Investment and Efficiency under Incentive Regulation:

The Case of the Norwegian Electricity Distribution Networks

Rahmatallah Poudineh

Department of Economics, Heriot-Watt University, UK

Tooraj Jamasb[1]

Durham University Business School, Durham, UK

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Abstract

Following the liberalisation of the electricity industry since the early 1990s, many sector regulators have recognised the potential for cost efficiency improvement in the networks through incentive regulation aided by benchmarking and productivity analysis. This approach has often resulted in cost efficiency and quality of service improvement. However, there remains a growing concern as to whether the utilities invest sufficiently and efficiently in maintaining and modernising the networks to ensure long term reliability and also to meet future challenges of the grid. This paper analyses the relationship between investments and cost efficiency in the context of incentive regulation with ex-post regulatory treatment of investments using a panel dataset of 126 Norwegian distribution companies from 2004 to 2010. We introduce the concept of "no impact efficiency" as a revenue-neutral efficiency effect of investment under incentive regulation which makes a firm "investment efficient" in cost benchmarking practice. Also, we estimate the observed efficiency effect of investments in order to compare with no impact efficiency and discuss the implication of cost benchmarking for investment behaviour of network companies.

Keywords: Investments, cost efficiency, incentive regulation, distribution network

JEL classification: L43, L51, L94, D21, D23, D24

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[1] Corresponding author: Durham University Business School, 23/26 Old Elvet, Durham DH1 3HY, United Kingdom, Phone: +44 (0)191 33 45463, Email: tooraj.jamasb@durham.ac.uk. The authors are grateful to Luis Orea for very valuable comments on this paper. Financial support from UK ESRC and The Research Council of Norway (SusGrid - Sustainable Grid Development Project) are gratefully acknowledged.

1 Introduction

In recent years, achieving a sustainable energy sector, security of supply, and reliability of service have emerged as overarching energy policy objectives in many countries. A sustainable energy economy is highly dependent on decarbonising the electricity sector. Meanwhile, further electrification of the economy is generally regarded as desirable for a sustainable energy-economy. These goals are pursued through large scale deployment of renewable energy sources, more efficient use of energy, and active participation of the demand side.

Achieving the above goals requires a transformation of the electricity networks through expansion of grids, adoption of new technologies for managing the variability of the supply side, accommodating an active demand side, and focused research and development. Such transformation can only be reached through substantial capital investments. Given the anticipated scale of the required investments in the coming years, ensuring sufficient and efficient investments in the networks presents itself as a policy and regulatory priority.

Following the liberalisation of the electricity industry since the early 1990s, many sector regulators have recognised the potential for cost efficiency improvement in the networks through incentive regulation aided by benchmarking and productivity analysis. Although, benchmarking has achieved efficiency (mainly in operating costs) new challenges have emerged as how to address the issue of network investments. The problem is whether a system of regulation can be designed that provides right incentives for delivery of cost effective services while ensuring there is no systematic underinvestment or overinvestment. Hence, regulators need to balance the cost and risk of underinvestment against the cost of overinvestment in maintaining and modernising the networks. The incentive regulation accentuates static cost efficiency while investment is a dynamic and long term activity. On the other hand, benchmarking is a relative concept in the sense that firm’s efficiency depends not only on its own performance but also on the performance of other companies. The paradoxical effect of incentive regulation concerning investment and the peculiar specifications of benchmarking total costs complicate the relationship between investment and cost efficiency under the incentive regulation with ex-post regulatory treatment of investment cost.

This paper analyses the relationship between cost efficiency and investments under incentive regulation with ex-post regulatory treatment of capital expenditure using the case of Norway. The contribution of this paper is two-folded. Firstly, we introduce the concept of “no impact efficiency” as a revenue-neutral efficiency effect of investment under incentive regulation which makes the firm “investment efficient” and immune from cost disallowance in benchmarking process. Secondly, we estimate the “observed” efficiency effect of investment in order to compare with no impact efficiency and hence; discuss the implication of cost benchmarking for the investment behaviour of distribution companies in Norway. Despite the important role of regulatory treatment of capital expenditure, using benchmarking total costs, for investments behaviour and efficiency improvement in the networks, the topic has not been formally studied in the empirical literature.

The next Section discusses the relationship between network investments and incentive regulation with reference to the Norwegian regulation regime. Section 3 describes the methodology used to conceptualise the efficiency implications of investment under incentive regulation and also presents the stochastic frontier analysis procedure. The empirical results are presented and discussed in Section 4. Finally, Section 5 is the conclusions.

2 Investment and regulation

Electricity networks are regulated natural monopolies and investments by network companies are not governed by market mechanisms where decisions are normally based upon expected higher returns than the incurred cost of capital. In a regulated environment such as the electricity networks, the investment behaviour of firms is strongly influenced by the regulatory framework and institutional constraints (Vogelsang, 2002; Crew and Kleindorfer, 1996). The low-powered regulatory regimes such as pure “rate of return regulation” are often associated with poor incentive for efficiency. Averch-Johnson (1962) showed that regulated monopolies have an incentive to overinvest when the allowed rate of return is higher than the cost of capital.

The Incentive-based regimes such as price or revenue caps aim to overcome the efficiency problem by decoupling prices from utilities’ own costs. However, they give rise to new challenges regarding the level of investments. The issue of cost efficiency at the expense of investments or service quality has been discussed in the literature (see e.g., Giannakis et al., 2005; Rovizzi and Thompson, 1995; Markou and Waddams Price, 1999). Also, when rewards and penalties are weak or uncertain, the incentive for cost reductions outweighs the inducement to maintain quality of service and investment. Furthermore, implementing incentive regulation is complicated and evaluation of the associated efficiency is more difficult than it is often implied (Joskow, 2008).

The empirical evidence concerning investment behaviour of companies under incentive regime is not conclusive. While some initially argued that incentive regulation leads to underinvestment, the later empirical works demonstrated that the outcome of the incentive regulation concerning the investment behaviour can be in either direction. Waddam Price et al. (2002), state that a high-powered incentive regulation might lead to overinvestment. Roques and Savva (2009) argue that a relatively high price cap can encourage investment in cost reduction as in an unregulated company. Nagel and Rammerstorfer (2008) showed that a strict incentive regulation regime is more likely to create disincentive for investments. However, it is generally agreed that in incentive regimes, due to separation of firms’ own cost from prices, the motivation for cost reducing investment is higher than under the rate of return regulation (Ai and Sappington, 2002; Greenstein et al., 1995).

