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Productivity Differences in Multiple Output Industries: An Empirical Application to Electricity Distribution

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Abstract

Given that electricity distribution is undertaken via a network, it is expected that costs of production are affected both by the nature of the network and the volume of physical output distributed via the network. This two-dimensional concept of firm size, that is involving network size (number of customers) and the level of physical output (kWh), also corresponds to the distinction between productivity measures of returns to density and returns to scale.

This approach has been used to specify a restricted multioutput cost function and to estimate this function for the Norwegian electricity distribution industry through the use of a flexible functional form (translog). The results indicate that no economies of scale are present in the industry even for small plants when measured correctly, but that economics of density are present.

1. Introduction

A proper specification of the underlying production technology is essential in making inferences about public policies (based on the derived productivity measures). For instance, in industries where output is delivered via a network to spatially distributed points with distinct demand characteristics and thus a continuum of outputs exists, a traditional approach with a single output to represent firm size to facilitate econometric estimation may have serious implication for measuring productivity differences. We analyze this problem and suggest that the characteristics of the network affect costs and should be included by a measure for the number of nodes supplied. This approach was originally suggested by Caves, Christensen and Tretheway [1984] for the airline freight industry in the USA, but was criticized by Panzar [1989]. We show in this paper that Panzar's [1989] proof is not valid and that the measures for productivity from this approach is relevant for measuring productivity differences for multioutput industries.

In addition, to ensure a proper specification of the production technology, the derived productivity measures are dependent on the appropriateness of the estimated function representing the technology in terms of satisfying the requirements of economic theory. Using flexible functional forms, these requirements have to be tested for. The importance of this latter point has lately been focused on in a paper by Diewert and Wales [1991], where the conclusions derived from the important papers by Evans and Heckman [1983, 1984, 1986] are doubted.[1] The Evans and Heckman papers derived a test for productivity differences among firms, i.e., subadditivity of cost functions as a test for natural monopoly, and used it for testing whether the U.S. Bell system was a natural monopoly over their sample period. Subadditivity was rejected and this result was important in making policy inferences about whether the Bell system should be broken up. Diewert and Wales [1991] find that the requirement that the cost function is nondecreasing in outputs (implying positive marginal costs) is not satisfied for many data points and hence the conclusions concerning the productivity measure defined in the output space, is doubted. This is a requirement from production theory rarely tested for, but which have important implications for making inferences about the technology. Since flexible functional forms are only local second-order approximations about a point of expansion for a production technology, the properties required from economic theory must be checked for every observation point.

In the present paper we will use the electricity distribution industry as an example of an empirical analysis of the issues mentioned above since the distribution of the physical output is undertaken via a network and thus every firm in the industry potentially has a continuum of outputs, i.e., combinations of the amount of physical output (kWh) and characteristics of the consumer. The existing literature on testing productivity differences for electricity distribution is also very scarce and the output vector is usually represented by an aggregate output measure. Norwegian data on electricity distribution will be used and a short-run cost function will be specified and estimated. The properties of the estimated cost function will be checked at every data point and long-run productivity measures will be derived from the estimated restricted cost function and the calculated optimal value of the restricted input factor. Having checked the appropriateness of the multioutput cost function in terms of specification and requirements from theory, the productivity measures are analyzed in terms of their implications for public policy, i.e., we calculate returns to density, returns to scale, M-locus and isoscale curves. Further, the stability of these measures are checked.

2. Methodology

To facilitate econometric estimation of a production technology, usually a single physical measure of output has been constructed from the many distinct outputs in a multioutput industry. The *level of output* has been the traditional measure of firm size in productivity studies. For network technologies in particular, this procedure of aggregating output may have serious implications for the measurement and interpretation of concepts describing industry structure, i.e., the returns to scale measures [Panzar, 1989]. By network industries we understand technologies in which services are provided over a network of spatially distributed points with distinct demand characteristics. Demand characteristics vary over customer groups, over space and time and in quantities supplied. Furthermore, marginal costs will vary for the different uses of delivered electricity services. For instance, an electricity distribution firm providing kWh to end users via a network, although the amount of physical output (kWh) might be similar, can be considered to provide a considerable number of distinct products; every combination of kWh and customers served represents an output. Hence, the vector of outputs for a firm providing services via a network can be represented in the following manner:

$$\mathbf{y} = (y_1, y_2, \ldots\ldots, y_i, 0, \ldots., 0), \quad i \leq n, \tag{1}$$

where i is the number of customers for a specific firm and the elements y_j, ($j = 1, 2, \ldots, i$), is the physical output served to j'th customer. The dimension of the vector $\mathbf{y}$ is fixed and given by n. Since a specific firm in the industry does not necessarily serve all possible customers, we also assume that $i \leq n$. A multioutput cost function c as a function of output, $\mathbf{y}$, and the vector of relevant input prices, $\mathbf{w}$, will represent the underlying technology, $c = c(\mathbf{y}, \mathbf{w})$. Returns to scale are calculated thus:

$$s = s(\mathbf{y}, \mathbf{w}) \equiv c(\mathbf{y}, \mathbf{w})/\mathbf{y}^t \nabla_{\mathbf{y}}\, c(\mathbf{y}, \mathbf{w}), \tag{2}$$

$\mathbf{y}^t$ is the transposed vector $\mathbf{y}$, and $\nabla_{\mathbf{y}} c(\mathbf{y}, \mathbf{w})$ is the gradient vector of the cost function with respect to the output vector, see Panzar [1989].

