# Cost-Efficiency and Quality Regulation of Energy Network Utilities

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## Abstract

This paper studies linear cost-efficiency and quality incentives that are increasingly being used to regulate electricity and gas network utilities. The analysis shows that cost and quality incentives have asymmetric impacts on firms' choices of efficiency and quality, and that the incentive powers should be equal and less than maximal when there is information asymmetry about firm costs and a dislike for network utility surplus. As in most existing regulations quality incentives have a higher power than cost-efficiency incentives, the model predicts that supplied quality is too high. Finally, the paper discusses examples of linear sliding-scale incentive regulation in Norway and Great Britain. The findings of this study provide guidance for regulators and policymakers looking to optimally use linear incentives to regulate energy network utilities.

*Keywords:* Energy Network Regulation, Quality Regulation, Incentive Power, Incentive Regulation, Energy Transmission, Energy Distribution
*JEL:* L43, L51, L90, L94, L95, Q4

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## 1. Introduction

As energy network utilities, such as electricity and natural gas networks, are natural monopolies, many aspects of their performance are subject to regulation. Historically, regulatory efforts have focused primarily on improving cost efficiency, but regulators are now increasingly targeting other areas such as innovation, investment, and the quality of energy provision. For example in Europe, the number of countries imposing both cost-efficiency and quality incentives on their electricity distribution system operators has gradually increased from two in 1999 (the Netherlands and the United Kingdom) to 22 in 2021, as shown in Figure 1.[1] At the same time, the number of countries without any incentives for their electricity distribution system operators has decreased from 22 to five.

Incentives for cost efficiency are typically implemented by decoupling allowed prices or revenues from realized costs. High-powered incentive schemes, such as fixed price or revenue caps, provide regulated utilities with strong incentives to reduce costs by completely decoupling revenues from realized costs. In contrast, low-powered incentive schemes, such as cost-of-service regulation, remunerate regulated utilities based on their realized costs and do not provide incentives to reduce costs. In practice, most regulatory schemes fall between a pure cost-of-service regulation (power=0) and a pure price cap (power=1), as some types of costs are exempt from the cap or only a fraction of total costs falls under the cap (0 < power < 1). This type of regulation is also known as profit-sharing (Sappington and Sibley, 1992), cost-sharing (Laffont and Tirole, 1993), or sliding-scale regulation (Lyon, 1996).

Quality regulation, on the other hand, focuses on ensuring that energy network utilities meet certain levels of service quality, reliability, and safety. Quality incentives can take various forms.[2] For example in the case of energy distribution utilities (CEER, 2022), quality is simply monitored in some countries, like Iceland, while in others, like Greece and Romania, utilities must meet minimum quality standards. Some utilities face penalty/reward incentives that impact their revenues based on their level of realized quality. These incentives may depend linearly on the realized quality level without any bounds (e.g. in the Netherlands and Norway), or with bounds on the effect on the utility's yearly return (e.g. ±15% and ±33% in Finland and Sweden, respectively). In other countries, like Lithuania, the penalties and rewards depend non-linearly and asymmetrically on the realized quality level.[3]

This paper studies a linear sliding-scale regulation with unbounded and symmetric penalty/reward incentives for both cost efficiency and quality. This form of regulation is commonly used to regulate electricity and gas network util-

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[1] In 2021, Luxembourg added quality incentives to its regulation and Greece introduced quality and cost incentives.

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

[3] The yearly return of electricity network utilities in Lithuania is reduced by 1% for each reliability indicator between 5-10% worse than the target and 2% for each indicator more than 10% worse.

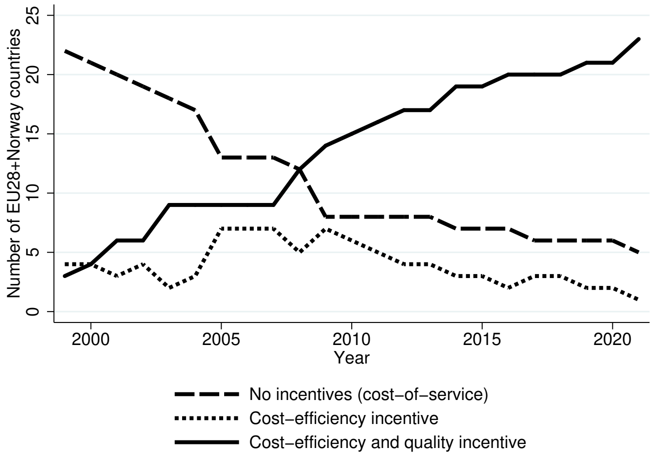

Figure 1. Regulatory regime of electricity distribution system operators in the EU28+Norway for 1999-2020, extended from Schmidthaler et al. (2015), using (CEER, 2016, 2020, 2021, 2022).

ities in countries such as Australia, Belgium, the Netherlands, Norway, and the United Kingdom. The paper explores whether this regulatory practice is effective and appropriate, and finds that the incentive powers should be equal in order to achieve the right balance between efficiency and quality. Under conditions of perfect information, the incentive powers should be maximal in order to maximize effort and quality. However, when there is information asymmetry regarding firm costs and a dislike for network utility surplus, the optimal power of the cost-efficiency and quality incentives should be less than maximal. In most jurisdictions that use this type of regulation, the incentive for quality is maximal while the incentive for cost is less than maximal, causing an overvaluation of quality and a realized quality that is higher than optimal.