Thus, the main challenge of the regulator is to choose the right incentives in order to prevent any systematic overcapitalisation or underinvestment. The ability to disallow excessive costs can help regulators achieve more efficient levels of investment which otherwise firms would tend to overinvest in risky projects (Lyon and Mayo, 2005). However, following periods of cost disallowances there is a greater possibility of disincentive for investments.

The regulatory opportunistic behaviour is also a concern for the regulated firm as it introduces uncertainty into the regulatory contract. Gal-Or and Spiro (1992), for example, argue that a sudden shift in regulatory regime which allows for the use of cost disallowance instruments will decrease the propensity to invest. Regulatory uncertainty is an important issue in network industries such as electricity networks and can have serious implications for investments. This is because under uncertainty, delaying investments may be beneficial even though a project may indeed recover its capital costs (Dixit and Pindyck, 1994). There is also non-regulatory uncertainty, such as future demand, that the regulated company needs to take into consideration when deciding to invest.

From the regulatory viewpoint, it is important that decisions influencing the investments of the firms are based upon economic efficiency. For example, the cost of reducing service interruptions through investments should be lower than the socio-economic costs of service interruption. In effect, the regulator seeks an efficient level of investment in the grid although realising this goal through regulation is a challenging task. This is because theory does not provide clear indications of the conditions under which “efficient” levels of investment are achieved and what factors lead to over and underinvestment (von Hirschhausen, 2008). Moreover, the empirical evidence from cases of overinvestment or underinvestment is rare. Therefore, the outcome of incentive regulation regarding investments is ambiguous, and that regulators in practice tend to adopt a combination of different regulatory incentive mechanisms in order to achieve their objectives.

2.1 Power sector reform and network regulation in Norway

Norway was among the first countries, after Chile and the UK, to embark on power sector reform by unbundling the different elements of electricity industry across the value chain. This means generation and retail supply which are potentially competitive were separated from the transmission and distribution that are natural monopolies. Hence; the distribution and transmission networks are subject to regulation. The Norwegian Water Resource and Energy Directorate (NVE) were appointed as the sector regulator since Norwegian Energy Act came into effect in 1991. Unlike the other countries where regulatory reform was often accompanied by transfer of ownership, the Norwegian power industry mainly remained under the state or local municipalities’ control after reform. Also, companies that involve in both monopolistic (distribution or regional transmission) and competitive business (generation or retail supply) are required to keep them separated either legally and/or financially[2].

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[2] In 2010, about 67 companies were involved in generation, grid operation, and supply to end users. Vertically integrated companies with more than 100,000 customers are obliged to separate their monopolistic operation from competitive activities (legal unbundling). The Energy Act requires the integrated companies to keep separate accounts for their monopolistic and competitive businesses (NVE, 2010).

At the early years of the reform, there were approximately 230 distribution networks and 70 generation units in Norway. The high number of utilities reflects the dispersed nature of hydroelectric resources as the main source of power generation as well as the historical development of the sector in the country. In December 2010, around 167 companies were engaged in gird operation (NVE, 2010). The marked reduction in the number of distribution companies is the result of mergers and acquisitions among network companies in pursuit of scale efficiency gains.

After the reform, initially the distribution companies were operating under the rate of return regulation. However, due to lack of incentives for cost efficiency, since 1997, the regulatory regime was changed to incentive regulation. From 2007, NVE implemented a new regulatory model which also uses Data Envelopment Analysis (DEA) as an efficiency benchmarking method. The companies are regulated with a revenue cap regime that covers their costs annually based on their distance from the efficient frontier (best practice) in the sector.

2.2 Investments under Norwegian regulatory regime

A feature of the Norwegian incentive regulation is to prevent systematic overinvestment or underinvestment in the networks. The incentives are provided through a combination of economic and direct regulation (NordREG, 2011). Along with the profit motivation, the network companies need to undertake substantial investments in order to meet their obligations as stated in the Energy Act. For example, Section 3-4 of amended Energy Act states that distribution companies are obliged to connect new generation sources and consumers that are not covered by the supply requirement.

Moreover, distribution companies are incentivised to maintain a high level of quality of service. The cost of network energy losses and cost of energy not supplied (CENS) due to interruptions or capacity constraints in the grid are incorporated in the regulatory model so that the firms take them into account. Therefore, firms normally should not have an incentive to tune out their reinvestments as this would increases their total costs due to deterioration of their quality of service over time. In addition, a profit incentive is provided through a minimum guaranteed return on capital. The regulation states that all companies should achieve a reasonable (minimum 2%) return on capital, given effective management, utilization, and development of the networks[3]. Similarly, overinvestment will increase the total costs and will negatively affect their relative efficiency in the cost benchmarking exercise which will impact their revenue adversely.

Figure 1 shows total investments, new investments, and reinvestments by the distribution companies between 2004 and 2010. As shown, total investments are strictly increasing since 2006. The investment data indicates that the source of investment increase is reinvestment and not the new investments. Although new investments remained almost constant, they have

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[3] Any network company that falls below this minimum level will receive a correction in its revenue so that they achieve a minimum 2% return on capital. The normal return for Norwegian distribution companies is currently 5.62%.

had a higher share in total investments than reinvestments. For instance, 68% of the investments observations during the period of study have a share of new investments to total investments that is higher than 50%. This can be an indication of strong investment incentives which have motivated the networks to undertake new investments, possibly beyond their minimum reinvestment needs. Such a change can be attributed to the regulator's view in recent years that social costs of underinvestment are higher than social benefits of overinvestment (Helm and Thompson, 1991).