To make an econometric estimation of a technology with a large number of outputs feasible, some kind of aggregation must be undertaken in order to reduce the number of parameters to be estimated. In this type of technology where a continuum of outputs exists, the concept of hedonic cost functions has been introduced in the literature to obtain a discrete number of outputs or mix of outputs as an approximation to the output vector in $\mathbf{y}$. This can be considered as a compromise between defining a scalar aggregate measure and a multioutput representation. The classical approach using hedonics in economics is the hedonic price analysis where price indexes are corrected for quality differences of commodities, see Griliches [1961]. Instead of taking into account a multiple of commodities by incorporating quality proxies in price indexes as in the hedonic price literature, including hedonic parameters account for a multiple output vector in the cost function. Utilizing a hedonic output measure in the context of specifying a production process was first used in the trucking industry in the US by Spady and Friedlander [1978]. Spady and Friedlander [1978] showed that the physical measure (ton-miles) created a misspecified model which provided biased results concerning the economies of scale in the industry. Instead of specifying an output vector consisting of a large number of different types of freight, origin and destination pairs, output was defined as a function of the aggregate ton-miles (Y) and the hedonic variables haul-length (q_1), load-size (q_2) etc. Quality differences in output are taken into account in that the value of the hedonic function $\Psi = \Psi(Y, q_1, q_2, \ldots, q_n)$ served as the effective output measure in the cost function specification, where Y is the physical output and q_i output qualities.

Given that an industry provides services via a network, the network aspects should be incorporated when specifying the technology. One way suggested in the literature to approximate the output vector for an industry when output must be distributed via a network, is to explicitly incorporate the structure of the network in a multioutput cost function (Braeutigam and Daughety [1984], Caves, Christensen and Tretheway [1984] and Kim and Ben-Zion [1989]). Understanding the structure of the network in these industries as a confounding control of natural monopolies and the resulting effects on cost is crucial in deriving more precise and relevant measures of industry structure and for formulating public policy. Basically, the idea is to make an approximation to the output vector in equation (1) by defining the effective output as a function of an aggregate output and the number of nodes served to characterize the network, i.e., the number of customers. The cost function representing this network technology can be expressed as:

$$C = C(Y, N, \mathbf{w}) \tag{3}$$

where Y = aggregate output, N = number of customers and $\mathbf{w}$ is the vector of relevant input prices.

Implicit in this framework is also a distinction between firm size and the level of output, and hence a distinction between returns to scale and returns to density. Following the example of Caves, Christensen and Tretheway [1984] and Caves, Christensen, Tretheway and Windle [1985], we define returns to density in equation (3), as the inverse of the cost elasticity with respect to output (kWh):

$$RTD = 1/(\partial lnC/\partial lnY) \tag{4}$$

Thus, returns to density measures the economies of increasing the amount of kWh produced where the network (N) is fixed. Returns to density is increasing, constant or decreasing when RTD is greater than unity, equal to unity or less than unity. Returns to density measures the output effect on efficiency measured in average production costs. To measure the effect of increasing firm size, a combined effect of increases in output and in network is constructed. Returns to scale is defined as:

$$\mathrm{RTS} = 1/(\partial lnC/\partial lnY + \partial lnC/\partial lnN) \tag{5}$$

where $\partial lnC/\partial lnN$ is the cost elasticity of the network. Returns to scale are said to be increasing, constant or decreasing when RTS is greater than one, equal to one or less than one.

Panzar [1989, p. 43–44] criticizes Caves et al.'s measures of RTS and RTD and uses an example to show in their case that RTS is always equal to 1, and RTD is always equal to s as defined in equation (2). As an example he uses a cost function linear in outputs, $c(\mathbf{y}, \mathbf{w}) = k(y_1 + y_2 + \ldots + y_i) + ri$, where k and r are strictly positive constants. Panzar defines $Y = y_1 + y_2 + \ldots + y_i$, and the number of customers as i, which in (5) corresponds to N. Since the cost function in Panzar's example is linear in Y and N, obviously Caves et al.'s RTS is always equal 1. Panzar treats the number of customers served, i, as exogenous, and he therefore obtains $s = (kY + ri)/kY$ = RTD. However, given that the output vector is defined by (1) it can be shown that returns to scale, defined by (2), in the point $\mathbf{y} = (y_1, y_2, \ldots, y_i, 0, 0, 0)$ is

$$s(\mathbf{y}, \mathbf{w}) = c(\mathbf{y}, \mathbf{w}) / \left(\sum_{j=1}^{i} y_j \frac{\partial c(\mathbf{y}, \mathbf{w})}{\partial y_j} + \sum_{j=i+1}^{n} \lim_{t \to 0} [tc(\mathbf{y} + t\mathbf{e}_j, w) - c(\mathbf{y}, \mathbf{w})]/t] \right)$$

$$= (kY + ri)/(kY + (n - i)r)$$

since $\lim t[c(\mathbf{y} + t\mathbf{e}_j, \mathbf{w}) - c(\mathbf{y}, \mathbf{w})]/t = r$ when $t \to 0$ from above, where $\mathbf{e}_j$ is a vector with j'th element equals to 1, and the rest of the elements equal to 0, for $j = i + 1, \ldots, n$. Return to density, RTD, is equal to $(kY + ri)/kY$ which is different from $s(\mathbf{y}, \mathbf{w})$. Hence, a multioutput or hedonic cost function approach focusing on the network aspect provides a relevant concept of firm size. Useful concepts for assessing policies, for instance regarding horizontal integration are obtained from this model as well. These concepts thereby bring together the different approaches for modeling the industry as discussed in the literature.

However, in order to apply the productivity measures given in equations (4) and (5) for inference purposes about public policy, the estimated cost function which the productivity measures are derived from, have to meet the requirements from duality theory. The regularity conditions from production theory for cost functions are monotonicity, concavity and linear homogeneity in input prices and also nondecreasing in outputs. The latter requirement concerning outputs, is of particular importance in our case since it is the economies of scale and density properties defined in output space we are analyzing. Further, since we will use a flexible functional form, i.e., the translog, which will provide only a second order approximation to an arbitrary cost function at the point of approximation, the regularity conditions have to be checked at every observation point since the productivity measures will be calculated at every point.

