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Quality of Service, Efficiency, and Scale in Network Industries: An Analysis of European Electricity Distribution

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Abstract

Quality of service is of major economic significance in natural monopoly infrastructure industries. In this paper we present an efficiency analysis of electricity distribution networks from seven European countries. We apply the stochastic frontier analysis (SFA) method on multi-output translog input distance function models to estimate cost efficiency and scale economies. We show that introducing the quality dimension into the analysis affects estimated efficiency significantly, especially that smaller utilities' efficiency seems to decrease. Our results emphasise that quality of service should be an integrated part of efficiency analysis and in the economic review in regulated natural monopolies.

Keywords: efficiency, quality of service, scale economies, input distance function, stochastic frontier analysis.

JEL: L15, L51, L94

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1. Introduction

Infrastructure industries, such as electricity, telecommunications, gas, transport, and water continue to maintain their strategic importance in modern economies. Since the 1990s, the globally dominant paradigms governing the structure and ownership models of these industries, natural monopoly, vertical integration, and public ownership, have been challenged. Liberal models based on competition, economic incentives, and private ownership have been adopted to achieve internal and external efficiency improvements in these sectors and to benefit customers in the form of lower costs and higher service quality.

The electricity sector has witnessed considerable liberalisation activities in many countries around the world. The main tenets of electricity sector liberalisation have been restructuring, regulation, and privatization. Implementing the new model required restructuring of the industries to separate potentially competitive segments (generation and retail supply) from natural monopoly activities (distribution and transmission) that would need to be regulated. Independent regulation would oversee the successful functioning of competitive power markets and regulated transmission and distribution networks. Private ownership and profit incentive would promote internal efficiency in the firms. Moreover, two important aspects of the new industry structure have been widely neglected: the question of (efficient) optimal firm size in natural monopolies and its relation to quality of service (QoS).

In competitive markets, competition and market size are important determinants of firm size and market concentration (subject to rules and policy). In natural monopolies, in the absence of market forces, public intervention, regulation, and history are often factors that affect efficiency and scale of firms. Theory characterises natural monopolies to be the most technically efficient market structure when a single firm can produce a specific output vector at less cost than two or more firms (subadditivity). Subadditive cost structures have been theoretically and empirically shown in networks of infrastructure industries (e.g. Gilsdorf, 1995 and Salvanes and Tjøtta, 1998). However, the appropriate scale (of production) of natural monopolies is also of economic interest. Optimal firm size as well as technical efficiency is related to the underlying production technology

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and structure of an industry. Therefore, in any given industry, the relationship between efficiency and scale is an empirical question.

In the context of European electricity sector reform, the natural monopoly characteristics and economic importance of firm size and quality of service in distribution networks has led to public intervention and regulation in these activities. First, at the time of restructuring and unbundling, political decision-makers were faced with decisions regarding the number and size of firms. Second, in the post-reform period since the end of the 1990s, mergers and acquisitions – vertically and horizontally – increased market concentration dramatically and changed the size of the firms requiring an informed policy towards this development.[1] At the same time, the desirability of having a large number of utilities in small countries (e.g. Nordic countries) poses an interesting policy question. Third, adoption of incentive regulation models in recent years has given rise to concerns that, if left unregulated, the pursuit of profit maximisation is likely to result in deterioration of quality of service.

In particular, a formal treatment of QoS from an industrial organisation point of view and/or as an integrated part of regulatory analysis has been widely neglected. This is especially problematic as there are interactions and trade-offs between utilities' costs (capital as well as operating and maintenance expenditures) and their size and quality of services. A simple cost-only approach to efficiency in regulated utilities will, therefore, not take an essential aspect of their activities into account. It is conceivable that quality-incorporated efficiency and scale measures of firms might differ from those of a cost-only approach. It is therefore important to enhance understanding of the significance of quality of service for efficiency and scale in network industries. Specifically, it might be that small operations are justified even where they have high costs but provide higher service quality and vice versa.

This paper aims to fill the void in previous research and shed some empirical light on the effects of including quality dimensions into the analysis of technical efficiency and optimal firm size. We estimate technical efficiency and scale economies of a sample of

[1] For an overview of mergers and acquisitions activity in the European electricity supply industry, cp. Codognet et al (2002).

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about 500 electricity distribution utilities from seven European countries, applying stochastic frontier analysis (SFA) method and multi-output translog input distance function models. The outline for the remainder of this paper is as follows. The theoretical foundations and previous literature are presented in Section 2. Section 3 discusses the methodology, and the estimation method. In Section 4 we introduce the modelling approach and specify the estimated models. The data is described in Section 5. Estimation results are presented in Section 6. Section 7 contains conclusions and highlights policy implications and directions for future research.

2. Efficiency and Quality of Service

The nature of electricity distribution has been examined in a number of theoretical and empirical studies, which predominantly support the existence of natural monopoly conditions in distribution networks.[2] This section recapitulates the basic conditions of natural monopoly theory and reviews previous research on (international) productivity analysis, optimal firm size, and on quality of service in network industries. We then present two hypotheses regarding the relationship between quality of service, technical efficiency, and firm size in electricity distribution networks.

The natural monopoly characteristics in electricity distribution can be attributed to three major aspects (e.g. Growitsch and Wein 2004): the high degree of sunk investments in network assets (e.g. power lines and transformers), economies of scale in electricity supply, and economies of scope between the major services in electricity distribution, namely 'customer connection' and 'energy delivery'.[3] In economic theory, a natural monopoly is described as a market structure, where it is technically efficient to produce a certain output vector by a single firm. Technically, this condition occurs if the cost structure of such a market is strictly and globally subadditive for all output vectors Y^i, $i = 1,\ldots,m$:

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2 For example, *Gilsdorf* (1994, 1995), *Filippini* (1998), *Salvanes and Tjøtta* (1998), and *Yatchew* (2000).

3 For a detailed description of outputs in electricity distribution, see Section 4.

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$$C(\sum_{i=1}^{m} Y^i) \leq \sum_{i=1}^{m} C(Y^i) \qquad (1)$$

In the case of a single-product firm, economies of scale (declining average costs) and concavity (falling marginal costs) are sufficient conditions for subadditivity and therefore existence of natural monopoly.[4] Baumol (1977) and Baumol et al. (1982) first discussed the economic concept of natural monopoly in the context of multi-product industries. In multi-output settings, economies of scale and the related property of declining-ray average costs are neither necessary nor sufficient for subadditivity of cost functions. Instead, in the multi-output context, subadditivity also requires presence of economies of joint production, either in the form of cost complementarity or trans-ray convexity.[5] Cost complementarity holds if inequality 1 is true for incremental as well as for total costs (Sharkey, 1982). Figure 1 illustrates the concept of transray convexity (here: in connection with economies of scale both in separate and joint production of outputs Y_1 and Y_2). A cost function C for two outputs Y_1 and Y_2 satisfies the property of transray convexity at a point Y if a line through Y shows a negative slope proving economies of joint production. The joint production cost function $C(Y_1+Y_2)$ in Figure 1 is also concave along all rays through the origin, indicating additional economies of scale. Being concave and transray convex, the illustrated cost function satisfies sufficient conditions of subadditivity.