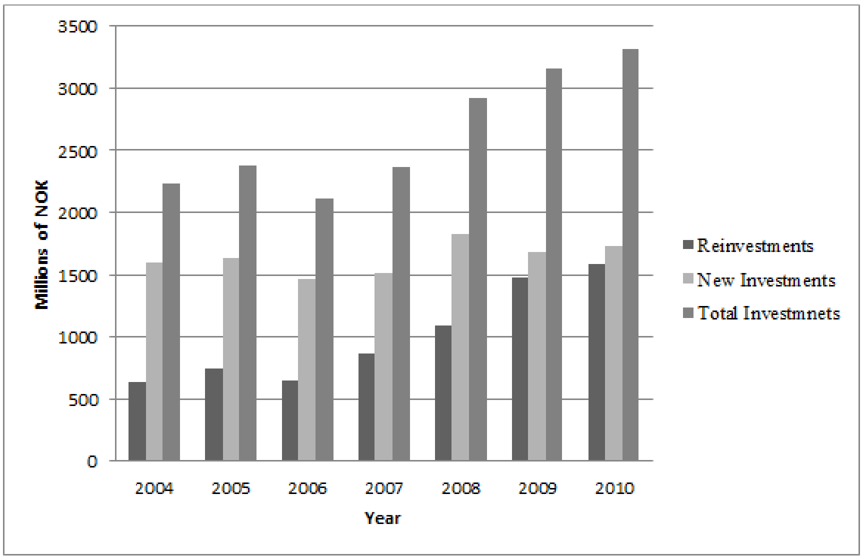

Figure 1: Investments in Norwegian distribution companies

3 Methodology

In this Section, we first present a model of the incentive regulation of electricity distribution networks in Norway and then analyse the relationship between investments by the utilities and change in their relative efficiency under incentive scheme. We then describe the econometric approach and the models estimated in order to explore the efficiency effects of investments.

3.1 Modelling Incentive Regulation

The allowed revenues of regulated networks are determined by incentive regulation and cost efficiency benchmarking. Within this framework, investments are encumbered indirectly such that overinvestment can result in partial disallowance of investment costs. The Norwegian regulator computes the allowed revenue (RE_t) of the firms using Equation (1), which, in essence, is the generic incentive regulation formula representing the trade-off between cost reduction incentive and rent transfer to the consumer, given the presence of asymmetric information between the firm and the regulator (Newbery, 2002; Joskow, 2005).

$$RE_t = C_t + \lambda(C_t^* - C_t) \qquad (1)$$

Where C_t is the actual (own) costs of a network company, C_t^* is the norm cost obtained by using the frontier-based benchmarking method Data Envelopment Analysis (DEA), and λ is the power of incentive in terms of the weight given to benchmarked costs vs. actual costs in setting the allowed revenue. The power of incentive is important for motivating the firms to move as close as possible to their norm (benchmarked) cost as they lose revenue when deviating from the efficient frontier. The share of actual costs and norm costs in determining the revenue caps is currently 40 and 60% respectively (i.e. $\lambda = 0.6$). Placing more weight on norm costs increases the incentive power of regulation and promotes indirect competition among the utilities to improve their cost efficiency relative to best practice.

Actual costs include operating and maintenance costs, capital costs, and depreciation costs. In addition, the regulator deducts the cost of energy not supplied (CENS) from the firms' revenue cap[4] and adjusts the allowed revenue for tax and other non-controllable expenses. The regulator uses data with a two year lag which is updated with an inflation index. The allowed revenue is then corrected at the end of the year when final actual data becomes available[5].

We divide both sides of (1) with C_t and rearrange such that it yields:

$$RE_t = C_t[1 + \lambda(e_t - 1)] \qquad (2)$$

where $e_t = \frac{C_t^*}{C_t}$ is the firms' efficiency in period t. When a firm invests the amount In, this will impact its revenue by changing its relative efficiency in cost benchmarking. The variables for before and after undertaking investments are denoted by subscripts 1 and 2 respectively. The change in a firm's revenue due to an investment can be computed from equation (3).

$$\Delta RE = RE_2 - RE_1 = C_2 - C_1 + \lambda[C_2(e_2 - 1) - C_1(e_1 - 1)] \qquad (3)$$

The change in actual cost of the firms after undertaking investments is equal to the amount of investments ($\Delta C = C_2 - C_1 = In$). We substitute for C_2 in the bracket and rearrange (3) as presented in (4) to show the change in revenue as a result of investments.

$$\Delta RE = \Delta C + \underbrace{\lambda[C_1(e_2 - e_1) + In \times (e_2 - 1)]}_{\text{Revenue effect of investments due to benchmarking}} \qquad (4)$$

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[4] In order to incentivise network companies to improve service quality.

[5] While the current and previous year investments (years *t* and *t-1*) are not included in the regulatory asset base (RAB) due to a time-lag, the companies can start to calculate a return on investment into their allowed revenue (i.e. tariff base) from the commissioning year.

Equation (4) presents the main framework for the network companies' incentive to undertake investments. In the absence of cost benchmarking (i.e. when $\lambda = 0$) the firm would automatically earn a return on its investments because the change in the firm's revenue is the same as the change in its cost ($\Delta RE = \Delta C$), and the company can pass all its investment costs to its customers. However, as investments are included in cost benchmarking, the firms' revenue also depends on their relative cost efficiency before investments (e_1) and after investments (e_2). This is reflected in the second component of (4), to which we refer as Q in (5), and shows the (gross) revenue effect of investments due to benchmarking.

$$Q = [C_1(e_2 - e_1) + In \times (e_2 - 1)] \qquad (5)$$

As seen from (5), the revenue effect of investments consists of two parts. Clearly, we always have $(e_2 - 1) \leq 0$. However, the outcome of the component $(e_2 - e_1)$ of (5) is not certain as it is not clear whether, following an investment, the cost efficiency increases, decreases, or remains constant[6].

Depending on the initial and after investment measured cost efficiency, Q can take different values. If $Q < 0$, the firm gains less from investing compared to the case of no cost benchmarking (ceteris paribus). However, when $Q = 0$, investment costs are fully recovered as there is no benchmarking. If $Q > 0$, investment creates synergy by excessive increase in efficiency although this may not happen under normal condition[7] so in most situations one expects $Q \leq 0$.

$$\Delta RE = \Delta C + \lambda Q \qquad (6)$$

Thus, as shown in (6), the change in revenue after investments is not necessarily equal to the change in cost and it crucially depends on the value that Q takes. Although the revenue also depends on the power of incentive (λ), it is a predetermined parameter which is beyond the control of the firm. Thus, the feasible outcome can only be achieved when $Q = 0$ and benchmarking has no adverse impact on the firms' revenue. - i.e. when the efficiency after investments increases (due to productivity of capital) to an amount that results in $Q = 0$ (note that also when the firm is on the efficient frontier and remains there after investments we have $e_2 = e_1 = 1,$ and consequently Q becomes zero). This efficiency can be obtained by solving (5) with respect to e_2 as in (7).

$$e_{no\ impact} = e_2 = \frac{C_1 e_1 + In}{C_1 + In} \qquad (7)$$

Equation (7) shows how the Norwegian incentive regulation links investments to efficiency improvement. In order for a firm to earn a profit on its investments as if there was no cost benchmarking (ceteris paribus), its efficiency should be, at least, $\frac{C_1 e_1 + In}{C_1 + In}$ after the investment.