This paper contributes to the literature studying how to regulate profit-maximizing firms in the presence of regulatory constraints such as asymmetric information (Baron and Myerson, 1982; Laffont and Tirole, 1986, 1993). Specifically, this paper builds on the regulatory incentives framework of (Laffont and Tirole, 1993, section 3.2) by embedding a second stage in which a regulated utility makes profit-maximising choices regarding cost-efficiency and quality based on second-best regulated linear sliding-scale incentives for each.[4] Anticipating the regulated utility's choices, the regulator in an earlier stage chooses the incentive powers for quality and cost efficiency that maximize the weighted sum of consumer and producer surplus.[5]

This paper is organized as follows. Section 2 provides an overview of linear sliding-scale regulation with cost-efficiency and quality incentives, and includes examples of its use in Norway and Great Britain. Next, section 3 studies how this type of regulation affects effort and quality by the regulated monopolist, both in general terms and with specific functional forms. In section 4, I study the regulator's optimization problem when there is asymmetric information between the regulator and the regulated utility. Finally, section 5 concludes.

## 2. Sliding-scale regulation with linear incentives for cost efficiency and quality

This paper studies the following revenue cap $R$ with cost-efficiency and quality incentives:

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

Each year the regulated energy network utility earns a revenue $R$, which depends on the realized costs $C$, Zrealized quality level $q$, a cost norm $\overline{C}$, and a quality norm $\overline{q}$. The allowed revenue $R$ increases with both realized costs and realized quality.[6] However, the regulated energy network 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 network utility's historical costs, on benchmark analyses of other energy network utilities (Schleifer, 1985)[7], on assumptions of the growth rate of the retail price minus the anticipated rate of technological progress (RPI-X) (Littlechild, 1983), or in a negotiation with the regulated utility (Brennan, 2018). The fraction $b_C$ is the power of the cost incentive. A higher value of $b_C$ means that a larger portion of the network utility's revenue is allocated independently of realized costs, whereas a lower value of $b_C$ means that its costs are more closely tied to the realized costs.

A regulatory scheme with $b_C = 1$ amounts to a pure revenue cap, while $b_C = 0$ amounts 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, I refer to (Joskow, 2014; Liston, 1993; Laffont and Tirole, 1993) and (Decker, 2014).

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[4] Linear sliding-scale incentives are known for their robustness and effectiveness in a wide range of situations (Hawdon et al., 2007; Holmstrom and Milgrom, 1987; Schmalensee, 1989). However, they are not necessarily first-best optimal (Laffont and Tirole, 1993).

[5] Meade (2015) also studies a regulated utility's choice of quality and unobserved effort, and adds a third-stage of firm ownership and manager profit-sharing, but without explicit incentives on quality.

[6] I 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).

[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). See (Estache et al., 2004; Giannakis et al., 2005) and (Jamasb and Söderberg, 2010) for examples of electricity network benchmarking.

To revenue cap (1), a quality incentive is added. If quality $q$ is above the quality norm $\overline{q}$, the network utility earns additional revenue $b_q V(q - \overline{q})$. If the quality is below the quality norm, a penalty $b_q V(q - \overline{q})$ is subtracted from its allowed revenue. The parameter $b_q$ is the power of the quality incentive. Like the power $b_C$ of the cost incentive, a high-powered quality incentive means that deviations from the quality norm have a greater impact on the network utility's allowed revenue. The parameter $V$ represents the (average) quality valuation of consumers.

The cost norm $\overline{C}$ and quality norm $\overline{q}$ are chosen such that the network utility earns a non-negative profit. Since regulators are generally not able to directly tax or subsidize the network utility, I assume that these costs are completely covered by consumer payments.[8] For example, network tariffs for electricity transmission and distribution networks and capacity and commodity charges for gas. Most energy network 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 sets the consumer charges such that the excess or deficit revenue balance is zero over time.

Table 1 shows the value of the incentive power of cost and quality in a set of countries. The incentive power of costs is below one in most regions, while the incentive power of quality equals one, except in Norway and Sweden.

