Economies of Scale and Technological Progress in Electric Power Production: The Case of Brazilian Utilities

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ABSTRACT

This paper examined the cost structure of the electricity generation companies in Brazil during the period 2000-2010 by using a translog cost function that imposes no restrictions on production technology and allows for the existence of non-homotheticity. The hypothesis that economies of scale are a typical feature of the generation market in Brazil and, in general, are not exhausted at lower levels of production is not rejected. This result supports the vision that indivisibilities restrict efficiency gains from free-market competition in the Brazilian electricity generation and most of the last restructuring in the industry regulation was based on this assumption. Furthermore, over the sample period, technological progress led to cost reductions in electric power supply. These technological improvements take the form of both a neutral technological effect as well as a non-neutral fuel effect, which prevails over the capital and labor saving technical changes.

KEY WORDS: Power supply; scale economies; technical change; translog function; seemingly unrelated regressions; panel model.

JEL CODES: D24; C33; L94.

1. INTRODUCTION

Since the seminal paper by Christensen and Greene (1976), many other studies have claimed that economies of scale may not prevail in power generation and/or are exhausted at a much smaller scales. Indeed, most of the restructuring in the electricity industry is based on the assumptions that the generation operates under constant or decreasing returns to scale at current levels of production (Wolak, 1997; Joskow, 1997). According to this view, the largest firms may not gain significant cost advantages over the smaller ones thus making this segment more prone to competition (Huettner and London, 1977; Goto and Tsutsui, 2008). Technological and economic factors are consistent with those findings.[1] The reduction of the minimum efficient size of modern generation technologies along with the lead-time for the completion of generating plants increased the potential for competition in this segment of the electricity markets. In addition, larger plants may have higher maintenance and reserve requirements costs as well as higher forced outage; technological advances in electricity transmission, by expanding the number of potential buyers for small firms, also contribute to reducing the advantages of economies of scale and thus hinder market concentration in power generation.

Corroborating those views, recent regulatory reforms are promoting the development of open markets for electric power and encouraging competition among firms in order to boost efficiency. However, even as the industry is being reshaped to increase the role of competitive market forces, the existing structure of the electric power industry in many countries, with a few utilities retaining a significant share of the market, may counteract the movement towards more competition in this industry. This is the case of the Brazilian electric power generation, where the market share of the four largest firms accounted for 42% of the market share in 2010 (Empresa de Pesquisa Energética, 2012).

In addition, the literature reports that for the larger firms, the installed capacity is still based on technologies characterized by indivisibilities. Their higher efficient production levels provide them with the advantages of natural monopolies, where economies of scale prevail on the relevant output range (Hisnanick and Kymn, 1999; Berry and Mixon, 1999).

The tradeoff between enforcing competition and benefitting from economies of scale in the power supply industry is also present in the discussion among those who advocate the vertical

[1] In the US, Kamerschen *et al* (2005) highlights the effect of technological factors in the reduction of concentration in the electric power production.

integration of the electricity industry and the prevalence of larger firms (Joskow and Schmalense, 1983; Kaserman and Mayo, 1991; Nemoto and Goto, 2004) and the defenders of unbundling (Gilsdorf, 1994). The former allude to the significance of economies of scope and scale whereas the latter point out the benefits of divestiture and competition. Hence, a relevant issue to investigate is how the industry will react to this new environment, characterized by those contradictory forces, particularly with respect to its efficient scale of operation for individual firms. Indeed, if the efficient scale requires a substantially higher (lower) production than the output levels of most firms, the number of utilities in the industry will decline (increase) and competition will be weakened (enhanced). In a post-deregulation world, this question is better addressed by appraising the production levels that exhaust economies of scale in the power generation industry. Here, the analysis of economies of scale and technological progress are important issues to be investigated.

The present study contributes to this debate. Its objective is to examine the cost structure of the electricity generation utilities in Brazil that are dominated by hydroelectric power plants. In 2010, this technology accounted for 77% of the installed capacity in the market, with thermoelectric accounting for 19% and other technologies the remaining 4% (Empresa de Pesquisa Energética, 2012).

To achieve the objective of the paper, a flexible translog cost function is used for 21 firms during the period 2000-2010. Particular emphasis will be given to the analysis of the minimum efficient scale for different utility sizes. In addition, the paper will report on investigations of (1) substitution possibilities among inputs; (2) the different contributions to technological progress and (3) the impact of a sample of the firms' observable technical and institutional characteristics on their production cost.

The paper proceeds as follows. Section 2 briefly describes the regulatory framework in Brazil. Section 3 presents the methodology used to estimate the cost structures for power generating utilities in Brazil while section 4 describes the data and the choice of the variables used in the translog cost function. Section 5 discusses the econometric results for three distinct technology specifications and investigates the possibilities of input substitution in this segment of the electricity market. Section 6 estimates the economies of scale and discusses the efficient scale. Section 7 discusses technological progress for the utilities analyzed. Finally, section 8 summarizes the main conclusions.

2. POWER SUPPLY INDUSTRY IN BRAZIL: THE REGULATORY FRAMEWORK

In Brazil, the electricity industry[2], following the pattern of the international restructuring of this economic activity, has substantially changed over the last two decades. This restructuring started in the mid-1990s and was anchored in an extensive privatization program. The reform was intended to foster competition in the generation segment and to break-up the vertical integration in the industry (Santana and Oliveira, 1999; Ramos-Real *et al*., 2009). The underlying supposition behind this reform was the idea that the gains from competition would outweigh the losses of economies of scale and de-verticalization.

The incentives to competition and "unbundling" required regulation and coordination structures that were provided by two institutions: the Electricity National Agency (ANEEL) and the National Electricity System Operator (ONS). The former mediates conflicts between the agents in the industry, investigates and fines opportunistic actions as well as anticompetitive behaviors. The ANEEL also evaluates the performance of monopolies in charge of managing the transmission network (high voltage power lines) or the distribution infrastructure, which delivers the power to individual customers (Santos *et al*, 2011).

The National Electricity System Operator (ONS) coordinates supply and demand in the electricity market. The electricity producers cannot, *a priori*, connect their production to a given customer. They control only the electricity they add to the transmission system. Equivalently, the consumer cannot choose a specific supplier, selecting only the energy taken from the distribution network. The ONS coordinates physical transactions within the electricity industry. Besides matching demand and supply, the ONS also identifies lower cost producers, directing demand, instantaneously towards those suppliers. Transactions not satisfied by specific contracts are financially settled by the Power Commercialization Chamber (Pinto *et al*., 2007; Carpio and Pereira, 2007).

The electricity rationing schemes implemented in 2001-2002 demonstrated that previous reforms were not sufficient to adjust the power supply to rapid demand growth. In 2005, a new cycle of regulatory changes was introduced to cope with the power shortage. Among the elements of

[2] This industry is composed basically of three markets: i) the electric power generation, where the electricity producers operate; ii) the transmission market, whose network transports electricity through long distances in high voltages and; iii) the distribution market, whose network transports electricity in low voltages to the final consumers. The focus of this paper is the first market.

these reforms, two distinct market environments were created: the ACR – Ambiente de Contratação Regulada (Regulated Contract Market) and the ACL – Ambiente de Contratação Livre (Free Contract Market). The ACL market deals basically with final electricity consumers (companies, electro-intensive manufacturers, etc.) that demand substantial amounts of electricity (in comparison to households and small business), but are not individually significant as a proportion of the total demand for electricity; contracts established in this market are not mediated by the regulatory authority (ANEEL).