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[6] $i.e. (e_2 - e_1 < 0, e_2 - e_1 > 0 \; or \; e_2 - e_1 = 0)$.

[7] The reason is that if the share of investments to other costs (before investments) increases, the efficiency required to satisfy the inequality rises considerably. However, under certain circumstance we can have $Q > 0$ which we refer to it in Section 4.

An efficiency level below this will result in lower revenue relative to the no benchmarking case. We use the term ‘no impact efficiency’ to refer to the ‘revenue-neutral efficiency effect of investment under cost benchmarking as presented in (7). In other words, a firm is considered ‘investment efficient’ when it meets the ‘no impact efficiency’ criteria under regulation[8].

The Norwegian incentive regulation links investment and efficiency to ensure that firms do not undertake undue investments. This means that the regulator does not need to interfere in the firms’ investment decisions, but indirectly incentivises them to be investment efficient. A limit analysis of (7) shows that as C_1 increases, the efficiency e_2 will approach e_1. The opposite of this implies that when the ratio of investment to other cost[9] increases, the firm needs to achieve a higher efficiency level (which in limits is equal to unity) in order to avoid revenue loss. This means that the expected interval of the no impact efficiency change is $e_1 \leq e_{no\ impact} \leq 1$, which depending upon the investment to cost ratio would be closer to lower or upper boundary.

Figure 2 shows the possible outcomes of efficiency effect of investment in the Norwegian regulation as an ex-post regulatory model for treatment of investments. When a firm (with an initial cost and efficiency level) undertakes an investment, it achieves a new level of efficiency (A). On the other hand, regulation links the initial cost, efficiency, and investment to no impact efficiency and rewards or penalises the firm based on the efficiency effect of their investments (B). In practice, this reflects the incentive mechanism pertaining to investments.

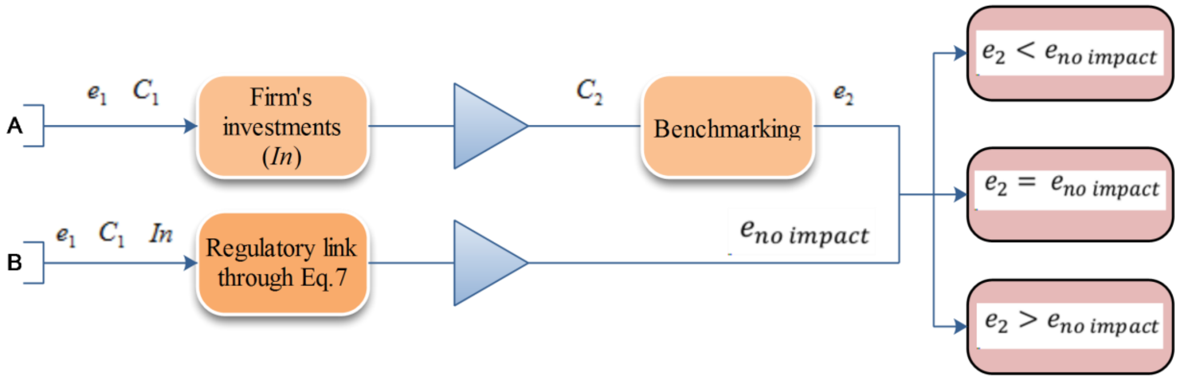

Figure 2: Possible efficiency effects of investment under Norwegian incentive regulation

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[8] For simplicity, we assume that the frontier firms are genuinely efficient though, in practice, this may not be the case.

[9] The ratio of ‘investment to other costs before investments’, the average of this ratio for the Norwegian networks is currently 34%. The maximum is 168% and the minimum is 1.3%.

3.2 Modelling a Stochastic Efficient Frontier

This section presents the efficiency measurement techniques and empirical model estimated in this study. We estimate the efficiency of firms before and after investments and use the efficiencies to calculate the ‘no impact efficiency’ for current investment levels of the networks. We use an input distance function which allows us to estimate the efficiency of the firms when input price data is not available (Färe and Lovell, 1978; Coelli, 1995). Other advantages of distance functions are that they do not depend on explicit behavioural assumptions such as cost minimization or profit maximization and they can accommodate multiple inputs and outputs (Kumbhakar and Lovell 2000; Coelli et al., 2005).

Input distance functions have been used in empirical studies for efficiency and productivity analysis of industrial units as in Abrate and Erbetta (2010) and Das and Kumbhakar (2012) as well as those of electricity networks such as Tovar et al. (2011), Hess and Cullmann (2007), and Growitsch et al. (2012). The output of electricity networks is determined exogenously by demand for energy and connection thus companies can only adjust inputs (i.e. costs) to deliver a given service efficiently.

An input distance function can be defined as in (8):

$$D^I(x,y) = max\left\{\psi : \left(\frac{x}{\psi}\right) \in L(y)\right\} \tag{8}$$

where $L(y)$ represents the input vectors x that produce the output vector y, and ψ indicates a proportional reduction in input vector. The function has the following characteristics: (i) it is linearly homogenous in x, (ii) it is non-decreasing in x and non-increasing in y, (iii) it is concave in x and quasi-concave in y, and (iv) if $x \in L(y)$ then $D^I \geq 1$ and $D^I = 1$ if x is on the frontier of input set.

Input-oriented technical efficiency can be obtained from (9):

$$TE = 1/D^I(x,y)\,, \quad 0 < TE \leq 1 \tag{9}$$

This means that technical efficiency is defined as the inverse of the distance function. When a firm is operating on the frontier it shows a distance function value equal to unity and consequently has a technical efficiency score of 1. The general form of an input distance function is as in (10):

$$\begin{aligned} lnD^I_{it} = {} & \alpha_0 + \sum_{m=1}^{M} \alpha_m \, lny_{mit} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \alpha_{mn} \, lny_{mit} lny_{nit} \\ & + \sum_{k=1}^{K} \beta_k \, lnx_{kit} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \, lnx_{kit} lnx_{lit} \\ & + \sum_{k=1}^{K}\sum_{m=1}^{M} \delta_{km} \, lnx_{kit} lny_{mit} + \theta_1 t + \frac{1}{2}\theta_{11} t^2 + v_{it} \end{aligned} \tag{10}$$

where D^I_{it} represents the distance function, y_{mit} is output, x_{kit} is input, t represents time trend, subscript i=1…N denotes the number of the firms, and t=1…T indicates number of years. Also, $m = 1 \dots M$ and $k = 1 \dots K$ show the number of outputs and inputs respectively. Parameters α, β, δ, and θ are to be estimated.