Table 1. Examples of regions having a regulation with cost ($b_C$) and quality ($b_q$) incentives in 2017 for their electricity and gas transmission (T) and distribution (D) network utilities (AER, 2015; CREG, 2015; OFGEM, 2017; ACM, 2022; CEER, 2022).

| Region | Sector | $b_C$ | $b_q$ |
|---|---|---|---|
| Australia | Electricity T&D | 0.3 | 1 |
| Belgium | Electricity T | 0.15[a]/0.5[b] | 1 |
| Great Britain | Electricity T&D | 0.4689-0.5 | 1 |
| Great Britain | Gas D | 0.63-0.64 | 1 |
| Netherlands | Electricity D | 1 | 1 |
| Norway | Electricity T&D | 0.6 | 0.6 |
| Sweden | Electricity T | 1[b] | 0.5 |

[a] Incentive on influenceable costs.

[b] Incentive on controllable costs, e.g. grid losses and staff.

In the Norwegian regulation of electricity transmission and distribution networks, both incentive powers equal 0.6.[9] As a result, equation 1 simplifies to:

$$R = 0.6\overline{C} + 0.4C + 0.6V(q - \overline{q}) \tag{2}$$

The cost and quality norms are based on historical values and on benchmarking analysis. The quality incentive adjusts the allowed revenue cap of Norwegian transmission or distribution system operators to account for improvements or deteriorations in quality. This allows for the socialization of these changes among all consumers, but does not provide direct compensation to affected individuals. The quality incentive focuses on interruption costs ($IC$), which are calculated as the product of energy not supplied (ENS) and the valuation of ENS, the so-called value of lost load (VOLL), expressed as €/MWh (Ovaere et al., 2019). Importantly, interruption costs are calculated for different consumer groups $c$, and both the time $t$ and duration $d$ of interruptions affect the VOLL (Kjolle et al., 2008). This incentivizes system operators to differentiate the quality level between consumer groups. (Söderberg, 2008). In summary:

$$R = 0.6\overline{C} + 0.4C + 0.6(\overline{IC} - \sum_{c,t,d} VOLL(c,t,d)u(c,t,d)) \tag{3}$$

In Great Britain, the three transmission owners are regulated using the RIIO regulatory framework, which gives cost and quality incentives over the seven years from 2013 - 2021 (electricity transmission and gas and electricity distribution) or 2015-2023 (electricity distribution). In Great Britain, energy network utilities are regulated through the RIIO framework, which gives, i.a., cost and quality incentives.[10] The power of the cost incentive for the three British transmission owners is determined by OFGEM, the regulator of electricity and gas, based on the transmission owners' proposal of costs. A proposal that is closer to efficient costs, as determined by OFGEM, receives a higher incentive power (OFGEM, 2021). Table 2 shows that National Grid Electricity Transmission (NGET), Scottish Hydro Electric Transmission (SHET), and SP Transmission (SPT) have incentive powers of 0.4689, 0.5, and 0.5, respectively. The table also shows the cumulative results of RIIO-ET1 from April 1, 2013 to March 31, 2020 for all three transmission owners. NGET spent £2,835 million less than allowed and retained 46.89% of this amount, or £1,329 million, as higher allowed revenue. SHET and SPT made profits of £157 million and £235 million, respectively.

In addition to the cost incentive discussed above, British electricity networks are subject to a range of other incentives in the areas of safety, reliability, availability, customer satisfaction, connections, and the environment (OFGEM, 2021). I will focus on the reliability incentive, which is measured in energy not supplied (ENS) [MWh]. Table 3 shows the ENS of the electricity networks for the period from 2013 to 2020. The VOLL is considered to be

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[8] Pricing of a natural monopoly is an important question but is not dealt with in this paper, as I 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).

[9] As of 2023, the incentive power equals 0.7 (CEER, 2022).

[10] RIIO stands for Revenue = Incentives+Innovation+Outputs (Jamasb, 2021). The first phase covered the 2015-2023 period for electricity distribution and the 2013-2021 period for electricity transmission and gas distribution (OFGEM, 2022).

Table 2. Cumulative allowed and realized costs and resulting profits of the three electricity transmission network utilities in Great Britain for RIIO-ET1 from 1 April 2013 to 31 March 2020 (source: OFGEM (2021)). National Grid Electricity Transmission (NGET) in England and Wales, Scottish Hydro Electric Transmission (SHE) in the north of Scotland, and SP Transmission (SPT) in the south of Scotland.

| m£ 2019-20 Prices | NGET | SHET | SPT |
|---|---|---|---|
| Allowed costs $\overline{C}$ | 11,487 | 2,334 | 3,328 |
| Realized costs $C$ | 8,652 | 2,020 | 2,857 |
| Overspending $C - \overline{C}$ | -2,835 | -314 | -471 |
| Incentive power $b_C$ | 0.4689 | 0.5 | 0.5 |
| Allowed revenue $b_C\overline{C} + (1 - b_C)C$ | 9,981 | 2177 | 3092 |
| Profit $R - C$ | 1,329 | 157 | 235 |

£16,000/MWh in Great Britain, regardless of the consumer group, time of interruption, or duration. The target ENS is constant throughout the seven-year period of RIIO 2013-2021. The table shows that ENS is consistently below the target for each transmission network operator (-88% on average), meaning that the reliability of the networks is much higher than the target. The rewards resulting from these reliability incentives range from £10.7 million to £31.2 million over the seven-year regulatory period of RIIO-ET1.