The ACR market was inspired by the "single-buyer" model where an entity buys all electricity from producers and sells it to distributors. Here, demand comes solely from firms operating in the distribution segment; they have to buy in this market 100% of their electricity requirements. The ANEEL aggregates the demand of the electricity distribution utilities and acts as the single buyer, so that the aggregated demand of these companies – instead of the individual ones – is brought to the power suppliers. The price that prevails in this market is defined by auctions organized by the regulatory agency. Bilateral contracts traded in the ACR market have up to a five-year horizon for the physical delivery of electricity (Pinto *et al*., 2007).

The 2005 counter reform affected mainly the small consumers (households, small businesses, etc.), who buy electricity from the electricity distribution companies, instead of directly from the electric power producers. From this time on, the provision of electricity for this group could be carried out only in the regulated market (ACR). On the other hand, large final consumers may choose to purchase electricity in the regulated and/or in the free market (ACL); it is important to point out that the last option was available to them since the reforms in the 1990s.

Regarding the ACL, note also that it works as a back up to the regulated market, filling the gaps between predicted demand and supply in the latter. Moreover, the free market: (1) provides electricity for consumers not accessed by the electric power transmission and distribution network, or large final consumers not willing to pay the costs of these infrastructures and respective regulations; and (2) is a useful information source about electricity scarcity (for private and government agents), since the long term contracts in ACR may be not be able to reflect sharp changes in the supply and demand balance.

Note that the creation of a regulated market, the ACR, is a step back in the move to a more competitive model pursued by the reforms in the 1990s. The segmentation into free and regulated markets is based on the assumption that indivisibilities in electricity generation are significant enough to justify the aggregation of the demand of the electricity distribution companies. If so, sparse and incremental increases in the installed capacity of the generation market will prove to be too costly and should be avoided. Thus, it is better to aggregate the demand of the distribution companies in order to make concentrated and larger increases in the installed capacity, because this will contribute to reduce costs and enhance efficiency. In this vision, the supposed indivisibilities are assumed to be a real constraint to efficiency gains driven by free-market competition.

Hence, the 2005 reform relies heavily on the presence of indivisibilities e.g., on the prevalence of economies of scale in the power supply market. In this context, the measurement of cost and economies of scale carried out in this paper is crucial to the evaluation of the performance of the Brazilian model with respect to its ability to provide a reliable supply of electricity at competitive prices.

3. A TRANSLOG COST FUNCTION FOR POWER SUPPLY UTILITIES

Since the seminal work of Christensen and Greene (1976), there has been an increasing interest in the identification of the factors that determine electricity costs such as scale of operation, type of ownership, vertical integration, and competition at the different stages of the electric power industry. These factors are best analyzed by using a cost function, which can be derived from the following production possibility frontier:

$$f(q,k,l,e;\ z) = 0 \qquad [1]$$

Where q is the electricity output generated and z stands for the utilities' characteristics; k and l represent, respectively, the production factors capital and labor; f stands for fuel and water inputs, including eventually electricity purchased from other utilities. If the transformation function has a strictly convex input structure and firms minimize costs, there is a unique cost function, given by the following expression:

$$C = C(q, p_r, p_w, p_f;\ z) \qquad [2]$$

C is the cost of producing output q. Input prices are given, respectively, by $p_{r,}$ p_w and p_f.

Due to its flexibility and convenient properties – it imposes no restrictions on production technology and accommodates non-homotheticity – the translog functional form has been widely used to estimate cost functions such as the one specified in [2]. This function, that constitutes a local, second-order approximation to an arbitrary cost function (Christensen and Greene, 1976), may be written as:

$$\ln C = \beta_0 + \beta_q \ln q + \sum_i \beta_i \ln p_i + \beta_t t + \frac{1}{2}\sum_i \sum_j \beta_{ij} \ln p_i \ln p_j + \frac{1}{2}\beta_{qq}(\ln q)^2$$
$$+ \frac{1}{2}\beta_{tt} t^2 + \sum_i \beta_{iq} \ln p_i \ln q + \sum_i \beta_{it} \ln p_i\, t + \beta_{tq} \ln q\, t \qquad [3]$$

$with\ i = r, w, f;$

Economic theory requires that a cost function should be concave, linearly homogeneous in input prices and non-decreasing in input prices and output. These assumptions, together with the symmetry hypothesis, imply that the following restrictions should be imposed on the parameters of equation [3]:

$$\sum_i \beta_i = 1; \quad \beta_{ij} = \beta_{ji}; \quad for\ all\ i, j;$$
$$\sum_i \beta_{ij} = \sum_j \beta_{ji} = \sum_i \beta_{iq} = \sum_i \beta_{it} = 0; \qquad [4]$$

Applying Sheppard´s lemma to equation [3], the following factor share equations can be derived:

$$s_i = \frac{\partial \ln C}{\partial \ln p_i} = \beta_i + \sum_j \beta_{ij} \ln p_j + \beta_{iq} \ln q + \beta_{it} t \qquad [5]$$

As these cost shares sum to unity, there are only two independent equations to be estimated. Moreover, the translog parameter estimates allow computation of the relevant elasticities as well as productivity indexes. Note that the translog function does not impose restrictions on the elasticities of substitution. Consider the Allen-Uzawa partial substitution elasticities, σ_{ii} and σ_{ij}, that yield the extent of substitution among factor inputs. These parameters depend on the estimated factor shares s_i:

$$\sigma_{ij} = [\beta_{ji} + s_i s_j] / s_i s_j \qquad for\ i \neq j;$$
$$\sigma_{ii} = [\beta_{ii} + s_i^2 - s_i] / s_i^2 \qquad for\ i = j; \qquad [6]$$

The cross partial elasticities of substitution (σ_{ij}) are positive if inputs are substitutes and negative if they are complements. Concavity of the cost function requires that the own-price elasticities (σ_{ii}) should be negative. also It is possible also to compute the Morishima Elasticities of

Substitution (*MES*), more appropriate for the evaluation of cross-substitution. MES elasticities are:

$$MES_{ij} = \varepsilon_{ji} - \varepsilon_{ii} \qquad for\ i \neq j; \tag{7}$$

where the input demand price elasticities are given by:

$$\begin{aligned} \varepsilon_{ij} &= \frac{\beta_{ij}}{s_i} + s_j \qquad for\ i \neq j; \\ \varepsilon_{ii} &= \frac{\beta_{ii}}{s_i} + s_i - 1 \qquad for\ i = j; \end{aligned} \tag{8}$$

The asymmetry of the MES measure of substitution (Blackorby and Russell, 1989) comes from the fact that the partial derivatives are evaluated in the direction of the input price that actually changes. For any cost function with more than two inputs, the MES is symmetric only in the special case where the cost function is of the constant elasticity of substitution variety. Finally, the translog cost function permits the incorporation of technological change and its effects on input factors. The rate of technical change (TC) is given by the following expression:

$$TC = \frac{\partial \ln C}{\partial t} = (\beta_t + \beta_{tt} t + \sum_i \beta_{it} \ln p_i + \beta_{tq} \ln q) \tag{9}$$