Condition of homogeneity of degree one in input is imposed by the following constraints:

$$\sum_{k=1}^{K} \beta_k = 1 \qquad \sum_{l=1}^{K} \beta_{kl} = 0 \qquad k = 1,2,\dots,K$$

and

$$\sum_{k=1}^{K} \delta_{km} = 0, \qquad m = 1,2,\dots,M.$$

Symmetry condition is met if:

$$\alpha_{mn} = \alpha_{nm} \quad m,n = 1,2,\dots\dots M, \quad and \quad \beta_{kl} = \beta_{lk\,,} \quad k,l = 1,2,\dots.,K \tag{11}$$

We transform the input distance function into econometric models to be estimated by the stochastic frontier analysis (SFA) method and to obtain technical efficiency of the firms. Imposing the homogeneity of degree one by deflating $K-1$ inputs by Kth input (we use other cost (C_1) to deflate) will lead to (12):

$$lnD^I_{it} - lnx_{Kit} = f[(lnx_{kit} - lnx_{Kit}), lny_{mit}, t] + v_{it} \tag{12}$$

where $f(.)$ is the translog functional form. For the purpose of estimation we rearrange the above equation as:

$$-lnx_{Kit} = f[(lnx_{kit} - lnx_{Kit}), lny_{mit}, t] + v_{it} - u_{it} \tag{13}$$

where $lnD^I_{it} = u_{it}$ represents the non-negative technical inefficiency. The error components have the following distributions.

$$v_{it} \sim iid\ N(0, \sigma_v^2) \qquad \text{and} \qquad u_{it} \sim iid\ N^+(0, \sigma_u^2) \tag{14}$$

v_{it} is a normally distributed random error term and u_{it} is a half-normal heteroscedastic random error term that capture inefficiency. As the efficiency is affected by the investments we model the heteroscedastic inefficiency variance (σ_u^{2het}) as in (15).

$$Log\sigma_u^{2het} = \rho_0 + \rho_1 Log(In) + \rho_2 Log^2(In) \tag{15}$$

$$\sigma_u^{2het} = exp(\rho_0 + \rho_1 Log(In) + \rho_2 Log^2(In))$$

where ρ_0 and ρ_1 are parameters that needs to be estimated and "In" is normalised investment level with respect to sample median. As shown in (16) we can separate the heteroscedastic variance into its homoscedastic component (σ_u^{2hom}) and the element related to investments.

$$\sigma_u^{2het} = exp(\rho_0)\, exp\big(\rho_1 Log(In) + \rho_2 Log^2(In)\big) =$$

$$\sigma_u^{2hom} \times exp(\rho_1 Log(In) + \rho_2 Log^2(In)) \quad (16)$$

This allows us to purge the effect of investments on inefficiency as seen from (17). In terms of estimation, equations (13) and (15) are estimated simultaneously based on the only observed data in (13). Having estimated them, homoscedastic inefficiency can be easily obtained as follows:

$$u_{it} \sim N^+(0, \sigma_u^{2hom} \times exp(\rho_1 Log(In) + \rho_2 Log^2(In)))$$

$$u_{it} \sim N^+(0, \sigma_u^{2hom}) \times exp(\rho_1 Log(In) + \rho_2 Log^2(In))$$

$$\hat{u}_{it} = exp(\hat{\rho}_1 Log(In) + \hat{\rho}_2 Log^2(In)) \times \hat{u}_{before} \quad (17)$$

It is clear that $\hat{u}_{it} = E[u_{it}|\epsilon_{it}]$ where $\epsilon_{it} = v_{it} - u_{it}$, On the other hand, $\hat{u}_{it} = \hat{u}_{after}$ thus we can write:

$$\hat{u}_{before} = \frac{\hat{u}_{after}}{\exp(\hat{\rho}_1 Log(In) + \hat{\rho}_2 Log^2(In))} \quad (18)$$

where, $\hat{u}_{before}$ is before-investment inefficiency and $\hat{u}_{after}$ is after-investment inefficiency ($\hat{u}_{it}$). The firm specific technical efficiency is then computed by $e_1 = exp(-\hat{u}_{before})$ and $e_2 = exp(-\hat{u}_{after})$. The “no impact efficiency” is calculated using Equation (7).

3.3 Data

We use a dataset comprising a weakly balanced panel of 126 distribution companies from 2004 to 2010. All the monetary data are in real terms adjusted to 2010 price level. Our distance function model consists of two inputs and two outputs. The inputs are capital expenditure (In) and other costs (C_1). Following the Norwegian regulatory approach, we incorporate quality of service into our benchmarking model by adding the cost of negative externalities (network energy losses and service interruptions) to the directly incurred elements of operating cost as presented in (19).

$$C_1 = Operational\ Expenditure + Cost\ of\ \ Losses\ +\ Cost\ of\ Energy\ Not\ Supplied \quad (19)$$

The cost of energy not supplied is calculated from the number minutes of interruptions times consumer willingness-to-pay for more reliable service.[10] The cost of network energy losses is computed by multiplying the physical losses with average annual system price of electricity as used by the regulator.

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[10] Consumer willingness to pay for quality of service is derived from consumer surveys and technical analysis.

We use “total number of customers” (residential plus recreational homes) and “energy density” (energy distributed per Km length of network) as outputs. Numbers of customers are commonly used in efficiency analysis of electricity networks (e.g. Growitsch et al., 2012; Miguéis et al., 2011). Energy density captures the effect of asset utilisation and network congestion as cost drivers. Moreover, network reliability and consequently quality of supply is directly affected by the length of network (Coelli et al., 2010). In addition to the input and output variables we use three weather and geographical variables to capture the heterogeneity among the firms[11]. These factors can impact cost efficiency of the networks and controlling for their effects can help to account for unobserved heterogeneity among network utilities (Growitsch et al., 2011; Jamasb et al., 2012)[12]. Table 1 summarises the descriptive statistics of the data used.

