Sosyo
Ekonomi

Özel Sayı 2010-EN

Quality of Supply and Efficiency: An Analysis of Portuguese Electricity Distribution Networks

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Arz Kalitesi ve Etkinlik: Portekiz Elektrik Dağıtım Şebekelerinin Analizi

Abstract

Efficiency and productivity analysis is a standard part of the tool-box of electricity and gas network regulators. In this paper the data envelopment analysis approach to benchmarking the performance of electricity networks is applied to a group of regional networks which differ in the quality of supply measured by, for example, interruptions. We show that efficiency comparisons differ when quality of supply is allowed for. We extend the efficiency comparisons to construct quality-adjusted Malmquist productivity indices in a manner which can be employed in both intra-firm management review and in regulatory benchmarking.

Key Words : Regulation and Industrial Policy, Electricity Distribution, Supply Quality.

JEL Classification Codes : L15, L51, L94.

Özet

Etkinlik ve verimlilik analizi elektrik ve doğalgaz şebeke regülatörlerinin alet çantalarının standart bir parçasıdır. Bu çalışmada elektrik şebekeleri performansını kıyaslamaya yönelik veri zarflama analizi, örneğin elektrik kesintileriyle ölçülen, arz kalitesi bakımından farklılıklar gösteren bir grup bölgesel şebekeye uygulanmaktadır. Çalışmada arz kalitesi hesaba katılarak yapılan etkinlik karşılaştırmalarında farklılıklar olduğu gösterilmektedir. Ayrıca etkinlik karşılaştırmaları kaliteyi de dikkate alan Malmquist verimlilik endeksi oluşturularak firmaiçi yönetimin tetkikine ve regülasyon kıyaslamasına el verecek şekilde genişletilmektedir.

Anahtar Sözcükler : Regülasyon ve Endüstriyel Politika, Elektrik Dağıtımı, Arz Kalitesi.

1. Introduction

There is both a regulatory and a management interest in the performance of integrated regional electricity networks. Where the networks are integrated into a single holding company with separate regional management structures and an overall corporate management, data collection procedures are standardized and audited centrally. This lends itself to the application of non-parametric DEA methods, and it is this type of sample that we are able to use in this paper, in order to evaluate the levels of efficiency of the Portuguese electricity distribution networks. There is strong interest in quality of supply amongst the outputs, but, in electricity networks, quality of supply is usually associated with undesirable outputs.

In this paper, following a brief description of the efficiency and productivity analysis model using mathematical programming, we show how quality of supply can be incorporated into the analysis. This can be done in two ways. In the first we examine a model in which network efficiency is adjusted for the quality of supply, but assuming that quality of supply is not a variable that the individual networks try to optimise. Subsequently, we model a situation in which the networks are able to choose quality of supply as a strategic variable which they can improve in order to show their efficiency and productivity in a better light.

2. The Electricity Distribution Networks in Portugal

EDP Distribuição Energia, operates the regulated distribution in Portugal and its activity is regulated by ERSE (Energy Services Regulator) which defines the tariffs, parameters and prices for electricity and other.

EDP Distribuição owns approximately 99% of the electricity distribution networks in mainland Portugal and the company needs to guarantee the level of quality defined by the regulatory parameters and in accordance with customer expectations, while the number of electricity customers in mainland Portugal has been increasing on average, by 1.1% each year for the past five years. The company's need to adapt to new market conditions resulting from the liberalization process in the electricity sector imposed a priority objective of increasing customer satisfaction, focusing on the improvement of the Quality of Service. In the context of the Electricity Sector's Service Quality, ERSE (Energy Services Regulator) assures the fulfillment of Service Quality Regulation partly through the annual publication of the Service Quality Report. Technical Service Quality is measured by the TIEPI - Interruption Time Equivalent to Installed Capacity - index. This indicator has registered significant improvements in recent years and in the past five years; the TIEPI has decreased by approximately 70%.

In structure, the company has changed its management strategy in response to market liberalization and regulatory trends. In the sample examined here, covering the period 2003-2006, the primary focus is on the 14 regional distribution networks which are separately managed within an overall holding company structure. The network managers have responded differentially to central incentives to deliver efficiency improvements under regulatory guidelines, so that it is an important aspect of the analysis that the different networks have targeted different areas of efficiency improvement in order to show each network in the best light. This is exactly the approach which is embodied in the data envelopment analysis model. An extensive data gathering exercise was carried out within the company for this study.

3. Network Input and Outputs

The analysis is based on Data Envelopment Analysis for efficiency measurement, according to which the technical efficiency measure for a given network (*TE)* can take a value between zero and 100 percent. This model is stated as follows:

$$\begin{aligned}
&\text{find network weights to:}\\
&\min \theta\, TE\\
&\text{such that for each output and input:}\\
&\sum(\text{network output} \times \text{network weight}) \geq (\text{network output})_{\text{network being measured}}\\
&\sum(\text{network input} \times \text{network weight}) \leq TE \times (\text{network input})_{\text{network being measured}}\\
&\text{all network weights} \geq 0
\end{aligned}$$

Technical efficiency therefore measures the percentage of network's input which an efficient network on the frontier would use, to meet the same output targets as the network being evaluated. If the network is efficient, this will be 100%. If it is less than 100% then the network is inefficient. This model displays an input orientation. This means that the networks are assumed to choose the efficient level of their inputs in order to meet output targets that are not under their immediate control. This orientation seems to fit the real situation of the networks better than an output orientation, in which the networks choose the number of customers, and energy delivered with a fixed input budget of operating expenses.

Input: OPEX (€): In this network analysis we concentrate on operating expenditures as the only controllable input used by the networks in the short term. A further critical reason for concentrating on this input is that it is the chief target of the electricity regulatory authority during the relevant period. ERSE in its initial regulatory reviews focused strongly on operating expenditure for price-capping, as has been the case for many other regulatory authorities. As with many other regulators, capital expenditure is the focus of a different and longer term regulatory oversight.

We use three categories of output:

1. Energy delivered (kWh)
2. Number of customers connected (‘000s)
3. Network lines, circuit length (km)

The choice of these outputs reflects a standard classification used in many models, Bagdadioglu et al (2007), Jamasb and Pollitt (2001). The use of lines as an output reflects the difficulty of reaching customers in some areas relative to others. It also reflects the provision of a service connection as a separate output. The initial results apply the envelopment method to a set of models combining OPEX with these outputs separately and in combination. Each model is also estimated under different scale assumptions.

Note that as extra outputs are added, each is represented by a new constraint in the envelopment method calculation. Each new constraint makes it more difficult for the envelopment method calculation to minimise the measured efficiency, *TE*. Therefore each new constraint increases the measured relative efficiency of the network being studied. Our objective is to investigate how these measured efficiencies increase as more variables and constraints are added. We ask whether there is any measured inefficiency left after many variables and constraints have been added as explanatory factors. If there is, then that inefficiency may require some work by network managers to reduce OPEX.

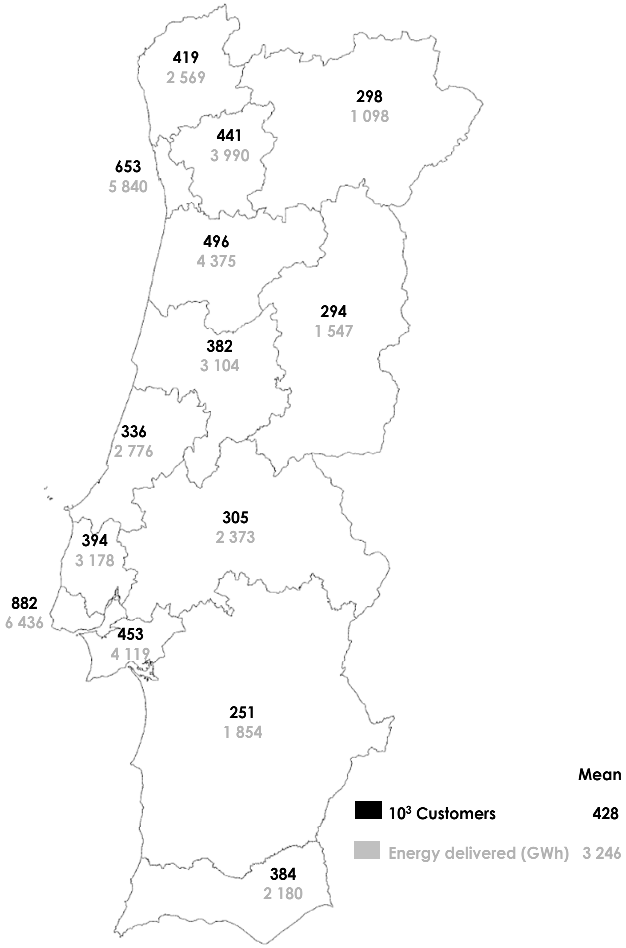
4. Operating Characteristics or Uncontrolled Environmental Variables

Each network will have characteristics of its operating environment which are outside its control. These should be included in the analysis, so that its measured efficiency is not distorted, Coelli et al (2003). We use three variables as uncontrolled operating characteristics:

1. Customer density: measured by (area/number of customers) (km^2/customers)
2. Requirement to bury lines underground: measured by (subterranean network length/total network length)
3. Requirement to connect low voltage customers relative to medium voltage customers: measured by (LV energy delivered/total energy delivered).