Because technological progress leads to cost reduction, we expect TC < 0. Using equation (8), it is possible to distinguish three sources of technological changes: T_1, which represents neutral technological progress, T_2 that is the non-neutral technological effect and T_3, the scale augmenting effect. Those effects may be written as:

$$T_1 = \beta_t + \beta_{tt} t; \qquad T_2 = \sum_i \beta_{it} \ln p_i; \qquad T_3 = \beta_{tq} \ln q \tag{10}$$

T_1, the neutral technological effect, accounts for factors such managerial improvements and learning-by-doing. This “pure” technological change measures cost reductions by holding constant the efficient scale of production required to produce any output and the input shares. T_2, the Hicks non-neutral technological change, accounts for biased technical changes with respect to factor prices. Factor–using (factor-saving) technical changes are indicated by positive (negative) values for β_{it}. Hicks neutrality implies $\beta_{it} = 0$ for all i, and so is directly testable.

Finally, T_3, the scale-augmenting technical change reflects the changes in the sensitivity of total cost to variations in the efficient scale of production. If $\beta_{qt} < 0$ ($\beta_{qt} > 0$), the cost minimizing scale of production is increasing (decreasing) over time.

4. DATA AND VARIABLES

The costs for power supply utilities considered here include labor, fuel and capital costs. Yearly data for 21 power production utilities were taken from the utilities' financial accounting sheets available from Bolsa de Valores, Mercadorias e Futuros S.A. (2011) and Centrais Elétricas Brasileiras (2011), for the period 2000-2010, constituting an unbalanced panel of 198 observations. The selected utilities represent roughly 73%[3] of the installed capacity in the Brazilian electric power production (Empresa de Pesquisa Energética, 2012). Labor prices (p_w) were obtained by dividing annual labor costs by the number of employees; fuel prices (p_f) were computed by dividing annual fuel costs by their respective output. The price of capital (p_r) was based on the weighted average capital costs (*WACC*) that correspond to the cost associated with a firm's capital structure. The two main components of the *WACC* are calculated as follows: debt (d), which is composed of all the loans entered as Liabilities in the section Liabilities and Shareholders' equities in the balance sheets; equities (eq), the amount of Capital in the aforementioned section. The *WACC* is computed by using equation [10]:

$$wacc = \delta_d k_d + \delta_{eq} k_{eq} \qquad [10]$$

Where δ_i ($i = eq, d$) represent the relative weights of each component of the capital structure in total capitalization and k_i ($i = eq, d$) is the component's cost.

<<insert table 1 here>>

5. ECONOMETRIC RESULTS

Zellner's iterative method for seemingly unrelated regressions (SUR) was used to estimate the system of equations [3] and [5]. By doing so, our estimates are invariant to the share equation that is deleted. The theoretical hypothesis of linear homogeneity was imposed by dividing total cost, capital and labor input prices by the price of fuel and water inputs (p_f), whose share

[3] This proportion increases to 85% when the firms that produce electricity mostly to their own power consumption are not considered (Empresa de Pesquisa Energética, 2012).

equation was excluded. Symmetry hypotheses were also imposed. Since total cost and most of the explanatory variables are in logarithms and have been normalized around the industry's sample median, the first order coefficients represent cost elasticities, evaluated at the sample median.

Table 3 provides the estimated parameters for three different hypotheses concerning the production technology: non-homotheticity, homotheticity and homogeneity functional form specifications. All models take into account fixed effects across firms. First, note that the non-homotheticity parameters – β_{rq}, β_{fq} and β_{wq} – are significant indicating that the hypothesis that the cost function is separable in output and factor prices can be rejected. In addition, assumptions that the technology could assume more restrictive forms were tested by using a likelihood ratio test.[4] To test for homotheticity, all coefficients of the cross terms between output and other independent variables were set equal to 0 (β_{rq}, β_{wq}, β_{fq} and β_{tq}= 0). Adding the restriction that β_{qq}= 0, the homogeneity assumption was also tested. The Cobb-Douglas hypothesis was tested by setting all second derivative parameters to zero.

The results shown in table 2 reveal that all three hypotheses can be rejected: homotheticity, homogeneity and a Cobb-Douglas specification, thus emphasizing the appropriateness of the translog's more flexible framework to analyze the cost structure in the electricity power industry in Brazil. Hereafter, to conserve space, the results for the unrestricted model only will be presented. Turning now to the results (table 3), notice first that for the core variables of the cost model – output and input prices – the coefficients are significant and have the expected signs. The results point to a well-behaved cost function that is increasing in output and input prices.

<<insert table 2 here>>

Consistent with a capital-intensive industry, the coefficient for the capital cost is larger than the one attached to wages. Values estimated for the first order coefficients, β_r and $\beta_{w,}$ indicate that, at median production, capital and labor represent, respectively, 50.97% and 18.28% of total production costs. The capital share slightly decreases over the period analyzed; indeed, the coefficient β_{rt} = -0.0075 is negative and significant. Moreover, the estimated value for β_{wt} is negative but not significant. This may signal that the gains from subcontracting and other labor

[4]This likelihood-ratio test statistic $\chi^2 = -2\ln\lambda$, where $\lambda = L_r / L_{un}$, where L_r and L_{un} is the log-likelihood ratio from the restricted and unrestricted models, respectively. This statistic is distributed chi-square, with one degree of freedom for each restriction.

saving devices as an instrument to reduce labor costs are restricted. Therefore, in the post-reform era, a constant labor share may limit the power of labor to extract rents.

Fuel and water costs represent approximately one third of total generation costs as shown by the positive and significant coefficient $\beta_f = 0.307$. Moreover, this share is increasing during the period analyzed as attested by the positive and significant coefficient $\beta_{ft} = 0.0096$. This finding may be explained by the fact that the increasing use of thermoelectric technology by the new firms contributes to increasing the water/fuel cost shares. Indeed, faced with the risk of electricity rationing, the government took urgent measures, including the use of those costlier plants (Schaeffer and Szklo, 2001; Marreco and Carpio, 2006). For hydroelectric companies, increasing environmental costs – financial and bureaucratic ones – are another possible cause of the increase in the share of fuel and water on total costs (Sternberg, 2010).

<<insert table 3 here>>

To test whether vertically integrated firms have cost advantages or not, a dummy variable was included in the translog function; VER is equal to one when the observation accounts for this type of firm. The dummy is significant and negative, preventing the rejection of the hypothesis that the vertical integration provides cost advantages. In other words, the results suggest the existence of substantial costs of vertical disintegration, as pointed out by previous studies (Kwoka 2002; Fraquelli *et al*., 2005; Arocena, 2008; Arocena *et al*., 2012). Hence, the benefits of separating natural monopoly and potentially competitive segments to foster competition should also consider the unbundling costs resulting from de-verticalization. This is a particularly relevant issue for Brazil as the restructuring of its electrical sector was based on unbundling.

