentive is higher than the power of the cost-efficiency incentive, the model predicts that supplied quality is too high.

Keywords: Quality Regulation, Incentive Power, Incentive Regulation, Public Utility Regulation

JEL: K23, L51, L90

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1 Introduction

Public utilities are essential for the wellbeing of our society, as they supply necessity goods and services like electricity, gas, water, sewage treatment, waste disposal, telecommunications and transport. Inadequate quality of these services has far-reaching effects, ranging from decreased comfort and economics losses to diseases and deaths. However, high quality comes at a cost. Depending on their income, households in the United States spend between 4.4% and 7.2% of their income on utilities (Bureau of Labor Statistics, 2016); in developing countries on average 3.1% (The World Bank, 2010); and in the European Union on average 8.1% (OECD, 2014).[1] To strike a balance between the cost and quality of these services, both cost-efficiency and quality incentives are essential.

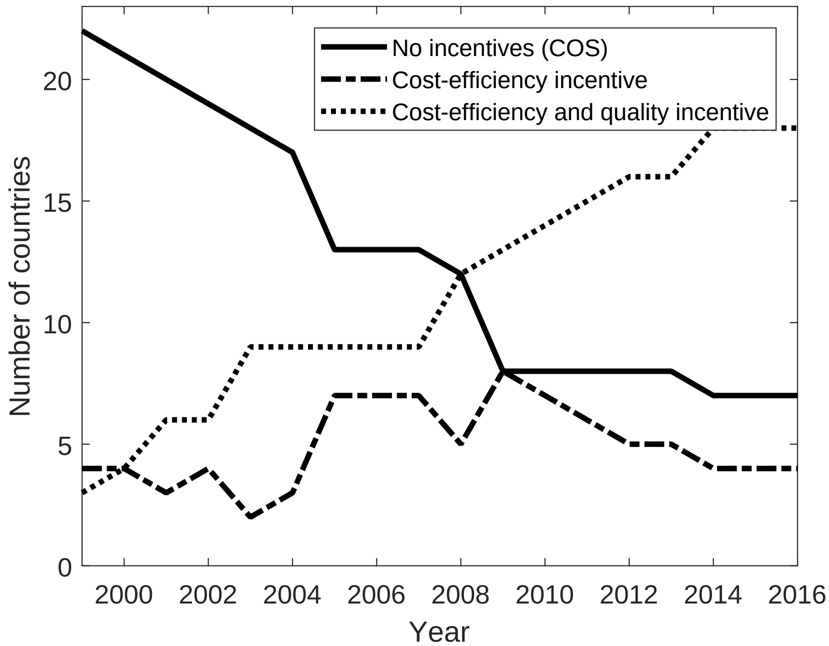
Historically, many public utilities were not subject to any kind of explicit cost-efficiency or quality incentives. Being part of an integrated government-owned company, costs were repaid on a cost-of-service basis and incentives for cost-efficiency and quality were implicit. However, starting in the nineties, incentives were gradually introduced in the wake of widespread deregulation of many public utility industries. For example, in 1999 in Europe only three countries imposed both cost-efficiency and quality incentives on their electricity distribution system operators (DSOs) (Netherlands, Norway and United Kingdom). Four countries imposed cost-efficiency incentives only (Hungary, Ireland, Spain and Sweden). Figure 1 shows that the number of countries with both cost-efficiency and quality incentives gradually increased from 3 in 1999 to 18 in 2016, and another four countries have intentions to implement quality incentives (Austria, Greece, Luxembourg and Romania) (CEER, 2016). Most of these countries starting by imposing cost-efficiency incentives, while quality incentives were introduced on average 3.5 years later.

Many of the results in the literature on quality regulation[2] depend on the consumer demand curve. Spence (1975) has shown that an unregulated monopolist may over- or undersupply quality depending on consumers' marginal and average valuation of quality. Sheshinski (1976) extended this analysis to monopolies facing price, quantity and quality regulation. His results of optimal and regulated quality depend on quality and quantity being complements or substitutes. Similarly, the result of Besanko et al.

[1] The EU28 data is biased upwards as it also includes expenditures on fuel.

[2] For an excellent overview of this literature we refer to (Sappington, 2005), and (Ajodhia and Hakvoort, 2005) for an overview focused on quality regulation of electricity distribution networks.

Figure 1: Regulatory regime of electricity distribution system operators in the EU28+Norway for 1999-2016 (Schmidthaler et al., 2015; CEER, 2016).



(1987), who study the effect of price ceilings and minimum quality standards on a monopolist supplying a range of products, depends on the willingness to pay for quality. Lewis and Sappington (1992); Laffont and Tirole (1993); Weisman (2005) and Kidokoro (2002) introduce effort into their model, but they assume that costs are separable in quality and effort. They find that a price cap decreases quality, but the results of Lewis and Sappington (1992) and Laffont and Tirole (1993) hinge on quantity and quality being complements or substitutes, while Weisman (2005) assumes these cross derivatives are small. Kidokoro (2002) additionally finds that a price cap decreases investment-related quality but increases effort-related quality.

This paper contributes to three strands of literature. First, quality regulation of a monopolist (Spence, 1975; Sheshinski, 1976; Kidokoro, 2002; Weisman, 2005; Fraser, 1994). By introducing an incentive power for both cost and quality, this paper explicitly identifies the effect of incentive power on quality and on cost-reducing or quality-increasing effort. In addition, we analyze the role of a monopolist's cost function inseparable in quality and effort.

Second, quality regulation in a principal-agent framework. That is, finding the optimal regulation in the presence of asymmetric information or moral hazard (Lewis and Sappington, 1992; Laffont and Tirole, 1993). These papers mainly deal with issues such as unverifiability of quality and experience goods, while the current paper assumes quality is verifiable. This paper does not focus on finding the optimal regulation, but instead focuses on the optimal parameter values for a specific linear regulation, while assuming asymmetric information and moral hazard.

Third, a small literature that studies the properties of existing regulation. (Reichelstein, 1992; Schmalensee, 1989; Weitzman, 1976; Gasmi et al., 1994; Cossent and Gómez, 2013). The model studied in this paper is a stylized version of current regulation of public utilities in Australia, Great Britain, Netherlands, Norway, Sweden, etc. This regulatory scheme is a linear hybrid regulation with cost and quality incentives. In the spirit of Schmalensee (1989), we depart from the optimal regulation literature and focus on 'good' linear regulatory regimes in the presence of real-life constraints such as (i) the regulator's inability to tax or subsidize the public utility, (ii) limited information, and (iii) the regulator's and the public utility's uncertainty about future parameter values. Because of the incentive power of the hybrid regulation, we can study the continuum between pure rate-of-return (ROR) or cost-of-service (COS) regulation, and pure price-cap (PCR) or revenue-cap regulation.

This paper is organized as follows. Section 2 introduces the studied regulation with linear cost-efficiency and quality incentives. Examples of this regulation in Norway and Great Britain are discussed. Next, section 3 studies the properties of the linear regulation, both in general terms and with specific functional forms. The analysis shows that both quality and effort increase with the power of the quality incentive. The effect of the power of the cost incentive is ambiguous but under reasonable assumptions it increases effort and decreases quality. Section 4 studies the regulator's optimization problem under both uncertainty and asymmetric information. Because a higher incentive power increases both socially-costly profit, and cost-reducing effort and quality, we show that the power of the cost-efficiency incentive and the quality incentive are optimally below one. The higher the uncertainty and extent of asymmetric information, the lower the incentive power. In section 5, the theoretical model is compared with regulation in practice by analyzing case studies in gas and water. Finally, section 6 concludes.