Each of these factors may make it more difficult to control costs. We treat them as uncontrolled additional output variables. If a network is disadvantaged relative to the others by any of these variables, its measured efficiency in using OPEX is raised. In an input oriented model such as the one we are using, there is no distinction between outputs in the sense that they are all regarded as outside the networks' control. The basic model we use for the efficiency and productivity analysis therefore has one input, operating expenses: OPEX, six output variables and minutes of lost load. The data sources for all the data are EDP Distribuição Energia. The following map of the Portuguese mainland illustrates the areas of the different networks, including also some data on the outputs used (number of customers and energy delivered).

Networks' Customers and Energy (2006)



5. Quality of Supply

The number of studies of quality of supply in electricity distribution networks is relatively small. However a general review of the issue is discussed in Burns et al (2006). These authors argue that one consequence of price cap regulation is that the utility may have an incentive to reduce quality of service (outputs) in order to earn a higher return, and in response to this distortion regulators have developed quality of service regulatory mechanisms alongside, or within, price control mechanisms. One of the earliest examples is electricity distribution in Norway, where revenue caps are used to regulate electricity distribution companies, with a minimum and maximum return on capital. In 2002 a further element was added to the assessment of allowed revenue, an adjustment for quality of service performance, Langset (2001). The quality measure used is the value of energy not supplied to consumers. Before introducing the revenue adjustment the Norwegian energy regulator, NVE, introduced mandatory reporting of interruptions greater than 3 minutes for end-users at all voltage levels in 2000 (data was collected from 1995). Those surveyed provided information on the direct costs associated with interruptions of different lengths and at different points in time. The survey results were updated to reflect information on average interruption duration throughout the year (not at peak load times only) and general price increases.

More generally, researchers have used variables similar to those reported by EDP Distribuição. Examples are the work of Giannakis et al (2005) and Growitsch et al (2009). Both sets of authors argue that data envelopment analysis and other types of efficiency study of electricity distribution networks should make use of data on minutes of lost load and numbers of interruptions to augment the usual input and output variables, as we have done in this paper. Different networks have different performances in quality of supply: interruptions, minutes of lost load, etc. We can adjust downwards the measured efficiency of networks that have poor quality of supply performance, by treating these bad qualities of supply variables in one of three different ways, e.g. see Scheel (2001):

1. as a negative output
2. as an inverted output
3. as an input

A network with a high negative value for quality of supply violations should appear as less efficient than one with a low negative value for quality of supply violations. Negative outputs have an impact similar to additional inputs. Firms with higher negative outputs or higher use of inputs should appear to be less efficient than others. An alternative procedure is to treat the inverse of quality of supply as an output. Networks with poor quality of supply performance (high number of minutes of lost load) would have a low value for this inverse output measure of quality of supply, and therefore would appear as inefficient. The theoretical impact on the model is not necessarily the same for each different way of treating the quality of supply variable, but the availability of different types of modelling software also plays a role in choosing the precise type of model we can use. In the productivity measurement we wish to carry out, the available software cannot accommodate negative outputs when productivity change over time is to be measured. (This was not the case when we were concerned with efficiency measurement only.) Consequently we use the other two measures. The inverse of quality of supply is used as an output, and quality of supply itself is measured as an input.

Both versions are important. We can maintain an input orientation, and treat quality of supply as an uncontrolled variable outside the networks' control by using the inverse of quality of supply as an uncontrolled output. Then, still in an input orientation, we can treat quality of supply as strategic variable that could be controlled by the networks, by modelling it as an input. The result is that we have three models of productivity measurement in an input orientation[1]:

1. Without quality of supply
2. With quality of supply measured by the inverse of minutes of lost load as an uncontrolled variable (uncontrolled output)
3. With quality of supply measured by minutes of lost load as a controlled variable (controlled input)

6. Productivity Change

In measuring relative efficiency, we were concerned only with the relative performance of the different networks in a particular year. We now wish to investigate the evolution of the network performance over a number of years. This requires us to measure productivity change. An obvious way to measure productivity is output per unit of input. However an economic decomposition finds many additional layers in this simple relationship. The decomposition can be built up in stages:

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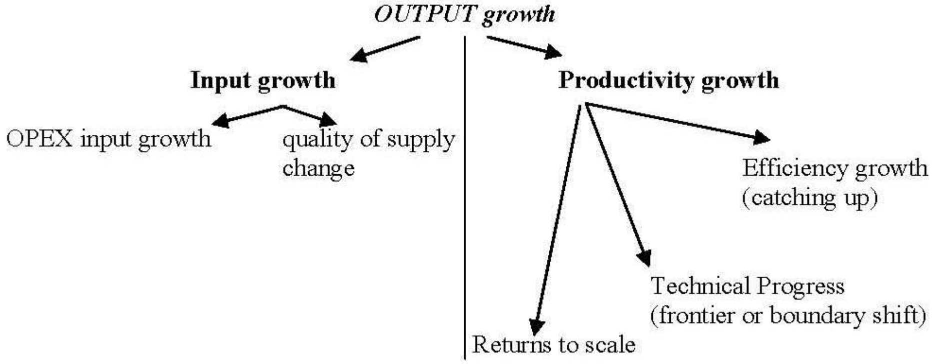
[1] *The orientation only becomes important when we need to adjust productivity change to allow for different network scale.*



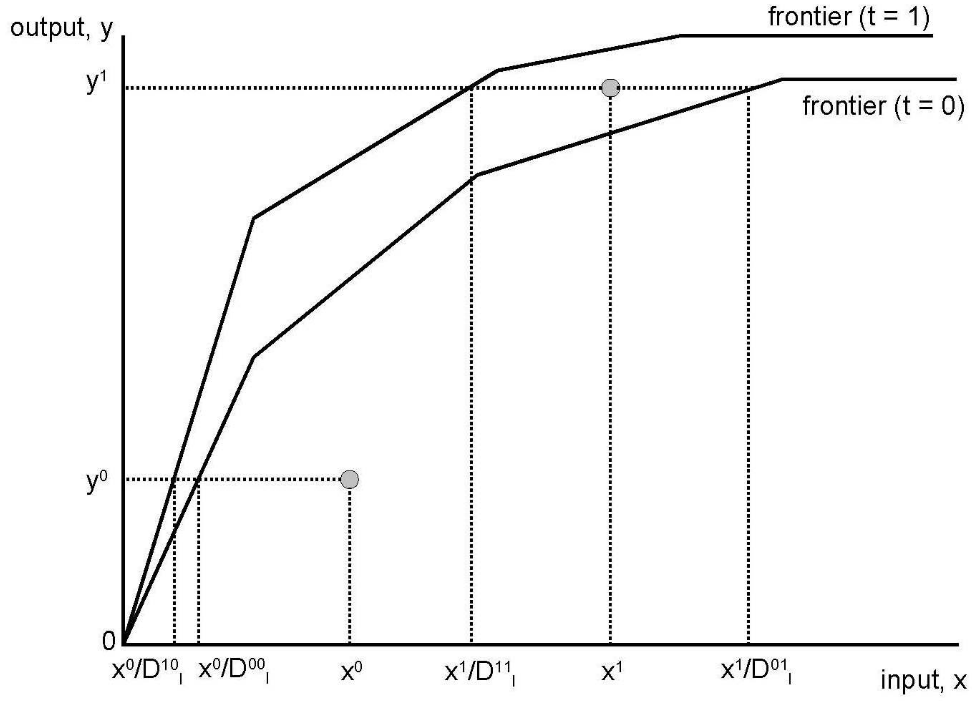
When this form of analysis is carried out allowing for many outputs, we obtain: *a total factor productivity growth decomposition*, see for example Fried et al (2007). This may often show different results compared to simple ratios of output to input.