Firms were also differentiated according to ownership. The negative and significant coefficient for state owned utilities (dummy variable EST) indicates that those firms have lower costs than their private counterparts; even controls for size and utility characteristics are made, public utilities cost advantages are as high as 16%. This unsurprisingly result can be easily explained. First, financial costs are much higher in private and new utilities because they had to borrow in the period to build up their assets. The scenario is quite different for the older and bigger SOC companies, in that their capacity had already been installed. Additionally, our database shows that the *WACC* for the SOC is 25% lower than for their private counterparts. This is a significant cost advantage in a capital-intensive market and may reflect institutional failures of the Brazilian economy, which has a state-owned bank (BNDES) as the major player in the capital provision for new enterprises in the electric power production and other infrastructure sectors. Together, these factors contribute to lower the relative financial costs for the state-owned companies.

The variable, DQ, separates the firms into two groups: small firms producing at most five thousands GWh per year – below the output of the median firm – and those that produce at least ten thousands GWh. DQ takes a value of 1 if the firms are in the first group and zero otherwise. The positive and significant coefficient attached to the variable DQ indicates that the smallest firms exhaust their economies of scale at a much lower level of production; further, the significant and positive coefficient β_{qq} shows that scale economies are decreasing with the level of production.

As expected, utilities based on thermoelectric technology present higher costs as shown by the positive and significant coefficient for the dummy variable, *TER*, which stands for thermoelectric plants. Indeed, notwithstanding their lower investment costs, operating costs tend to be higher for utilities producing thermoelectricity when compared with the hydroelectric ones (Santana, 2005; Barroso *et al*., 2006).

5.1 SUBSTITUTION POSSIBILITIES AMONG INPUTS

The Allen-Uzawa elasticities of substitution, as well as the input demand elasticities were computed from equations (6) and (7) by using A-U and Morishima definitions. Tables 4a and 4b present the estimated values for these parameters. As required by concavity assumptions, the own partial estimated substitution elasticities are negative (σ_{ii}). Capital, labor and fuel are substitutes as attested by the positive Allen-Uzawa and Morshima substitution elasticities among these inputs.

These results corroborate those obtained by previous studies (Nerlove, 1963; Christensen and Green 1976; Lee, 1995) and confirm that possibilities of substitution among inputs – capital, labor and fuel - are quite high in power generation in Brazil, especially for labor.

<<insert tables 4a and 4b here>>

The MES reported in table 4b are presented so that each row represents a change in the price of a particular input. Hence, the first row shows the variation in labor/capital and labor/fuel ratios due to a change in the labor price. Note that the AES estimates overstate the substitution between capital and labor. On the other hand, the inherent asymmetry of MES is higher for the substitution among fuel and the other inputs.

The own price input demand elasticities – labor, capital and fuel – are, as expected, negative but their values are less than unity indicating that the conditional inputs demands are inelastic. Consistently with the values obtained for the Allen-Uzawa elasticities, the positive values for the cross-price elasticities corroborate the substitution possibilities among inputs.

6. ECONOMIES OF SCALE IN POWER GENERATION

Long run scale economies (ES), computed by holding output and input prices constant, are given by the following expression:

$$ES = 1 - \frac{\partial \ln C}{\partial \ln q} \qquad [11]$$

where $\frac{\partial \ln C}{\partial \ln q}$, the elasticity of cost with respect to output, is obtained by differentiating [3] with respect to ln*q:*

$$\frac{\partial \ln C}{\partial \ln q} = \frac{\partial C}{\partial q}\frac{q}{C} = \beta_q + \beta_{DQ} DQ + \sum_i \beta_{iq} \ln p_i + \beta_{qq} \ln q + \beta_{tq} t \qquad [12]$$

Marginal costs for the j^{th} firm may be computed by using equation [12]:

$$\frac{\partial C}{\partial q_j} = \frac{\partial \ln C}{\partial \ln q_j}\frac{C}{q_j} = [\beta_q + \beta_{DQ} DQ + \sum_i \beta_{iq} \ln p_i + \beta_{qq} \ln q_j + \beta_{tq} t]\frac{C_j}{q_j} \qquad [13]$$

From (11) and (12), ES may be written as:

$$ES = 1 - \beta_q - \beta_{DQ} DQ - \sum_i \beta_{iq} \ln p_i - \beta_{qq} \ln q - \beta_{tq} t \qquad [14]$$

Hence, a positive value for ES indicates the presence of economies of scale; a zero value stands for constant returns to scale whereas a negative value points to diseconomies of scale. Notice that at the median value for the variables, ES is simply ($1 - \beta_q - \beta_{DQ}DQ$) for the corresponding model. Evaluating ES for the Brazilian power supply utilities at the median level, the cost elasticity with respect to output (EL) is given by β_q, whose estimated value is 0.5345 (table 3). The value for ES = ($1 - \beta_q$) is 0.4655 for the utilities producing above the sample median output level, indicating the presence of economies of scale for this group. Hence increasing production would lead to a less than proportional rise in costs, thus benefitting the largest utilities.

Considering that in our sample, ITAIPU's production is slightly above 20% of total electricity generated by all companies – corresponding to 8 times the median output –the impact of this firm was evaluated to see whether the economies of scale of the largest companies are driven by this one observation. Results shown in table 5 indicate that the estimated cost elasticities and scale economies for the sample that excludes ITAIPU are very similar to the ones estimated for the whole sample. Therefore, the significant economies of scale of the largest companies are not driven by this outlier.

Table 5 shows that the estimated elasticity and scale economies are quite different between the two groups. For the smallest companies, at the median level, their EL is given by ($\beta_q + \beta_{DQ}$), whose estimated value is 1.1280 (table 3). The value for ES = $1 - (\beta_q + \beta_{DQ})$ is -0.1280 suggesting that, at the median output and prices, this group faces diseconomies of scale.

<<insert table 5 here>>

The results of one additional exercise are presented in table 6. For both groups of utilities (large and small), the presence of scale economies was estimated for different levels of output, simulating a continuum interval for these levels and holding factor prices constant. The results revealed that economies of scale are exhausted for production levels slightly above 6,200 MWh when the group of firms producing below the median output is considered.

Table 6 shows that economies of scale diminish with output level in the non-homothetic model, but are exhausted at a relatively low production level only for the group with smaller firms. Notice that for this output level, the largest utilities, as expected, show substantial scale economies because their installed capacity is being underutilized. To exhaust scale economies, large firms would have to produce more than 90,000 MWh.

<<insert table 6 here>>

Figure 1 plots marginal and average cost curves for simulated levels of production for utilities producing less than the median output. Here, as required by the translog cost function, those curves and the others in Figures 2 and 3 were fitted by normalizing the explanatory variables around the median of each mentioned group. Up to 6,200MWh, marginal costs are lower than average costs, so that unit costs are decreasing. For higher output levels, the average costs are slightly increasing and marginal costs continue to rise, driving unit costs upwards.

Notice that for output levels between 6,200 and 11,700 MWh, the median output of the complete sample, the average cost curve is slightly increasing. Indeed, for those production levels, average costs stay between US$ 116 and US$ 121 per MWh, so thatthe hypothesis of a relatively flat ACC in this range of output cannot be rejected.

Complementing the above information, figure 2 shows also that small utilities have lower average costs than the largest companies up to 2,400 MWh. This means that particular markets or consumers with an electricity demand lower than 2,400 MWh could be more efficiently provided by companies without scale economies, since the largest firms are more costly below this level of output.