2 Regulation with cost efficiency and quality incentives

2.1 The studied regulation

As Holmstrom and Milgrom (1987) and Schmalensee (1989) have noted, most incentive schemes observed in practice are linear. In addition, Holmstrom and Milgrom (1987) note that linear contracts enjoy a robustness that makes them effective in a wide range of situations. Therefore, as in (Schmalensee, 1989), we propose a linear regulatory scheme that leads to 'good' results in many settings, but is not optimal for all functional forms and distributions of uncertainty. This paper studies the following revenue cap R with cost-efficiency and quality incentives:

$$R = C - b_C(C - \overline{C}) + b_q V(q - \overline{q}) \text{ with } b_C, b_q \in [0, 1] \tag{1}$$

Each year the regulated public utility earns a revenue R, which depends on a cost norm $\overline{C}$, its realized costs C, a quality norm $\overline{q}$, and its realized quality level q. The allowed revenue R increases with both realized costs and realized quality.[3] However, the regulated public utility is remunerated only a fraction (1-b_C) of its realized costs and earns the remaining fraction b_C of the ex-ante determined cost norm $\overline{C}$, also called justified costs. This cost norm is determined by the regulator based on the regulated public utility's historical costs, on benchmark analyses of other public utilities (Schleifer, 1985)[4], and on assumptions of the growth rate of the retail price minus the anticipated rate of technological progress (RPI-X) (Littlechild, 1983). The fraction b_C is the power of the cost incentive.[5] The higher b_C, the more the public utility's revenue is allocated independently of realized costs; the lower b_C, the more its costs are remunerated in function of realized costs.

A regulatory scheme with $b_C = 1$ amounts to a pure revenue cap, while $b_C = 0$ amounts

[3]We assume that quality is verifiable, such that a regulator can use observed quality, without needing to resort to sales incentives and threats to reputation (Laffont and Tirole, 1991; Lewis and Sappington, 1991).

[4]See (Estache et al., 2004) and (Giannakis et al., 2005) for examples of electricity network benchmarking.

[5]We assume that the rate of return on realized costs $(1 - b_C)C$ is equal to the weighted average cost of capital (WACC) and thus does not end up in the profit of the public utility. If the rate of return is r [%] higher than the WACC, the analysis is still valid but the power of the cost incentive is adjusted downwards: $b_r = b_C - (r - WACC)(1 - b_C)$.

to cost-of-service regulation. There is a sizable literature that studies the properties, advantages and disadvantages of these two limits of the regulatory spectrum. For an excellent overview we refer to (Liston, 1993; Laffont and Tirole, 1993) and (Decker, 2014).

Revenue cap (1) is sometimes expressed in terms of a cost-sharing parameter, for example in the regulation of electricity networks in Great Britain (see section 2.2). The cost-sharing parameter s is the fraction of cost under- or overperformance that is paid for by consumers. In that case the cost incentive of the revenue cap is:

$$R = \overline{C} + s(C - \overline{C}) = (1 - s)\overline{C} + sC \tag{2}$$

which shows that the cost-sharing parameter is one minus the incentive power, i.e. $s = 1 - b_C$.

To revenue cap (1), a quality incentive is added. If quality q is above the quality norm $\overline{q}$, the public utility earns an additional revenue of $b_q V(q - \overline{q})$; if the quality is lower than the quality norm, a penalty of $b_q V(q - \overline{q})$ is subtracted from its allowed revenue. The parameter b_q is the power of the quality incentive. Similar to the power b_C of the cost incentive, a high power of the quality incentive means that deviations from the quality norm have a larger effect on the public utility's allowed revenue. The parameter V is the (average) quality valuation of consumers.

The cost norm $\overline{C}$ and quality norm $\overline{q}$ are chosen such that the public utility earns a non-zero profit. Since regulators are (generally) not able to directly tax or subsidize the public utility, we assume that these costs are completely covered by consumer payments.[6] For example, network tariffs for electricity transmission and distribution networks, capacity and commodity charges for gas, access charges for telecommunication services, infrastructure charges for railroads, tolls for toll roads, airport fees, etc. Most public utilities are not free to choose the price structure independently. Since consumer charges are often set at the beginning of a year or regulatory period, and total consumption and realized costs are only known at the end, an excess or deficit of raised revenue is possible. However, the regulator set the consumer charges such that the excess or deficit revenue balance is zero over time.

[6] Pricing of a natural monopoly is an important question but is not dealt with in this paper, as we assume demand to be inelastic to changes in price and quality. In practice average cost pricing and uniformly increasing prices above marginal costs are used (Laffont, 1994), while Ramsey-Boiteux pricing is the theoretical optimum (Boiteux, 1956).

2.2 Regulation in practice

A regulation with cost and quality incentives, as introduced in the previous section, is currently used to regulate public utilities in a number of countries. Table 1 shows the value of the incentive power of cost and quality in a set of countries. The incentive power of costs is around 0.5, while the incentive power of quality equals 1, except in Norway and Sweden.

Table 1: Regions having a regulation with cost (b_C) and quality (b_q) incentives

Region	Sector	b_C	b_q
Australia	Electricity transmission & distribution	0.3	1
Belgium	Electricity Transmission	0.15[a]/0.5[b]	1
England and Wales	Water	0.44-0.59	1
Great Britain	Electricity transmission & distribution	0.4689-0.5	1
Great Britain	Gas distribution	0.63-0.64	1
Great Britain	Railroad operation	0.25 (up) and 0.1 (down)	1
Netherlands	Electricity distribution	1	1
Netherlands	Electricity transmission	1	0
Norway	Electricity transmission & distribution	0.6	0.6
Sweden	Electricity transmission	1[b]	0.5

[a] Incentive on influenceable costs
[b] Cost incentive on controllable costs.

As both incentive powers equal 0.6 in the Norwegian regulation of electricity transmission and distribution networks, equation 1 simplifies to:

$$R = 0.6\overline{C} + 0.4C + 0.6V(q - \overline{q}) \tag{3}$$

In this regulation, cost and quality norms are based on historical values and on benchmarking analysis.[7] The quality incentive adds or subtracts an amount from the allowed revenue cap of the transmission or distribution system operator, so that the quality improvements or deteriorations are socialized over all consumers. There is no direct compensation to affected consumers. However, the treatment of quality incentives is much more elaborate than presented in equation (3). The quality norm is formulated on the basis of interruption costs, a method known as the cost of energy not supplied

[7] This is done for many distribution networks worldwide, but less for transmission networks. As there are relatively few of them, they depend on many variables (the distribution of generation and load, geographic topography, the attributes and age of the legacy network, population density, etc.), and there is no uniform definition of transmission networks (Joskow, 2014).