The appendix presents the full analysis in technical detail, but the essential ideas can be seen in figure 1, where a single input and a single output is assumed. In our network analysis we expand the models to include several inputs, and several uncontrolled characteristics of the networks. We measure input as operating expenses, and then try to adjust for quality of supply as measured by minutes of lost load.

In figure 1, we observe a network with input-output values (x^0, y^0) and (x^1, y^1) in periods 0 and 1 respectively. In each case the network is inefficient relative to the frontier of the reference technology of that period. The measurement problem requires that we determine the productivity growth of the network between these two periods. In period 1 the network lies closer to the relevant production frontier than in period 0, but the frontier itself has shifted. After allowing for input growth from x^0 to x^1, the productivity change can be decomposed into an efficiency change reflecting whether the network is catching-up with the frontier, and a technical change reflecting the shift in the frontier. Note that efficiency scores can be represented in figure 1 in terms of the values of the inverse of the distance to the chosen frontier reference technology. For example the technical efficiency of observation (x^0, y^0) relative to the period 1 frontier is:

$$\left[TE_I^1\left(y^0, x^0\right)\right] = \left[D_I^1\left(y^0, x^0\right)\right]^{-1} = \left(0x^0 / \left(0\left(x^0 / D_I^{10}\right)\right)\right)^{-1} = 1/D_I^{10}$$

Figure: 1
Efficiency Change, Technical Change and Productivity Change



efficiency change, technical change and productivity change

In terms of the diagram in figure 1, we can write the Malmquist index of total factor productivity change as follows. Let the distance function values be written as:

$$D_I^{00} = D_I^0\left(y^0, x^0\right)$$
$$D_I^{10} = D_I^1\left(y^0, x^0\right)$$
$$D_I^{01} = D_I^0\left(y^1, x^1\right)$$
$$D_I^{11} = D_I^1\left(y^1, x^1\right)$$

Then the Malmquist input oriented index of total factor productivity change is:

$$M_I\left(y^1,x^1,y^0,x^0\right)=\left(\frac{D_I^{10}}{D_I^{11}}\frac{D_I^{00}}{D_I^{01}}\right)^{0.5}=\left(\frac{D_I^{00}}{D_I^{11}}\right)\left(\frac{D_I^{10}}{D_I^{00}}\frac{D_I^{11}}{D_I^{01}}\right)^{0.5}$$

so that $M_I\left(y^1,x^1,y^0,x^0\right)=TFPCH=EFFCH\times TECH$

where *EFFCH* is technical efficiency change and *TECH* is technical change, see Coelli, Estache, Pereleman and Trujillo (2003) — p. 48, equations 3.35 and 3.36. Strictly we assume constant returns to scale in the reference technology for this measure to be a valid measure of TFPCH. Since the diagram in figure 1 allows for non-constant returns to scale, our measure should also allow for scale change. The DEAP software used in this analysis does do this and provides a Malmquist index that satisfies:

$$TFPCH=EFFCH\times TECH=PECH\times SECH\times TECH$$

where *PECH* is pure technical efficiency change and *SECH* is scale efficiency change. To calculate these measures we must specify the orientation of the DEA model.

7. Network Models and Results

We present three sets of results. All are based on the use of the full range of variables: Model A:

- Input: operating expenses (OPEX)
- Outputs: customers, energy, lines
- Environmental variables: inverse of customer density, proportion of low voltage distribution, proportion of subterranean network

Model B: model A with quality of supply measured as *the inverse of minutes of lost load*, and treated as an *output*. This has the effect of adjusting the efficiency scores and productivity changes for quality of supply but does not assume that the networks treat quality of supply as a strategic variable to be optimised.

Model C: model A with quality of supply measured as minutes of lost load and treated as an input. This adjusts the efficiency and productivity analysis for quality of supply, and assumes that networks choose whether to improve the quality of supply in addition to reducing OPEX.

The following charts and graphs illustrate for each of the three models, A, B and C:

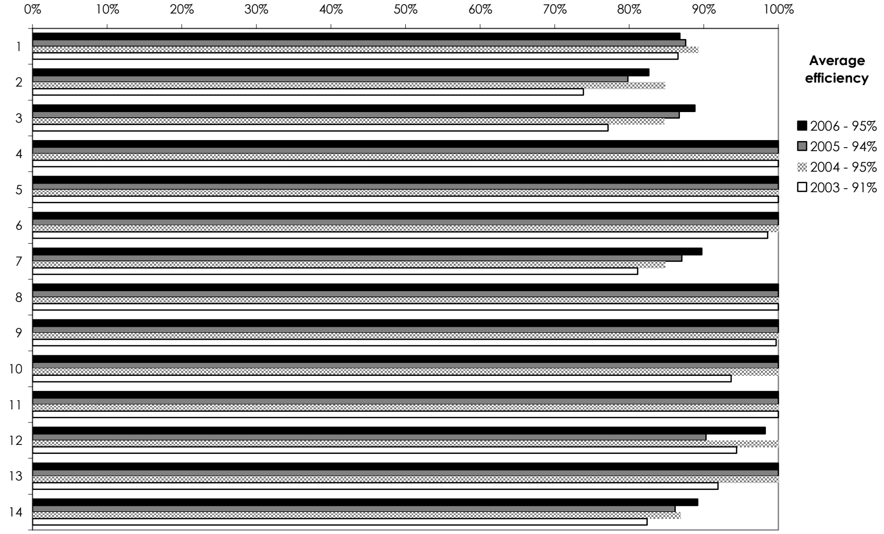
1. individual DEA efficiency scores with constant and with variable returns to scale
2. the Malmquist productivity growth index from 2003 to 2006 for networks performing better and worse than the mean productivity growth
3. the decomposition of this Malmquist productivity growth into efficiency change (catching up) and technical change (boundary shift).

All these results are summarized in charts D.

8. No Quality of Supply Adjustment

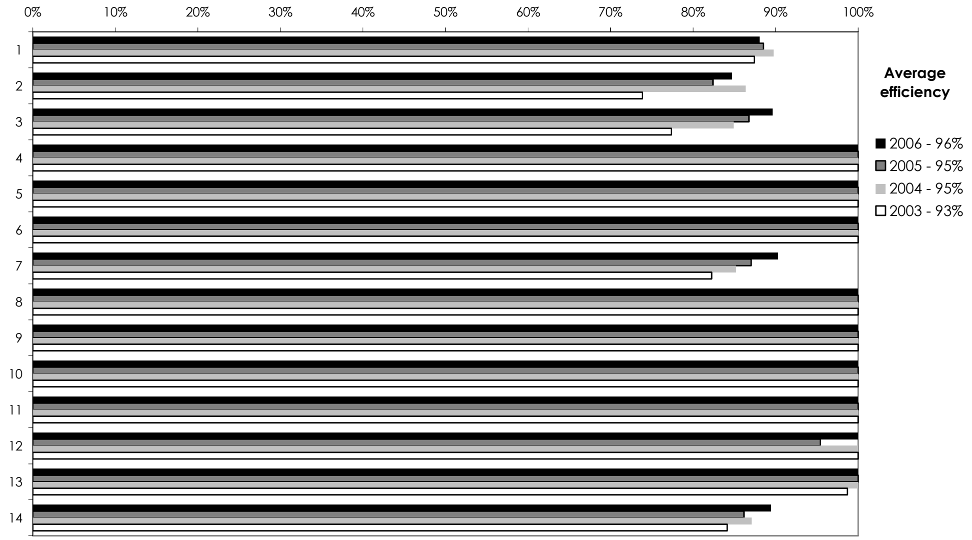
Beginning with model A, where there is no adjustment for quality of supply, it is nevertheless important to adjust for variable returns to scale (VRS), as two of the networks become fully efficient in all years of the sample, when allowing for the effect of scale at which the networks have to operate.

Chart A1
Efficiency Scores of Each of the Networks under Constant Returns to Scale



Model A: no quality of supply adjustment:
INPUTS: OPEX
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total.

Chart A2
Efficiency Scores of Each of the Networks under Variable Returns to Scale



Model A: no quality of supply adjustment:
INPUTS: OPEX
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total.