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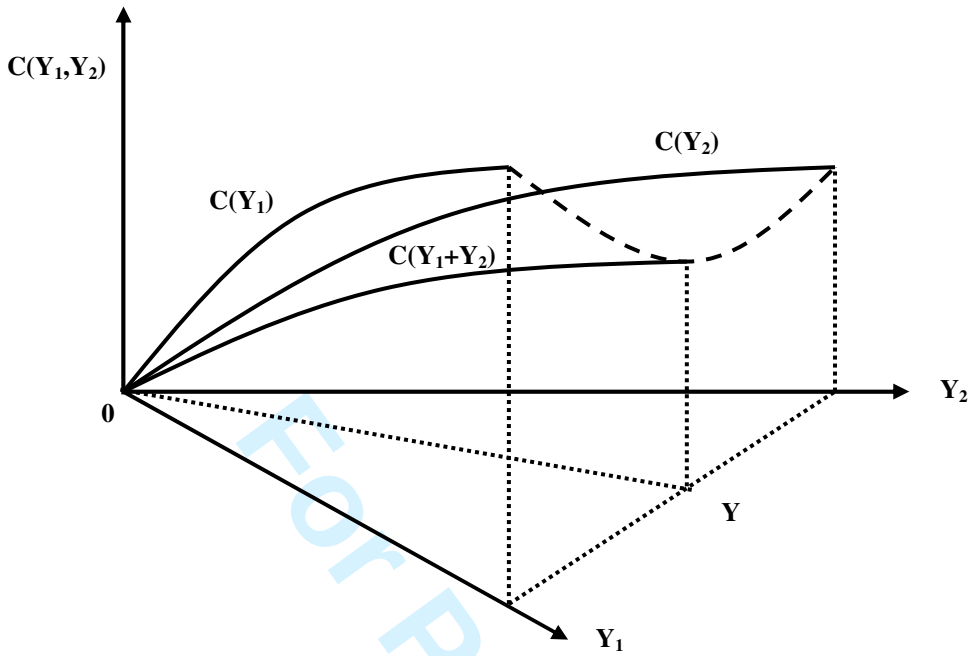
4 *Sharkey* (1982) presents numerous examples of subadditive cost functions to illustrate that neither economies of scale nor concavity are necessary conditions for subadditivity. As the existence of natural monopoly conditions in electricity distribution is an established notion, we are going to concentrate on more straightforward calculations rather than hypothetical exceptions.

5 See *Baumol* (1977) and *Baumol et al.* (1982) for a detailed description of these concepts and sufficient conditions for natural monopolies.

Figure 1:

Subadditivity in the two-output case



Applying the concept of multi-output production in natural monopolies to electricity distribution we focus on analysis of multi-product economies of scale (which is equivalent to identifying concavity of the joint cost function in Figure 1), testing for existence of economies of joint production, namely economies of scope (which is transray convexity in Figure 1). This is appropriate, as the aim of this study is to examine optimal utility/service size and the natural monopoly characteristics of electricity distribution networks are well-established. Although, there is ample evidence that there is considerable variation in efficiency of distribution utilities (e.g. IPART 1999, Jamasb and Pollitt 2003), the effects of size and quality of service on efficient operation and performance of these utilities is less clear.

The reviewed literature points to different economic and methodological aspects that are related to the subject matter of this paper. First, a branch of studies has focused on international comparisons of network industries including electricity distribution. Second, there is a line of literature that analyses most productive scale size in electricity distribution. Third, a limited body of literature has addressed the issue of quality of service aspect in network industries.

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Academic research and, to a lesser extent, regulation has used cross-country efficiency analyses partly to overcome problems due to a small number of observations, cross-border mergers, or/and the possibility of collusion among the regulated companies (Jamasb and Pollitt, 2003; Estache et al., 2004). Regulatory use of efficiency analysis has largely been limited to single country analysis. Cross-country studies of the performance of electric utilities are, however, rather few. In a comparison of UK and US distribution utilities, Pollitt (1995) finds a comparable performance in both countries. IPART (1999), in a study for the Independent Pricing and Regulatory Tribunal in Australia focuses primarily on Australian distribution companies, taking UK and New Zealand utilities as additional observations. In another comparison of seven Australian and 32 international electricity utilities Whiteman (1995) uses an international reference set to analyse the development of X-inefficiency in Australian electricity utilities.

In a comparison of Scandinavian and Dutch electricity distribution companies, Edvardsen and Førsund (2003) show the advantage of international comparisons in identifying peer companies. Jamasb and Pollitt (2003) compare the efficiency of 63 distribution utilities from six European countries using parametric and non-parametric benchmarking methods. They find that efficiency results tend to be rather sensitive in level, although not in rank order. Additionally, they report methods of introducing comparability in international samples. Analysing panel data of 84 South American electricity distributors from eight countries, Estache et al. (2004) point out the importance of international benchmarking and the coordination of regulators in order to reduce information asymmetries. In a recent study, Hattori et al. (2005) analyse the efficiency development of UK and Japanese distribution utilities using panel data from 1985-1998, reporting an acceleration of productivity growth over time and positive economies of scale for UK companies relative to Japanese firms.

Previous research on scale economies and optimal firm size commonly applies the Data Envelopment Analysis (DEA) technique to calculate the scale efficiency by comparing the efficiency results from constant and variable returns to scale models.[6] Empirical results from parametric models tend to be rather few and predominantly applied cost

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6 For an introduction see *Coelli et al.* (1998).

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functions for the analysis. For electricity distribution, an early contribution was by Nerlove (1963), who applies a cost function based on a generalized Cobb-Douglas production function and gives evidence for the possibility of substitution among factors of production. In two studies of Swiss electricity distribution utilities, Filippini (1996) and Filippini and Wild (2001) using a flexible translog and a linear average cost function find evidence of increasing returns to scale throughout their sample of 39 and 59 utilities respectively.

Other studies address the issue of minimum efficient scale size. Giles and Wyatt (1993) estimate a total cost function from a sample of 60 New Zealand electricity distributors, reporting an efficient scale for a sales range of 500 to 3500 GWh. Yatchew (2000) converted the results from Giles and Wyatt on a number of customer basis and reports a minimum efficient scale size at 30000 customers. Salvanes and Tjøtta (1994) in a cross-sectional analysis of 100 Norwegian electricity distribution utilities find an optimal firm size at about 20,000 customers and that is relatively independent from the GWh sales. These results confirm Yatchew's (2000) findings based on a four-year panel of 81 Canadian distributors. The study estimated a semi-parametric translog cost function and reports substantial scale economies and a minimum efficient scale achieved by firms with about 20000 customers.

Empirical research on quality of service in network industries is scarce and mostly concentrated on telecommunications sector (Resende and Façanha, 2004; Sappington, 2002; Ai and Sappington, 1998; Kridel et al., 1996). For the electricity sector, Ter-Martirosyan (2003) analyses the effect of incentive regulation on duration and frequency of electric outages for a panel of 78 U.S. utilities, reporting an increase in the duration of outages associated with incentive regulation. The study also finds that outages decrease when explicit quality benchmarks are introduced. Korhonen and Syrjänen (2003) find improvement in technical efficiency after incorporating quality of service (interruption time per customer) in their DEA analysis of 106 Finish distribution utilities. CEPA (2003) applies a two step DEA model to cross-sectional data for the UK and finds no significant correlation between technical efficiency measures and service quality in terms of minutes lost per customer. Ajodhia et al. (2004) apply a DEA and a Corrected Ordinary Least Squares (COLS) model to a cross-sectional sample of 44 electric utilities

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from four countries (UK, Netherlands, Hungary and Malaysia), reporting a significant efficiency increase when quality is taken into account especially for smaller utilities. Giannakis et al. (2005) carried out a quality incorporated efficiency study with panel data on UK electricity distribution. They show that technical efficiency does not necessarily also involve high service quality and state that quality incorporated regulatory benchmarking is superior to cost-only approaches.

The relationship of efficiency, firm size, and quality in regulated network industries has not been addressed previously. Kwoka (2005) is an exception, who in an analysis of private and public U.S. electric utilities estimates a quadratic cost function and reports lower distribution costs and higher quality in terms of lower duration of interruptions for smaller (public) companies. However, he did not apply frontier analysis and was not able to measure individual company efficiency.

Our review of natural monopoly theory and previous studies on electricity distribution suggests that important aspects of industry structure have not been addressed. The first issue is the relationship between technical efficiency and firm size. Insofar as economies of scale exist, larger firms are expected to demonstrate higher technical efficiency ceteris paribus. This relationship also applies to economies of scope between outputs (e.g. customer numbers and energy supplied). Natural monopoly theory would then suggest increasing service area size until scale economies are exploited.

