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INCENTIVE REGULATION AND THE ROLE OF CONVEXITY IN BENCHMARKING ELECTRICITY DISTRIBUTION: ECONOMISTS VERSUS ENGINEERS

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ABSTRACT:** *This note illustrates the potential impact of the specification of a convex production technology on establishing minimal costs compared to the use of a non-convex technology when benchmarking electricity distributors. This methodological reflection is mainly motivated by recent engineering literature providing evidence for non-convexities in electricity distribution. An empirical illustration using non-parametric specifications of technology illustrates this main point using a sample of Spanish electricity distribution firms earlier analysed in Grifell-Tatjé and Lovell (2003).*

1 Introduction

Recently, the electric power sector, along with other network industries, has been deregulated throughout the world in an effort to introduce market-oriented measures to improve sector performance.

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** *Résumé en fin d'article; Zusammenfassung am Ende des Artikels; resumen al fin del artículo.*

Typically, in the electricity industry these regulatory reforms have included, partially or completely, the following elements: (i) the privatization of public enterprises, (ii) a separation between potential competitive (generation and retail supply) and natural monopoly segments (distribution and transmission), (iii) the design of competitive markets at both the wholesale and retail levels, and (iv) the implementation of performance-based or incentive regulatory mechanisms (e.g., price cap regulation via the well-known RPI-X formula) to remaining regulated segments in an effort to complement traditional cost-of-service regulation (see Joskow (2006) for details on this broader framework). As stated, one important aspect of this new regulatory environment is the use of yardstick competition (Schleifer 1985) or frontier-based performance benchmarking to set the efficiency requirements (i.e., the X-factor) based on a relative efficiency assessment. While yardstick competition regulates the price of each firm based on the average costs of the other firms producing the same homogeneous good, many regulators have opted for frontier-based performance benchmarks to set expected or target growth rates of total factor productivity at the sector level or to define annual target changes in efficiency at the firm level. Jamasb and Pollitt (2001) provide a survey of the many countries implementing such performance benchmarking schemes in their electricity sector.

The distribution of electricity is one of the activities subject to this regulation. Traditionally, convex technologies, both parametric and non-parametric, are being used for this benchmarking purpose to define this X-factor representing the extracted information rents. The use of such benchmarks based on frontier notions of production technologies and value functions is now well integrated into what can be called applied regulation theory (see the Bogetoft (2000) survey) and is part and parcel of the handbooks for regulation developed by international institutions like the World Bank (e.g., Coelli et al. 2003). Examples of such studies in the electricity sector abound (see, e.g., Farsi, Filippini and Greene (2006) for a distribution study).

This approach is not without controversy. For instance, Cronin and Motluk (2007) contest the almost exclusive reliance in current regulatory practice throughout the world on technical efficiency notions and insist that regulators employ cost efficiency notions instead. Furthermore, they demonstrate how incomplete specifications of inputs, outputs and costs, and lack of panel data may seriously bias estimates and yield frontier results that are worse than using the simple Schleifer (1985) average cost formulas. Additional critical reflections along the same lines – with emphasis on electricity networks- are found in Shuttleworth (2005).

In economic theory, the single main argument against convexity of production correspondences is probably related to indivisibilities. For instance, in a series of contributions Scarf (1986, 1994) is among the authors forcefully arguing on the importance of indivisibilities in selecting among technological options. This general argument has been used to plea in favour of using non-convex instead of convex non-parametric technologies by Tone and Sahoo (2003). While the general validity of this claim opens up a vast research agenda, we simply contribute to the analysis of this controversy by focusing on the impact of convexity in benchmarking electricity distribution.[1]

The latter sector is selected given the existence of some general arguments in the academic literature pointing to the existence of indivisibilities. In the electricity power industry, it is well-known that the lumpiness of large infrastructural investments is pervasive both in generation and distribution activities (see Elmaghraby et al. 2004). The resulting non-convexities of technologies create enormous problems in defining auction and market mechanisms mimicking perfect competition (e.g. Anandalingam, Day and Raghavan 2005). Of particular relevance for our contribution, the discrete nature of network investments in transmission capacity and increasing returns to scale are among the main causes of non-convexities in electricity distribution (see, e.g., O'Neill et al. (2005b) and the survey by Brunekreeft, Neuhoff and Newbery (2005)).[2]

To put these general arguments in context, one should realize that the underlying technology of an electricity distribution network is discrete in nature and has been gradually built over decades in response to the evolving historical economic reality given by changes in demand and marked structure. Thus, there is at best piecemeal planning involved in its construction. Spain is a pioneer in regulating electricity distribution using an 'ideal' engineering benchmark network across the country rather than using yardstick

1 Non-convexity may also have been neglected because of the theoretical difficulty of designing Walrasian markets for integer constrained activities. However, O'Neill et al. (2005a) offer results for markets with non-convexities on the existence of market clearing prices and the economic interpretation of strong duality for integer programs.