The evolution of (Malmquist) total factor productivity growth without quality of supply adjustment is shown in charts A3 and A4. In most of the networks productivity growth has been positive when averaged over the years 2003 to 2006, with an average productivity growth rate of 6,1% per year. This is better than the overall productivity growth rate for Gross Domestic Product in the European Union, as well as in Portuguese economy, over this period, so that even without the adjustment for quality of supply improvements, the networks have on average performed at least as well as many other sectors of the European economies.

Chart A3
Malmquist Productivity Growth from 2003 to 2006
Networks Which Performed Better Than the Mean Productivity Growth (Excluding Quality of Supply)

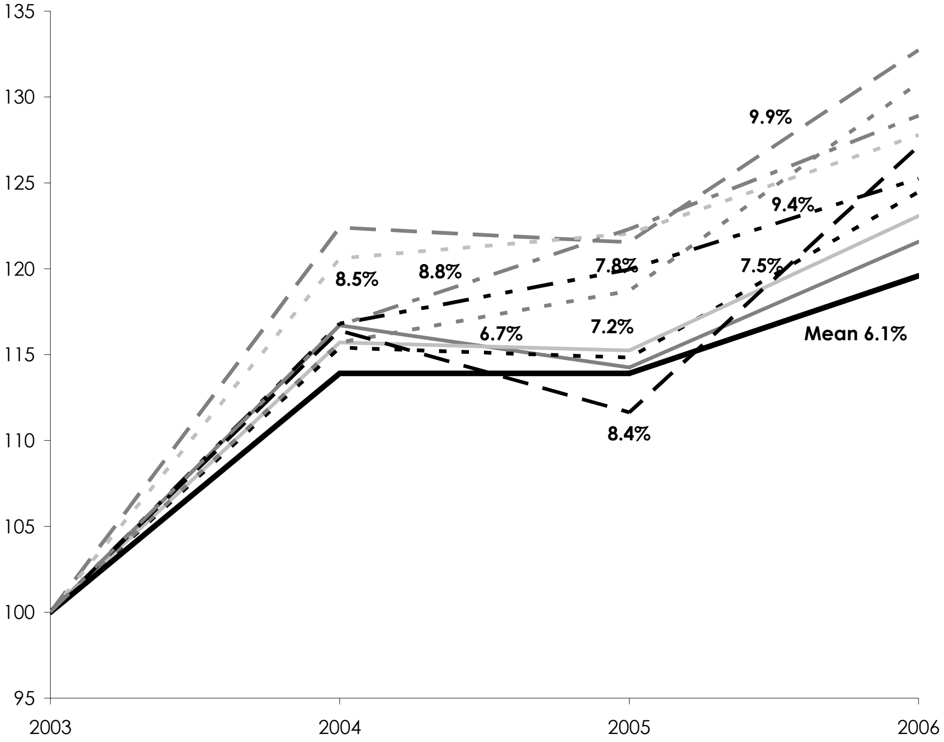
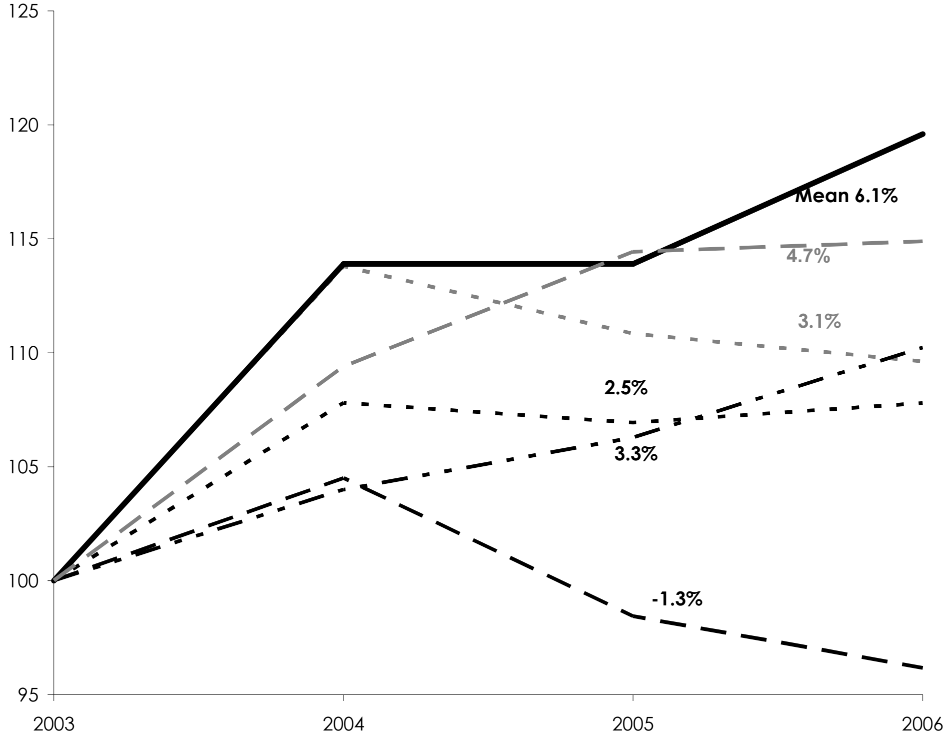
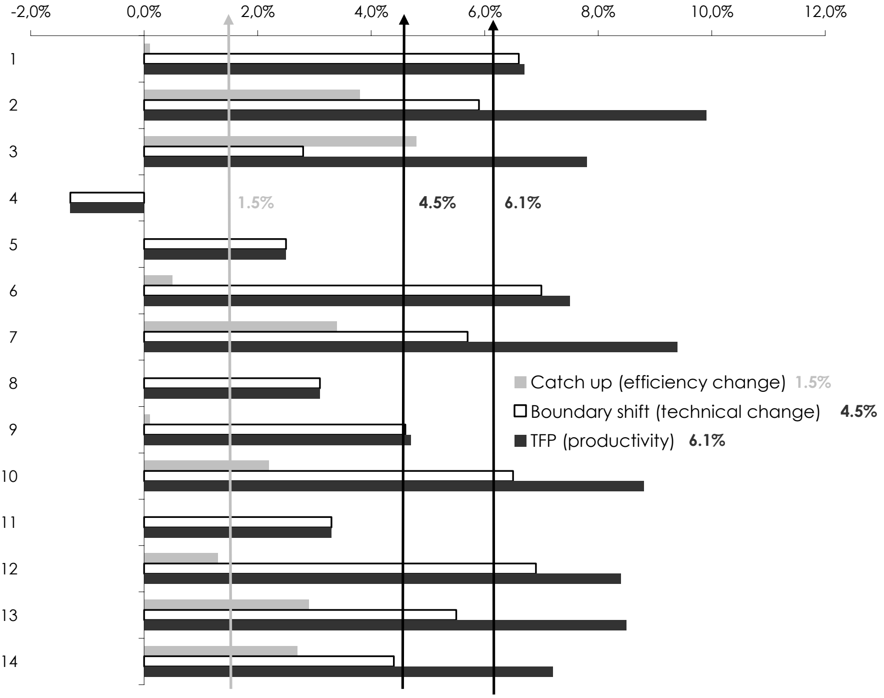


Chart A4
Malmquist Productivity Growth from 2003 to 2006
Networks which Performed worse than the Mean Productivity Growth (Excluding Quality of Supply)



Finally in chart A5, we display the decomposition of Malmquist productivity growth into efficiency change and technical change when there is no adjustment for quality of supply. In this model the presence of negative technical change in one network when the sample shows positive technical change on average means that this network in some years was only able to produce at levels below the frontier for earlier years.