Inclusion of the quality dimension into technical efficiency analysis might alter the optimal firm size. Kwoka presents the hypothesis, that smaller utilities supply higher quality, as they have easier access to local market and customer specific information (such as demand characteristics and special technical conditions), being important for service quality and reliability. Moreover, organizational aspects such as multiple objectives combined with observability of results and measurement problems in large firms can explain higher quality of service in small firms (Holmström, 1989 and Dixit, 1997). In addition, quality criteria are difficult to specify and to enforce (Kwoka, 2005). Also, it has been argued that closeness to customer leads to higher quality of service.[7] If

[7] However, it should be mentioned that some degree of self-selection may exist as small firms with low quality of service may have gradually been acquired by larger and more efficient firms.

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the above proposition holds, incorporating quality of service in electricity distribution utilities' production function and technical efficiency measurement could reduce economies of scale and decrease optimal utility size relative to a pure cost analysis. The following two main hypotheses can be drawn:

(i) In a pure cost efficiency analysis, the natural monopoly characteristics (economies of scale and scope) in electricity distribution can be assumed to produce a higher efficiency associated with firm size (*'economies of scale' hypothesis*).

(ii) The relative cost and efficiency advantage of large firms declines when quality of service is taken into account. (*'proximity to customers' hypothesis).*

We test these hypotheses by applying stochastic frontier analysis and distance functions to examine the technical efficiency, scale economies and scope economies of electricity distribution utilities using a pure cost and combined cost-quality analysis.

3. Methodology

Shephard (1953, 1970) proposed the distance function approach for specifying the production technology of a multi-output multi-input firm. When analysing regulated industries this approach has advantages over cost or revenue functions since the behavioural assumptions of the latter approaches are likely to be violated (Estache et al., 2004).[8] Distance functions can be differentiated into input and output distance functions. The former describes the maximum radial contraction of the input vector while keeping the output vector constant. The latter gives information about the maximum producible output given an input vector. For the purpose of this study, we use the input distance function approach as outputs of electricity distribution networks are exogenously determined due to the derived nature of demand (i.e. that is distribution of a given amount of energy demanded to a given number of customers) for their output.

8 Estache et al. (2004) refer to a violation of standard assumptions (for example profit maximisation or efficient production) in production economics due to regulation and public ownership.

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The input distance function summarizing all economically relevant characteristics of the production technology can be defined as

$$D^I(\mathrm{X},\mathrm{Y})=\max\{\rho : (\mathrm{X}/\rho) \in L(\mathrm{Y})\} \tag{2}$$

where the input set L(Y) represents the set of all input vectors X that can produce outputs Y. We assume this production technology satisfies the properties discussed in Färe and Primont (1995). From X∈L(Y) follows that $D^I(\mathrm{X},\mathrm{Y}) \geq 1$, equalling unity for any company on the frontier of the input set. The input distance function has some additional properties, it is linear homogenous and concave in X. The translog (transcendental logarithmic) functional form, originally introduced as a cost function model by Christensen et al. (1973), has several virtues, which apply to a distance function as well (Kumbhakar and Lovell, 2000). The translog input distance function is flexible and allows imposition of assumptions from microeconomic theory such as homogeneity, symmetry and monotonicity.

When defined for the case of K inputs and M outputs, the translog input distance function is specified as

$$\begin{aligned}\ln D_i^I &= \alpha_0 + \sum_{m=1}^{M}\alpha_m \ln y_{mi} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M}\alpha_{mn}\ln y_{mi}\ln y_{ni} \\ &+ \sum_{k=1}^{K}\beta_k \ln x_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K}\beta_{kl}\ln x_{ki}\ln x_{li} + \frac{1}{2}\sum_{k=1}^{K}\sum_{m=1}^{M}\delta_{km}\ln x_{ki}\ln y_{mi}\end{aligned} \tag{3}$$

with α, β and δ being parameters to be estimated and *i* denoting the *i*th firm of the sample. To impose the properties proposed by microeconomic theory, some constraints on the unknown parameters are required. Symmetry is given if the second order coefficients satisfy

$$\beta_{kl} = \beta_{lk} \text{ and } \alpha_{mn} = \alpha_{nm} \text{ for } k = 1,2,\ldots,K \text{ and } m = 1,2,\ldots,M\ . \tag{4}$$

The restrictions required for homogeneity of degree + 1 in inputs are

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$$\sum_{k=1}^{K}\beta_k = 1, \sum_{l=1}^{K}\beta_{kl} = 0, k = 1,2,...,K \text{ and } \sum_{m=1}^{M}\delta_{km} = 0, m = 1,2,...,M \,. \tag{5}$$

The monotonicity constraint is satisfied if and only if

$$\frac{\partial \ln D^I}{\partial \ln x_k} = \beta_k + \sum_{l=1}^{K}\beta_{kl}x_l + \sum_{m=1}^{M}\delta_{km}y_m \geq 0 \,. \tag{6}$$

and

$$\frac{\partial \ln D^I}{\partial \ln Y_m} = \alpha_m + \sum_{n=1}^{M}\alpha_{mn}y_n + \sum_{k=1}^{K}\delta_{km}x_k \leq 0 \,. \tag{7}$$

Based on the above formalisation, it is possible to calculate additional economic characteristics of the corresponding technology. A focal point of this study is the analysis of optimal firm size. As shown above, this is related to scale elasticities and returns to scale, which can be obtained from the input distance function as shown by Färe and Primont (1995). For the multi-output case, returns to scale can be defined as follows:

$$RTS = \frac{-1}{\nabla D^I(y,x)y} \,. \tag{8}$$

where $\nabla D^I(y,x)$ is the vector of first order partial derivatives of the distance function with respect to outputs (Rungsuriyawiboon and O'Donnell, 2004). Values of RTS greater than one indicate increasing returns to scale, whereas values smaller than one imply decreasing returns to scale. The optimal firm size is where RTS equals unity; constant returns to scale are a necessary and sufficient condition for optimal scale size in electricity distribution. Nevertheless, there is a distinction between scale economies and scale efficiency. The latter is, in a parametric setting, equivalent to the ray average productivity at the observed input bundle relative to the constant returns to scale input

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vector and differs from the scale economy value except for bundles of constant returns to scale (Morrison-Paul et al., 2004).[9] We calculate the returns to scale as the negative inverse of the scale elasticities: the (negative) scale elasticity is defined as the sum of production elasticities:

$$-\varepsilon_{DIY} = -\sum_m \frac{\partial \ln D^I}{\partial \ln y_m}. \tag{9}$$

As Morrison-Paul et al. (2004) state, this formula is consistent with Equation 8 and conceptually comparable to the multi-output cost elasticities in Baumol et al. (1982).

Indeed, this measure of multi-product scale elasticities includes economies of joint production. Denny and Pinto (1978) showed that economies of joint production (scope economies) exist in translog functions if $-\alpha_m * \alpha_n < \alpha_{mn}$. To control for joint production effects, we impose the constraint $\alpha_{mn} = -\alpha_m * \alpha_n$ into the scale elasticity formula and calculate a net scale elasticity measure. Subtracting net scale elasticity from the scale elasticity defined in formula 9 gives a measure of economies of scope.

Atkinson and Primont (2002) show that it is possible to calculate 'implicit input value shares' (Rungsuriyawiboon and O'Donnell, 2004) for any input k by

$$\frac{\partial \ln D^I}{\partial \ln x_k} = \frac{x_k}{D^I}\frac{\partial D^I}{\partial x_k}. \tag{10}$$

Ratios of these derivatives can be interpreted as a unit-less rate of input substitution (Rungsuriyawiboon and O'Donnell, 2004).