3. Model Specification of Electricity Distribution

In this section we will empirically specify a cost function as discussed above and undertake the estimation and stability testing using data from the Norwegian electricity distribution industry. In the literature on the electric distribution industry, the aggregate measure of output and hence the definition of firm size, has been either the amount of kWh produced, as in Heuttner and Landon [1978], Wyatt et al. [1989] or the number of customers served, as in Weiss [1975], Neuberg [1977] and Wangensteen and Dahl [1989]. Weiss [1975] and Neuberg [1977] both show that the number of customers and the level of kWh produced are important in explaining cost differences for electricity distribution firms. However, they end up with the number of customers as output level. Wyatt et al. [1989] specify as an alternative to kWh as a single output, a two output cost function including power produced (kW) in addition to kWh. However, no economies of scale measures are reported for the latter cost specification. Hence, the existing literature is based on very simple specifications of the production technology and also restrictive empirical specifications in terms of functional forms with one exception, Wyatt et al. [1989].

3.1. Industry Characteristics and the Data Set

The Norwegian electricity distribution industry comprises 235 companies, owned by local municipal or intermunicipal authorities; private companies are not involved in the distribution. The distribution companies are licensed by the government to distribute and sell electricity to end users in a specific geographic area. However, different financial decisions such as those regarding investment, financing and pricing of electricity to end consumers, are decentralized. Hence, the electricity distribution companies in Norway are public utilities behaving as local natural monopolies. Some of the distribution companies are vertically integrated with power generation plants, but the majority purchase their electricity, and long-term contracts are common. In this study, only distribution companies are included in the sample of approximately one hundred plants from 1988.

The production of electricity in Norway is based on hydropower, and a government-owned company accounts for about 30% of the production. Transmission is mainly effected by a public company. Inspecting the cost of providing electricity to the final consumer via the three stages of production, transmission and distribution, accounts for cost shares of 48%, 10% and 42%, respectively in Norway; Wangensteen and Dahl [1989]. Distribution activities include transportation of electricity to end users, installation and maintenance of equipment, and administration including customer contact. Distribution companies' labor expenses, purchased electricity and capital costs of the distribution net account for about 95% of the total annual costs of production; Wangensteen and Dahl [1989]. Other expenses such as material input and administration, except labor input, amount to only a small fraction.

Table 1 below provides the descriptive statistics of the variables in the data set. The data set has been provided by The Norwegian Water Resources and Energy Administration and The Norwegian Electric Power Research Institute.

Given that the electricity distribution industry provides services via a network, and the above description of the industry, the following short-run cost function is a reasonable specification of the economic behavior of the electricity utility.[2]

Y: kwh   N: # of customers

$$VC = g(Y, N, w_L, w_E, F) \tag{7}$$

where VC is the cost of the variable factors, i.e., labor and purchased electricity, and w_L and w_E are input prices of labor and purchased electricity. The wage rate is defined as the annual labor expenses divided by the total labor force. Since the distribution plants compete with other firms in different industries in the labor market, they are assumed to be price-takers in the labor market. As the price of purchased electricity (defined as NOK/kWh) is primarily determined on long-term contract basis, it is regarded as given for the individual utility, and hence exogeneously determined. The aggregate measure of output, GWh, is given by Y, and N is the number of customers. Factors explaining technology

Table 1. Descriptive statistics of actual cost shares, input prices, GWh and number of customers, 1988.

	Mean	Min.	Max.
Labor cost share	0.20	0.10	0.42
Electricity cost share	0.80	0.38	0.90
Wage (1000 NOK/year)	186	140	242
Electricity purchased price (NOK/kWh)	0.19	0.067	0.27
GWh produced	291.59	11.126	7503.4
Number of customers	11489	655	290560

differences or cost differences emphasized in previous studies, were specified as firm specific variables to characterize network differences. (See Caves, Christensen and Thretheway [1984]). In addition to a load or a density factor which is expected to influence cost of production in electricity distribution, three other quality attributes can be considered to be included as a hedonic output function; topography, the climate in the distribution area and a distinction between rural and urban areas. However, both a load factor and a proxy for topography were rejected by Wald tests.[3]

why isn't area in the cost function?

3.2. *Short-run or Long-run Cost Function*

Usually when assessing the scale economies in an industry, a long-run cost or production function is specified and estimated. This implies instantaneous adjustment of all inputs of price changes within the data period of one year, which is the data base utilized here. Given the nature of the indusry and the data set, it is reasonable to assume that the capital equipment, i.e., the physical network, is fixed within the data period. A possible approach is to specify a restricted or short-run cost function where capital is given as a fixed or quasi-fixed factor, see Caves, Christensen and Swanson [1981], Schankerman and Nadiri [1986] and Nelson [1985]. The grid comprises most of the capital equipment in the Norwegian electricity distribution industry, and we therefore utilize the distribution line as a proxy for the given capital input. Hence, F is defined in physical units as the number of meters of distribution line indexed to obtain a weighted average of the different line qualities in terms of voltages and whether it is sea-, air- or earth line. When specifying a partial equilibrium model of the industry, the quasi-fixed factor, F, is given for the individual plants in the data period and is an exogenous factor. Note that F is defined in (corrected) meters of distribution line to measure the fixed physical capital, and does not comprise the service dimension of the output vector which measures the intensity of the use of the distribution network.

The following measures of economies of density and economies of scale can be calculated from the estimated parameters of equation (6):

$$\begin{aligned} \text{RTD} &= (1 - \partial lnVC/\partial lnF)/(\partial lnVC/\partial \ln Y), \text{ and} \\ \text{RTS} &= (1 - \partial lnVC/\partial lnF)/(\partial lnVC/\partial lnY + \partial lnVC/\partial lnN). \end{aligned} \tag{8}$$

These measures will correspond to the proper long-run measures of scale and density given in equations (4) and (5) only if the underlying technology is homothetic, or if the fixed factor is optimally adjusted as shown by Panzar [1989].[4] However, it is possible to derive the long-run elasticity measures by a procedure in which the envelope conditions are utilized to derive the optimal level of the fixed factor F according to procedures described in Nelson [1985] and Braeutigam and Daughety [1983]. For the industry tested here, it is a reasonable hypothesis that the level of the network size is optimally adjusted since it is a well-established industry. However, given that industry have been regulated in terms of the area every firm could supply has been restricted this does not necessarily mean the optimal in the most general sense.