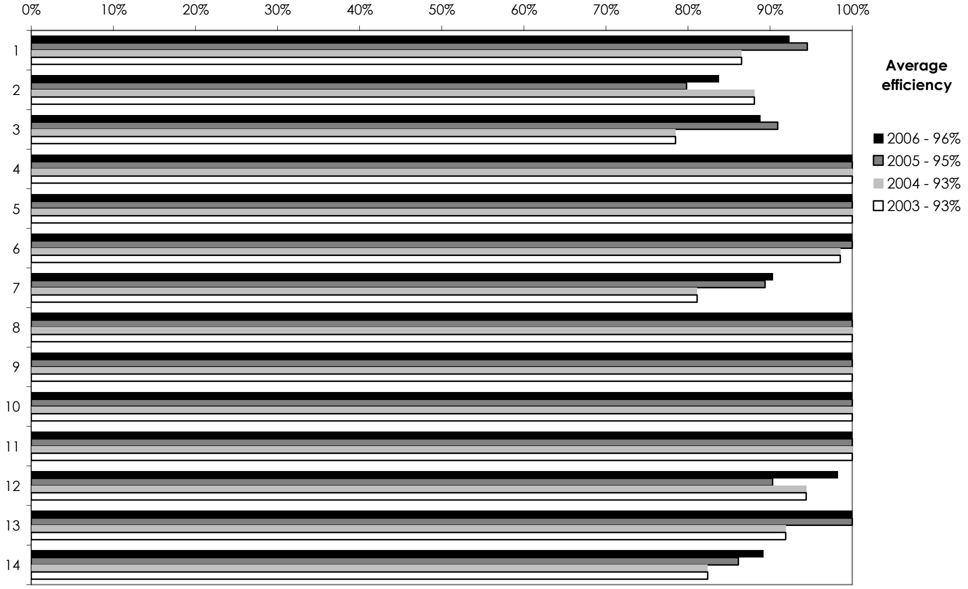
Chart A5
Decomposition of Productivity Growth for All Networks from 2003 to 2006
(Excluding Quality of Supply)



9. Adjusting for Quality of Supply as an Uncontrolled Variable

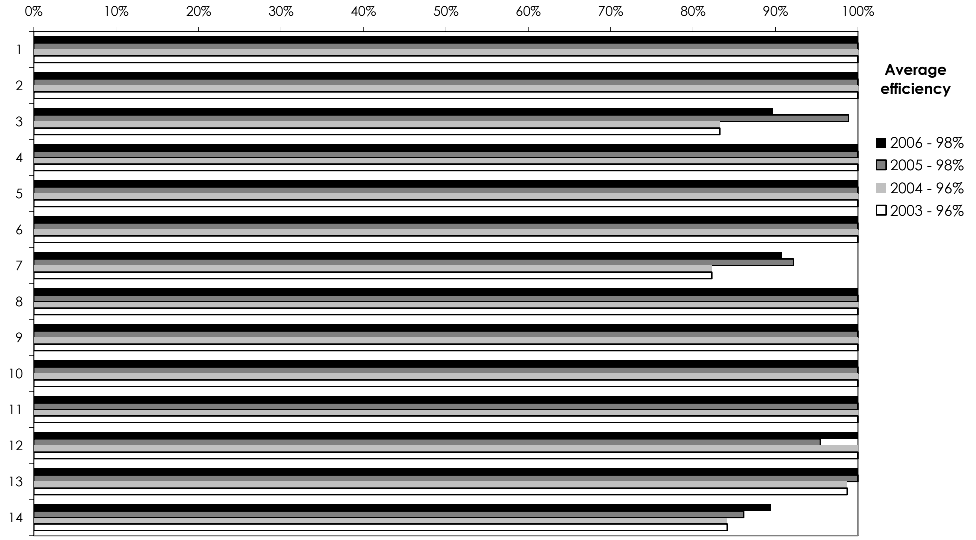
The charts labelled B1 through to B5 report the results for the model where the efficiency and productivity analysis has been adjusted for quality of supply by entering the inverse of minutes of lost load as an output variable. Once again, it is important to adjust for variable returns to scale, as shown in charts B1 and B2.

Chart B1
Individual Efficiency Scores Adjusted for Quality of Supply as an Uncontrollable Input under Constant Returns to Scale



Model B: quality of supply adjustment as an uncontrollable variable:
INPUTS: OPEX,
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total, inverse of minutes of lost load.

Chart B2
Individual Efficiency Scores Adjusted for Quality of Supply as an Uncontrollable Input under Variable Returns to Scale



Model B: quality of supply adjustment as an uncontrollable variable:
INPUTS: OPEX,
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total, inverse of minutes of lost load.

In charts B3 and B4, we show the effect of adjusting for quality of supply, as an uncontrolled variable, on the Malmquist productivity index for each of the networks over the period 2003 to 2006. Compared with the model which made no allowance for quality of supply, the mean rate of productivity growth has more than doubled from 6,1% per year to 12,4% per year. Clearly, when quality of supply improvements are counted, some of the networks show very significant increases in productivity growth. In some cases these are comparable to the improvements recorded in the UK networks after privatisation. It is noticeable that the spread of performance is widening, and that some networks are not showing such significant improvements.

Chart B3
Malmquist Productivity Growth from 2003 to 2006
Networks which Performed Better Than the Mean Productivity Growth after Adjusting for Quality of Supply as an Uncontrollable Variable

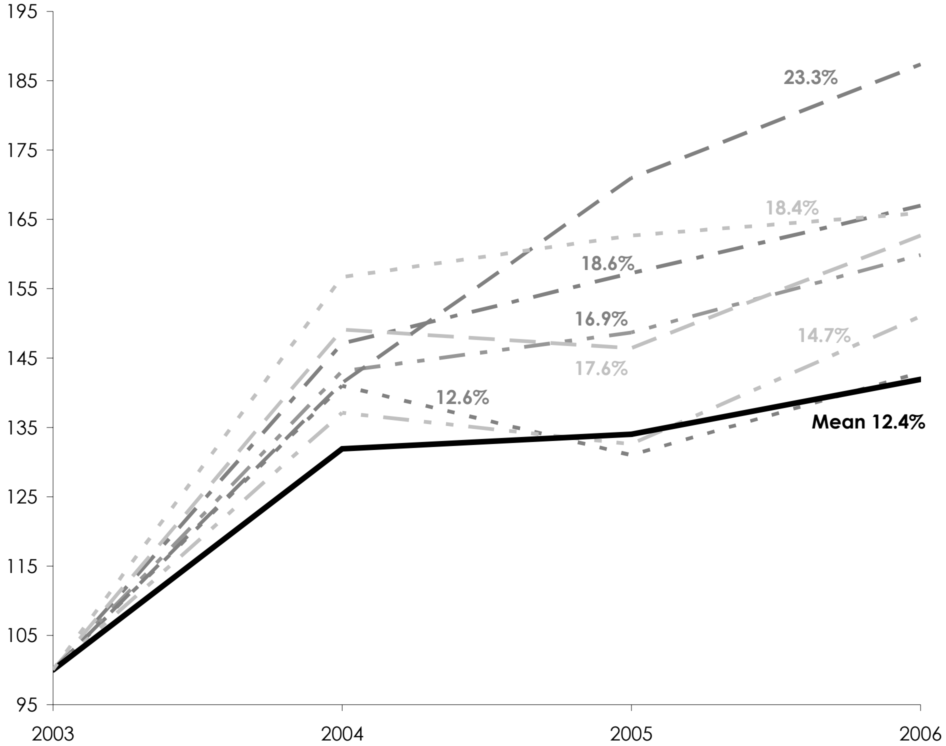
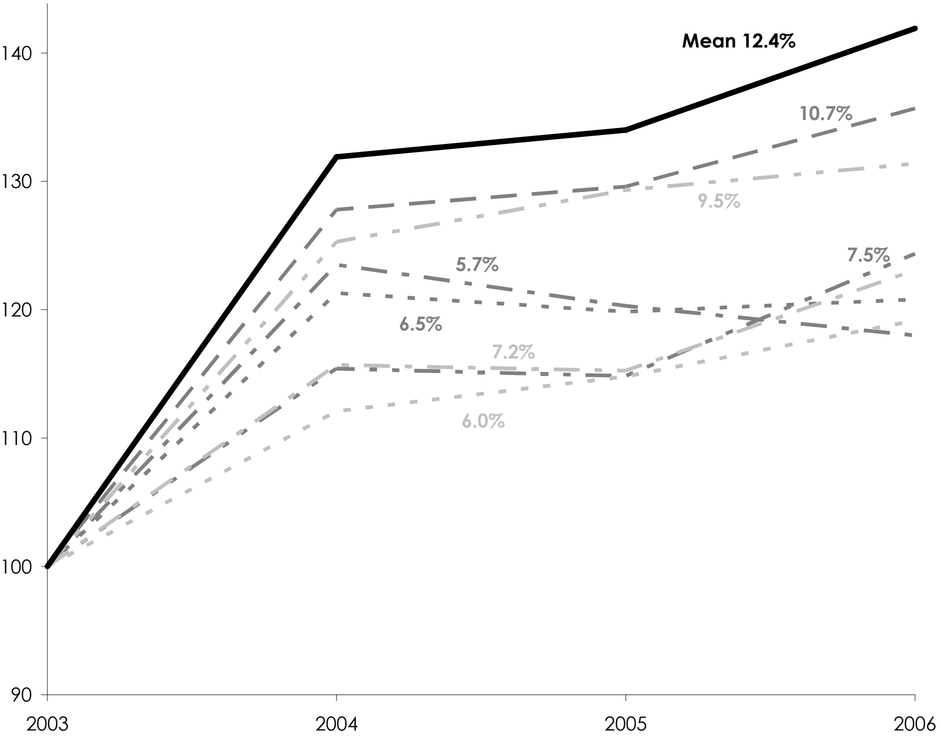
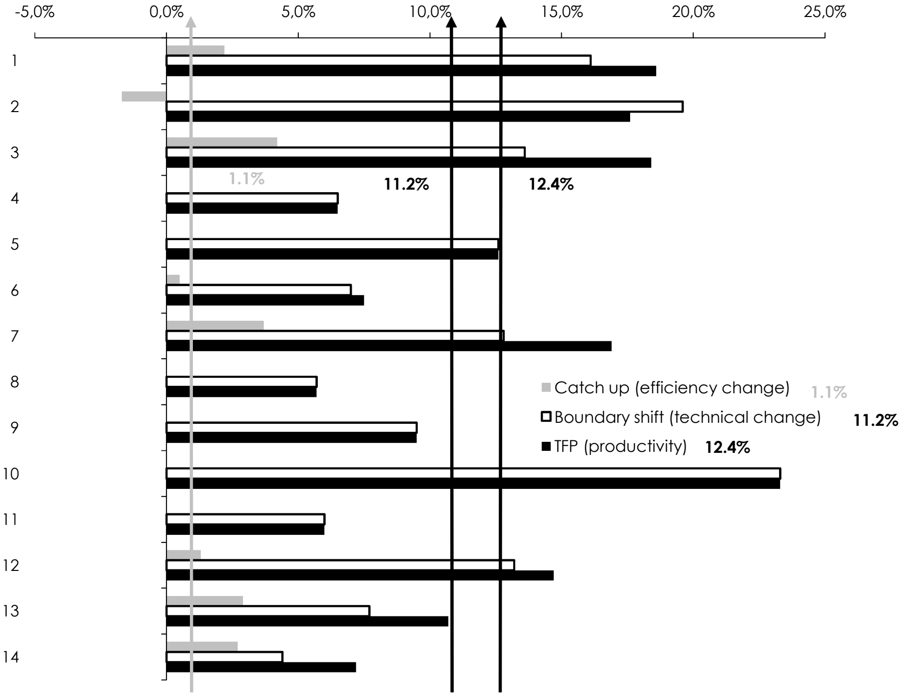