<<insert figures 1 and 2 here>>

These results suggest that submarkets with a relatively smaller electricity demand could be served efficiently by competitive suppliers. This is likely the case for the submarkets in the non-regulated segment of the electric power production, the ACL. The demand in this segment is mainly composed of large final consumers of electricity who are not individually significant as a proportion of the total demand for this good; it could also be generate by an unexpected increase in the consumption of the regulated market, the ACR, and in that sense may include the residual demand of these regulated transactions.

Notice that the above finding is consistent with the observed increase in the number of the utilities in the electricity industry and suggests that competition is being enhanced at least for the fraction of the market that supplies the consumers in the ACL. For utilities producing above the median output, the picture is rather different. When only those firms are considered, the average cost curve declines over the relevant output range and it is situated above the marginal cost curve (figure 3). Therefore, the findings are consistent with existence of significant indivisibilities in the electricity generation system. This outcome suggests also that the regulated market (ACR) may achieve welfare gains by aggregating the demand of the electricity distribution companies in order to support the operation (and the potential addition) of large plants in the electric power production.

<<insert figure 3 here>>

Table 8 reports the median output, average cost and economies of scale for the firms in the sample. For both output groups, as previously stated, economies of scale decrease with production. Note also that no firm has exhausted its economies of scale. However, unexploited economies of scale are much smaller for companies producing below the median output. As previously noted, average costs are higher for that group in most of the cases at the sample median output.

<<insert table 8 here>>

The analysis indicates that in the Brazilian power supply, monopolist elements seem to prevail over efficiency gains driven by a free and competitive market. The results provide support to those who believe that the largest firms have significant cost advantages over the smallest ones in the submarkets where the large demand of electricity allows exploitation of scale economies. Those findings advocate in favor of the last reform in the studied industry, which represents a step back in competition with the creation of the regulated transactions for the distribution utilities.

Yet, for submarkets with electricity demand below the sample median output, the picture is rather different. The smallest firms may be more efficient than the larger companies in the provision of electricity for these submarkets because their average costs do not seem to increase abruptly in supplying such demand.

Therefore, the relatively smaller firms can be efficient suppliers in the ACL, which was designed to (1) work as a backup for marginal adjustments between predicted demand and supply in the regulated market and (2) supply specific demands of electricity to those customers having no access to the electricity transmission and distribution infrastructures, or not willing to pay the costs of these services. Note also that the possibilities of competitive supply in the ACL are consistent with the increasing number of firms in this segment of the Brazilian electricity market.

How do economies (diseconomies) of scale vary with respect to the pattern of input utilization? A significant and negative (positive) value for the coefficient β_{iq} $(i = w, r, f)$ indicates the presence of economies (diseconomies) of scale with respect to use of that particular factor. Hence, when the power supply grows, a reduction (rise) in the input-output ratio with respect to the input is observed. The coefficient β_{rq} is not significant; however, the estimated coefficients β_{wq} and β_{fq} are, respectively, -0.047 and 0.0456 (table 3) indicating that, at this input level, labor creates economies of scale whereas fuel generates diseconomies of scale. This result indicates that the natural resources used in the electric power production, primarily water,[5] are already a constraint to the scale economies.

7. TECHNOLOGICAL CHANGE

A likelihood-ratio test was used to investigate three hypotheses concerning technological progress, as stated in equation (9). The results are shown in table 9. One cannot reject the hypotheses of zero scaled augmenting effect. Notice that these tests refer to the conjoint effects of the group of coefficients. They do not exclude the existence of the effect at a particular output/factor level.

<<insert tables 9 and 10 here>>

Table 10 reports the rate of technical change and its decomposition for the period 2000-2010. The results show that technical progress led to a cost reduction in the power generation sector, at the annual rate of 0.041 over the period analyzed, indicating the occurrence of technological progress in electricity generation.

As for the analysis by TC component, the Hicks neutral effect, T_1, is negative, with both estimates, for β_t and β_{tt}, negative; however, the latter is not significant at the usual significance levels. On the other hand, the Hicks non-neutral effect, T_2, is positive, signaling that, on average, the technical changes have been increasing the use of inputs to produce electricity. Note that the coefficients β_{wt} and β_{rt} are negative, whereas the coefficient for fuel is significant and positive. Thus, the factor-use of fuel is dominating the factor saving of the other inputs and leading to the increase input expenditures. This dominancy may reflect, as already noted, the greater presence of thermoelectric technology and the increasing environmental costs in the generation market. At least the upward movement of the expenditures in fuel, including water, signals the increasing scarcity of the natural resources used in the electric power production. As highlighted before, these resources are already a constraint to the estimated economies of scale, given the significant and positive coefficient β_{fq}. Thus, their increasing scarcity tends to restrict those economies even more.

Finally, the negative scale augmenting effect indicates that the scale efficient production level is augmenting over time in the full sample. However, β_{tq} is not significant; consequently, it is not

[5] The intense use of water is due to the mentioned fact that the hydroelectric power plants have been accounting for most of the installed capacity in the Brazilian electric power production (77% in 2010).

possible to dismiss the hypothesis that the efficient scale of production in the power electric supply did not change during the period analyzed.

8. CONCLUDING REMARKS

This paper has examined the cost structure of the electricity generation companies in Brazil during the period 2000-2010, by using a translog cost function that imposes no restrictions on production technology and allows for the existence of non-homotheticity. The results show that utilities' institutional and technological characteristics such as size, type of ownership and source of energy influence the costs of power supply in Brazil. As expected, smaller and/or thermal plants have higher costs when compared with the larger/hydroelectric ones. Vertically integrated firms tend to have lower costs even controlling for other utilities' characteristics, corroborating previous studies that unbundling is costly. Therefore, these costs need to be considered by the policy makers in creating further incentives to break up vertical integration in the industry.

Finally, the reduced investment expenses of the state owned companies and their lower *WACC*, by decreasing their financial obligations, contributes to curtail costs for those utilities. In particular, the lower *WACC* may reflect institutional failures of the Brazilian capital market. The policy implication of such circumstance goes beyond the regulation of the electricity industry; nevertheless, it highlights the remaining obstacles to the attraction of private investment in this market.

Concerning economies of scale, they decrease with production, for both output (large and small) groups. Note also that the results point to the existence of substantial economies of scale only for the group of the largest companies. Firms producing below the median output exhaust their economies of scale at production levels slightly above 7,000 MWh. Nevertheless, these companies have lower average costs in comparison to the largest ones up to 2,400 MWh and these costs do not increase sharply at lower level of outputs. This fact supports the possibility that submarkets with relatively smaller electricity demand can be provided efficiently by a competitive supply. This possibility is another policy implication of the results discussed. In addition, observe that these submarkets tend to be in the non-regulated segment of the electric power production transactions, the ACL.

This segment complements the regulated one, the ACR, supplying electricity for the demand that results from (1) errors on the forecasted consumption and production in the regulated market;

and (2) consumers that have no access, or those who prefer to avoid the costs derived from the use of the electricity transmission and distribution infrastructures.