As we use ‘other costs’ (C_1) to impose homogeneity of degree one, the dependent variable of model is $-Log(C_1)$. The parameters used in the model are obtained by maximum likelihood estimation procedure. The optimisation technique used is Berndt-Hall-Hall-Hausman (bhhh) algorithm. Furthermore, in order to facilitate the interpretation of the first order terms, all variables are divided by their sample median prior to estimation.

Table 1: Descriptive statistics

Variable Description	Variable Name	Min.	Max.	Mean	Std. Dev.
Inputs					
Other costs*	C_1	1205.25	1178987	40075.5	63466.03
Capital expenditures*	In	167.11	92899.7	12730.71	16024.87
Outputs					
Energy density (MWh/Km)	DE	137.12	6485.25	554.64	515.670
Number of customers (#)	CU	18	515152	12575	25430.4
Geographical variables					
Snow condition (millimetres)	$snow$	53	1193.61	373.99	196.18
Wind / distance to cost (ratio)	$wind$	0	0.1610	0.0162	0.0288
Forrest productivity (fraction)	$forest$	0	0.5489	0.1566	0.1199

*Monetary variables are in ‘000 NOK.

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[11] The three variables are: (1) snow conditions, in millimeters of snow per year at a given temperature (around 0 degrees C), (2) Wind and distance to coast, as a ratio (average extreme wind/distance to coast), and (3) forest productivity, a number between 0 and 1 showing the share of forest with this growth rate along the power lines.

[12] We examined the influence of asset age (ratio of depreciation to book value) as control variable. However, the variable showed inconsistencies in the sign of the age variable itself as well as for first order terms of other variables. Other measures of age may produce different results but these were not available. At the same time, the results indicated that inclusion of age does not change the efficiency scores significantly.

4 Results and Discussion

The profit motive implies that incentive regulated firms evaluate the cost and benefit of undertaking investments by comparing a possible reduction and increase in allowed revenue as a result of efficiency effect of the investments in cost benchmarking. However, the outcome depends on the net efficiency effect achieved by the investments.

Table 2 presents the results of the input distance function and heteroscedastic variance model estimations. As shown, the coefficients of first order terms for the number of customers, energy density and investments are statistically significant and have the expected signs. These coefficients can be interpreted as distance function elasticity with respect to outputs and inputs at sample median. The first order coefficients for snow and wind are significant and consistent in terms of sign which indicate that these geographic variables are cost drivers as well. However, only one interaction term of wind and snow variables with the outputs is statistically significant. The heteroscedastic inefficiency variance model shows significant coefficients both for first order and quadratic terms.

Figure 3 illustrates the changes in the efficiencies before and after investments. As shown, investments have impacted efficiency of the firms and within a relatively wide range. It is evident that the impact of investments on the efficiency variation among the firms is not uniform, in the sense that some of the firms gained while some others lost efficiency. This complies with the basic notion of ex-post regulatory treatment of investment based on benchmarking that efficiency effects influence investment behaviour of firms as high investments involve a risk of efficiency loss.

Figure 4 shows the distribution of efficiency variation following investments. The descriptive statistics of graph data is presented in Table 3. As seen from the graph and the table, the change in efficiency tends towards an asymmetrical distribution. The mean of efficiency variation presented in Table 3 implies that, on average, investment contributed to about 0.8% efficiency gain. However, the average might not be a very reliable measure for the performance of the whole sector, as it will be influenced by the outliers. Moreover, as shown in Table 3, the Jarque-Bera test of normality is rejected and distribution is right skewed. The maximum positive variation is 0.56 whereas on the negative side it is -0.34. In addition to implying that an increase in investments is associated with higher efficiency than with inefficiency, this can also be related to the notion that the fidelity of the estimations decrease as we begin to move away from the mean. The majority of the observations lie between -15% to 15% (one standard deviation) efficiency variations following investments.

Table2: Input distance function model estimation[13]

Dependent variable: $-Log(C_1)$		
Variables	**Coefficient**	**Std. Err**
$Constant$	-3.997***	(1.288)
$Log(CU)$	1.280***	(0.160)
$Log(DE)$	-0.891***	(0.238)
$Log(In)$	-0.593**	(0.257)
$0.5Log^2(CU)$	0.129***	(0.012)
$0.5Log^2(DE)$	0.169***	(0.040)
$0.5Log^2(In)$	-0.037	(0.025)
$Log(CU) * Log(DE)$	-0.133***	(0.011)
$Log(CU) * Log(In)$	0.052***	(0.015)
$Log(DE) * Log(In)$	0.070***	(0.023)
t	-0.012	(0.012)
$0.5t^2$	0.012***	(0.003)
$snow$	0.033**	(0.014)
$wind$	0.005***	(0.001)
$forest$	-0.008	(0.009)
$snow * Log(CU)$	0.040*	(0.024)
$snow * Log(DE)$	-0.004	(0.036)
$wind * Log(CU)$	0.000	(0.001)
$wind\ * \mathrm{Log}(DE)$	-0.004*	(0.002)
$forest\ * Log(CU)$	0.019	(0.015)
$forest\ * Log(DE)$	0.037	(0.023)
$Log(\sigma_u^2)$		
$Log(In)$	-2.323***	(0.831)
$Log^2(In)$	--0.467*	(0.276)
$Constant$	--4.64***	(0.750)

Note: * $p<0.10$; ** $p<0.05$; *** $p<0.01$

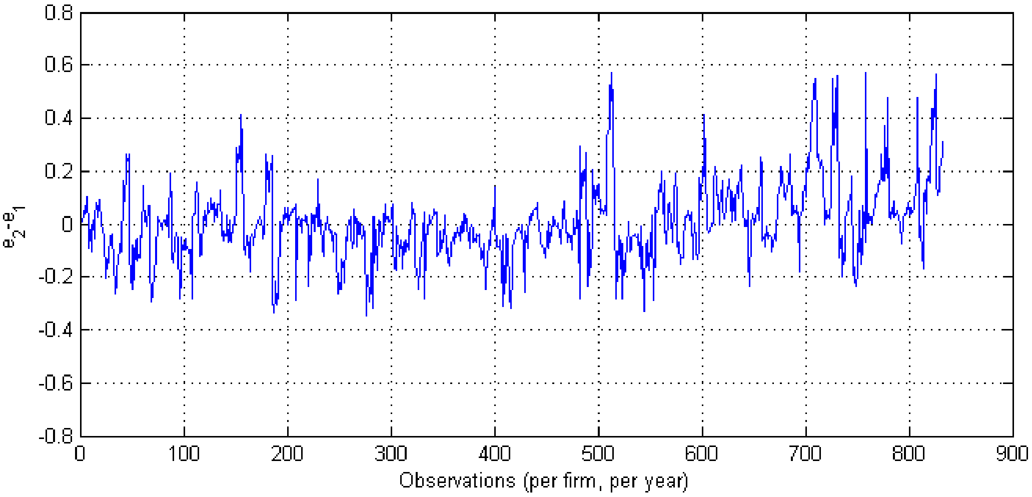

Figure 3: Efficiency change in firms before and after investments

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[13] For ease of interpretation, the model coefficients were multiplied by -1.