3.3. *Empirical Function*

It is necessary to specify a functional form for empirical estimation and in this analysis a translog approach to the cost function in equation (7) will be specified for estimation.

The translog function is defined here as a second-order Taylor expansion around the mean observations. Thus, for the cost function in equation (7) the translog approximation is:

$$\begin{aligned}\ln VC = {} & \beta_0 + \beta_Y lnY + \beta_N lnN + \beta_F lnF + \beta_L lnw_L + \beta_E lnw_E \\ & + 1/2\beta_{YY}(lnY)^2 + \beta_{YN} lnYlnN + \beta_{YF} lnYlnF + \beta_{YL} lnYlnw_L + \beta_{YE} lnYlnw_E \\ & + 1/2\beta_{NN}(lnN)^2 + \beta_{NF} lnNlnF + \beta_{NL} lnN\, lnw_L + \beta_{NE} lnNlnw_E \\ & + 1/2\beta_{FF}(lnF)^2 + \beta_{FL} lnFlnw_L + \beta_{FE} lnFlnw_E \\ & + 1/2\beta_{LL}(lnw_L)^2 + \beta_{LE} lnw_L\, lnw_E \\ & + 1/2\beta_{EE}(lnw_E)^2 + \epsilon_{vc},\end{aligned}$$

VC = variable costs

F = [illegible]

where all exogenous variables are normalized to the point of approximation of the function, i.e., the sample mean, symmetry of the Hessian matrix is imposed ($\beta_{ij} = \beta_{ji}$), and ϵ_{vc} is a random error term. To ensure efficient estimation, factor shares were estimated jointly with the cost function using a version of the Zellner [1962] technique. One of the share equations was deleted to overcome the problem of singularity in the covariance matrix, but the estimates are indifferent to which share equation deleted as shown by Barten [1969]. Using Shepard's lemma, the cost share m_i for input factor, x_i, can be obtained for the translog specification:

$$\begin{aligned}\partial lnVC/\partial lnw_i &= (\partial VC/\partial w_i)(w_i/VC) = w_i x_i = m_i \\ &= \beta_i + \beta_{iY} lnY + \beta_{iN} lnN + \beta_{ii} lnw_i + \beta_{ij} lnw_j,\end{aligned}$$

where $(i, j) = (L, E)$ and (E, L). To ensure the restrictions required by the theory of a well-behaved technology of linear homogeneity in input prices and the fixed factor, the following restrictions are imposed:

$$\begin{aligned}\beta_E + \beta_L &= 1, \\ \beta_{LL} + \beta_{LE} &= 0, \\ \beta_{EE} + \beta_{LE} &= 0, \\ \beta_{YL} + \beta_{YE} &= 0, \\ \beta_{NL} + \beta_{NE} &= 0 \text{ and} \\ \beta_{FL} + \beta_{FE} &= 0.\end{aligned}$$

Monotonicity in input prices is met if cost shares are positive, concavity in input prices is met if the Hessian matrix $[\partial^2 c/\partial w_i\, \partial w_j]$, is negative semidefinite. Nondecreasing in output levels is checked by calculating the cost elasticities with respect to output level N and Y, $\partial lnVC/\partial lnY$ and $\partial lnVC/\partial lnN$, which will be positive (negative) when $\partial VC/\partial Y$ and $\partial VC/\partial N$ are positive (negative).

The returns to density function and returns to scale function have the following forms for the translog variable cost function.

$$\begin{aligned}\text{RTD} = {} & (1 - \beta_F - \beta_{FF}\, lnF - \beta_{YF} lnY - \beta_{NF} lnN)/ \\ & (\beta_Y + \beta_{YY} lnY + \beta_{YN} lnN + \beta_{YF} lnF)\end{aligned} \tag{11}$$

$$\begin{aligned}\text{RTS} = {} & (1 - \beta_F - \beta_{FF}\, lnF - \beta_{YF}\, lnY - \beta_{NF} lnN)/ \\ & (\beta_Y + \beta_{YY} lnY + \beta_{YN}\, lnN + \beta_N + \beta_{NN}\, lnN + \beta_{YN}\, lnY + \beta_{YF}\, lnF + \beta_{NF}\, lnF)\end{aligned}$$

We assume that input prices are held constant at their sample means. Both actual levels, F, and optimal levels, F^*, of the fixed factor will be used in calculating (11) and (12).

4. Empirical Results

The estimated parameters of the restricted cost function with homogeneity of degree one in factor prices and symmetry of the Hessian imposed are presented in Table 2, along with their t-values.

Table 2. Estimation of a short-run cost function with GWh and number of customers as ouptuts for Norwegian electricity distribution plants using cross-section data for 1988 (number of observations = 91).