On the other hand, for utilities producing above the median output, economies of scales prevail over the relevant production range. For this group, scale economies persist for output levels as high as 90,000 MWhs. Hence, the hypothesis that economies of scale are a typical feature of the generation market in Brazil cannot be rejected and, in general, are not exhausted at lower levels of production. This result is likely related to the fact that the structure of the electric power industry is still very concentrated, with a few utilities dominating a significant share of the market. Such a concentration indicates that monopolist elements seem to have predominated over efficiency gains driven by competition from the new entrants. Hence the results support the vision that indivisibilities restrict welfare gains from free-market competition in the Brazilian electricity generation market and this is the main policy implication of the paper. Indeed, most of the last restructuring in the industry regulation is based on this assumption. In addition, the diseconomies of scale related to fuel use suggest that the endowment of natural resources – mainly the water used by the hydro power plants that are the major suppliers of the market – does not support further increases in those economies. Moreover, the use of fuel is already increasing the costs of power supply in the period analyzed, implying that the cited resources are increasingly restricting the exploitation of scale economies.

Note also that, over the sample period, technological progress led to cost reductions in the power electricity supply. These technological improvements take the form of both a neutral technological effect as well as a non-neutral capital and labor saving technical changes. Nevertheless, the fuel using technical change dominates the former saving effects, leading to higher inputs costs and signaling the increasing scarcity of natural resources available to the electric power production.

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TABLES AND FIGURES

Table 1 – Data Summary Statistics: 2000 a 2010

Variables (annual data) *	Median	Mean	Standard error	Maximum	Minimum
Electricity Production (GWh)	11,659.82	21,288.38	23,348.12	94,344.52	339.00
Cost of Capital	10.07%	11.24%	7.37%	48.17%	0.50%
Average Wage (US$ 1,000)	88.15	94.44	45.78	488.03	17.90
Capital costs (US$ 1,000)	268,868.27	472,349.49	864,949.73	6,121,238.11	1,341.84
Labor Costs (US$ 1,000)	49,784.20	90,753.20	122,384.32	691,088.51	642.74
Fuel and Water Costs (US$ 1,000)	118,677.10	380,261.96	942,687.19	8,161,349.52	793.15
Total Cost (US$ 1,000)	470,773.16	943,364.65	1,452,167.72	8,681,348.23	8,367.50
Capital share (%)	53.77%	49.76%	27.03%	91.61%	1.32%
Labor share (%)	11.47%	16.67%	16.96%	83.05%	0.26%
Fuel and Water share (%)	24.54%	33.57%	24.68%	95.02%	3.63%

*Price Index: IPCA (December 31, 2012 = 100). Exchange rate (R$/US$): 1.6662 (12/31/2010).

Source: Bolsa de Valores, Mercadorias e Futuros S.A. (2012), Centrais Elétricas Brasileiras (2012).

Table 2 – Specification Tests for the Cost Function

Null hypothesis	D. F	LR Statistics χ^2	Statistics χ^2 (0.99)	Prob> χ^2	Result
$\beta_{rq} = \beta_{wq} = \beta_{fq} = \beta_{tq} = 0$ Homotheticity	3	102.29	11.34	0.000	Reject null hypothesis by 1%
$\beta_{rq} = \beta_{wq} = \beta_{fq} = \beta_{tq} = \beta_{qq} = 0$ Homogeneity	4	108.75	13.28	0.000	Reject null hypothesis by 1%
$\beta_{rq} = \beta_{wq} = \beta_{fq} = \beta_{tq} = \beta_{qq} = \beta_{rw} = \beta_{fw} = \beta_{ff} = \beta_{fr} = \beta_{ww} = \beta_{rr} = \beta_{ft} = \beta_{rt} = \beta_{wt} = \beta_{tt} = 0$ Cobb-Douglas	10	563.04	23.21	0.000	Reject null hypothesis by 1%

Source: our computations

Table 3 – Cost Function Parameter Estimates

Parameter	Unrestricted		Homotheticity		Homogeneity	
	Coefficient	Std-error	Coefficient	Std-error	Coefficient	Std-error
βr	.509721*	.0112835	.512165*	.0115074	.5138792*	.0115799
βw	.1828783*	.0093898	.1915722*	.0106604	.1895074*	.0106709
βf	.3074007*	.0083294	.2962628*	.0084375	.2966134*	.0084591
βq	.5344766*	.0929164	.6649566*	.1059508	.8310779*	.0912965
βt	-.0463377*	.0050993	-.0462347*	.0058179	-.0475482*	.0061446
βrr	.0672424*	.0040257	.0666764*	.0044217	.0670704*	.0044441
βww	.03349288*	.0046616	.0384552*	.0051179	.0393732*	.0050027
βff	.0795013*	.0036542	.0762473*	.0039546	.0766333*	.0038756
βwr	-.0106169*	.0038982	-.0144422*	.0042929	-.0149051*	.0042512
βwf	-.0228759*	.0026465	-.0240131*	.0029613	-.0244681*	.0028889
βrf	-.0566254*	.0025197	-.0522342*	.002621	-.0521652*	.0025835
βqq	.1029702*	.0301362	.0903413*	.0337818		
βtt	-.0006177	.0008565	-.000518	.0009882	-.0002982	.0010008
βwt	-.0020677	.0024724	-.0005603	.002839	-.0007617	.0028522
βrt	-.0074966*	.0022703	-.0085527*	.0025312	-.0083812*	.0025586
βft	.0095643*	.0015961	.009113*	.0017904	.0091429*	.0018041
βrq	.0015432	.0066501				
βwq	-.0470939*	.0059276				
βfq	.0455507 *	.0051371				
βtq	-.0020214	.0018303				
DQ	.5935506*	.1646027	.5990758*	.188167	.174373***	.0983221
VER	-.3299407*	.0564066	-.1719047*	.0533019	-.1868465*	.0479796
TER	.3417279*	.1036738	.1786568***	.1047559	.0441567	.0551903
EST	-.1620985*	.0531731	-.2934465*	.0536486	-.3307266*	.0506224
Constant	.0716963**	.0355094	.1221506*	.0404572	.1125041*	.0413059

Levels of significance: * 99% confidence, ** 95%, *** 90%.

Source: our computations

Table 4a – Allen-Uzawa Elasticities of Substitution and Input Demand Elasticities

Inputs	Parameters[1]					
	Elasticities of Substitution			Input Demand Elasticities		
	Labor	Capital	Fuel	Labor	Capital	Fuel
Labor	-2.45			-.45	.36	.09
Capital	.76	-.51		.14	-.24	.10
Fuel	.27	0.30	-.57	.05	.14	-.19

1 – Computed at the sample median output, price and time levels.

Source: our computations

Table 4b – Morishima's Elasticities of Substitution

Inputs	Parameters[1]		
	Labor	Capital	Fuel
Labor		0.59	0.50
Capital	0.60		0.38
Fuel	0.28	0.29	

1 – Computed at the sample median output, price and time levels.

Source: our computations

Table 5 – Elasticity[1] (EL) of cost with respect to output by Group and Sample at the median output of each sample.