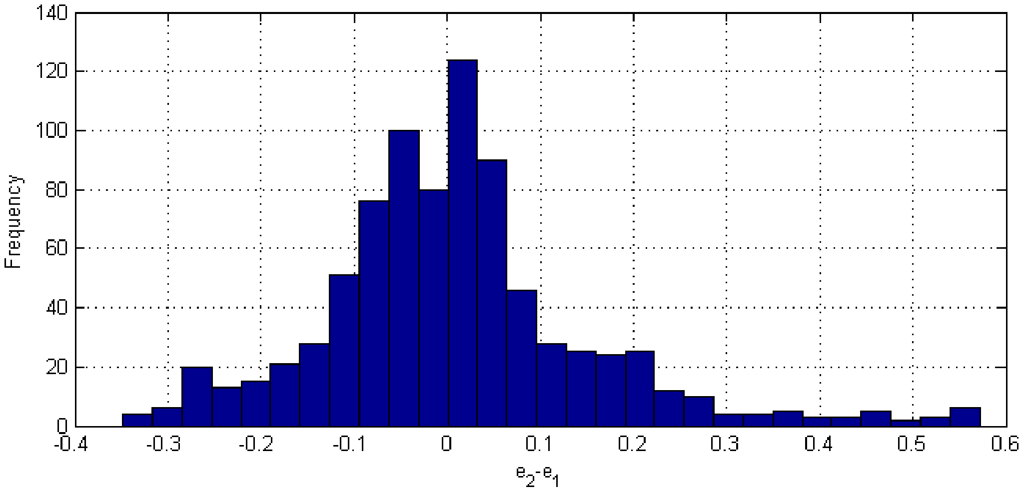

Figure 4: The distribution of efficiency change following investments

Table 3: Descriptive statistics of $e_2 - e_1$

Mean	0.007968
Median	0.001406
Maximum	0.571541
Minimum	-0.348183
Std. Dev.	0.145273
Skewness	0.875255
Kurtosis	5.195926
Jarque-Bera	273.7230
Probability	0.000000

Furthermore, as illustrated by the scatter plot in Figure 5, efficiency loss after investments is more prevalent among the companies with lower investment to total cost ratios. On the other hand, those companies with average investment levels show more efficiency gain following investments compared with companies with very high share of investment in total cost. This suggests that middle scale investments, typically, have been more productive than the larger and especially than the small ones. This can be an indication of complexity of investment and efficiency relation under benchmarking as lower capital expenditure might lead to an increase of other costs and hence; may not help with efficiency improvement. It also implies that small scale investments should be better scrutinized before implementation to avoid lower allowed revenue as a result of cost benchmarking.

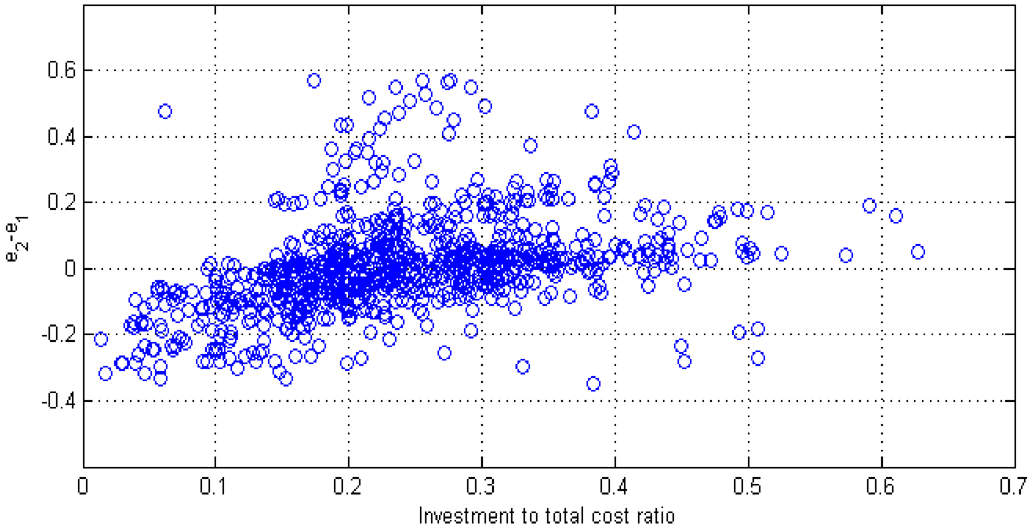

Figure 5: Efficiency change versus investments to cost ratio

Figure 6 summarises the distribution of before investment, after investment and no impact efficiency estimated in different years. As seen from the figure, in all cases the distributions do not show zero skewness rather the mass of distribution is concentrated around more efficient region without a noticeable change over different years. Additionally, the lower quartile is higher for the case of no impact efficiency compared with before investments and after investments efficiency, reflecting the fact that given the current level of investment efficiency improvement is required for many firms.

Table 3 compares the average of the same efficiencies in each year for all companies. As the table shows, apart from 2006, on average, investment made positive contribution to efficiency of the sector. However, the average efficiency gained after investment fall behind no impact efficiency by 1% in 2010 to 4.3% in 2006. The average usually becomes affected by outliers hence; in order to make a more reliable inference on the performance of sector we have weighted efficiencies by the share of their corresponding investment in the total investment of the sector. This is to ensure that the weight effect of firms on the total investment behaviour of sector is taken into account when looking at the sector level. As it is shown in Table 3, the difference between before and after investment efficiencies raised to 17%. At the same time, no impact efficiency reduced to reflect the fact that the sector still can increase the level of investment through new reallocations of investments and without lowering average efficiency gain of the sector.