β_O	11.14	1709
β_Y	0.83	31.1
β_N	0.094	3.15
β_F	0.066	3.58
β_L	0.154	168
β_E	0.846	168
β_{YY}	0.127	3.09
β_{YN}	-0.030	-0.87
β_{YF}	-0.096	-1.88
β_{YL}	-0.137	-9.54
β_{YE}	0.137	9.54
β_{NN}	-0.059	-0.74
β_{NF}	0.118	1.56
β_{NL}	0.074	4.10
β_{NE}	-0.074	-4.10
β_{FF}	-0.042	-0.81
β_{FL}	0.052	3.80
β_{FE}	-0.052	-3.80
β_{LL}	0.184	20.6
β_{LE}	-0.184	-20.6
β_{EE}	0.184	20.6

$\bar{R}^2 = 0.99$

Log-likelihood = 377

$+ \beta_{FL}\, \ln w_L + \beta_{FE}\, \ln w_E$

$\ln \bar{Y} = 5.7$

$\ln \bar{N} = 9.31$

$\ln \bar{F} =$ [illegible]

We notice that most of the parameters are significantly different from zero and that an $\bar{R}^2$ of 0.99 for the cost function provides a good fit for the underlying data set ($\bar{R}^2$ for the wage-equation was 0.80).

The specification of our model was tested. Using a Wald test, we tested whether a short-run cost function, where capital is a fixed factor, is an appropriate specification of the underlying technology. The null-hypothesis of no effect of the fixed factor was rejected at 1% significance level where the estimated χ^2 was 30.5 compared with the table value of 18.5 (with 7 degrees of freedom). Furthermore, a Wald test was undertaken to check the significance of specifying the network effect by incorporating the number of customers (N) in the cost function. The null-hypothesis of no effect was rejected, (the calculated χ^2 is 27.2, and the table χ^2 is 15.1 at 1% significance level and 5 degrees of freedom). Thus, these tests suggest that the capital factor should be included in the cost function for the industry, and the number of customers specified as a measure of output in the cost function.

The regulatory conditions for the cost function were checked in order to test the validity of the cost function. The estimated shares of the variable factors of the sample mean can be shown to be the first-order price variables, purchased electricity and labor comprise respectively 15 and 85 percent of total costs as seen from Table 2. Positive first-order price coefficients are required for monotonicity to hold and this requirement was met at every sample point. Linear homogeneity in input prices was also checked with a Wald test and could not be rejected. Further, we report in the Appendix a test at every observation for the sign of the cost elasticities with respect to Y and N, and for convexity of the technology. Columns one and two in the Appendix provide the cost elasticities with respect to Y and N, respectively. At every observation point the calculated cost elasticity is positive, ensuring a nondecreasing cost function. Columns three and four represent the first minor and the determinant of the Hessian, and we notice that the matrix is negative semidefinite and hence a convex technology is ensured. Hence, the cost model for electricity distribution is verified in terms of specification and in terms of requirement from production theory and we continue to analyze the qualitative results implied by the estimated model.

5. Scale and Density Properties

In this section we will analyze the implications for public policy of the derived productivity measures in terms of assessing productivity gains from merging distribution plants.

The elasticity of density from the restricted cost function for the mean firm in the sample, calculated from equation (11), is RTD = 1.12. A linear approximation to the standard error of the RTD has been calculated and a t-test was undertaken. The null-hypothesis of constant return to density was rejected (the calculated t-value is 3.73). Hence, there are unexploited economies in the Norwegian electricity distribution industry. These might be exploited by a decrease in unit costs through increasing the amount of GWh produced. However, RTD measures the effect on productivity of increasing the size of the firm in the narrow sense of increasing the physical level of output. When assessing the efficiency implications of merging distribution plants in connecting areas, RTD seems to be a less relevant measure. In testing the economics of merging in a network industry such as electricity distribution, the combined effect of the network effect and the physical output effect

of merging should be utilized. From equation (12), the measure of scale economics for the mean firm is calculated to be RTS = 1.01. A linear approximation to the standard error of the RTS was calculated and the null-hypothesis of constant returns to scale could not be rejected (the calculated t-value is 0.91). Hence, returns to scale in this industry is not different from 1.00; apparently no economies from merging exist for the average sized firm. This result will be modified and discussed below.

Returns to density and returns to scale are local measures of productivity properties and therefore measuring RTD = 1.12 and RTS = 1.01 at means does not imply that no firms exhibit increasing returns to scale in our sample.

In Figure 1 we plot the elasticity of density using equation (11) within the range of observed output levels (GWh). The actual values of the fixed factor and number of customers are used and input prices are fixed at their mean values.

The plot in Figure 1 confirms the above results at means indicating economies of density for most of the firms in the sample. These results are what one would typically expect for network industries, i.e., declining unit costs within a given network, as estimated for other industries in Caves, Christensen and Tretheway [1984] and Kim and Zion [1989]. By setting the number of customers and the fixed factor equal to the sample mean in equation (11) and setting RTD = 1.00, the optimal annual production in terms of GWh can

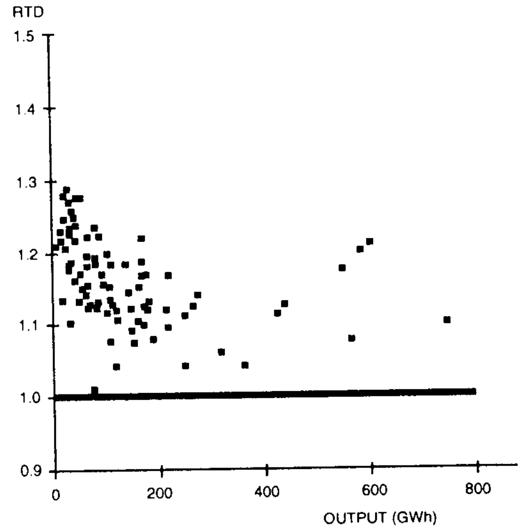


Figure 1. Returns to density as a function of output level in the Norwegian electricity distribution industry.

be retrieved. However, increasing returns to density were not exhausted within our sample although gains from expanding physical output within a given network are smaller for large firms than for small plants.

To assess the returns to scale characteristics of the industry in more detail, we evaluate returns to scale of all firm sizes in the sample, in terms of the physical output, Y, and the number of customers, N. We use equation (12) and assume input prices and the fixed factor are held constant at their sample means but combinations of physical output, Y, and the number of customers, N, are allowed to vary according to actual combination for each individual firm. To illustrate returns to scale as a function of the physical output and the number of customers, we created a three-dimensional plot of the returns to scale surface, presented in Figure 2.