Chart B4
Malmquist Productivity Growth from 2003 to 2006
Networks which Performed worse than the Mean Productivity Growth after Adjusting for Quality of Supply as an Uncontrollable Variable



In chart B5, we report the Malmquist decomposition for the networks. The results are, in general, more favourable than the situation when no allowance is made for quality of supply. Mean efficiency change is 1,1% per year, mean technical change is 11,2% per year and mean overall productivity change is 12,4% per year.

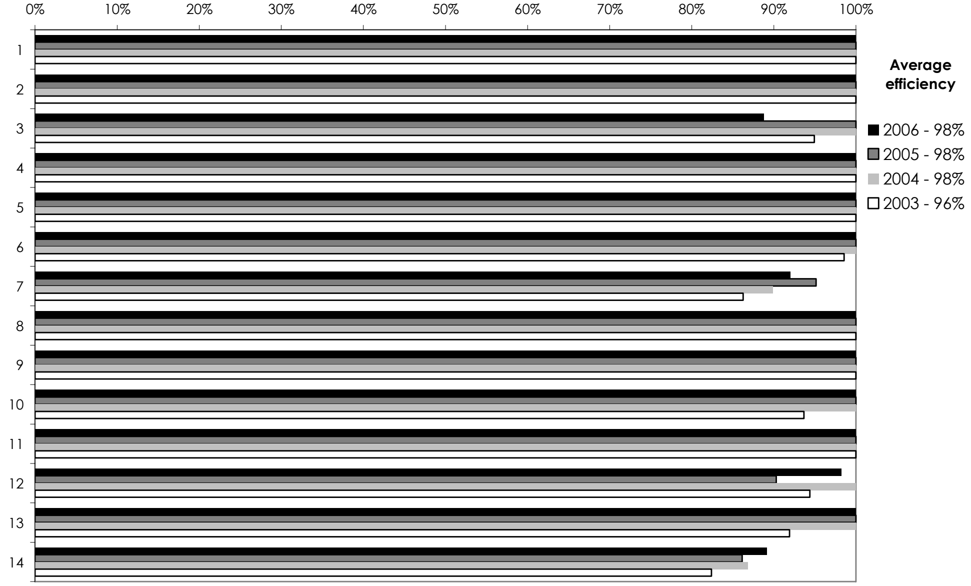
Chart B5
Decomposition of Productivity Growth as an Uncontrollable Variable for All Networks from 2003 to 2006



10. Adjusting for Quality of Supply as a Strategic Variable

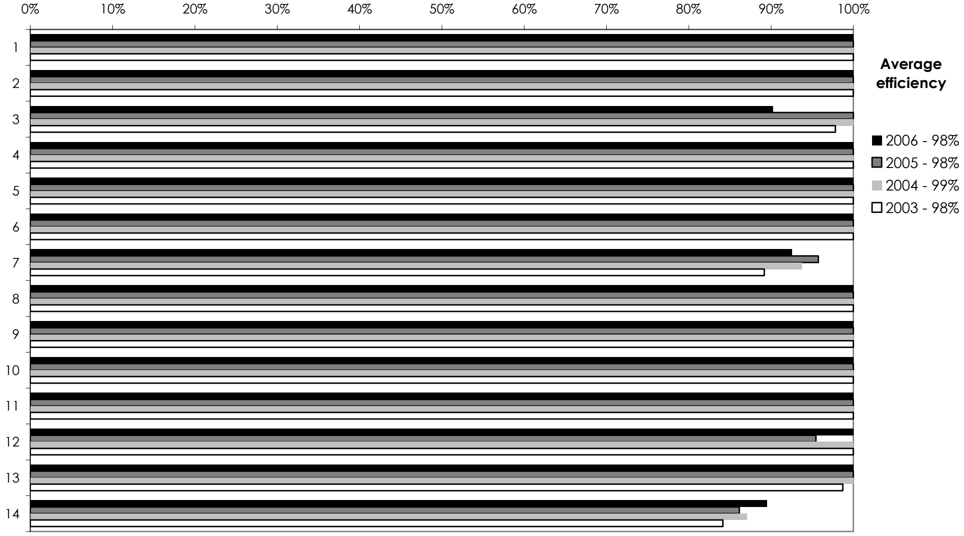
The networks have put resources into improving quality of supply, so it is important that this variable should be measured as a controllable input which is part of their strategic planning. The effect of doing this is to improve the results still further, as shown in charts C1 and C2.

Chart C1
Individual Efficiency Scores Adjusted for Quality of Supply as a Controllable Input under Constant Returns to Scale



Model C: quality of supply adjustment as a controllable input:
INPUTS: OPEX, minutes of lost load
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total.

Chart C2
Individual Efficiency Scores Adjusted for Quality of Supply as a Controllable Input under Variable Returns to Scale



Model C: quality of supply adjustment as a controllable input:
INPUTS: OPEX, minutes of lost load
OUTPUTS: Customers, Energy, Lines, Area/ Customer, Underground Lines/ Total, Energy LV/ Total.

In charts C3 and C4, we show the Malmquist productivity trends for the networks performing above and below the mean performance. The mean performance itself has improved to an annual rate of 13,6% productivity growth, with quality of supply as a strategic variable to be optimized.