Table 3. Energy not supplied (ENS) and cumulative reliability incentive reward of the GB electricity transmission networks for 2013-2020 (source: OFGEM (2021)).

| | NGET | SHET | SPT |
|---|---|---|---|
| Target ENS [MWh] | 316 | 120 | 225 |
| Actual ENS 2013-2014 | 135 | 35.6 | 42.2 |
| Actual ENS 2014-2015 | 8.7 | 106.1 | 2.8 |
| Actual ENS 2015-2016 | 4.5 | 0 | 13.9 |
| Actual ENS 2016-2017 | 6.8 | 4.4 | 10.3 |
| Actual ENS 2017-2018 | 39.7 | 24.3 | 3 |
| Actual ENS 2018-2019 | 12 | 0 | 41 |
| Actual ENS 2019-2020 | 54 | 1.2 | 2 |
| Average ENS 2013-2020 | 37.3 | 24.5 | 16.5 |
| Cumulative reward [m£] | 31.2 | 10.7 | 23.4 |

## 3. The model

### 3.1. Model assumptions

The most important element of our model is the cost function of the energy network utility. I assume a convex cost function $C(q, e)$ that is increasing in the quality level $q$ and decreasing in effort $e$:

$$C'_q > 0, \quad C''_{qq} \geq 0, \quad C'_e < 0, \quad C''_{ee} \geq 0 \quad \text{and} \quad C''_{qq}C''_{ee} - (C''_{qe})^2 \geq 0 \tag{4}$$

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) and Yu et al. (2009).

The effort $e$ can be interpreted as all actions that decrease the cost of supplying the network utility's service or good at a certain quality level $q$. By increasing effort, a network utility can decrease costs without decreasing quality or increase quality without increasing cost. Filippini et al. (2018) find suggestive empirical evidence of this idea. 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, or regular maintenance.[11] Exerting this effort $e$ entails a disutility $\psi(e)$ for the employees of the energy network utility. This cost is increasing and convex in effort (Laffont and Tirole, 1986, 1993):

$$\psi'(e) \geq 0 \text{ and } \psi''(e) \geq 0 \tag{5}$$

For example, cost-reducing efforts may involve changes to existing processes or practices, which may require a significant investment of time and which could be disruptive and cause discomfort or inconvenience to employees. Furthermore, cost-saving measures that involve reducing the number of employees or outsourcing certain activities may lead to job losses or reduced job security for the remaining employees. Abito (2020) estimates the effort function for electric utilities in the United States in 1988-1999 and finds that this function is indeed increasing and convex.

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:

$$v'(q) \geq 0 \text{ and } v''(q) \leq 0 \tag{6}$$

Quantity demanded is assumed to be fixed. Because of this assumption, quantity does not enter in our analysis and a revenue cap is equivalent to a price cap.[12] In the context of energy and gas network utilities, this assumption is reasonable as demand is fairly inelastic, especially in the short term (Labandeira et al., 2017).[13] In addition, many regulated utilities don't factor changes in demand into their profit function because they don't bear volume risk. This is because deviations between planned and actual volumes are often accounted for when setting tariffs in subsequent years (CEER, 2022).

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[11] It is worth noting that in this model, cost-reducing efforts and quality-increasing efforts are perfect substitutes. However, this may not always be the case. For example, in the model of Meade (2015), employees are incentivized via profit-sharing, which may lead them to prioritize cost-reducing efforts over quality-increasing efforts.

[12] If demand is elastic, the relative performance of a revenue cap and a price cap depends on the elasticity (Campbell, 2018).

[13] The short-term elasticity of electricity demand is approximately -0.2 (Zhu et al., 2018), while the elasticity of natural gas demand for residential and industrial consumers is -0.13 and -0.37, respectively, (Burke and Yang, 2016).

### *3.2. The energy network utility's optimization problem*

If a network utility is subject to revenue cap (1), its surplus function to maximize is:[14] (CEER, 2022).

$$\max_{\{e_u,q_u\}} b_C(\overline{C} - C(q_u, e_u)) + b_q V(q_u - \overline{q}) - \psi(e_u) \tag{7}$$

where $e_u$ and $q_u$ are the effort and quality chosen by the energy network utility. This leads to the following first-order conditions for the energy network utility's choice of quality and effort:

$$\begin{aligned} b_q V - b_C C'_q &= 0 \\ b_C C'_e + \psi'_e &= 0 \end{aligned} \tag{8}$$

The first-order conditions tell us that the energy network utility chooses the quality level such that the marginal increase in 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 in its regulated revenue from the cost incentive equals its marginal cost of effort. A global maximum exists because effort and costs are convex and the quality incentive is concave.