As seen from the legends of Figure 2, RTS is measured along the vertical axis and the physical output (GWh) and number of customers along the two horizontal axes. Figure 2 shows the RTS-surface for the part of the sample where most of the plants are located, between 0 and 800 GWh and 0 and 50 thousand customers. What is apparent from the RTS-surface is that returns to scale is increasing, i.e., RTS > 1, for the small firms in terms of GWh's produced and the number of customers. This is seen by the very steep portion of the surface, where returns to scale is above 1.05 for small firms. The steep portion of the returns to scale surface is followed by a large portion of physical output/number of customers combinations where the returns to scale function is flat, i.e., where no significant returns to scale are exhibited, and RTS is not different from 1.00. When interpreting the returns to scale surface given in Figure 2, one should however acknowledge the fact that only a limited number of shapes can be provided by equation (12). The reason is that

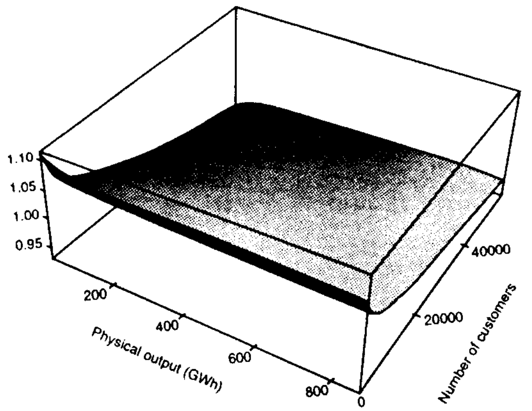
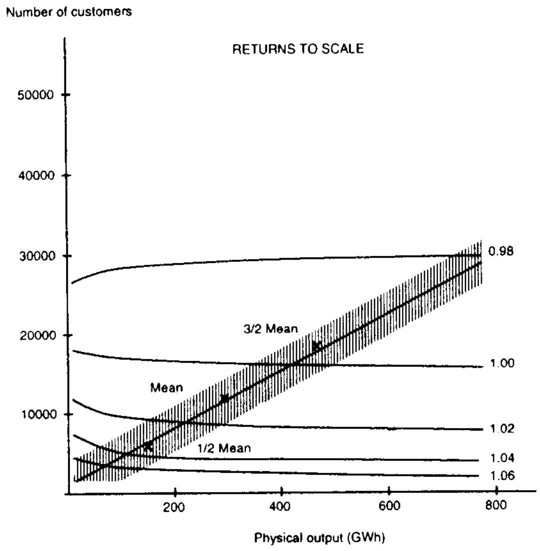


Figure 2. Returns to scale as a function of physical output (GWh) and network size in the Norwegian electricity distribution industry.

although the translog form is a second order approximation, the productivity measures are only first order approximations and thus the curvature may not be well captured.

In order to get a better impression of the gains from expanding electricity distribution firms, for instance through horizontal integration, we will utilize the RTS equation (12) and set it equal to one. Thus the optimal firm size will be obtained, i.e., interpreted as the optimal combinations of physical output and network size. This curve where RTS = 1, called *M*-locus in Panzar [1989], displays possible combinations of network size and physical output which are optimal for multioutput technologies. The *M*-locus is plotted in Figure 3 below denoted RTS = 1.00 in the physical output (horizontal axis) and network size (vertical axis) space. We notice that the RTS = 1.00 curve defining optimal size comprises plants serving about 20,000 customers and is relatively independent of the level of GWh produced. In addition, to plot the *M*-locus we have shown the physical output/network size for different returns to scale levels below and above 1.00, we refer to these as *isoscale* curves.



← integrasjon; if N = 5000
RTS = 1.04,
if N = 10000 RTS = 1.02

Figure 3. Isoscale curves as a function of physical output (GWh) and network size in the Norwegian electricity distribution industry.

Figure 3 indicates that according to these calculations there are only modest efficiency gains from expanding firm size in this industry. For instance a firm size of 1/2 mean firm size (Y = 146 GWh, N = 5744 customers) has economies of scale close to 1.04. But firms of mean size do not exhibit any returns to scale since RTS ≈ 1.00, and firms of the size 3/2 mean firm size, (Y = 438 GWh, N = 17234 customers) show slightly decreasing returns to scale, as indicated by Figure 3. Another feature of the cost structure revealed by figure 3, is that given the number of customers, RTS is relatively independent of the level of GWh. Hence, our conclusion so far is that these results give reason to argue for modest gains from the horizontal integration of small plants, but that for firms of mean size or larger, the gains from integration have already been exploited. As noted when discussing shape of the returns to scale function given in Figure 2, also the isoscale curves in Figure 3 can only take on a limited number of shapes and should therefore be interpreted with care.

6. Stability of the results

We are interested in checking how robust our results on economies of scale are for the electricity distribution plants. In order to get an impression of the actual sample, we have plotted the actual observation of firm sizes (physical output and network size combinations) represented by the regression function ($N = 0.280\ (1.22) + 0.0384\ Y\ (152)$, where t-values are in parentheses, and $R^2 = 0.99$) and its 95% confidence band in Figure 3. We notice that the 95% band is very narrow, which may indicate that one should be cautious about drawing conclusions outside the range close to our point of approximation for the cost function. Also, since the estimated translog function only has local regularity properties around the approximation point, we will check our results by estimating around different sample points. Furthermore, we will calculate the returns to scale, given in equation (12), also as a function of the actual fixed factor. Then the question is whether the actual or the optimal level of the fixed factor should be utilized. This is the first question we will deal with in the next section.