(CENS) regulation. In the CENS regulation, interruption costs IC are calculated for different consumer groups c, and both the time t and duration d of interruptions u [MWh] have an effect on interruption costs (Kjolle et al., 2008). In summary:

$$R = 0.6\overline{C} + 0.4C + 0.6(\overline{IC} - \sum_{c,t,d} V(c,t,d)u(c,t,d)) \tag{4}$$

Similar regulation exists in many other countries such as England, Wales, Scotland, the Netherlands (Hesseling and Sari, 2006) and Australia.[8] In Great Britain, the three transmission owners – National Grid Electricity Transmission (NGET TO) in England and Wales, Scottish Hydro Electric Transmission (SHE) in the north of Scotland, and SP Transmission (SPT) in the south of Scotland– and the system operator (NGET SO) are regulated using the RIIO regulatory framework,[9] which gives cost and quality incentives over the eight years from 2013 - 2021. The power of the cost incentive is about 0.5 for each of the British transmission owners. This incentive is chosen by OFGEM, the regulator of electricity and gas, based on the transmission owners' proposal of costs. A proposal closer to efficient costs (as determined by the OFGEM) received a higher incentive power (OFGEM, 2016).[10] Table 2 shows that NGET has an incentive power of 0.4689, while SHE and SPT have 0.5.[11] The same table also shows the results of RIIO in 2015-2016 for all three transmission owners and the system operator. NGET TO spent £644m less than allowed and retained 46.89 % of this as higher allowed revenue.

In addition to the above cost incentive, the British electricity networks are also subject to a range of incentives in the following categories: safety, reliability, availability, customer satisfaction, connections and environment (OFGEM, 2016). We focus on the reliability incentive.[12] The reliability incentive is expressed in energy not supplied (ENS) [MWh]. Table 3 shows the ENS of the electricity networks for 2013-2016. The value of lost load (VOLL)[13] is considered to be 16,000 £/MWh in GB, irrespective

[8] In Australia the incentive power is $b_C = 0.3$ for transmission and distribution system operators (Australian Energy regulator, 2013).

[9] RIIO stands for Revenue = Incentives+Innovation+Outputs

[10] For the period 2005-2006, the system operator was offered a menu of contracts where a higher cost norm was combined with a lower upside and higher downside sharing factor ($s = 1 - b$). Option 1: $\overline{C}$ = £480m with $s_{up} = 0.6$ and $s_{down} = 0.15$; Option 2: $\overline{C}$ = £500m with $s_{up} = 0.4$ and $s_{down} = 0.2$; Option 3 $\overline{C}$ = £515m with $s_{up} = 0.25$ and $s_{down} = 0.25$ (Joskow, 2014).

[11] RIIO does not use 'incentive power' b_C but 'sharing factor' $s = 1 - b$, defined as $R = \overline{C} + s(C - \overline{C})$.

[12] For an overview of quality of electricity supply in almost all European countries, we refer to (CEER, 2016).

[13] VOLL represents the cost of unserved electricity and is expressed per quantity demanded (e.g.

Table 2: Results of RIIO in 2015-2016 for the three electricity transmission networks (source: OFGEM (2016)).

m£ 2015-16 Prices		NGET TO	NGET SO	SHE	SPET
Allowed totex	$\overline{C}$	1,805	137	781	354
Actual totex	C	1,161	137	524	358
Over-/underspend	$C - \overline{C}$	-644	-1	-257	4
Incentive power	b_C	0.4689	0.4689	0.5	0.5
Allowed revenue	$R = b_C\overline{C} + (1 - b_C)C$	1,463	137	652	356

of consumer groups, time of interruption or duration, as in the CENS regulation of Norway. The target ENS is constant over the eight years of RIIO 2013-2021. Note that ENS is considerably below target, which leads to large rewards to the electricity networks.

Table 3: ENS of the GB electricity transmission networks for 2013-2016 (source: OFGEM (2016)).

	NGET	SHE	SPET
Target ENS [MWh]	316	120	225
ENS 2013-2014	135	36	42
ENS 2014-2015	9	106	3
ENS 2015-2016	4	0	14
Cumulative reward [m£]	12.8	3.5	9.9

3 The model

3.1 Model assumptions

The most important element of our model is the cost function of the public utility. The quantity demanded is fixed. We consider a convex cost function $C(q, e)$ that is increasing in the quality level q and decreasing in cost-reducing effort e:

$$C'_q > 0, \quad C''_{qq} \geq 0, \quad C'_e < 0, \quad C''_{ee} \geq 0 \quad \text{and} \quad C''_{qq}C''_{ee} - (C''_{qe})^2 \geq 0 \tag{5}$$

€/MWh) (Ovaere et al., 2016).

That is, the marginal cost increase of quality increases with quality and the marginal cost decrease of effort decreases with effort, in line with Coelli et al. (2013); Jamasb et al. (2012); Yu et al. (2009).

The effort e can be interpreted as all monetary and non-monetary actions that decrease the cost of supplying the public utility's service or good at a certain quality level q. If effort increases, a public utility can decrease costs without decreasing quality or similarly, increase quality without increasing cost. Examples of cost-reducing effort are investments in lower power losses in electricity networks or in better maintenance technologies for gas pipelines. Equivalently, examples of quality-increasing effort are cutting trees near electricity lines, controlling the pressure of gas pipelines, checking water quality, increasing the number of airport security guards, etc. Exerting this effort e entails a cost or disutility $\psi(e)$ for the public utility. This cost is increasing and convex in effort:

$$\psi'(e) \geq 0 \text{ and } \psi''(e) \geq 0 \tag{6}$$

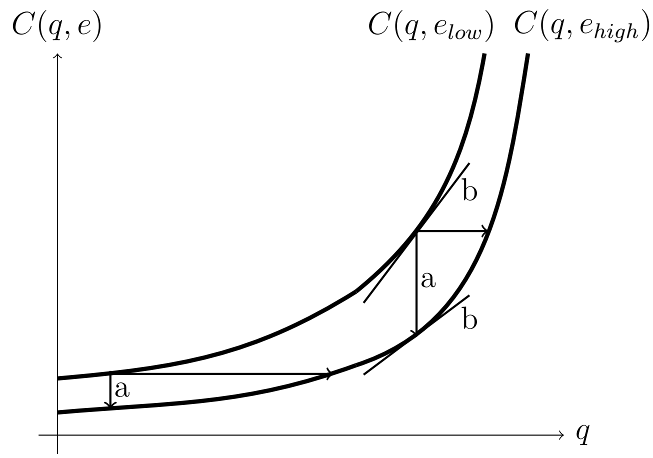
As in (Schmalensee, 1989), notation and prose are simplified by treating $\psi(e)$ as a pecuniary cost.

Consumers derive a total benefit $v(q)$ from consuming the good or service with quality level q. This benefit is increasing and concave in the quality level:

$$v'(q) \geq 0 \text{ and } v''(q) \leq 0 \tag{7}$$

Results of this paper depend crucially on the sign of the cross derivative of costs with respect to quality and effort. Figure 2 shows two cost functions if the cross derivative is negative. The upper curve is with low effort, the lower curve with higher effort. A negative cross derivative means that the marginal cost decrease of cost-reducing effort increases with the level of quality (vertical lines, a), or alternatively, the marginal cost of quality at a certain quality level decreases with effort (slopes, b). The cross derivative is unlikely to be positive, as this would mean that the marginal quality increase of quality-increasing effort increases with the quality level. That is, it would be easier to increase quality at higher quality levels than at lower quality levels. As a result, in the remainder of this paper I assume that the cross derivative is weakly negative.