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

**Proposition 1.** *If cost is convex (assumptions (4)) 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:*

$$\begin{aligned} \frac{dq_u}{db_q} &> 0 \quad \textit{and} \quad \frac{dq_u}{db_C} < or \geq 0 \\ \frac{de_u}{db_q} &\geq 0 \quad \textit{and} \quad \frac{de_u}{db_C} > or \leq 0 \end{aligned}$$

*Proof.* See Appendix A ☐

A negative cross derivative means that the marginal cost decrease of cost-reducing effort increases with the level of quality, or alternatively, the marginal cost of quality at a certain quality level decreases with effort. 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

However, if cost and disutility are sufficiently convex in respectively quality and effort, compared to the convexity of cost in effort, the cost incentive unambigiously increases effort and decreases quality. Appendix B shows that this is indeed the case for two evident functional form specifications.

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.

Proposition 1 predicts the effect of cost-efficiency and quality incentives on both quality and effort. Previous work has only considered the impact of cost incentives on quality. However, their predictions align with Proposition 1. Sheshinski (1976) found that, with a positive cross derivative of inverse demand with respect to quality and quantity, a price cap decreases quality if the cross derivative of profits is negative and increases quality if it is positive. The effect is uncertain when the cross derivative is negative. Similarly, Kidokoro (2002) found that a higher-powered cost-efficiency incentive increases effort-related quality but decreases investment-related quality. Weisman (2005) finds that revenue-share penalties can reduce quality, while profit-share penalties increase it.

The predictions of proposition 1 are supported by the limited empirical literature on quality in electricity networks. Ter-Martirosyan and Kwoka (2010) found that high-powered cost-efficiency incentives are associated with longer duration of service outages ($\frac{dq}{db_C} < 0$), but this reduction in quality is offset when regulation includes quality incentives ($\frac{dq}{db_q} > 0$). Similarly, Schmidthaler et al. (2015) found that the introduction of quality incentives leads to an average reduction of annual outage duration by 16.05% ($\frac{dq}{db_q} > 0$). 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 implemented simultaneously in many states, their individual effects are difficult to determine ($\frac{dq}{db_q db_C} >< 0$).

Proposition 1 does not allow us to make general conclusions about the effect of cost-efficiency and quality incentives on the cost function due to the general assumptions made about the cost function. In the next section, the results are unambiguous clear by assuming a specific functional form of the cost function.

### *3.3. Model with specific functional forms*

To arrive at unambiguous results, this section determines the energy network utility's chosen effort and quality for specific functional forms. Appendix B repeats the analysis of this section for alternative functional form assumptions of the cost and effort function and finds the

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[14] I assume that the received weighted average cost of capital (WACC) on realized costs $(1 - b_C)C$ is equal to the true financing cost of capital $r$ and thus does not lead to additional profits for the network utility. If the received WACC is higher than the true financing cost (Romeijnders and Mulder, 2022), the analysis is still valid but the power of the cost incentive is adjusted downwards: $b_r = b_C - (WACC - r)(1 - b_C)$. It is also worth noting that in some countries the cost-efficiency and quality incentives are not in the form of a monetary reward/penalty based on realized cost and quality but in the form of adjusting the WACC on realized costs. Examples are Austria (bandwidth of ±0.5% ), Finland, Lithuania, and Sweden, as discussed in the introduction.

same qualitative results. First, I consider the following cost function, which satisfies assumptions (4):

$$C(q,e) = \frac{\beta}{e(1-q)}, \quad q \in [0,1], \quad \beta, e > 0 \tag{9}$$

where the cost parameter $\beta$ determines the cost for a given level of cost-reducing effort $e$ and quality $q$. The cost parameter $\beta$ 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, 2018).

Second, effort costs have the following functional form:

$$\psi(e) = \frac{\gamma}{2}e^2, \quad \gamma > 0 \tag{10}$$

where the effort cost parameter $\gamma$ is strictly positive. Increasing effort can either result in higher quality for the same cost, or lower cost for the same quality. If effort is greater than one, costs decrease; if effort is less than one, costs increase. Lastly, consumer benefit is linear in quality: $v(q) = Vq$.

Inserting these functional forms into the energy network utility's objective function (7), its chosen quality and effort are:

$$\begin{aligned} q_u &= 1 - \left(\frac{b_C^2 \gamma \beta^2}{b_q^3 V^3}\right)^{0.2} \\ e_u &= \left(\frac{b_q b_C V \beta}{\gamma^2}\right)^{0.2} \end{aligned} \tag{11}$$

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. Similarly, effort is higher but quality is lower for network utility's with a higher cost ($\beta$ higher).

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 (11) show that the energy network utility's quality decreases with effort cost and the cost parameter, 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.

Inserting the network utility's chosen effort and quality (11) into the assumed cost function (9), the network utility's cost is:

$$C(q,e) = (\gamma \beta^2 V^2)^{0.2} \frac{b_q^{0.4}}{b_C^{0.6}} \tag{12}$$

This shows that the network utility's costs increase with the power of the quality incentive and decrease with the power of the cost-efficiency incentive - in line with empirical evidence (Hellwig et al., 2020; Söderberg, 2011). In addition, the network utility's costs increase with the cost parameter $\beta$, if effort is more costly and if quality is more valued.