In order to estimate firm specific technical efficiency, we apply stochastic frontier analysis (SFA), originally introduced by Aigner et al. (1977) and Meeusen and van den Broeck (1977). SFA is a parametric method which can also estimate an efficient or best practice frontier from a distance function model and firm specific deviations (i.e. inefficiency) from the frontier in the form of technical efficiency scores (see e.g. Coelli

9 See *Ray* (1999, 2003), *Balk* (2001), and *Orea* (2002) for more detailed discussions.

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et al. 1998). The estimated technical efficiency scores range between 1 and 0 where a score of 1 means that a firm is the most efficient in the sample and is on the efficient frontier while 0 represents the least efficiency.

Imposing the restrictions specified above, a stochastic frontier model of firm *i* can be modelled as follows (Coelli and Perelman 1999, Rungsuriyawiboon and O'Donnell, 2004):

$$
\begin{aligned}
-\ln(x_{Ki}) = & \\
& \alpha_0 + \sum_{m=1}^{M} \alpha_m \ln y_{mi} + \frac{1}{2} \sum_{m=1}^{M} \sum_{n=1}^{M} \alpha_{mn} \ln y_{mi} \ln y_{ni} \\
& + \sum_{k=1}^{K-1} \beta_k \ln(\frac{x_{ki}}{x_{Ki}}) + \frac{1}{2} \sum_{k=1}^{K-1} \sum_{l=1}^{K-1} \beta_{kl} \ln(\frac{x_{ki}}{x_{Ki}}) \ln(\frac{x_{li}}{x_{Ki}}) \\
& + \frac{1}{2} \sum_{k=1}^{K-1} \sum_{m=1}^{M} \delta_{km} \ln(\frac{x_{ki}}{x_{Ki}}) \ln y_{mi} + v_i - u_i
\end{aligned}
\tag{11}
$$

where α, β and δ are unknown parameters, ν is a random error term, and $u_i = \ln D_i^I$ is the (non-negative) technical inefficiency term. The error term ν is distributed as iid $N(0, \sigma^2)$, for u we assume a truncated normal distribution $N^+(m, \sigma^2)$ as suggested by Stevenson (1980).

In order to capture systematic differences in exogenous factors between firms, we also include environmental variables to allow variation of a company's mean efficiency, assuming environmental factors directly affecting technical efficiency. As suggested by Battese and Coelli (1995), we assume the mean of the truncated normal distributed inefficiency term to be a linear function of environmental variables z (here as country dummies or density factors). For our model, *m* is specified as:

$$
m_i = \lambda_0 + \sum_{s=1}^{S} \lambda_s z_{si} \tag{12}
$$

Following Battese and Coelli (1995), we estimate the coefficients α, β, δ and λ, the standard deviations of the error components σ_u and σ_v, the total error variance $\sigma^2 = \sigma_u^2 + \sigma_v^2$ and the ratio of the variance of the inefficiency component to the total

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error variance $\gamma = \sigma_u^2 / \sigma^2$. γ is bounded between zero and unity and indicates the relative contribution of inefficiency to total error variance.

The technical efficiency scores are calculated following the procedure by Coelli et al. (1999). Technical efficiency for the *i*-th firm in a set of cross-sectional data is defined by:

$$TE_i = E[\exp(-u_i | \varepsilon_i)]$$
$$= \left\{ \exp\left[-\mu_i + \frac{1}{2}\sigma_*^2 \right] \right\} \cdot \left\{ \frac{\Phi\left[\frac{\mu_i}{\sigma_*} - \sigma_* \right]}{\Phi\left[\frac{\mu_i}{\sigma_*} \right]} \right\} \tag{13}$$

with

$$\mu_i = (1-\gamma)\left[\delta_0 + \sum_{s=1}^{S} \delta_s z_{s,i} \right] - \gamma \varepsilon_i \tag{14}$$

and

$$\sigma_*^2 = \gamma(1-\gamma)\sigma^2 \tag{15}$$

4. Modelling Approach and Estimation Strategy

We now turn to the modelling of the electricity distribution technology. First, we specify the relevant input and output variables for the stochastic frontier model. Second, we specify the functional form of the models to be estimated. Concerning the variables, previous research on efficiency measurement in electricity distribution has used a variety of variables and models (Jamasb and Pollitt, 2001). This may be explained partly by lack of data and partly by the nature of issues addressed (Hattori et al., 2005).

In order to estimate relative efficiency and optimal firm size when taking the quality dimension into account, we specify two basic models. The first model (Cost-Only) focuses on efficiency only and consists of one input variable and three output variables. A single cost input is used to represent *total expenditures* (TOTEX) or total cash cost in

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monetary terms defined as the sum of operating expenditures (OPEX) and capital expenditures (CAPEX). While OPEX represents operating and maintenance (O&M) costs, CAPEX represents the annual gross capital outlays of a company. Using a single monetary measure for inputs facilitates international comparison, as it reflects differences in relative factor prices and substitution between OPEX and CAPEX among the countries. The issues of differences in cost levels, accounting rules, currencies conversion and other input level influencing factors will be discussed later.

The second model (Cost-Quality) incorporates quality of service by using the number of *customer minutes lost* (CML) for each firm. CML represents the continuity dimension of quality of service, it measures the average duration of outages per connected customer and is a proxy for service reliability. Following Yaisawarng and Klein (1994) and Giannakis et al. (2005), we treat outage duration as an undesirable input, assuming a substitutive relationship between total spending and duration of outages. In an input distance function model, an efficient firm can reduce CML and cost while maintaining a given level of outputs.

Electricity distribution utilities operate in a regulated environment and provide a required amount of energy to a given number of customers as a joint service. The two elements of this service, electricity delivered and number of customers supplied, can be treated separately, as they (i) drive different costs, and (ii) interact with each other technically. Therefore, we use two output variables in the cost-only and the cost-quality models. These variables have been identified based on the "separate marketability of components" property suggested by Neuberg (1977), that is total *number of customers* and *number of energy units supplied* measured in Gigawatt-hours (GWh). The two output variables also reflect the structure of a two-part tariff, i.e. a fixed charge per customer as well as a variable part dependent on consumed energy. In addition, economies of scope between customers and supplied energy have been theoretically identified based on advantages in load-management due to a lower risk of stochastic demand effects (law of large numbers) and the possibility of pooling non-perfectly correlated demands to flatten total demand (Brunekreeft, 2003). These effects gain importance with increasing number of customers, relating economies of scope to

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economies of scale. A separate analysis of number of customers and energy units delivered allows the identification of economies of scale and scope.

In addition to input and output variables, environmental factors can influence the technical efficiency of a firm but are beyond managerial control. We use *customer density* (number of customer per network kilometre) as an environmental variable to control for density advantages. A set of country dummy variables is used to capture national differences such as ownership structure, regulation (antitrust rules), different objectives for utilities as well as differences in historical developments regarding size of service area and regulation regime.

Since the translog functional form requires an approximation of an underlying function to a specific point of the sample, we correct the variables by sample means. This procedure reduces the influence of outliers without affecting the structure of data. In addition, the first order coefficients can be interpreted as estimates of production elasticities at sample means (Coelli et al., 2003).