Figure 2: Cost-reducing effort (vertical lines) and quality-increasing effort (horizontal lines) for a negative cross derivative of costs.



3.2 The public utility's optimization problem

If a public utility is subject to revenue cap (1), its profit function (or alternatively, its utility function) to maximize is:

$$\max_{\{e_P,q_P\}} b_C(\overline{C} - C(q_P, e_P)) + b_q V(q_P - \overline{q}) - \psi(e_P) \tag{8}$$

where e_P and q_P are the effort and quality chosen by the public utility. This leads to the following first-order conditions for the public utility's choice of quality and effort:

$$\begin{aligned} b_q V - b_C C'_q &= 0 \\ b_C C'_e + \psi'_e &= 0 \end{aligned} \tag{9}$$

The first-order conditions tell that the public utility chooses the quality level such that the marginal increase of its regulated revenue from the quality incentive equals the marginal increase of its regulated revenue from the cost incentive; and it chooses its effort such that the marginal increase of its regulated revenue from the cost incentive equals its marginal cost of effort. As before, a global maximum exists because effort and costs are convex and the quality incentive is concave.

Total differentiation of the public utility's first-order conditions leads to the following proposition:

Proposition 1. *If cost is convex (assumptions* (5)*) and the cross derivative of effort and quality is weakly negative, the quality incentive increases both quality and effort,* *while the power of the cost incentive b_C has an ambiguous effect on both quality and effort:*

$$\frac{dq_P}{db_q} > 0 \qquad \textit{and} \qquad \frac{dq_P}{db_C} < \textit{or} \geq 0$$
$$\frac{de_P}{db_q} \geq 0 \qquad \textit{and} \qquad \frac{de_P}{db_C} > \textit{or} \leq 0$$

Proof. See Appendix A □

If the cross derivative of costs is zero (e.g. $C = q - e$, as in (Laffont and Tirole, 1993, Chapter 4)), all signs are identified. The quality incentive increases quality but has no effect on effort, while the cost-efficiency incentive increases effort and decreases quality.

When the cross derivative is negative, the effect of the cost-efficiency incentive is not clear. However, if cost and disutility are sufficiently convex in respectively quality and effort, compared to the convexity of cost in effort. Appendix B shows that this indeed the case for two evident functional form specifications.

In addition, because of the concavity of the cost function, $\frac{dq_P}{db_C} < 0$ implies $\frac{de_P}{db_C} > 0$ and vice-versa.

Proposition 1 predicts the effect of both the cost-efficiency and the quality incentive on quality and effort. The theoretical literature has so far only focused on the effect of the cost incentive on quality. Their prediction is in line with proposition 1. Sheshinski (1976) finds that with a positive cross derivative of inverse demand with respect to quality and quantity ($p_{qx} > 0$), a price cap decreases quality if the cross derivative of profits is negative ($\pi_{qx} < 0$) and increases quality if the cross derivative of profits is positive ($\pi_{qx} > 0$). The effect is ambiguous for a negative cross derivative of inverse demand. Similarly, Kidokoro (2002) finds that quality decreases with incentive power for investment-related quality and increases with incentive power for effort-related quality.

The theoretical predictions of proposition 1 are confirmed by the (small) empirical literature of quality in electricity networks. Ter-Martirosyan and Kwoka (2010) find that incentive regulation is associated with significantly longer duration of service outages ($\frac{dq}{db} < 0$), but that this quality reduction is offset when regulation includes quality incentives ($\frac{dq}{db_q} > 0$). Similarly, Schmidthaler et al. (2015) find that the introduction of quality incentives leads to reductions of the annual outage duration by 16.05% on average ($\frac{dq}{db_q} > 0$). In the telecommunications industry, the empirical results (in the U.S.) have been mixed (Banerjee, 2003; Sappington, 2003; Ai et al., 2003). However, since cost and quality incentives were introduced simultaneously in many states, their effects are difficult to disentangle ($\frac{dq}{db_q db} >< 0$).

3.3 Model with specific functional forms

To arrive at more unambiguous results, this section determines the public utility's chosen effort and quality for specific functional forms.[14] First, we consider the following cost function, which satisfies assumptions (5):

$$C(q,e) = \frac{\beta}{e(1-q)}, \quad q \in [0,1], \quad \beta, e > 0 \tag{10}$$

where the cost parameter β determines the cost for a given level of effort e and quality q. The cost parameter β is exogenous and depends, inter alia, on consumer density, geography, climate, employee wages, yearly demand, size of the network, economies of scale, and economies of scope. Quality varies between zero and one, with a value of one indicating a perfect quality level and zero indicating no quality. The costs $C(q,e)$ increase with quality.[15] The cost of reaching a perfect quality level ($q = 1$) is infinite. For example, a completely reliable gas or electricity network requires large reliability margins and thus many redundant lines and pipelines (Ovaere and Proost, 2016). Similarly, to completely eliminate congestion, an airport needs many runways, a railway network many tracks, a toll road many parallel lanes, and a telecommunications network many links and towers.

Second, effort costs have the following functional form:

$$\psi(e) = \frac{\gamma}{2}e^2, \quad \gamma > 0 \tag{11}$$

where the effort cost parameter γ is strictly positive. A higher effort leads to a higher quality level for the same costs or lower costs for the same quality level. If effort is higher than one, costs decrease; if effort is lower than one, costs increase. Lastly, consumer benefit is linear in quality: $v(q) = Vq$.

[14] Appendix B repeats the analysis of this section for different functional forms and finds similar results.

[15] Reichl et al. (2008) confirm that the reliability level of transmission networks increases with costs. They find that annual average interruption duration increases by 1.36 minutes if average costs decrease by 1€/MWh. Likewise, in a case study of Italian distribution system operators (DSOs), Cambini et al. (2016) find that operating expenditures and capital expenditures affect service quality.

Inserting these functional forms into the public utility's objective function (8), its chosen quality and effort are:

$$q_P = 1 - (\frac{b_C^2 \gamma \beta^2}{b_q^3 V^3})^{0.2}$$
$$e_P = (\frac{b_q b_C V \beta}{\gamma^2})^{0.2} \tag{12}$$

These expressions show that both quality and effort increase with the power b_q of the quality incentive – as predicted by proposition 1, because $C'''_{qe} < 0$ for our assumed cost function. Proposition 1 is ambiguous on the effect of b_C on quality and effort, but the above expressions show that for our assumed cost function, quality decreases and effort increases with the power b_C of the cost incentive. In addition, expressions (12) show that the public utility's quality decreases with effort cost and cost, and increases with V. Its effort level decreases with effort cost, increases with cost and increases with V. The alternative functional forms in Appendix B yield similar results.

4 The regulator's optimization problem

The previous section determined the public utility's chosen effort and quality in response to cost and quality incentives. This section studies the upper-level question of choosing optimal norms and incentive powers for cost-efficiency and quality under different assumptions of asymmetric information and uncertainty.