Group[2]	Sample (results at the median of each sample)			
	Complete		Without ITAIPU	
	Coefficient	St-error	Coefficient	St-error
Below median output: EL = $\beta q + \beta_{DQ} DQ$, where $DQ = 1$.	1.128027*	.1012982	1.087768*	.0944811
Above median output: EL = βq, since $DQ = 0$.	.5344766*	.0929164	.4978151*	.0911343

Level of significance: * 99% confidence; 1 – Elasticity computed at the sample median output, price and

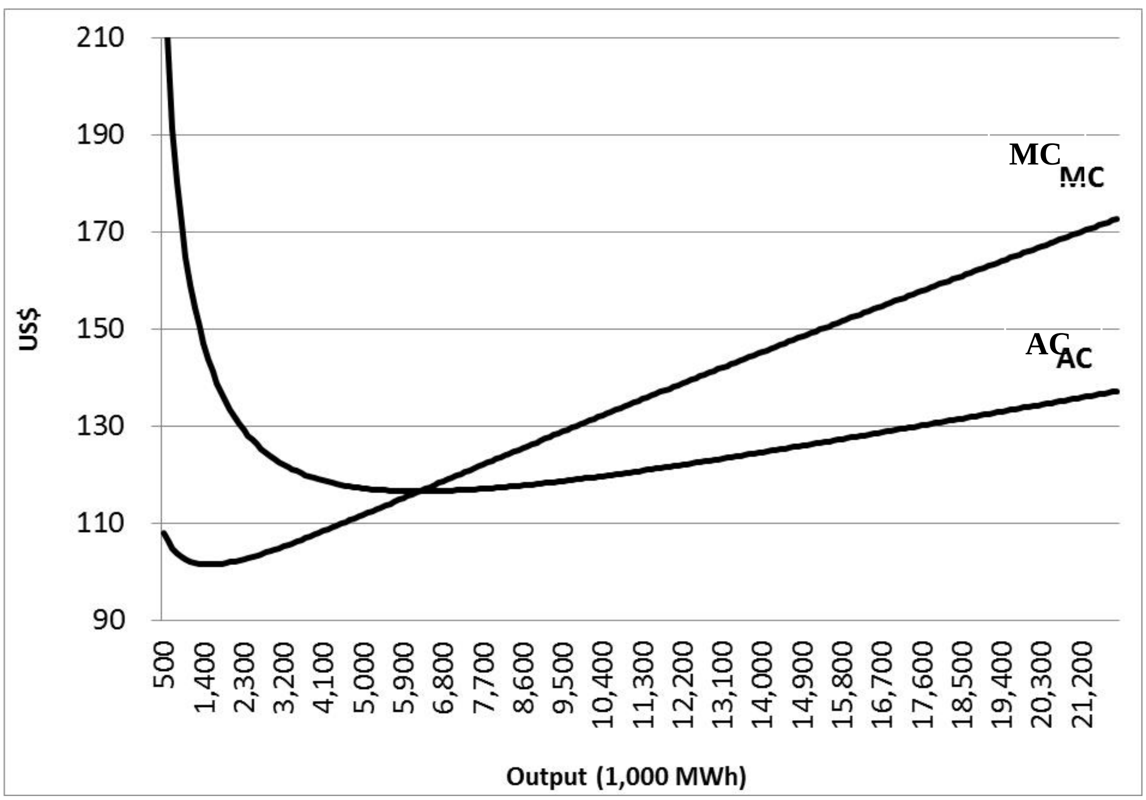
Source: our computations

Table 6 – Economies of Scale by Group and Output Levels: 2000/2010

Output level (1,000 MWh)	Scale Economies by Group*	
	Below median output	Above median output
2,000	23.50%	82.86%
6,200	0.20%	59.56%
12,000	-13.39%	45.96%
30,000	-32.27%	27.09%
94,000	-55.79%	3.57%

* Computed at the median output of each group and at the sample median prices and time levels. It is given by equation [14] and at the sample median price and time levels this equation becomes:
$ES = 1 - (\beta q + \beta_{DQ} DQ) - \beta qq ln q$, DQ = 1 if small, and 0 otherwise.
Source: our computations.

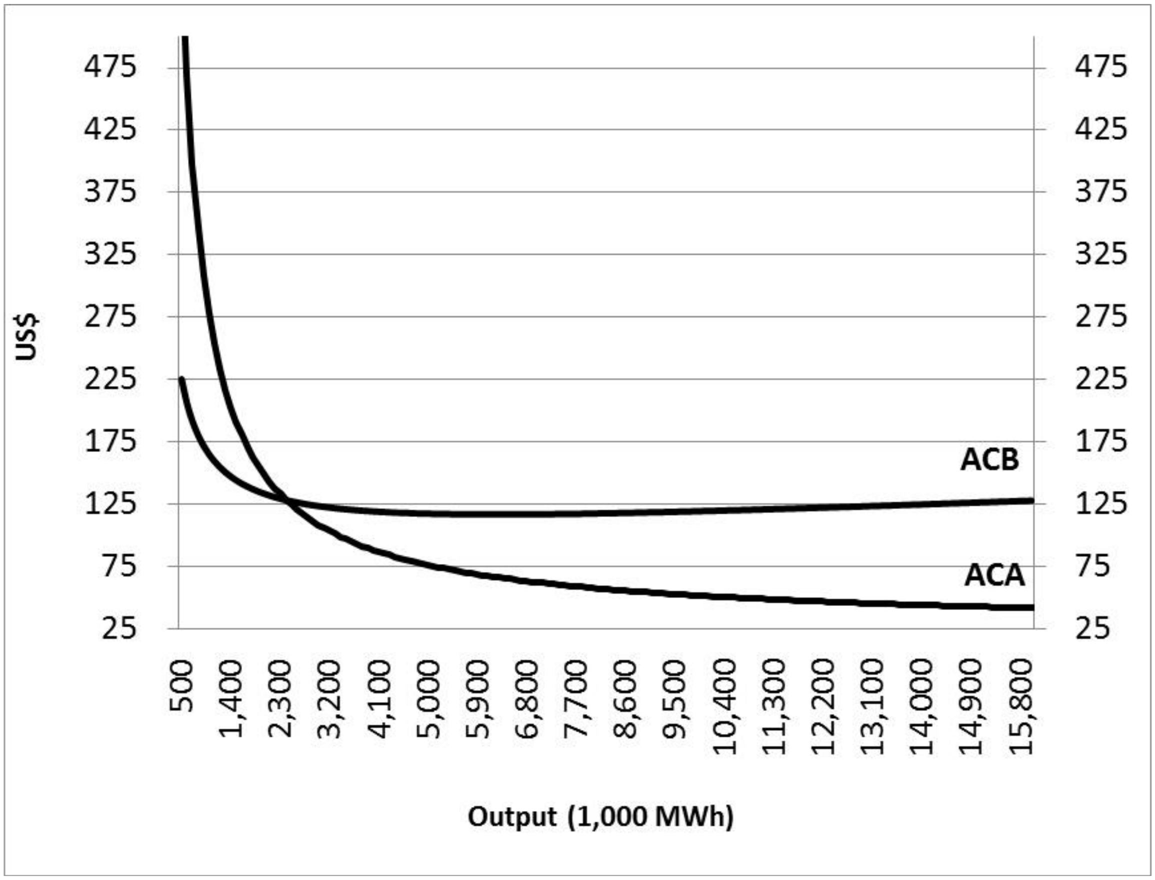
Figure 1 – Average (AC) and Marginal Costs (MC) for the Group with Average Production Below Median Output



Price Index: IPCA (December 31, 2012 = 100). Exchange rate (R$/US$): 1.6662 (12/31/2010).