For the cost-only model (Model I), the outputs are energy delivered and number of customers, and the single input is total expenditures (TOTEX). Inclusion of country dummies as environmental variables allows us to adjust estimates of relative efficiency for structural differences which might be attributed to the regulatory regime, historical industry structure and results of former regulation. Moreover, we control for the differences in customer density which is expected to have an effect on firm-specific technical efficiency.

$$\begin{aligned} -\ln\left(TOTEX_i\right) = & \\ & \alpha_0 + \alpha_1 \ln energy + \alpha_2 \ln customers \\ & + \frac{1}{2}\alpha_{11} \ln energy^2 + \frac{1}{2}\alpha_{22} \ln customers^2 \\ & + \alpha_{12} \ln energy * \ln customers \\ & + v_i - u_i \end{aligned} \tag{16}$$

and,

$$\mu_i = \lambda_0 + \lambda_{UK} + \lambda_{Fi} + \lambda_{Sw} + \lambda_{No} + \lambda_{It} + \lambda_{Neth} + \lambda_{cust_dens} \tag{17}$$

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We now extend the discussion to a cost-quality model (Model II), which incorporates customer minutes lost as a second input.

$$
\begin{aligned}
-\ln\left(TOTEX_i\right) = & \\
& \alpha_0 + \alpha_1 \ln energy + \alpha_2 \ln customers \\
& + \frac{1}{2}\alpha_{11} \ln energy^2 + \frac{1}{2}\alpha_{22} \ln customers^2 \\
& + \alpha_{12} \ln energy * \ln customers \\
& + \beta_1 \ln(\frac{CML}{TOTEX}) + \frac{1}{2}\beta_{11} \ln(\frac{CML}{TOTEX})^2 \\
& + \delta_1 \ln(\frac{CML}{TOTEX}) * \ln energy + \delta_2 \ln(\frac{CML}{TOTEX}) * \ln customers \\
& + v_i - u_i
\end{aligned}
\tag{18}
$$

and,

$$
\mu_i = \lambda_0 + \lambda_{UK} + \lambda_{Fi} + \lambda_{Sw} + \lambda_{No} + \lambda_{It} + \lambda_{Neth} + \lambda_{cust_dens} \tag{19}
$$

Table 1 shows the inputs, outputs, and environmental variables used in our models.

Table 1:
Specification of models

Variable	Model I	Model II
Inputs		
TOTEX	√	√
CML		√
Outputs		
No. of customers	√	√
Units of energy (GWh)	√	√
Environmental Factors (z)		
Country dummies	√	√
Customer density	√	√

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5. Data and Descriptive Information

The data set used for this study consists of 505 electricity distribution utilities from eight European countries, namely Finland, Ireland, Italy, the Netherlands, Norway, Spain, Sweden and the United Kingdom. The data was collected from national regulators and utility associations for the financial year 2002. This section describes in detail how the data was harmonized and processed.

Using monetary values of input variables from an international data set bears some problems, the most relevant being comparability. As stated in Edvardsen and Førsund (2003), the range of practical alternatives for harmonizing is small. We convert the financial data to a single monetary unit, the euro, as suggested in Jamasb and Pollitt (2003). Five of eight countries in the sample have euro as their common currency. As conventional exchange rates do not fully cover country specific differences in price level and purchasing power, we adjusted the OPEX and CAPEX with the comparative price levels for 2002 using purchasing power parities (OECD, 2004).[10] Table 2 shows descriptive information of the data set, the variables and their average values. Table 3 describes the variables and summary statistics of data used.

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[10] Jamasb and Pollitt (2003) in a Data Envelopment Analysis of efficiency of electricity distribution networks (in Norway, UK, Netherlands, Italy, Spain, Portugal) found a correlation coefficient of 0.99 between the efficiency scores when using PPP vs. using exchange rates. Furthermore, 4 out of 7 countries share a common currency, bearing difficulties accounting for relative price level differences when using currency rates.

Table 2:
Number of utilities in the sample

Country	Number of utilities (mean)	Energy supplied (GWh) (mean)	No. of customers (mean)	Network length (km) (mean)	TOTEX (in 000) (mean)	CML (mean)
United Kingdom	14	22,249	1,953,809	54,669	218,733	86.36
Ireland	1	21,208	1,737,616	164,553	658,016	398.00
Netherlands	7	13,340	851,894	254,835	254,835	16.66
Finland	99	483	32,879	4,126	30,436	136.23
Norway	143	504	17,872	2,084	8,248	240.72
Sweden	223	398	20,576	1,807	6,495	34.62
Italy	8 Enel departments	26,626	3,658,791	129,505	176,766	142.26
Spain	4	50,689	5,784,686	154,707	2,256,987	0.14

Table 3:
Variables and summary statistics

Variable	Min	Max	Mean	Median
No. of customers (in 000)	0.004	10,262.00	197.38	10.34
Energy supplied (GWh)	0.290	85,080	2,128	220
Network length (km)	10	280,166	7,866	987
TOTEX (in 000)	79.14	3,812,540	43,668	4,224
CML	.00	4834.68	117.02	43.39

As shown in the Table 2, the number of companies and the mean parameter values per country varies widely. For the UK, Ireland, Finland, Norway, Sweden and Spain, our sample is a near complete inventory count of utilities. For the Netherlands, separate financial data was not available for 2002 and we aggregated the technical and quality variables at the holding company level. Data for Italy's Enel distribution region information was aggregated from 19 sub-departments to 8 departments. Despite the data aggregation in both Italy and the Netherlands, our data set covers nearly the whole of the national distribution networks. The large differences between the countries (Table 2)

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and the minimum and maximum values of variables (Table 3) demands interpretation of results with care; on the other hand, it allows an unbiased identification of optimal firm size across a wider range.

Concerning our hypotheses, the descriptive statistics show interesting relationships between costs, firm size, and quality of service. The plot of total expenditures against number of customer shows a decreasing increase in costs (Figure 2). On a per customer basis, Figure 3 indicates a cost advantage for larger companies, supporting the economies of scale hypothesis.

Figure 2:

Total expenses and firm size

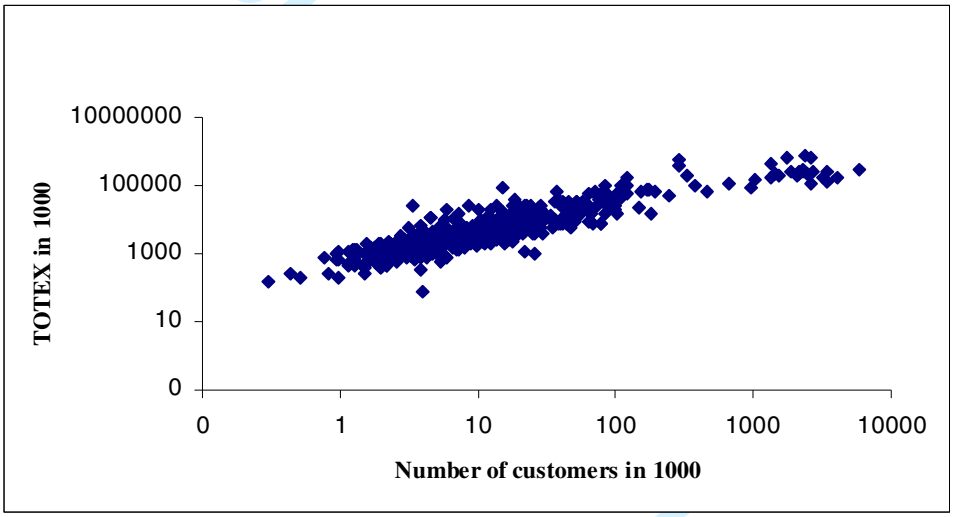

Figure 3:

Total expenses per customer and firm size

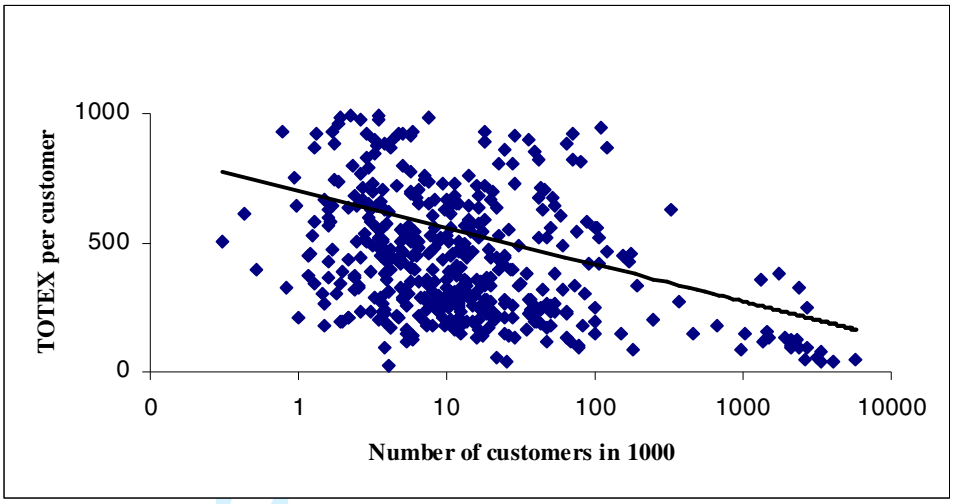

Figure 4 shows a scatter plot of the quality dimension (i.e. customer minute lost) against the number of customers as the relevant dimension of firm size. The figure shows that smaller firms exhibit a higher degree of service quality, supporting our proximity to customer hypothesis.