We suppose that the regulator values consumer surplus (CS) more than monopoly profit (Π), i.e. social welfare = CS + $(1-\alpha)\Pi$, with $\alpha \geq 0$ (Baron and Myerson, 1982; Armstrong and Sappington, 2004). In addition, the public utility should be guaranteed a non-zero profit. As a result, the regulator's optimization problem is:

$$\begin{aligned} \max_{\{b_C, b_q\}} \quad & v(q_P) - \Big(C(q_P, e_P) + \Pi + \psi(e_P)\Big) + (1-\alpha)\Pi \\ & = v(q_P) - \Big(C(q_P, e_P) + \psi(e_P)\Big) - \alpha\Pi \\ & \text{s.t. } \Pi \geq 0 \end{aligned} \tag{13}$$

where q_P and e_P are determined by (8). As monopoly profit is socially costly, the public utility's profit should be as low as possible. Under perfect information, cost and quality norms can be chosen such that profit equals zero. In that case, the incentive powers are chosen such that the public utility's effort and quality satisfy the first-order conditions of (13):

$$\begin{aligned} v'_q - C'_q &= 0 \\ C'_e + \psi'_e &= 0 \end{aligned} \tag{14}$$

Comparing (14) and (9) reveals that under perfect information the incentive powers equal one. In the next sections, we study the effect on the optimal incentive powers of weakening the perfect information assumption.

4.1 The regulator's optimization problem with uncertainty

Suppose that both the regulator and the public utility are uncertain about future cost realizations. As the regulator should guarantee the public utility a non-negative profit in all possible states of nature, he can at best choose the norms such that the public utility's profit is zero in the worst-case scenario. In other states of nature the public utility's profit will be positive and his expected profit E[Π] will thus be positive. The regulator's maximization problem is:

$$\begin{aligned} \max_{\{b_C, b_q\}} \quad & V(q_P) - \Big(C(q_P, e_P) + \psi(e_P)\Big) - \alpha\,\mathbb{E}\Big[\Pi(q_P, e_P, \epsilon)\Big] \\ & \text{s.t. } \Pi(q_P, e_P, \epsilon = \bar{\epsilon}(x\%)) \geq 0 \end{aligned} \tag{15}$$

where $q_P(b_C, b_q)$ and $e_P(b_C, b_q)$ are determined from equation (9). The parameter ϵ represents the uncertainty about the public utility's parameters (Arve and Martimort, 2016). A higher ϵ means higher uncertainty (Schmalensee, 1989). We assume that the public utility does not have more information about future parameter values than the regulator or that he does not use this asymmetric information to his benefit. The constraint ensures that the public utility's profit is at least non-negative for x% of all parameter realizations. To derive meaningful analytical results, we assume the functional forms of section 3.3 and assume that the regulator knows these functional forms but is uncertain about the values of the parameters γ, β and V. Suppose that his aggregate uncertainty about these parameters is characterized by $\Big(\gamma\beta^2V^2\Big)^{0.2}(1+\epsilon)$, where the regulator knows that ϵ has a symmetric probability density function f(ϵ) with $\mathbb{E}[\epsilon] = 0$ and $x = F(\bar{\epsilon})$ the probability that the positive cost shock is below $\bar{\epsilon}$.

This leads to the following lemma:

Lemma 1. *Under the above assumptions, the fixed payment and the expected profit increase with* $\epsilon(x), x, b_C$ *and* b_q*.*

Proof. Using expressions (12) of the public utility's choice of effort and quality, expressions for costs, effort costs and the cost of unreliability (1-q) are:

$$C(q,e) = A\frac{b_q^{0.4}}{b_C^{0.6}},\ \psi(e) = \frac{A}{2}b_q^{0.4}b_C^{0.4} \text{ and } (1-q)V = A\frac{b_C^{0.4}}{b_q^{0.6}}, \text{ with } A = \Big(\gamma\beta^2V^2\Big)^{0.2} \quad (16)$$

To have $\Pi(\overline{\epsilon}) = 0$ (participation constraint), fixed payments should equal:

$$b_C\overline{C} + b_qV(1-\overline{q}) = 2.5\mathbb{E}[A]b_q^{0.4}b_C^{0.4}(1+\overline{\epsilon}) \quad (17)$$

The expected profit is:

$$\mathrm{E}\Big[\Pi(q_P, e_P)\Big] = 2.5Ab_q^{0.4}b_C^{0.4}\int_{-\overline{\epsilon}}^{\overline{\epsilon}}(\overline{\epsilon}-\epsilon)f(\epsilon)\mathrm{d}\epsilon = 2.5Ab_q^{0.4}b_C^{0.4}\overline{\epsilon} \quad (18)$$

because $\int_{-\overline{\epsilon}}^{\overline{\epsilon}}(\overline{\epsilon}-\epsilon)f(\epsilon)\mathrm{d}\epsilon = \overline{\epsilon}$ for symmetric distributions. □

This result is in line with the simulation model of Gasmi et al. (1994) and empirical evidence in the telecommunications industry (Sappington, 2002; Hauge and Sappington, 2010). Since this lemma shows that expected profit increases with the power of both the cost and quality incentives, the regulator faces a trade-off between optimal cost and quality incentives, and higher expected profit for the public utility. Increasing the incentive powers increases socially-costly profit but increases cost-reducing effort and quality. This results in the following proposition:

Proposition 2. *In the presence of uncertainty* ($\overline{\epsilon} > 0$) *and socially-costly profit, and assuming the above functional forms, the optimal power of the cost incentive and the quality incentive are equal and below one:*

$$b_C^* = b_q^* = \frac{1}{1+5\alpha\overline{\epsilon}(x)} < 1 \quad (19)$$

Proof. Inserting the functional forms and the expression for expected profit from

Lemma 1 into the regulator's maximization (15) yields the following expression:

$$\max_{\{b_C,b_q\}} V - A\frac{b_C^{0.4}}{b_q^{0.6}} - \Big(A\frac{b_q^{0.4}}{b_C^{0.6}} + \frac{A}{2}b_q^{0.4}b_C^{0.4}\Big) - 2.5(1-\alpha)Ab_q^{0.4}b_C^{0.4}\bar{\epsilon} \tag{20}$$

Which leads to the following first-order conditions:

$$\begin{aligned} 2\frac{b_C}{b_q} - 3 + b_C + 5\alpha\bar{\epsilon}b_C = 0 \\ -3 + 2\frac{b_q}{b_C} + b_q + 5\alpha\bar{\epsilon}b_q = 0 \end{aligned} \tag{21}$$

which results in $b_C^* = b_q^* = \frac{1}{1+5\alpha\bar{\epsilon}}$. Appendix B shows that the result is robust for a second functional form. □

This proposition shows that the power of the cost and quality incentives (i) should be equal, and (ii) should decrease with increasing uncertainty and increasing dislike for monopoly profit. This last result is similar to Schmalensee (1989) who states that ROR regulation is preferred at high levels of uncertainty. However, in our case the incentive power decreases with the level of uncertainty and only equals ROR regulation in the limit. Looking at expressions (12), both effort and quality are thus lower under uncertainty than under perfect information. Table 1 shows that the incentive power of the cost incentive is generally between 0.46 and 0.63. This value is in line with the prescription of equation (2). For example, if $\alpha = 0.5$ and $\bar{\epsilon} = 0.4$, i.e. monopoly profit is valued 50% less than consumer surplus and the public utility has an uncertainty of [-40%,+40%] over the parameter values, optimal incentive power equals 0.5.