## 4. The regulator's optimization problem

The previous section determined the energy network utility's chosen effort and quality in response to linear cost and quality incentives. This section studies the upper-level question of a regulator choosing surplus-maximizing norms and incentive powers for cost-efficiency and quality, while anticipating the utility's reaction to these incentives.

### *4.1. The regulator's optimization problem with perfect information*

The regulator's objective is to maximize social welfare, which consists of consumer surplus (CS) and producer surplus (S), but where producer surplus is valued less than consumer surplus (Armstrong and Sappington, 2007; Baron and Myerson, 1982; Gasmi et al., 1994; Meade, 2015):

$$\text{social welfare} = \text{CS} + (1-\alpha)S, \text{ with } 0 < \alpha \leq 1 \tag{13}$$

The approach of distributional preferences ($\alpha > 0$) leads to similar conclusions as the approach using a shadow cost of public funds $\lambda$ (Laffont and Tirole, 1993). According to O'Callaghan and Prior (2018, Table 4.2), the estimated value of $\lambda$ is between 1.2 and 1.3, which means that the valuation parameter $\alpha = 1 - 1/\lambda$ is between 0.17 and 0.23.

In addition to maximizing the surplus of consumers and the (devalued) surplus of producers, the regulator should guaranteed the energy network utility a non-negative surplus, which is the difference between its profit and its effort cost. The regulator's optimization problem is:

$$\begin{aligned} \max_{\{b_C, b_q\}} \quad & v(q_u) - \Big(C(q_u,e_u) + S + \psi(e_u)\Big) + (1-\alpha)S \\ & = v(q_u) - \Big(C(q_u,e_u) + \psi(e_u)\Big) - \alpha S \\ & \text{s.t. } S \geq 0 \end{aligned} \tag{14}$$

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[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, Cambini et al. (2016) find that operating expenditures and capital expenditures affect service quality.

where $q_u$ and $e_u$ are determined by (8). As monopoly profit is socially costly, the energy network 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 energy network utility's effort and quality satisfy the first-order conditions of (14):

$$\begin{aligned} v'_q - C'_q &= 0 \\ C'_e + \psi'_e &= 0 \end{aligned} \tag{15}$$

Comparing (15) and (8) reveals that under perfect information the incentive powers equal one. The next section studies the incentive powers when the perfect information assumption is weakened.

### *4.2. The regulator's optimization problem with asymmetric information*

Suppose that the energy network utility has more information about its cost parameter $\beta$ than the regulator. The energy network utility exactly knows its cost parameter, while the regulator only knows that it belongs to the two-point support $[\underline{\beta}, \overline{\beta}]$ with cumulative distribution function $F()$ and 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 energy network utility, but should also ensure that an efficient energy network utility ($\beta$ low) has a higher quality and an inefficient energy network utility ($\beta$ high) has a higher effort.

In line with Laffont and Tirole (1993, Chapter 3), this incentive compatibility constraint is added to the regulator's optimization problem:

$$\begin{aligned} \max_{\{b_C, b_q\}} \quad & \int_{\underline{\beta}}^{\overline{\beta}} \Big[ v(q_u) - \Big( C(q_u, e_u) + \psi(e_u) \Big) - \\ & \qquad \alpha S(q_u, e_u, \beta) \Big] f(\beta) d\beta \qquad (16) \\ \text{s.t.} \quad & S(\overline{\beta}) \geq 0 \\ \text{s.t.} \quad & \dot{S}(\beta) = -\psi'_e E'_\beta \geq 0 \end{aligned}$$

To derive meaningful analytical results, I assume the functional forms of section 3.3

**Lemma 1.** *Under the above assumptions, the expected surplus of the network utility increases with the power of the cost and quality incentives, as well as with the valuation of quality and the cost of effort.*

*Proof.* See Appendix C ☐

As this lemma shows that expected surplus increases with the power of both the cost and quality incentives, the regulator faces a trade-off between higher cost and quality incentives, and higher expected surplus for the energy network 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 asymmetric information and a dislike for network utility surplus, 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 of the linear regulation 1 are equal and below one:*

$$b^*_C = b^*_q = \frac{1}{1 + \alpha \Big[ (\frac{\overline{\beta}^{0.4}}{\underline{\beta}^{0.4}} - 1) + 0.4(1 - \frac{\underline{\beta}}{\overline{\beta}}) \Big]} < 1 \tag{17}$$

*Proof.* See Appendix D ☐

Proposition 2 shows that the power of the cost-efficiency and quality incentives (i) should be equal, (ii) should decrease with increasing dislike for monopoly profit ($\alpha$), and (iii) should decrease when there is more asymmetric information ($\underline{\beta}$ lower or $\overline{\beta}$ higher). That is, concerns for rent extraction under asymmetric information reduce the incentive powers, moving the regulation from a high-powered revenue cap towards more low-powered cost plus. Looking at expressions (11), both effort and quality are thus lower under asymmetric information than under perfect information. Appendix B shows that the results are very similar for alternative functional form assumptions of the cost and effort function.