6.1. *Elasticities Evaluated at the Actual and Optimal Level of the Fixed Factor*

Our results concerning productivity differences between small and large firms are based on parameter estimates from a restricted or short-run cost function for the industry. These estimates have been prepared in order to avoid biased estimates of economies of density and scale. The calculated RTS and RTD measures provided in this study represent the approach suggested in Caves, Christensen and Swanson [1984] and Caves, Christensen and Tretheway [1981] where the fixed factor is evaluated at the observed or actual levels. As shown by Panzar [1989], this measure is identical to the long-run elasticity of scale under the assumption that the technology is homothetic or that the fixed input is at its cost-minimizing level. Utilizing a Wald test, homotheticity was rejected for the Norwegian electricity distribution industry.[5] Hence, to retrieve appropriate long-run measures of returns to scale and density, the long-run cost function has to be derived. Following the approach suggested in Nelson [1985] and Friedlander and Spady [1981], the envelope conditions for given output levels will provide the optimal level of the fixed factor.[6] The calculated optimal fixed factor, F^*, is compared to the actual fixed factor. Once the optimal level of capital is obtained, F^*, it is put into equations (11) and (12) to obtain the proper long-run estimates of RTD and RTS elasticities. The results are reported in Table 3, part two, below. Before discussing the results, another stability feature concerning the elasticities of production is tested.

6.2. *Estimation at Different Points of Expansion*

The flexible functional form applied in this study to represent firm behavior in the electricity distribution industry, and thus the elasticity measures derived from the parameter estimates, have only been tested by expanding the flexible functional form from the mean of the sample. To test the stability of the elasticities focused on in the present study, we estimated the variable cost function where 1/2 mean and 3/2 mean where used as points of expansion in addition to the sample mean.[7] The calculated RTS and RTD are presented in Table 3.

Table 3. Returns to scale and density calculated for different levels of the fixed factor (F = expansion point and F^* = optimal), different points of calculation, and from different points of approximation of the cost function.

Results from Figure 3

	Points of calculation		
	1/2 Mean	Mean	3/2 Mean
RTS	1.04	1.01	0.99

Calculations of Optimal F^*

	Points of Approximation		
	1/2 Mean	Mean	3/2 Mean
Fixed-Factor F, F^*	782, 607	1565, 1522	2347, 2522

Stability testing

	Points of Approximation					
	1/2 Mean		Mean		3/2 Mean	
	RTS	RTD	RTS	RTD	RTS	RTD
Points of calculation						
—Optimal F^*	1.01	1.06	1.01	1.12	1.01	1.14
—1/2 mean	1.01	1.10	1.01	1.10	1.01	1.10
—Mean	1.01	1.12	1.01	1.12	1.01	1.12
—3/2 mean	1.00	1.13	1.00	1.13	1.00	1.13

Table 3 consists of three parts, where part one is included to show the benchmark results, part two reports the results of testing the fixed factor's optimality, and part three provides information on productivity measures when the cost function is expanded from different data points and the productivity measures are evaluated at different data points. First of all, it is obvious from Table 3, part two, that as would be expected *a priori*, the physical capital, in terms of network line, is close to optimally adjusted since F is close to F^* for all three points of expansion of the cost function. Hence, almost identical RTS and RTD are derived when F and F^* are used. This confirms our expectations that the Norwegian electricity distribution industry is well established, and the actual level of the fixed factor can be used without bias in calculating elasticities of scale and density.

A striking result indicated in Table 3, part three (the underlined results), is that the returns to scale at 1/2 mean, mean and 3/2 mean are not different from one, i.e., constant returns to scale, when the translog function is expanded at the sample points where the economies of scale are evaluated.

These results are in accordance with the results from Figure 2 and Figure 3, reported as part one in Table 3, which indicate that there are only modest if any gains from expanding firm size as measured by RTS. The methodological result is that there is, in this case, little or no bias in results from expanding the translog flexible functional form from different sample points, compared to just calculating productivity measures at different points. In fact, the productivity measures are very stable both for RTS and for RTD (underlined results); RTD are present at the three levels tested and equal to the initial results.

7. Analysis of Policy Implications

In conclusion, we will present a brief discussion of the implications of our results for policy purposes. Our main finding for the Norwegian electricity distribution industry is that modest gains are possible through increasing the size of the firms defined as both physical output and network size. Although some efficiency gains from expanding the size of plants below mean size level, seemed to exist, the returns to scale are diffferent from one for small firms only. A possible interpretation of this finding, is that the Norwegian electricity distribution industry is well established and that the size of the distribution plants is thus well adjusted to the size of the market segments they serve. Supporting this interpretation is the test of how well adjusted the fixed factor of capital equipment (mainly network capital) is. This indicates that actual levels are close to optimal levels. However, economies of density exist in the industry meaning that for a given network size, lower unit costs of increasing the GWh produced exist.

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Notes

1. Other papers focusing on the U.S. Bell system include Röller [1990 a, b] and Charnes, Cooper and Sueyoshi [1988].
2. When formulating a cost function we are assuming that a local natural monopoly, e.g., a electricity distribution firm, is minimizing cost. This may be a strong assumption to monopolies since a possible way of exploiting the monopoly rent is slack in the use of input factors, e.g., too many employees etc.
3. See Salvanes and Tjøtta [1990] for empirical estimation and testing of different hedonic cost functions for the Norwegian electricity distribution industry.
4. Homotheticity implies that all isoquants have the same shape as the unit isoquant, i.e., the factor ratios are constant and independent of the level of output and the fixed factor of production.
5. In terms of the translog multioutput restricted cost function, homotheticity implies $\beta_{Y_i} = 0$, $\beta_{N_i} = 0$ for $i = L$ and E. The calculated χ^2 was 122 compared to the critical value 9.21 at 1% significance level.
6. The procedure used can be outlined in the following way. The total costs equal the sum of variable costs plus fixed costs: $TC = VC + P_F F$. Given optimal use of the fixed factor, F^*, the following statement is true, $\partial TC/\partial F^* = 0$, which implies that the envelope condition can be expressed as $\partial TC/\partial F^* = \partial VC/\partial F^* + P_F = 0$, where P_F is the price of the fixed factor. To solve for the optimal level of the fixed factor, the envelope condition must be expressed in terms of the restricted translog functional form:

$$\beta_F + \beta_{FF} lnF^* + p_F F^*/VC'(F^*) = 0,$$

where $VC'(F^*)$ is the estimated value of the restricted cost function, and factor prices and outputs are equal to their respective expansion points. The input price of the capital was computed as capital expenditures as an index of depreciation and the rate of interest, divided by total capital. Numerical methods were used to obtain F^*, since no closed-form analytical solution exists for the translog functional form.
7. The estimated cost functions have not been presented due to space limitations.