From proposition 2 it is straightforward to show the following corollary:

Corollary 1. *Under the above assumptions, expected cost of the public utility increases with the power of the quality incentive, and decreases with the power of the cost incentive, except for very high uncertainty ($\bar{\epsilon}$) and a very low preference for monopoly profit (α).*

Proof.

$$\begin{aligned} TC &= C(q_P, e_P) + \psi(e_P) + \alpha\,\mathbb{E}\Big[\Pi(q_P, e_P)\Big] \\ &= Ab_q^{0.4}\Big(\frac{1}{b_C^{0.6}} + \frac{b_C^{0.4}}{2} + 2.5\alpha\bar{\epsilon}b_C^{0.4}\Big) \end{aligned} \tag{22}$$

□

When the parameters γ, β and V are expressed on a per quantity basis, the above result also applies to the average price or consumer tariff. The theoretical prediction of corollary 1 is also confirmed by the empirical literature of price-cap regulation in the U.S. telecommunications industry. After the introduction of price-cap regulation, Mathios and Rogers (1989) find significantly lower rates, Kaestner and Kahn (1990) find lower prices, Ai and Sappington (2002) find that costs are generally lower, and Blank et al. (1998) find no evidence of reduced prices.

4.2 The regulator's optimization problem with asymmetric information

Suppose that the public utility has more information about its cost parameter value β than the regulator. The public utility exactly knows its cost parameter, while the regulator only knows that it is drawn from a cumulative distribution function $F()$ on $[\underline{\beta}, \overline{\beta}]$ with density $f()$. In that case, the choice of the norms and incentive powers of cost and quality should not only ensure a nonzero profit to the public utility (IR), but should also ensure that an efficient public utility (β low) has a higher quality and an inefficiency public utility (β high) has a higher effort. In line with Laffont and Tirole (1993, Chapter 3), this incentive compatibility (IC) constraint is added to the regulator's optimization problem:

$$\begin{aligned} \max_{\{b_C, b_q\}} \quad & \int_{\underline{\beta}}^{\overline{\beta}} \left[V(q_P) - \Big(C(q_P, e_P) + \psi(e_P) \Big) - \alpha \Pi(q_P, e_P, \beta) \right] f(\beta) d\beta \\ & \text{s.t. } IR : \Pi(\overline{\beta}) \geq 0 \\ & \text{s.t. } IC : \dot{\Pi}(\beta) = -\psi_e' E_\beta' \geq 0 \end{aligned} \tag{23}$$

As before, we assume the functional forms of section 3.3 to derive meaningful analytical results.

Lemma 2. *Under the above assumptions, the profit increases with the power of both the cost and quality incentive.*

Proof. Assuming the function forms of expressions (12), the profit needed to satisfy the incentive compatibility constraint is:

$$
\begin{aligned}
\Pi(\beta) &= \int_{\beta}^{\overline{\beta}} -\psi'(e) E_{\beta} d\beta \\
&= \int_{\beta}^{\overline{\beta}} -(b_C b_q V \gamma^3 \beta)^{0.2} 0.2 (\frac{b_C b_q V}{\gamma^2 \beta^4})^{0.2} d\beta \\
&= \int_{\beta}^{\overline{\beta}} -0.2 \frac{(\gamma V^2)^{0.2} b_C^{0.4} b_q^{0.4}}{\beta^{0.6}} d\beta \\
&= 0.5(\gamma V^2)^{0.2} b_q^{0.4} b_C^{0.4} (\overline{\beta}^{0.4} - \beta^{0.4})
\end{aligned}
\tag{24}
$$

Because $\Pi(\overline{\beta}) = 0$. □

As in the previous section with uncertainty, profit increases with both the cost-efficiency and quality incentive. As a result, the regulator agaian faces a trade-off between higher public utility profit and better cost-efficiency and quality incentives. This results in the following proposition:

Proposition 3. *In the presence of asymmetric information and socially-costly profit, assuming a uniform distribution on the cost parameter and assuming the above functional forms, the optimal power of the cost incentive and the quality incentive are equal and below one:*

$$
b_C^* = b_q^* = \frac{1}{1 + \alpha \Big[(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}} - 1) - 0.4(1 - \frac{\beta}{\overline{\beta}}) \Big]} < 1 \tag{25}
$$

Proof. According to (Laffont and Tirole, 1993, p.206) the Hamiltonian is:

$$
\Big[(1-q)V + C(q,e) + \psi(e) + \alpha \Pi \Big] f(\beta) - \alpha F(\beta) \psi'(e) E_{\beta} \tag{26}
$$

Inserting the functional forms and the profit expression from Lemma 2 into the regulator's maximization (15) yields the following Hamiltonian:

$$
\Big[A \Big(\frac{b_C^{0.4}}{b_q^{0.6}} + \frac{b_q^{0.4}}{b_C^{0.6}} + \frac{b_q^{0.4} b_C^{0.4}}{2} \Big) + 0.5\alpha(\gamma V^2)^{0.2} b_q^{0.4} b_C^{0.4} (\overline{\beta}^{0.4} - \beta^{0.4}) \Big] f(\beta) - \alpha F(\beta) \frac{(\gamma V^2 \beta^2)^{0.2} b_C^{0.4} b_q^{0.4}}{5\beta} \tag{27}
$$

This leads to the following first-order conditions:

$$
\begin{aligned}
2\frac{b_C}{b_q} - 3 + b_C + \alpha b_C(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}} - 1) &= \alpha\frac{F(\beta)}{f(\beta)}\frac{0.4b_C}{\beta} \\
-3 + 2\frac{b_q}{b_C} + b_q + \alpha b_q(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}} - 1) &= \alpha\frac{F(\beta)}{f(\beta)}\frac{0.4b_q}{\beta}
\end{aligned}
\qquad (28)
$$

which results in proposition 3, as $\frac{F(\beta)}{f(\beta)} = \beta - \underline{\beta}$ for the uniform distribution on $[\underline{\beta}, \overline{\beta}]$. □

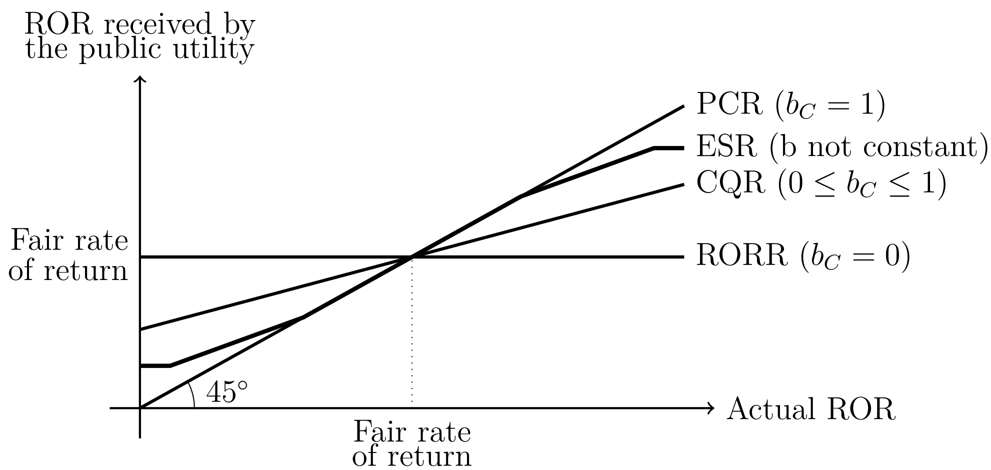
Similarly to proposition 2, proposition 3 shows that the power of the cost-efficiency and quality incentives (i) should be equal and (ii) should decrease with increasing asymmetric information and increasing dislike for monopoly profit. In addition, the optimal incentive power depends on the public utility's cost parameter. Looking at expressions (12), both effort and quality are thus lower under asymmetric information than under perfect information.