## 5. Conclusions

Linear sliding-scale incentives are increasingly being used by regulators to control the cost efficiency and quality of electricity and gas network utilities. This paper's two-level model assesses the impact of these incentives on cost-reducing efforts and the quality provided, and identifies the optimal level at which the regulator should set the incentive powers.

The paper has three main findings. First, the analysis shows that a quality incentive leads to higher quality and effort, while a cost-efficiency incentive increases effort but reduces quality. Second, the regulator should set the incentive powers at the same level in order to achieve the optimal balance between efficiency and quality. In many jurisdictions, quality incentives have a higher incentive power than cost incentives, as rewards and penalties are based on system-level realized quality, while cost-efficiency incentives do not target capital expenditures or only apply to controllable costs, such as grid losses and staff. This asymmetry leads to higher quality than is optimal. Third, if there is information asymmetry regarding firm costs and a dislike for network utility surplus, the optimal power of the cost efficiency and quality incentives should be less than maximal and should increase with decreasing information asymmetry and increasing dislike for network utility surplus. Other reasons for why the incentive power should be lower than maximal, such as uncertainty, competition, dynamics, and regulatory commitment, are not studied in this paper (Laffont and Tirole, 1993).

By focusing on cost efficiency, I have necessarily neglected the issues of optimal pricing issues and quantity decisions. Although I have argued that inelastic demand is a suitable assumption for energy network industries, it would be interesting to extend the analysis to consider elastic demand. Since lower prices and higher quality of energy can increase its demand and hence consumer surplus, I conjecture that optimal (second-best) incentive powers might be pushed upwards by including price- and quality-dependent demand in the analysis. Another interesting extension of the analysis would be to examine the effects of bounded rewards and penalties on incentives for cost efficiency and quality, as well as the optimal incentive powers. Finally, the setup of the model is static, making it impossible to study how the optimal incentive power of the studied linear regulation depends on dynamic issues, such as the effect of fixed costs of investment, the trade-off between capital and operating expenditures (Cambini et al., 2016; Giannakis et al., 2005; Meade and Söderberg, 2020), and the ratchet effect (Freixas et al., 1985; Weisman, 2022). These important questions are left for future research.

This paper focused on the regulation of energy network utilities but many of the findings also hold for other regulated network utilities with fairly inelastic demand and influenceable quality, like water supply, sewage treatment, and waste disposal.

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## Appendix A. Proof of proposition 1

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

$$\begin{bmatrix} b_C C''_{qq} & b_C C''_{qe} \\ b_C C''_{eq} & \psi''_{ee} + b_C C''_{ee} \end{bmatrix} \begin{bmatrix} dq_u \\ de_u \end{bmatrix} = \begin{bmatrix} V \\ 0 \end{bmatrix} db_q \tag{A.1}$$

$$\begin{bmatrix} b_C C''_{qq} & b_C C''_{qe} \\ b_C C''_{eq} & \psi''_{ee} + b_C C''_{ee} \end{bmatrix} \begin{bmatrix} dq_u \\ de_u \end{bmatrix} = \begin{bmatrix} -C'_q \\ -C'_e \end{bmatrix} db_C \tag{A.2}$$

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

$$\begin{aligned}
\frac{dq_u}{db_q} &= \frac{V(\psi''_{ee}+b_C C''_{ee})}{b_C C''_{qq}(\psi''_{ee}+b_C C''_{ee})-b_C^2 C''^2_{qe}} = \frac{>0}{>0}\\
\frac{de_u}{db_q} &= \frac{-b_C C''_{eq}}{b_C C''_{qq}(\psi''_{ee}+b_C C''_{ee})-b_C^2 C''^2_{qe}} = \frac{\geq 0}{>0}\\
\frac{dq_u}{db_C} &= \frac{-C'_q(b_C C''_{ee}+\psi''_{ee})+b_C C'_e C''_{eq}}{b_C C''_{qq}(\psi''_{ee}+b_C C''_{ee})-b_C^2 C''^2_{qe}} = \frac{<\mathit{or}\geq 0}{>0}\\
\frac{de_u}{db_C} &= \frac{-b_C C''_{qq}C'_e+b_C C''_{eq}C'_q}{b_C C''_{qq}(\psi''_{ee}+b_C C''_{ee})-b_C^2 C''^2_{qe}} = \frac{>\mathit{or}\leq 0}{>0}
\end{aligned} \tag{A.3}$$

□

The denominator is positive if the cost function is convex, because $C''_{qq}C''_{ee}-(C''_{qe})^2 \geq 0$, $\psi''_{ee}\geq 0$, and $C''_{ee}\geq 0$ (see equation 4). Note that, because of the concavity of the cost function, $\frac{dq_u}{db_C}<0$ implies $\frac{de_u}{db_C}>0$ and vice-versa. However, the exact sign of the last two expressions depend on the convexity of both cost and disutility.