We controlled the data for outliers by applying the method suggested by Hadi (1992, 1994), which identifies multiple outliers in multivariate data. For the Model I, 15 observations were dropped and another 5 observations due to missing data. Data for Model II is adjusted for 34 outliers in total; after dropping 17 observations due to missing data, another 17 cases where eliminated based on Hadi's method.[11]

[11] Applying the procedure suggested dropping all observations from Spain. To avoid systematic biases, we dropped the Spanish utilities for the cost-only model as well.

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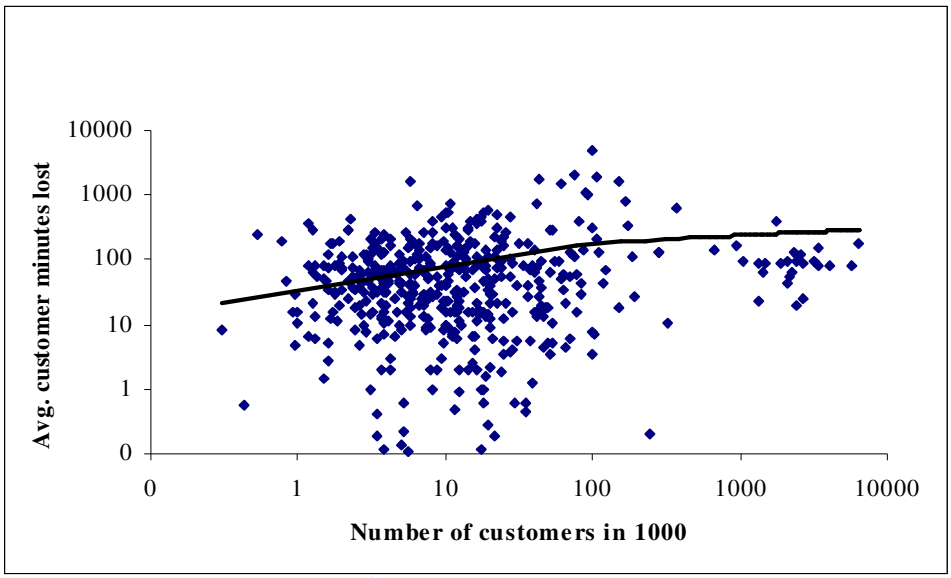
Figure 4:

Quality of service and firm size



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6. Results

In this section we discuss the results of the estimated models, beginning with an analysis of technical efficiency and economies of scale for the cost-only Model I. We then extend the discussion to the quality incorporated model Model II.

Analysing the cost-only Model I (Table 4) the following conclusions can be drawn. The first order coefficients of *ln energy* and *ln customer* are statistically significant and show the expected signs. Also, the input TOTEX increases with both increasing energy delivered and number of customers. The country dummies and customer density influencing technical efficiency scores produce the following results. Five out of seven country variables are significant and can be interpreted as that the dummies for Nordic countries are all positive, indicating significant higher technical inefficiency for companies from Sweden, Norway or Finland. Customer density influences the technical efficiency score as expected, with increasing customer density, technical efficiency scores increase as well (to be exact, the negative sign represents a negative effect on

inefficiency).[12] The monotonicity restriction is not violated and the Wald χ^2 test confirms a systematic influence by explanatory variables at 99% level of significance.

Table 4:

Cost-Only Model I

ln Energy	-0.4993*** [-2.79]	$\ln \sigma^2$	-1.037*** [-8.29]
ln Customer	-0.4054** [-2.40]	inv log γ	0.004 [0.01]
½ (ln Energy)^2	0.4092 [1.50]	σ^2	0.3546
½ (ln Customer)^2	0.4194* [1.69]	γ	0.5011
ln Energy * ln Customer	-0.4138 [-1.61]	σ_v^2	0.1769
Constant	0.4383*** [3.72]	σ_u^2	0.1777
z UK	-0.212 [-0.19]	Log-likelihood	-403.5747
z Finland	1.613*** [8.45]	Wald χ^2	1476.23 [0.000]
z Sweden	0.544* [1.69]	N	485
z Norway	1.094*** [4.68]		
z Italy	-15.453 [-0.45]		
z Netherlands	1.193*** [2.92]		
z Customer / km	-10.547* [-1.83]		
Significant on 10%-. 5%-. and 1%-level: *, **, and ***; z value in parentheses.			

The relationship between technical efficiency and utility size in Model I indicates presence of considerable economies of scale: While the mean technical efficiency score is 0.45 for small utilities and 0.49 for medium sized utilities respectively, the larger

12 We suppressed the environmental variables constant to obtain better interpretable results.

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utilities show a mean score of nearly 0.80.[13] This relation holds for the different countries as well, while the UK (0.84) and Italy (0.82) show very efficient distribution utilities, firms from Nordic countries tend to be rather inefficient. An interesting and not expected result are the comparatively low efficiency scores for Ireland (0.54) and the Netherlands (0.45). However, the confidence intervals of the efficiency scores are large and to some extent overlap. This indeed coincides with other research and does not alter the results in general.[14]

Also, returns to scale in relation to number of customers, economies of scale can be found throughout the sample. The RTS measure remains constant at about 1.1, which is the observed scale economies at the sample mean as well.[15] Concerning the issue of optimal firm size, these findings suggest that even the largest firms in the sample have not exploited all scale economies; a further increase of the joint output vector seems reasonable for the entire sample.

For the Model II with incorporated customer minutes lost as an additional input factor, we estimated a two input two-output translog input distance function (Table 5). The first order coefficients of *ln energy*, *ln customer*, and *ln cml* (normalized by TOTEX variable) are highly significant and show the expected signs. While total expenditures increase with energy delivered and number of customers, customer minutes lost decrease with cost, indicating a trade-off relation between cost and quality. Again, five out of seven environmental variables are significantly influencing firm's technical (in) efficiency.[16] The Nordic firms as well as those from the Netherlands are significantly less efficient. The control variable for customer density shows a highly significant

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13 This analysis is based on the gross technical efficiency scores (see *Coelli, Perelman and Romano* 1999). Calculating net technical efficiency scores as suggested by Coelli et al. reduces the efficiency differences between small and large firms but does not alter the relation in general.

14 To estimate the confidence intervals of the technical efficiency scores, we applied the procedure suggested in *Horrace and Schmidt* (1996) and *Kumbhakar and Lovell* (2000). In *Kumbhakar and Lovell* (2000), formula (3.2.34) contains a typo. We thank William C. Horrace for bringing this to our attention. The interested reader may be referred to *Horrace and Schmidt* (2000).

15 Applying the procedure of testing for economies of joint production (*Denny and Pinto* 1978) indicates that this result of constant scale economies throughout the sample cannot be explained by scope economies. This seems to be counter-intuitive, as a comparable RTS measure for Model 2 can clearly be described by increasing economies of scope with firm size (see below).