Chart C3
Malmquist productivity growth from 2003 to 2006
Networks which Performed better than the Mean Productivity Growth after Adjusting for Quality of Supply as a Controllable Input

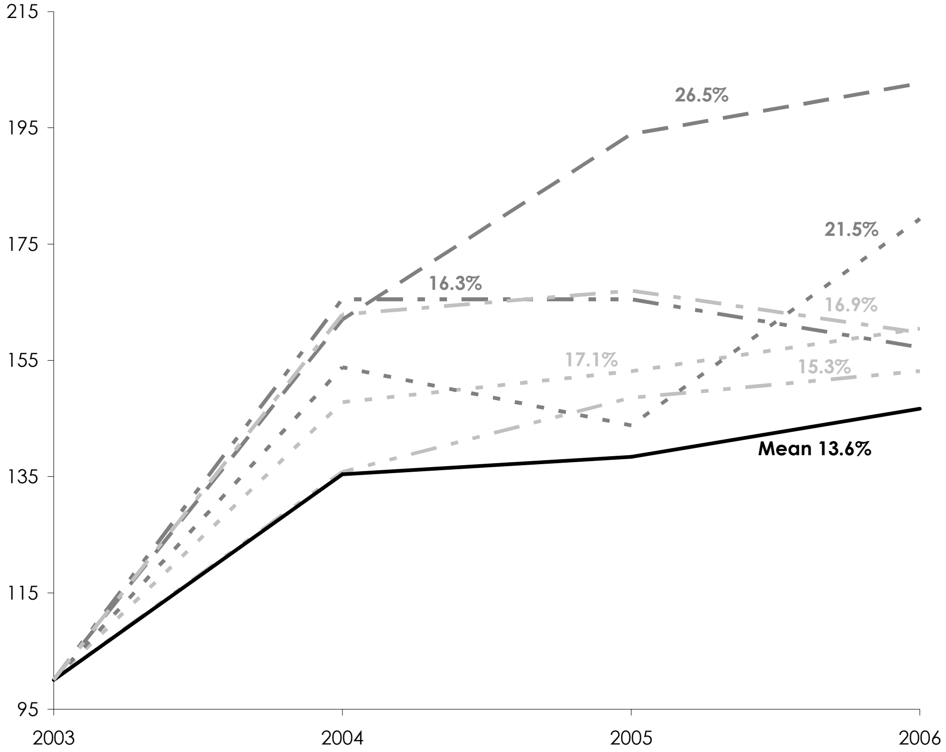
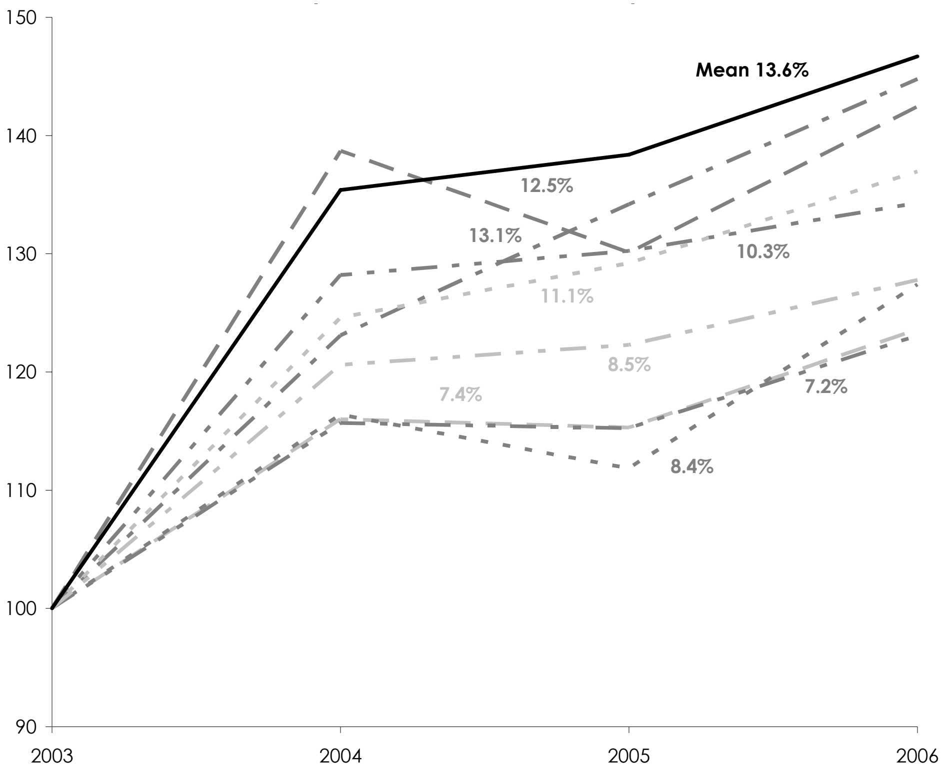
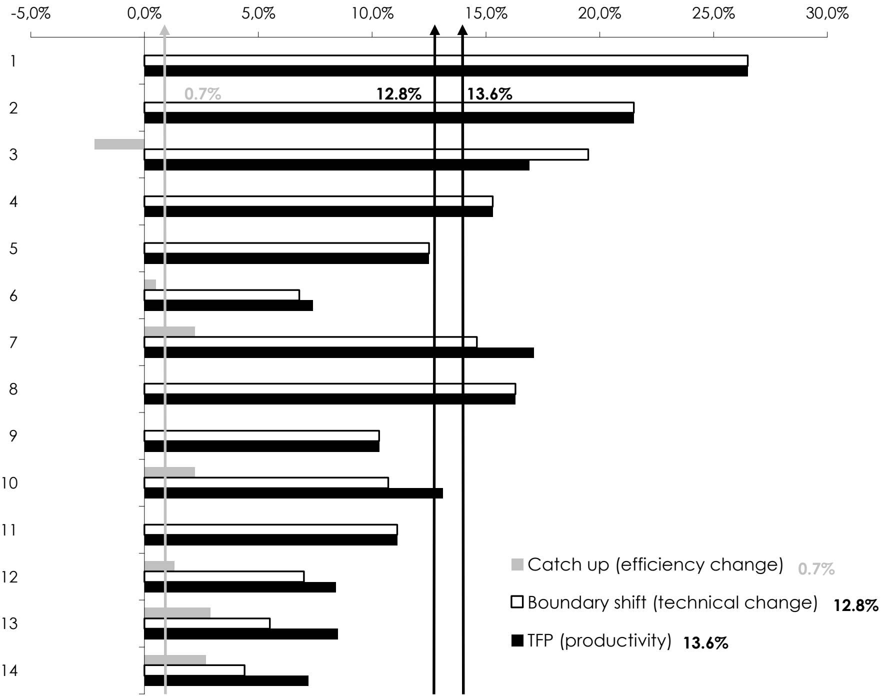


Chart C4
Malmquist Productivity Growth from 2003 to 2006
Networks which Performed worse than the Mean Productivity Growth after Adjusting for Quality of Supply as a Controllable Input



Turning to the decomposition of productivity growth adjusted for quality of supply as a controllable input, we find that the total factor productivity change (13,6% per year) is composed of 0,7% average efficiency change and 12,8% average technical change.

Chart C5
Decomposition of Productivity Growth Adjusted for Quality of Supply as a Controllable Input for all Networks from 2003 to 2006



All these results are summarized in charts D1 and D2, showing that two of the networks become efficient when quality of supply is taken into account. These results also show that by considering quality of supply as a strategic variable, modelled in the form of a controllable input, we have a more accurate evaluation of each network's total factor productivity growth.

Chart D1
Effect of Quality of Supply on Networks' Efficiency Scores
(Variable Returns Scale – 2006)