Appendix

EQY: Elasticity with respect to output Y
EQN: Elasticity with respect to output N
FIM: First minor in the Hessian matrix
HEM: Determinant of the Hessian matrix

EQY	EQN	FIM	HEM
0.8588	0.0868	0.2935	-0.0642
0.7836	0.1199	0.3339	-0.1000
0.8605	0.0925	0.2957	-0.0660
0.6608	0.1102	0.4067	-0.1810
0.7052	0.1457	0.3941	-0.1655
0.7501	0.1465	0.3292	-0.0956
0.8337	0.0661	0.3276	-0.0940
0.8203	0.0914	0.3731	-0.1410
0.7222	0.1165	0.3619	-0.1287
0.7201	0.1625	0.3626	-0.1294
0.8256	0.0734	0.3213	-0.0882
0.8804	0.0709	0.3138	-0.0814

EQY	EQN	FIM	HEM
0.7910	0.0915	0.3123	–0.0801
0.8129	0.0946	0.3168	–0.0840
0.8039	0.0807	0.3248	–0.0914
0.7784	0.0880	0.3391	–0.1051
0.9046	0.0375	0.2735	–0.0489
0.8742	0.0525	0.2900	–0.0614
0.7957	0.1168	0.3216	–0.0884
0.8286	0.0865	0.2974	–0.0674
0.8855	0.0350	0.2865	–0.0587
0.8458	0.0310	0.2978	–0.0677
0.8334	0.0864	0.2972	–0.0672
0.8075	0.0752	0.3220	–0.0888
0.8136	0.0999	0.3395	–0.1055
0.7453	0.1398	0.3465	–0.1125
0.8690	0.0916	0.3146	–0.0821
0.8152	0.1015	0.4044	–0.1782
0.7658	0.0950	0.4131	–0.1892
0.7933	0.0809	0.3419	–0.1079
0.7256	0.1340	0.3877	–0.1579
0.8474	0.0943	0.2605	–0.0398
0.8442	0.0610	0.2609	–0.0400
0.7919	0.0838	0.3124	–0.0802
0.6823	0.1589	0.3740	–0.1420
0.7355	0.1442	0.3336	–0.0997
0.8181	0.1056	0.3165	–0.0838
0.7616	0.0988	0.3704	–0.1380
0.8347	0.0523	0.3312	–0.0974
0.8005	0.1538	0.3203	–0.0872
0.8079	0.0768	0.3413	–0.1073
0.7565	0.1040	0.3584	–0.1249
0.7835	0.0792	0.3539	–0.1202
0.8260	0.1036	0.3250	–0.0916
0.8085	0.0888	0.3454	–0.1114
0.8737	0.0006	0.3097	–0.0778
0.7484	0.0835	0.3644	–0.1314
0.7889	0.1020	0.3490	–0.1151
0.7937	0.0908	0.3333	–0.0994
0.6943	0.1230	0.4341	–0.2170
0.8061	0.1056	0.3772	–0.1457
0.7437	0.1174	0.3945	–0.1660
0.8126	0.0869	0.3318	–0.0980
0.7020	0.1530	0.3815	–0.1506
0.7655	0.0697	0.3804	–0.1494

EQY	ECN	FIM	HEM
0.7867	0.1240	0.4124	–0.1884
0.7163	0.1053	0.4265	–0.2068
0.7836	0.1190	0.3560	–0.1224
0.8184	0.1277	0.2971	–0.0671
0.7888	0.1605	0.3300	–0.0962
0.8112	0.1483	0.2805	–0.0540
0.7770	0.1128	0.3939	–0.1653
0.8325	0.1183	0.2987	–0.0684
0.8430	0.1156	0.2937	–0.0643
0.7590	0.0969	0.3630	–0.1298
0.7740	0.1109	0.3402	–0.1062
0.7323	0.1281	0.3726	–0.1405
0.7628	0.1290	0.3455	–0.1116
0.7924	0.1015	0.4192	–0.1971
0.7883	0.0831	0.3524	–0.1186
0.7642	0.1042	0.3342	–0.1003
0.8330	0.0740	0.3568	–0.1232
0.8471	0.0550	0.3078	–0.0762
0.6935	0.1532	0.3580	–0.1245
0.7861	0.0964	0.3074	–0.0758
0.7974	0.0887	0.3278	–0.0942
0.7999	0.1030	0.3062	–0.0748
0.8073	0.0541	0.3096	–0.0777
0.7010	0.1599	0.3353	–0.1013
0.7725	0.1224	0.3904	–0.1610
0.7128	0.1292	0.3553	–0.1217
0.7920	0.1175	0.3053	–0.0740
0.7465	0.1370	0.3426	–0.1086
0.8122	0.1367	0.2939	–0.0646
0.8011	0.0866	0.2671	–0.0443
0.7672	0.1417	0.3028	–0.0719
0.7148	0.1347	0.3762	–0.1445
0.8346	0.1614	0.3002	–0.0697
0.8163	0.1803	0.3130	–0.0807
0.8336	0.1522	0.3472	–0.1132
0.8911	0.1159	0.3839	–0.1534

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