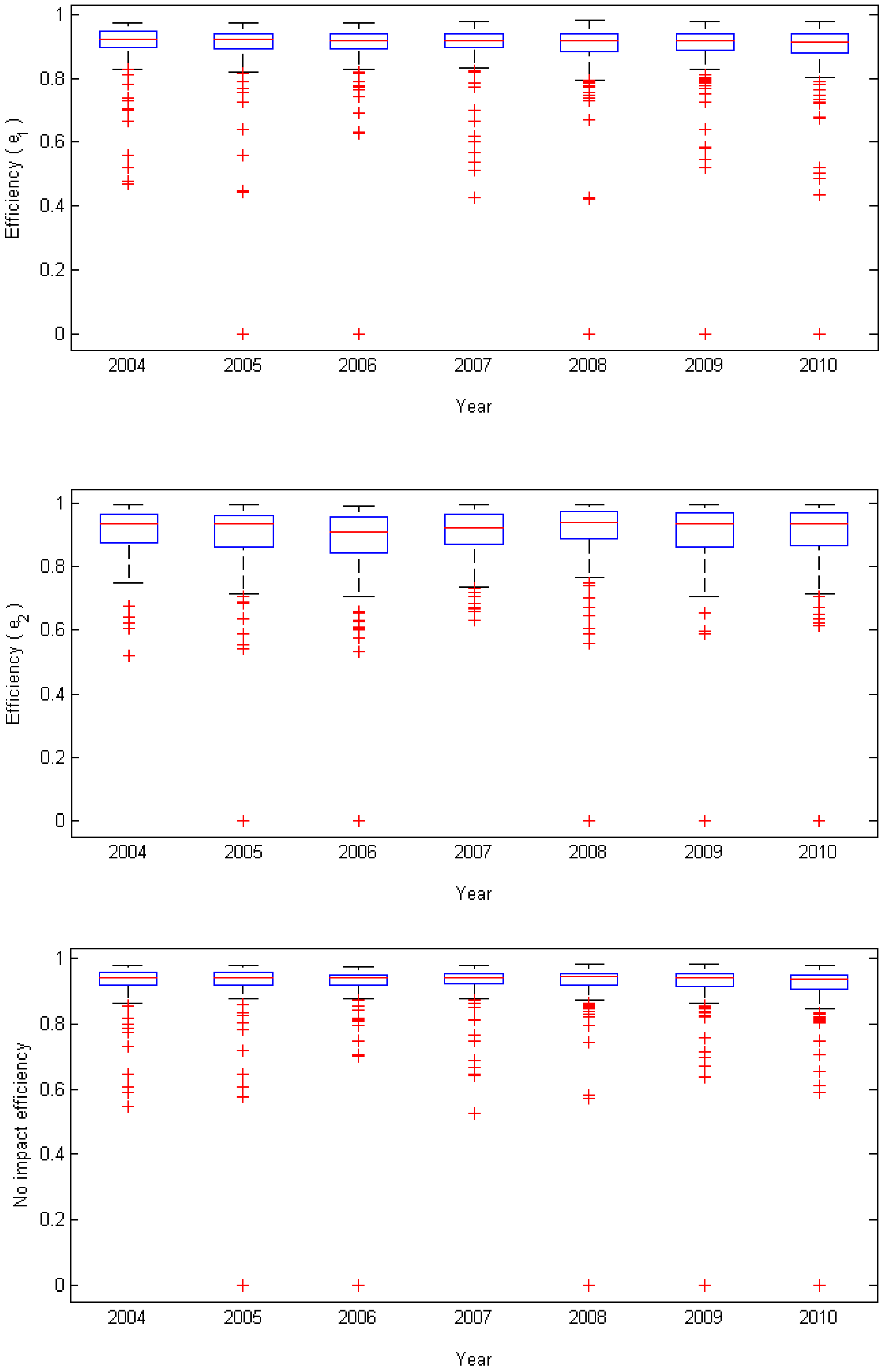

Figure 6: Distribution of efficiencies estimated

Table 3: Average 'before investment', 'after investment', and 'no impact' efficiency

Efficiency measured	2004	2005	2006	2007	2008	2009	2010
Average of e_1	0.896	0.897	0.902	0.892	0.894	0.892	0.883
Average of e_2	0.905	0.902	0.881	0.902	0.911	0.905	0.905
Average of $e_{no\ impact}$	0.921	0.923	0.924	0.918	0.923	0.921	0.915
Weighted average	$e_1 = 0.788$ $e_2 = 0.964$ $e_{no\ impact} = 0.846$						

The reallocation of investments can increase total investments in the sector because there are significant performance discrepancies among the companies as depicted in Figures 3 and 4. The very efficient firms that surpassed no impact efficiency may wish to increase their investment levels in order to gain from their efficiency level. The investment increase can be continued until efficiency after investment reduces to no impact efficiency, in which state, some form of optimality will be achieved. On the other hand, those firms that their efficiency after investment falls short of no impact efficiency needs to reduce their investment level in order to avoid inefficiency associated loss[14]. The net effect of new reallocation is an increase in total investments without reducing the average efficiency of the sector.

As discussed above, the outcome of ex-post regulatory treatment of investments through total cost benchmarking is that some firms will lose part of their capital cost while some other recover all their investment and some make above normal profit. For example, the few firms that appear to have outperformed the investment efficiency requirement – i.e. their efficiency after investments exceeded the no impact efficiency considerably (the instance of $Q > 0$ discussed in Section 3.1) can earn more compared to the no benchmarking case. Under the circumstance that an "investment efficient frim" gains and an "investment inefficient" loses; the ex-post regulatory treatment of investment is effective in rewarding efficient and penalising inefficient firms.

However, this might not always be the case as the condition under which benchmarking produce reliable results does not always hold. This is because efficiency, in benchmarking terms, is a relative concept and only reveals information about firm performance in relation to other firms. Thus, the relative efficiency of a firm can also improve when the peer companies are not performing well. For instance, when companies are capital productive and their investments are proportional to their capital productivity, they might move to a higher level of relative efficiency after investments. However, the same can happen when they underinvest, something which gives them the appearance of cost efficiency. Therefore, unless

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[14] In this analysis we ignore the concept of dynamic efficiency hence; we do not take into account cost effect of investments that takes more than one regulatory period to become realised. This is because our positive analysis is based on the current form of incentive regulation with ex-post regulatory treatment of investment practiced in Norway and many other countries.