5 Regulation in practice

5.1 The difference between different regulations

Figure 3 compares the the cost and quality regulation of this paper (CQR) with rate-of-return regulation (RORR), price-cap regulation (PCR) and earning-sharing regulation (ESR) (Schmalensee, 1989; Gasmi et al., 1994; Lyon, 1996; Weisman, 2005; Blank and Mayo, 2009). The figure links the actual rate of return with the rate of return received by the public utility. Under RORR the rate of return received by the public utility is always the same, irrespective of its cost-reducing efforts or exogenous cost shocks. On the other side of the spectrum, under PCR the public utility receives all changes of the actual rate of return, irrespective whether it is due to exogenous factors or endogenous cost-reducing effort by the public utility. The cost and quality regulation (CQR) of this paper is in between these two extremes. The public utility receives only fraction b_C of changes of the actual rate of return. This linear regulation is a simple form of earning-sharing regulation (ESR), or equivalent profit-sharing or sliding-scale regulation, which has a non-constant power of the cost incentive and caps on minimum and maximum received rate of return. As this allows for more degrees of freedom than the linear model of this paper, ESR probably leads to a higher efficiency, if designed properly.[16] Therefore, having a more intricate regulation is a trade-off between providing better incentives to the public utility and the cost of needed information. As an example, in their search for explanations for the short tenure of ESR in the US telecommunications industry, Sappington and Weisman (2010, p.246) state that ESR introduces contentious technical issues because the sharing rule depends on the level of measured earnings. This is not a problem for linear regulation as the incentive power is constant.

Figure 3: Comparing rate-of-return regulation (RORR), earning-sharing regulation (ESR), the cost and quality regulation of this paper (CQR) and price-cap regulation (PCR).



5.2 Scope of the revenue cap

Up to now, we assumed that all costs of a public utility are included under the revenue cap. However, if only a part of a public utility's costs are subject to cost incentives and his other costs earn a regulated rate of return, the public utility may distort the relative use of its costs, similar to the famous Averch-Johnson effect (Averch and Johnson, 1962).[17] For example, in the regulation of transmission networks in Sweden, cost incentives only apply to operating costs (OC), while capital costs (CC) earn a regulated rate of return (NordREG, 2012).

[16]However, since analytical expressions are not possible anymore, simulations are needed to assess if ESR is more optimal than our analyzed CQR, and which extensions lead to the largest welfare gain: caps, asymmetry and the number of steps in the incentive power. This is an interesting avenue for future research, a point also noted by (Joskow, 2014).

[17]Giannakis et al. (2005) find a trade-off between operating and capital expenditures in UK electricity distribution networks.

If operating costs are decreasing in capital costs, e.g. $OC = \frac{\beta/CC}{e(1-q)}$, public utilities with cost incentives on operating costs and a regulated rate of return on capital costs have a tendency to overinvest in capital costs to decrease operating costs. If a quality incentive is included, the public utility's effort and quality will be (similar to equations (12)):

$$\begin{aligned} e_P &= (\frac{b_C b_q V \beta}{E^2 CC})^{0.2} \\ q_P &= 1 - (\frac{b_C^2 E \beta^2}{b_q^3 V^3 CC^2})^{0.2} \end{aligned} \tag{29}$$

In theory this leads to zero effort and perfect quality, but in reality the decrease of operating costs and the increase of capital costs are limited by regulatory, societal and political constraints.

As a reaction to this distortion of costs, OFWAT, the Water Services Regulation Authority of England and Wales, changed its regulation from one where operating and capital costs were regulated separately (2010-2015), to one where all costs are regulated under the same revenue cap (2015-2020).

5.3 Case studies

This sections analyzes additional case studies in gas and water networks, where hybrid revenue caps are used in combination with quality incentives. The incentive power of the quality incentive is equal to one in all case studies, except for regulation of electricity networks in Norway, where it is equal to 0.6. On the other hand, the incentive power of the cost incentive is between 0.46 and 0.63 in all case studies.

5.3.1 Regulation of gas distribution networks in Great Britain

The eight British gas distribution networks are also regulated according to the above RIIO regulation (OFGEM, 2017). Table 4 shows that the incentive power for the eight British gas distribution networks is between 0.63 and 0.64 over the eight years from 2013 - 2021. This table shows that all distribution utilities underspend and earn a higher allowed revenue.

Just as in the RIIO regulatory framework for electricity, gas networks are also subject to a range of additional incentives in the following categories: network safety, customer

Table 4: Results of RIIO in 2015-2016 for the eight gas distribution networks (source: OFGEM (2017)).

£m 2015-16 Prices		EoE	Lon	NW	WM	NGN	Sc	So	WWU
Allowed totex	$\overline{C}$	316	303	237	186	261	196	406	254
Actual totex	C	297	238	226	172	227	165	336	209
Over-/underspend	$C-\overline{C}$	-19	-65	-11	-14	-34	-31	-70	-45
Incentive power	b_C	0.63	0.63	0.63	0.63	0.64	0.637	0.637	0.632
Allowed revenue	$R=b_C\overline{C}+(1-b)C$	309	279	233	181	249	185	380	238

service, social obligations, network reliability, new connections and environmental protection. Some of them have a pecuniary reward or penalty, others are reputational.

5.3.2 Regulation of water and wastewater utilities in England and Wales

Water and wastewater utilities in England and Wales are privately owned and operated. An independent economic regulator (OFWAT) supervises the private utilities and applies various forms of benchmarking or yardstick competition to encourage performance improvements (Decker, 2014). Regulation of quality is of paramount importance as it directly affects human health and consumers are generally not able to assess the safety of the water.

As already explained in section 5.2, OFWAT uses a Totex-approach for its 2015-2020 regulatory period. This means that all costs of a water utility are regulated under the same revenue cap. OFWAT's 2014 price review for the 2015-2020 period consisted of two steps. First, water utilities had to submit business plans that specified their detailed proposal of objectives ($\overline{C}$ and $\overline{q}$), penalty and reward schemes (V) and efficiency sharing factors ($s=1-b$) (OFWAT, 2013). Based on their business plans, water utilities were awarded an 'enhanced' or 'non-enhanced' status. As many water utilities had provided their proposals in words instead of numbers, only two utilities were awarded the enhanced status. In a second step, OFWAT proposed a menu of incentives to the utilities, based on all submitted business plans and historical data. Table 5 and Table 6 show respectively the menu choice of the cost incentive for the enhanced and non-enhanced utilities in wholesale water and wastewater services. Water utilities with enhanced status received menus with higher incentive power and higher additional income for equal menu choice. The menu choice indicates how much this choice differs from OFWAT's estimate of efficient costs. For example, a menu choice of 85 means that the company's expenditure choice is 15% lower than the estimate of efficient costs. An enhanced water utility that chooses the 85 menu receives a cost norm of 96.25% of its allowed expenditure and an additional bonus of 2.55%, while a non-enhanced utility only receives a bonus of 2.3%.