16 Again, we suppressed the environmental variables constant to obtain better interpretable results.

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negative relation between number of customers per kilometre of network length and technical inefficiency. As in Model I, the monotonicity restriction is not violated. The Wald χ^2 test confirms a systematic influence by explanatory variables at 99% level of significance.

The estimated efficiency scores clearly contradict the proximity to customer hypothesis. While small firms show the lowest mean efficiency scores (0.38), technical efficiency increases to 0.44 for medium sized and 0.81 for large firms.[17] Again, this relationship holds for the countries as well. Italy (0.99) and the UK (0.82) show rather high mean efficiency scores while Finish (0.22) and Norwegian (0.30) utilities are inefficient on average. An exception among the Nordic countries is Sweden with a mean quality adjusted technical efficiency of the companies of 0.55. In cost-quality terms a comparatively inefficient utility can be found in Ireland (0.37), Dutch firms show a mean technical efficiency of 0.51. As in Model I, the confidence intervals of the technical efficiency score are rather large and indicate coincidental differences in technical efficiency to a certain extent.

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17 The net technical efficiency scores are less different between small and large firms; but again, this relation still holds in general.

Table 5:

Cost-Quality Model II

ln Energy	-0.3944** [-2.51]	ln σ^2	-1.262*** [-13.84]
ln Customer	-0.3440** [-2.43]	inv log γ	0.929** [2.20]
½ (ln Energy)^2	-0.0483 [-0.18]	σ^2	0.2830
½ (ln Customer)^2	0.2070 [0.90]	γ	0.7168
ln Energy * ln Customer	-0.0685 [-0.28]	σ_v^2	0.0801
ln (CML/TOTEX)	0.2764*** [6.12]	σ_u^2	0.2028
½ (ln CML/TOTEX)^2	0.0420*** [4.09]	Log-likelihood	-333.1597
ln (CML/TOTEX) * ln Energy	-0.1796*** [-3.24]	Wald χ^2	2561.28 [0.000]
ln (CML/TOTEX) * ln Customer	0.2169*** [3.93]	N	471
Constant	0.7067*** [6.79]		
z UK	0.068 [0.09]		
z Finland	1.847*** [12.43]		
z Sweden	0.809*** [4.39]		
z Norway	1.384*** [8.12]		
z Italy	-16.234 [-0.36]		
z Netherlands	1.227*** [3.34]		
Significant on 10%-. 5%-. and 1%-level: *, **, and ***; z value in parentheses.			

Analysing the returns to scale in relation to number of customers, economies of scale can be found throughout the sample with RTS at about 1.2 on average. Testing for economies of joint production (Denny and Pinto 1978) shows decreasing net returns to scale as well as increasing economies of scope with firm size. Net returns to scale are

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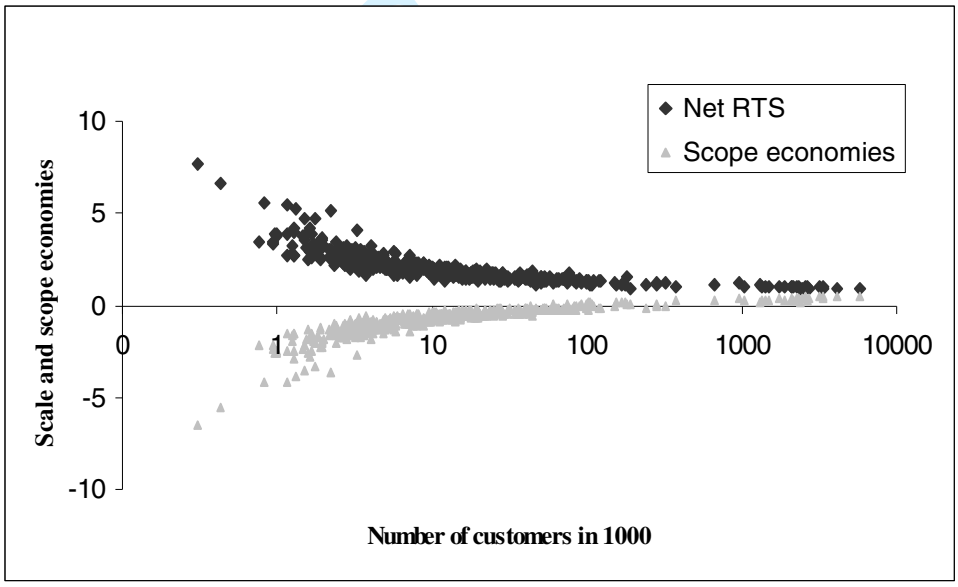
homogenously decreasing throughout the sample, scale economies can be found for utilities below 183,000 customers (see Figure 5, dark squares).[18] We calculated positive scope economies for utilities with more than 108,000 customers (Figure 5, light triangles).[19] These findings support the assumed relation of energy supplied and number of customers: At a certain utility size, stochastic scale advantages or positive effects of pooling demand seem to develop. Our findings emphasize that the existence of scale related scope economies drive optimal firm size. Indeed, gross RTS scores above one for even the largest companies militate for an optimal utility size beyond the maximum observed number of customers in our sample. This result has to be treated with care as it is sensitive to the curvature of our estimated function. Nevertheless, for the given data set the results are viable.

Figure 5:

Net RTS, scope economies, and number of customers



18 We obtained this result be estimating a logged trend function in a scatter plot diagram of returns to scale and number of customers, setting the trend equation to one and solving for the number of customers ($R^2 = 0.2317$).

19 This result was obtained by estimating a logged trend function in a scatter plot diagram of economies of scope and number of customers, setting the trend equation to one and solving for the number of customers ($R^2 = 0.2477$).

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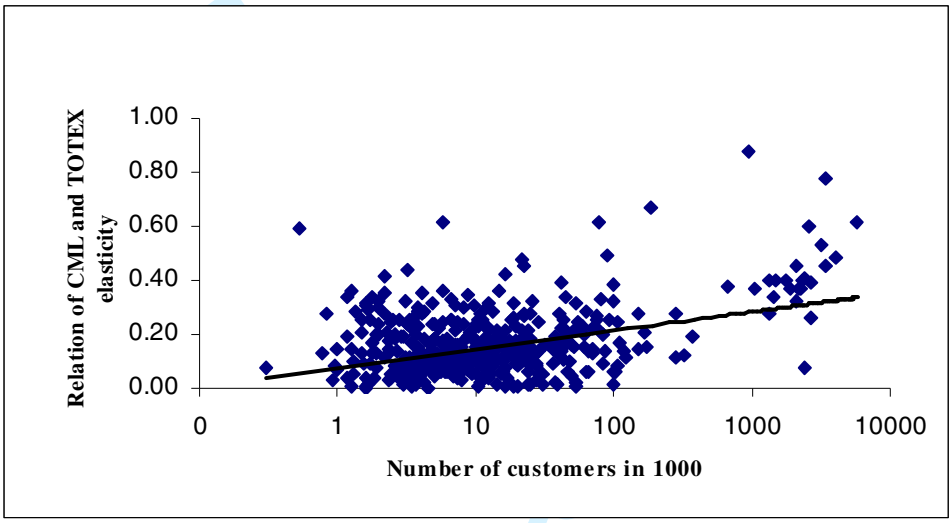
The relationship between the two inputs total expenditures and customer minutes lost, indicates that the ratio of the CML elasticity to the TOTEX elasticity increases with firm size (Figure 6). This measure of factor substitutability indicates that large utilities might be technically better able to increase quality of service at a given output level (by increasing total costs) while small utilities cannot substitute total expenses against quality to such an extent.

Figure 6:

Input substitution and firm size - Model II



Comparing and recapitulating the results from Models I and II, empirical evidence clearly supports the economies of scale hypothesis. In both the pure and the quality adjusted model, technical efficiency increases with firm size. Additionally, the efficiency differences are rather substantial. The efficiency differences in relation to firm size reflect the differences across countries as well. Countries with large utilities such as Italy and the UK show considerably higher mean technical efficiency scores than countries with smaller companies as the Nordic countries.