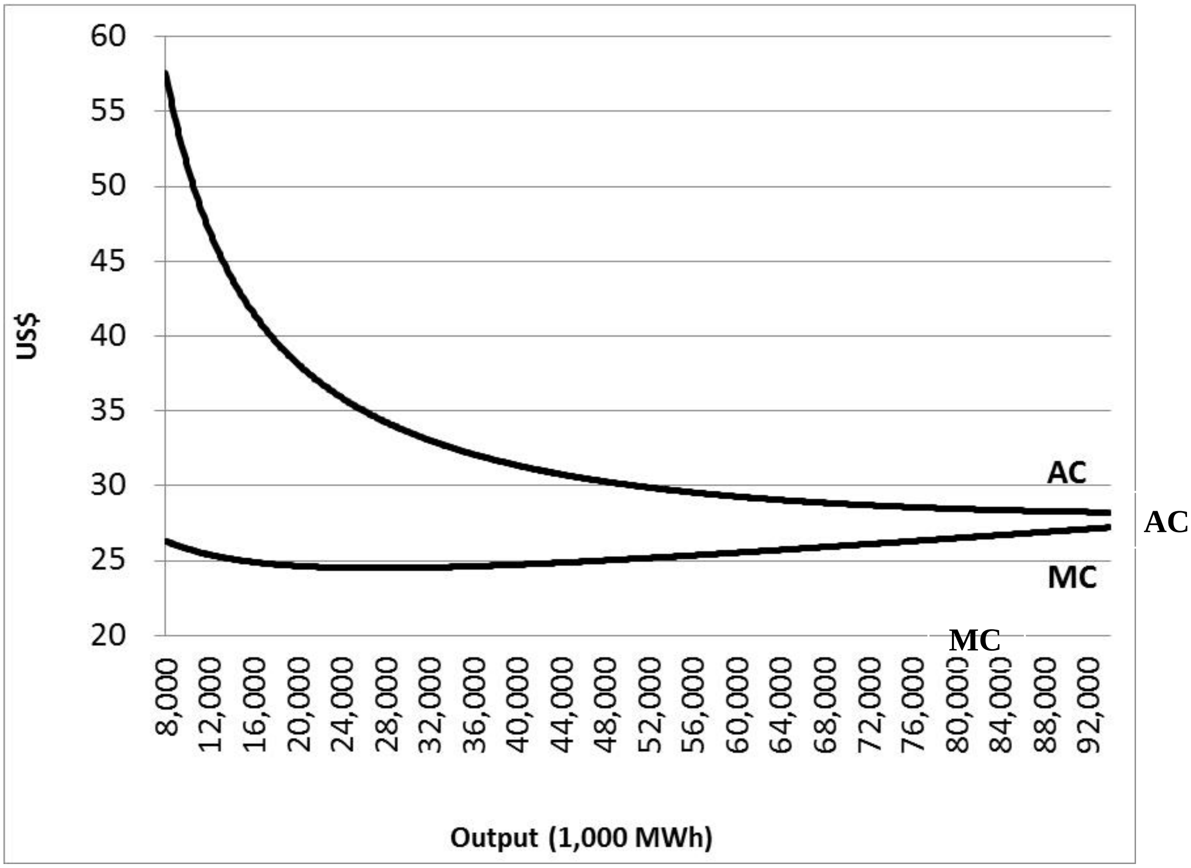
Source: our computations

Figure 2 – Average Costs for the Group with Average Production Above (ACA) and Below (ACB) the Median Output.



Price Index: IPCA (December 31, 2012 = 100). Exchange rate (R$/US$): 1.6662 (12/31/2010).
Source: our computations

Figure 3 – Average (AC) and Marginal Costs (MC) for the Group with Average Production Above Median Output.



Price Index: IPCA (December 31, 2012 = 100). Exchange rate (R$/US$): 1.6662 (12/31/2010).
Source: our computations

Table 8 – Median Output, Average Cost and Economies of Scale by firm

Group	Firm	Median Output (GWh)	Average Cost (US$/MWh)	ES
BELOW MEDIAN OUTPUT	CELESC	495	88.61	52%
	ELEJOR	1,186	60.73	34%
	CERON	1,413	57.38	31%
	EMAE	1,695	54.45	27%
	ITAPEBI	2,075	51.78	23%
	CGTE	2,182	51.21	22%
	TERMOPE	3,986	46.64	9%
	CEEE	4,060	46.56	9%
	CPFL	4,574	46.13	6%
	LIGHT	4,967	45.92	5%
ABOVE MEDIAN OUTPUT	DUKE	9,908	51.40	50%
	TERMONUCLEAR	12,415	46.17	45%
	AES-TIETE	12,475	46.07	45%
	COPEL	19,111	38.72	36%
	TRACTABEL	29,822	33.61	27%
	CEMIG	30,412	33.44	27%
	ELETRONORTE	38,871	31.50	22%
	CESP	40,725	31.19	21%
	CHESF	49,911	30.03	17%
	FURNAS	55,743	29.52	14%
	ITAIPU	89,082	28.23	5%

1 – Computed at the median output of each firm and normalized around the industry's sample median output and input prices. Price Index used: IPCA (December 31, 2012 = 100). Exchange rate (R$/US$): 1.6662 (12/31/2010).
2 – Given by equation [11], since it is computed at the median output of each firm and at the sample median prices and time levels.
Source: our computations

Table 9 – Likelihood Tests for Different Effects Concerning Technological

Null hypothesis	D.F	LR Statistics X^2	Statistics X^2 (0.99)	Prob>X^2	Result
$\beta_{rt}= \beta_{wt}= \beta_{ft}0$ Non-neutral technological effect	2	35.18	9.21	0.00	Reject null hypothesis by 1
$\beta_{qt}= 0$ Scaled augmenting effect	1	1.19	6.63	0.28	Not reject null hypothesis by 1
$\beta_{tt}= \beta_{t}= 0$ Neutral technological effect	2	66.68	9.21	0.00	Reject null hypothesis by 1

Source: our computations

Table 10 – Technological Progress and Its Components – Unrestricted Model

Year	TC	T_1	T_2	T_3
2000	-0.03568	-0.03893	0.00287	0.00038
2001	-0.02948	-0.04016	0.01042	0.00026
2002	-0.03712	-0.04140	0.00417	0.00011
2003	-0.03774	-0.04263	0.00449	0.00040
2004	-0.03687	-0.04387	0.00647	0.00053
2005	-0.04026	-0.04510	0.00440	0.00044
2006	-0.04323	-0.04634	0.00242	0.00069
2007	-0.04507	-0.04757	0.00186	0.00064
2008	-0.04624	-0.04881	0.00220	0.00037
2009	-0.04886	-0.05004	0.00085	0.00034
2010	-0.05266	-0.05128	-0.00134	-0.00003
2000-2010	-0.04120	-0.04510	0.00353	0.00038

Source: our computations.