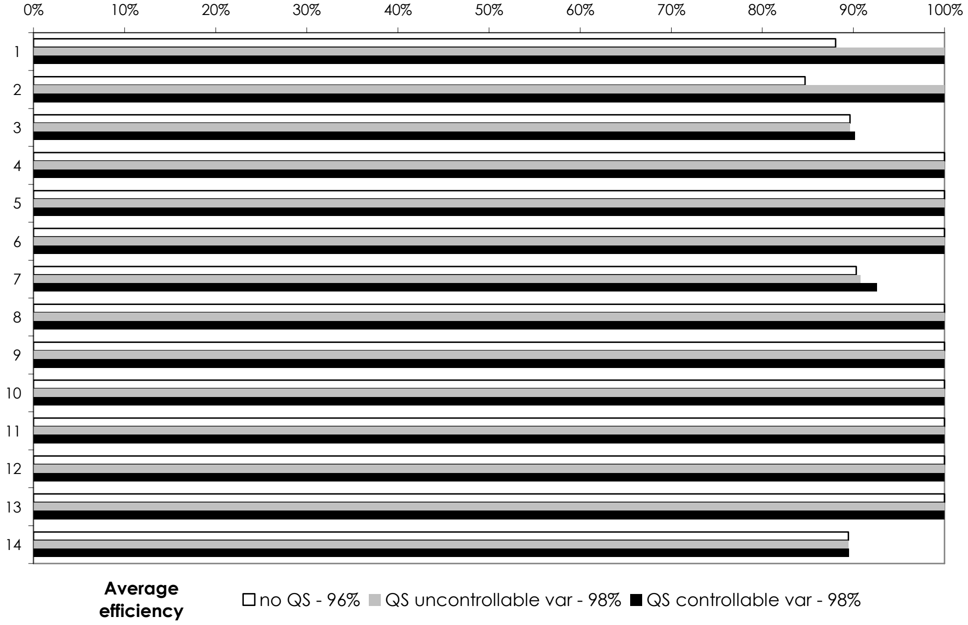
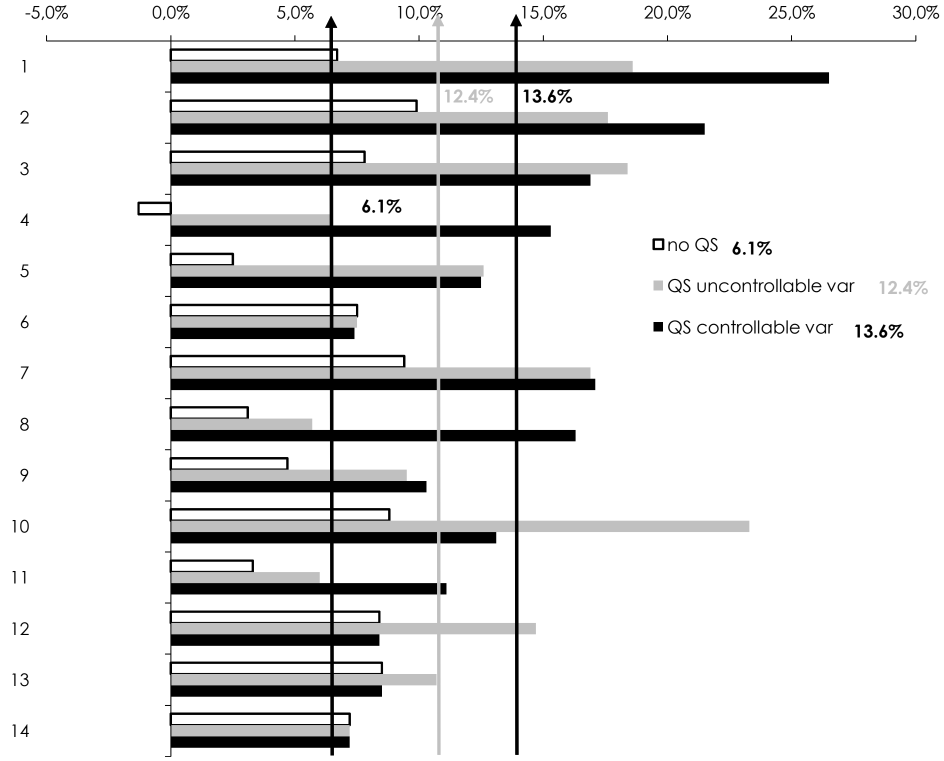


Chart D2
Effect of Quality of Supply on the Decomposition of Productivity Growth 2003/2006



11. Conclusions on Quality of Supply and Efficiency and Productivity Analysis

In this analysis, we have modelled technical efficiency of the Portuguese electricity distribution networks, and its rate of improvement, i.e. the total factor productivity change. We used three models, leaving out quality of supply, including quality of supply as an uncontrolled variable, and including quality of supply as a strategic variable under the networks' control. We measured both constant and variable returns to scale in our models.

The results are relatively clear. First it is important to allow for variable returns to scale since the feasibility of re-scaling different networks is not possible under the current company and regulatory structure in the short run. Variable returns to scale technology adjusts the efficiency scores for this factor. More significantly, adjusting for quality of supply is also extremely important, and it raises the measured productivity growth rate of the networks.

Allowing quality of supply to be a variable that can be strategically optimised by the networks offers a further improvement in measured productivity growth. This is particularly important for networks which have invested in quality of supply improvements.

Average rates of productivity growth are very high in some cases, close to the very high rates experienced in UK distribution after adjustment to privatisation in the mid 1990s. This suggests that the company has responded strongly to the regulatory impact of efficiency benchmarking in Portugal.

We observe a widening of the spread of productivity growth consistent with the experience in other European countries after deregulation. This has policy implications for the whole of the European Union energy market development. We are able to conclude that efficiency benchmarking by regulators based on internal comparisons within a single regulated entity can deliver productivity gains. Nevertheless, to ensure that these comparisons remain meaningful in price-capping regulatory system, it is important to make quality of supply adjustments to benchmarked efficiency scores. We have demonstrated in this paper a number of useful ways that this can be achieved.

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Appendix 1: Malmquist Index Construction

This analysis can first be applied to input distance functions. To ensure that positive productivity growth appears as an index value exceeding unity in value, we use the inverse of the input distance functions in the Malmquist index definition. There are two possible Malmquist input based productivity indices depending on the year chosen as base.

$$M_{It} = \left[\frac{D_I^t(x_{t+1}, y_{t+1})}{D_I^t(x_t, y_t)}\right]^{-1} = \left(\left[\frac{D_I^{t+1}(x_{t+1}, y_{t+1})}{D_I^t(x_t, y_t)}\right]\left[\frac{D_I^t(x_{t+1}, y_{t+1})}{D_I^{t+1}(x_{t+1}, y_{t+1})}\right]\right)^{-1}$$

i.e., total factor productivity change = [efficiency change] x [technical change]

and

$$M_{It+1} = \left[\frac{D_I^{t+1}(x_{t+1}, y_{t+1})}{D_I^{t+1}(x_t, y_t)}\right]^{-1} = \left(\left[\frac{D_I^{t+1}(x_{t+1}, y_{t+1})}{D_I^t(x_t, y_t)}\right]\left[\frac{D_I^t(x_t, y_t)}{D_I^{t+1}(x_t, y_t)}\right]\right)^{-1}$$

i.e., total factor productivity change = [efficiency change] x [technical change].

Fare et al (1994) introduced the Fisher ideal index version of these indices to remain neutral with respect to the base:

$$M_I(x_{t+1}, y_{t+1}, x_t, y_t) = \sqrt{M_{It} M_{It+1}}$$

$$M_I(x_{t+1}, y_{t+1}, x_t, y_t) = \left[\frac{D_I^{t+1}(x_{t+1}, y_{t+1})}{D_I^t(x_t, y_t)}\right]^{-1}\left(\left[\frac{D_I^t(x_t, y_t)}{D_I^{t+1}(x_t, y_t)}\right]\left[\frac{D_I^t(x_{t+1}, y_{t+1})}{D_I^{t+1}(x_{t+1}, y_{t+1})}\right]\right)^{-0.5}$$

i.e., total factor productivity change = [efficiency change] x [technical change].

Each index can therefore be decomposed into a measure of efficiency change and technical change.

To maintain the result that the Malmquist productivity indices show M > 1 for positive total factor productivity growth, the input based technical efficiencies are used. These are the reciprocals of the input based distance functions.

$$M_I\left(x_{t+1}, y_{t+1}, x_t, y_t\right)=\left[\frac{TE_I^{t+1}\left(x_{t+1}, y_{t+1}\right)}{TE_I^t\left(x_t, y_t\right)}\right]\left(\left[\frac{TE_I^t\left(x_t, y_t\right)}{TE_I^{t+1}\left(x_t, y_t\right)}\right]\left[\frac{TE_I^t\left(x_{t+1}, y_{t+1}\right)}{TE_I^{t+1}\left(x_{t+1}, y_{t+1}\right)}\right]\right)^{0.5}$$

These indexes are calculated on the assumption of constant returns to scale. However, a further decomposition is possible:

i.e., total factor productivity change

= [efficiency change] x [technical change]

= [pure efficiency change] x [scale change] x [technical change]

This is the procedure we followed. Note that the overall productivity change is the same whichever decomposition is used and whichever orientation is used. However, the decomposition into scale and pure efficiency change does depend on the orientation used.

Each distance function is calculated as linear programme. For example the relative efficiency of a network observed in year *s* compared to the reference technology frontier of a different period *t* is:

$$\begin{aligned}
&TE_I^t\left(y^s, x^s\right)=\left(D_I^t\left(y^s, x^s\right)\right)^{-1}=\min\theta \\
&s.t. \\
&X^t\lambda \le x_0^s\theta \Rightarrow X^t\lambda + s^- = x_0^s\theta \\
&Y^t\lambda \ge y_0^s \Rightarrow Y^t\lambda - s^+ = y_0^s \\
&\lambda, s^-, s^+ \ge 0
\end{aligned}$$