Table 5: Menu of cost incentives for enhanced utilities in wholesale water and wastewater services (source: OFWAT (2014)).

Menu choice	80	85	90	95	100	105	110	115
Incentive power b_C	59%	58%	57%	56%	55%	54%	53%	52
Cost norm $\overline{C}$ [%]	95	96.25	97.5	98.75	100	101.25	102.5	103.75
Additional income [%]	2.55	1.95	1.33	0.68	0	-0.70	-1.43	-2.18

Table 6: Menu of cost incentives for non-enhanced utilities wholesale water and wastewater services (source: OFWAT (2014)).

Menu choice	80	85	90	95	100	105	110	115	120	125	130
Incentive power b_C	54%	53%	52%	51%	50%	49%	48%	47%	46%	45%	44%
Cost norm $\overline{C}$ [%]	95	96.25	97.5	98.75	100	101.25	102.5	103.75	105	106.35	107.5
Additional income [%]	2.3	1.76	1.2	0.61	0	-0.64	-1.30	-1.90	-2.70	-3.44	-4.20

Subsequently, the resulting allowed revenue is complemented with the different quality incentives, such as leakage, compliance with quality standards, unplanned interruptions, Satisfaction with taste and odour, etc. Some of them have a pecuniary reward or penalty, others are reputational.

6 Conclusions

This paper studied a linear cost and quality regulation of public utilities confronted with inelastic demand. This is a suitable assumption for network industries, such as electrical grids, gas pipelines, water supply, sewage treatment, waste disposal and (rail)roads. The main regulatory issues in these industries are incentives for quality and cost-reducing effort, instead of quality and quantity. As the literature on quality regulation of a public utility has so far mainly focused on optimal quantity and quality, this paper complements the literature by studying the public utility's cost function instead of its demand curve.

The analysis shows that a quality incentive increases both quality and effort, while a cost-efficiency incentive increases effort and decreases quality. Next, introducing uncertainty and asymmetric information, I show that the power of the cost-efficiency and quality incentive should optimally be equal and below one. The incentive powers decrease with increasing uncertainty and increasing dislike for public utility profit. Last, three case studies in electricity, gas and water show that hybrid revenue caps with quality incentives are increasingly used in network industries. As in most cases the power of the quality incentive is higher than the power of the cost-efficiency incentive, the model predicts that supplied quality is too high. This paper proposes a simple and straightforward model to study behavior of a public utility under these regulatory schemes.

By focusing on cost efficiency, we necessarily neglect optimal pricing issues and quantity decisions. Although we have argued that this is a suitable assumption for network industries, it would be interesting to extend the analysis to quantity, quality and effort, probably with specific functional forms to obtain unambiguous results. Another interesting extension of the analysis would be to include multiple separate quality incentives, as is done in reality. The current quality variable can be interpreted as a vector and thus contains many aspects of quality, but this does not allows us to explicitly study trade-offs between quality aspects. These important questions are left for future research.

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A Proof of proposition 1

Proof. The total derivatives of the first-order conditions with respect to b_C and b_q are:

$$\begin{bmatrix} b_C C''_{qq} & b_C C''_{qe} \\ b_C C''_{eq} & \psi''_{ee} + b_C C''_{ee} \end{bmatrix} \begin{bmatrix} dq_P \\ de_P \end{bmatrix} = \begin{bmatrix} V \\ 0 \end{bmatrix} db_q \tag{30}$$

$$\begin{bmatrix} b_C C''_{qq} & b_C C''_{qe} \\ b_C C''_{eq} & \psi''_{ee} + b_C C''_{ee} \end{bmatrix} \begin{bmatrix} dq_P \\ de_P \end{bmatrix} = \begin{bmatrix} -C'_q \\ -C'_e \end{bmatrix} db_C \tag{31}$$

Solving by Cramer's rule and assuming that $C''_{eq} \leq 0$, leads to the following expressions:

$$\begin{aligned}
\frac{dq_P}{db_q} &= \frac{V(\psi''_{ee} + b_C C''_{ee})}{b_C C''_{qq}(\psi''_{ee} + b_C C''_{ee}) - b_C^2 C''^2_{qe}} = \frac{>0}{>0} \\
\frac{de_P}{db_q} &= \frac{-b_C C''_{eq}}{b_C C''_{qq}(\psi''_{ee} + b_C C''_{ee}) - b_C^2 C''^2_{qe}} = \frac{\geq 0}{>0} \\
\frac{dq_P}{db_C} &= \frac{-C'_q(b_C C''_{ee} + \psi''_{ee}) + b_C C'_e C''_{eq}}{b_C C''_{qq}(\psi''_{ee} + b_C C''_{ee}) - b_C^2 C''^2_{qe}} = \frac{< or \geq 0}{>0} \\
\frac{de_P}{db_C} &= \frac{-b_C C''_{qq} C'_e + b_C C''_{eq} C'_q}{b_C C''_{qq}(\psi''_{ee} + b_C C''_{ee}) - b_C^2 C''^2_{qe}} = \frac{> or \leq 0}{>0}
\end{aligned} \tag{32}$$

□

Note that, because of the concavity of the cost function, $\frac{dq_P}{db_C} < 0$ implies $\frac{de_P}{db_C} > 0$ and vice-versa. However, the exact sign of the last two expressions depend on the convexity of both cost and disutility.

B Robustness of results with respect to functional forms

Table 7 shows the public utility's quantity and effort depending on functional form assumptions. The first row shows the results of section 3.3. Row 2 yields similar results as row 1. For row 3, however, effort decreases with the power of the cost incentive. That is, it is profitable to decrease quality so much that effort can also be decreased. The last column of this table shows that all three functional forms lead to similar results for optimal incentive power under uncertainty.

Table 7: The public utility's quantity and effort depending on functional form assumptions.

	$C(e,q)$	$\psi(e)$	e_P	q_P	Uncertainty: $b_C^* = b_q^*$
(1)	$\frac{\beta}{e(1-q)}$	$\frac{\gamma}{2}e^2$	$\left(\frac{b_C \beta b_q V}{E^2}\right)^{0.2}$	$1 - \left(\frac{b_C^2 \beta^2 \gamma}{b_q^3 V^3}\right)^{0.2}$	$\frac{1}{1+5(1-\alpha)\bar{\epsilon}}$
(2)	$\frac{(1-e)\beta}{1-q}$	$\frac{\gamma}{1-e}$	$1 - \left(\frac{\gamma^2}{b_C \beta b_q V}\right)^{1/3}$	$1 - \left(\frac{b_C \beta \gamma}{b_q^2 V^2}\right)^{1/3}$	$\frac{1}{1+3(1-\alpha)\bar{\epsilon}}$