## Appendix B. Robustness of results with respect to functional forms

Table B.4 shows the energy network utility's quantity and effort for two alternative functional form assumptions for the cost and effort function. The first row shows the results of section 3.3. Row 2 yields similar results as row 1. The last column of this table shows that both functional forms lead to similar results for optimal incentive power under asymmetric information.

## Appendix C. Proof of lemma 1

*Proof.* Assuming the function forms of expressions (11), the producer surplus needed to satisfy the incentive compatibility constraint is:

$$\begin{aligned}
S(\beta) &= \int_{\underline{\beta}}^{\overline{\beta}} -\psi'(e)E_\beta d\beta\\
&= \int_{\underline{\beta}}^{\overline{\beta}} -(b_C b_q V\gamma^3\beta)^{0.2}0.2(\frac{b_C b_q V}{\gamma^2\beta^4})^{0.2}d\beta\\
&= \int_{\underline{\beta}}^{\overline{\beta}} -0.2\frac{(\gamma V^2)^{0.2}b_C^{0.4}b_q^{0.4}}{\beta^{0.6}}d\beta\\
&= 0.5(\gamma V^2)^{0.2}b_q^{0.4}b_C^{0.4}(\overline{\beta}^{0.4}-\beta^{0.4})
\end{aligned} \tag{C.1}$$

Because $S(\overline{\beta})=0$. □

## Appendix D. Proof of proposition 2

*Proof.* Following (Laffont and Tirole, 1993, p.206) the Hamiltonian is:

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

Inserting the functional forms from section 3.3, the expressions (11) of the network utility's choice of effort and quality, and the surplus expression from Lemma 1 into the regulator's maximization (16) leads to the following Hamiltonian:

$$\begin{aligned}
&\Big[(\gamma\beta^2V^2)^{0.2}(\frac{b_C^{0.4}}{b_q^{0.6}}+\frac{b_q^{0.4}}{b_C^{0.6}}+\frac{b_q^{0.4}b_C^{0.4}}{2})\\
&+\alpha 0.5(\gamma V^2)^{0.2}b_q^{0.4}b_C^{0.4}(\overline{\beta}^{0.4}-\beta^{0.4})\Big]f(\beta)\\
&+\alpha F(\beta)\frac{(\gamma V^2\beta^2)^{0.2}b_C^{0.4}b_q^{0.4}}{5\beta}
\end{aligned} \tag{D.2}$$

This leads to the following first-order conditions:

$$\begin{aligned}
&2\frac{b_C}{b_q}-3+b_C+\alpha b_C(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}}-1)+\alpha\frac{F(\beta)}{f(\beta)}\frac{0.4b_C}{\beta}=0\\
&-3+2\frac{b_q}{b_C}+b_q+\alpha b_q(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}}-1)+\alpha\frac{F(\beta)}{f(\beta)}\frac{0.4b_q}{\beta}=0
\end{aligned} \tag{D.3}$$

which results in equation 17, as $\frac{F(\beta)}{f(\beta)}=\beta-\underline{\beta}$ for the uniform distribution on $[\underline{\beta},\overline{\beta}]$. The denominator is larger than one, because $\underline{\beta}\leq\beta\leq\overline{\beta}$. □

Table B.4. The energy network utility's quantity and effort, as well as the optimal incentive powers under asymmetric information,

for two functional form assumptions.

| | $C(e,q)$ | $\psi(e)$ | $e_u$ | $q_u$ | Asymmetric information: $b_C^* = b_q^*$ |
|---|---|---|---|---|---|
| (1) | $\frac{\beta}{e(1-q)}$ | $\frac{\gamma}{2}e^2$ | $\left(\frac{b_C \beta b_q V}{\gamma^2}\right)^{0.2}$ | $1 - \left(\frac{b_C^2 \beta^2 \gamma}{b_q^3 V^3}\right)^{0.2}$ | $\frac{1}{1+\alpha\left[\left(\frac{\overline{\beta}^{0.4}}{\beta^{0.4}}-1\right)+0.4\left(1-\frac{\underline{\beta}}{\beta}\right)\right]}$ |
| (2) | $\frac{(1-e)\beta}{1-q}$ | $\frac{\gamma}{1-e}$ | $1 - \left(\frac{\gamma^2}{b_C \beta b_q V}\right)^{1/3}$ | $1 - \left(\frac{b_C \beta \gamma}{b_q^2 V^2}\right)^{1/3}$ | $\frac{1}{1+\alpha\left[\left(\frac{\overline{\beta}^{\frac{1}{3}}}{\beta^{\frac{1}{3}}}-1\right)+\frac{1}{3}\left(1-\frac{\underline{\beta}}{\beta}\right)\right]}$ |