An interesting and somewhat unexpected result is that the proximity to the customer hypothesis can be rejected with confidence; empirical observations even give evidence to the contrary (Table 6). While incorporating quality of service increases average technical efficiency of large firms (and countries with predominantly large firms),

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efficiency of small firms decreases substantially. Regressing the (logged) TE scores of Model II by those of Model I clearly support this finding; the TE scores are significantly negatively correlated, correlation is around 0.96.

Table 6:

Comparison of technical efficiency of Models I and II

	Model	Mean	Std. Dev.	Min	Max	Average Change
Small firms*	Cost-only TE	0.4503	0.1722	0.1129	0.9255	-16.40%
	Cost-quality TE	0.3765	0.1768	0.0591	0.8193	
Medium firms*	Cost-only TE	0.4926	0.2004	0.1234	0.9885	-11.66%
	Cost-quality TE	0.4352	0.2176	0.0946	0.9868	
Large firms*	Cost-only TE	0.7963	0.1985	0.3380	0.9894	1.80%
	Cost-quality TE	0.8106	0.1788	0.3661	0.9891	
UK	Cost-only TE	0.8353	0.0274	0.7727	0.8854	-1.94%
	Cost-quality TE	0.8191	0.0658	0.6350	0.9106	
Finland	Cost-only TE	0.2507	0.1164	0.1129	0.7922	-11.39%
	Cost-quality TE	0.2222	0.1345	0.0738	0.8883	
Sweden	Cost-only TE	0.6189	0.1235	0.1281	0.9255	-10.76%
	Cost-quality TE	0.5523	0.1659	0.0591	0.8671	
Ireland	Cost-only TE	0.5381	0.0000	0.5381	0.5381	-31.96%
	Cost-quality TE	0.3661	0.0000	0.3661	0.3661	
Norway	Cost-only TE	0.3782	0.0549	0.2647	0.5516	-20.46%
	Cost-quality TE	0.3008	0.0676	0.1749	0.5472	
Italy	Cost-only TE	0.8169	0.0265	0.7720	0.8436	21.07%
	Cost-quality TE	0.9891	0.0003	0.9885	0.9894	
Netherlands	Cost-only TE	0.4445	0.1058	0.3380	0.5951	15.26%
	Cost-quality TE	0.5123	0.1143	0.3355	0.6477	

* Small firms are defined as being part of the 50% percentile of number of customers, medium firm are within the 50% to 95% percentile, large firms are the largest 5%.

Figure 7 visualizes the differences in level and distribution of TE scores between Models I and II. The scatter plots of technical efficiency and number of customers show size advantages for both models; the distribution of the scores however is different. In Model I, the scores are less dispersed and the average technical efficiency is slightly higher. The scatter plot of Model II supports the results shown in Table 6. While small and especially less efficient firms seem to suffer from the inclusion of service quality

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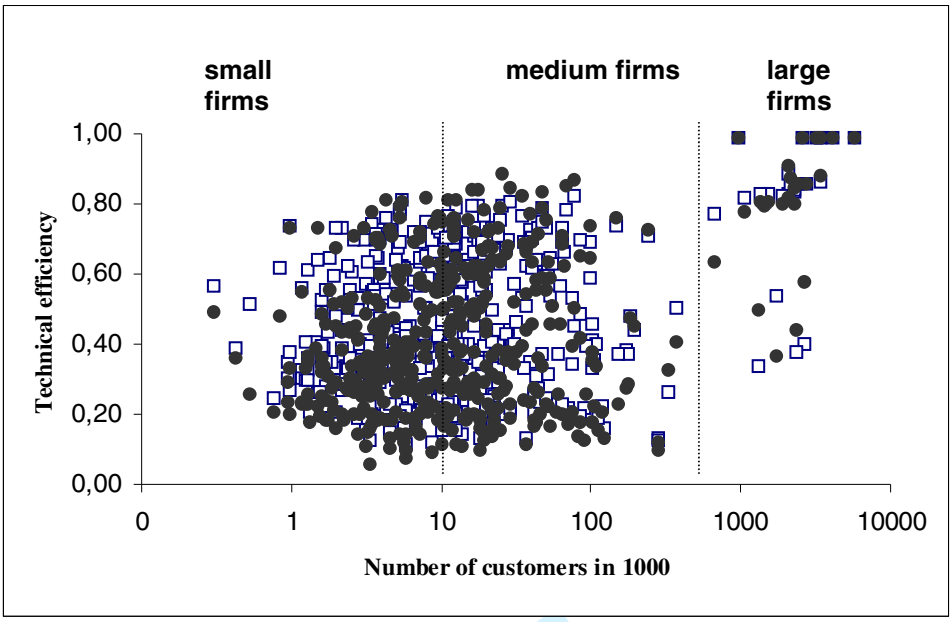
into the analysis, large and efficient firms seem to benefit in terms of efficiency scores. This result shows, illustrated in Figure 6, that large firms can supply quality at lower cost.

Figure 7:

Technical efficiency and firm size - Models I and II



7. Conclusions

Our analysis of the relationship between firm size, technical efficiency, and quality of service for European electricity distribution utilities shows evidence of significant economies of scale in electricity distribution networks. In addition, we found economies of scope between energy delivered and number of customers can be observed among larger firms.

Concerning quality of service and firm size, the results are ambiguous: our descriptive results indicate that small firms perform better in terms of quality of service. Since provision of quality is related to level of costs, this finding alone is not conclusive; the cost-quality models revealed that large utilities are technically more efficient even when

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quality is controlled for, indicating that larger firms can supply a given level of quality of service at lower cost. Therefore, the hypothesis of customer proximity was rejected.

Regarding natural monopoly theory, the "proper" size of the natural monopoly utility does not appear to be affected when quality is incorporated in the analysis. Our analysis of the mean technical efficiency of utilities confirms the findings on firm size; we found significant differences among the countries and showed that smaller utilities and countries with smaller firms (i.e. Nordic utilities) tend be significantly less efficient than large utilities from, for example, Italy or the UK. Additionally, the relationship between input elasticities (factor substitution) indicates that larger companies might, in contrast to small utilities, be able to increase quality more easily by increasing total expenses. These findings contradict previous studies on optimal utility size, such as Yatchew (2000) and Salvanes and Tjøtta (1994). While they found optimal size at a rather low scale; our analysis shows unexploited scale economies throughout the sample, indicating that utility size should be increased further even for large companies. These differences might be explained by basically three different factors. First, our analysis is based on a significantly larger sample with a broader range of firms. Second, in contrast to those previous studies, our sample includes a variety of comparably very large firms. And third, the positive scale ecnomies throughout the sample can be explained by the relationship of firm size and economies of scope between number of customers and delivered energy, which has not been analysed in detail before.

The policy implications from our study are threefold. First, the possibility of factor substitution indicates the option of an increase in quality of service when appropriately regulated especially in countries with large utilities. This might diminish the current quality advantages of small utilities. Second, countries with a large number of small utilities should allow mergers in order to exploit potential gains. Third, in order to avoid collusion among utilities against regulatory agencies, we suggest a European harmonisation of data definition and collection and regulatory accounts to facilitate international comparisons and benchmarking.

Future research on technical efficiency, firm size and quality of service in network industries in general and electricity distribution in particular should address the issue of

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productivity development over time. This would require panel data analysis to control for cyclical effects and to overcome the shortcomings of cross-sectional analyses. Another important aspect, not addressed in this study, is the relationship between efficiency, quality, and ownership structure. Publicly owned utilities may, due to differing managerial or corporate objectives, exhibit different performance in terms of efficiency from private companies. Finally, the socio-economic costs of outages as well as the cost of quality improvement need to be incorporated in the analysis in order to improve incentive regulation schemes for quality of service.

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