2 In electricity generation, start-up costs, minimum output levels, and minimum up and down time constraints, among others, also seem to create non-convexities (see Arroyo and Conejo (2000), Makkonen and Lahdelma (2006), among others).

competition. Thus, it gives us a rare opportunity of studying how an actual electricity distribution network is built and how an ideal one could have been built.

This discussion triggers the question what exactly the empirical impact of convexity is when analyzing cost functions in industries where this assumption is debatable. The discrete nature of these networks being beyond doubt, the real question at stake is the relevance of convexity when comparing costs across these networks. To reassess the convexity property of the cost function in electricity distribution, we compare a sample of Spanish distributors analysed earlier by Grifell-Tatjé and Lovell (2003) (henceforth GTL) using convex versus non-convex cost functions. The comparison between historical and ideal Spanish networks with their specific discrete nature could help to assess the convenience of the standard economic convexity assumption.

Staying firmly within the economic approach, we estimate convex versus non-convex cost functions with the help of non-parametric specifications developed in Briec, Kerstens and Vanden Eeckaut (2004) (henceforth BKVE). This choice is motivated by two theoretical reasons. First, to the best of our knowledge, there does not seem to be a pair of parametric alternative specifications allowing testing for convexity. Second, this non-parametric framework is in line with the non-parametric nature of the fundamental axioms being scrutinized. Or, in the words of Fuss, McFadden and Mundlak (1978: 223): 'Given the qualitative, non-parametric nature of the fundamental axioms, this suggests … that the more relevant tests will be non-parametric, rather than based on parametric functional forms, even very general ones.'

In addition, these non-convex estimators turn out to possess rather attractive statistical properties.[3] Imposing only strong disposability, these are consistent estimators for any monotone boundary. Asymptotically there is no reason for imposing convexity. When the true cost function is convex, the non-convex estimator converges to the true estimator, albeit at a slow rate. By contrast, a convex model causes specification error when the true cost function is non-convex.

The structure of this note is as follows. The second section develops the specification of technologies and cost functions. Section three first describes the data used by GTL as well as their decomposition methodology to assign sources to the observed cost difference between

3 See Park, Simar and Weiner (2000), or the literature review in Simar and Wilson (2000).

actual and ideal networks. The final subsection presents the empirical results for both cost functions estimated using convex and non-convex specifications of technology. A concluding section offers some final thoughts.

2 Cost functions on non-convex and convex non-parametric technologies

This section introduces the necessary definitions of the convex and non-convex non-parametric specifications of the production possibility set, the input distance function and the corresponding cost functions (see BKVE for details). Assume there are K observations characterized by an input vector $x \in \mathbb{R}^{n}{}_{+}$ and an output vector $y \in \mathbb{R}^{m}{}_{+}$. The production possibility set or technology defines the set of feasible production combinations: $S = \{(x,y) \mid x \text{ can produce } y\}$. Associated with S, the input set denotes all input vectors x capable of producing a given output vector y: $L(y) = \{x \mid (x,y) \in \mathrm{S}\}$.

The input distance function offers a complete characterization of technology and it is defined as:

$$D_i(x, y) = \begin{cases} \max\{\theta : \theta \geq 0, x/\theta \in L(y)\} & \text{if} \quad y \neq 0, \\ +\infty & \text{if} \quad y = 0. \end{cases} \tag{1}$$

The radial measure of input technical efficiency ($E_i(x,y)$) is simply the inverse of this input distance function ($E_i(x, y) = \left[D_i(x, y)\right]^{-1} = \lambda$). It denotes the proportional reduction in inputs that are feasible while maintaining production of a given output vector and it has a cost interpretation.

A unified algebraic representation of the convex and non-convex technologies is:

$$L^{\Lambda}(y) = \left\{x : x \geq \sum_{k=1}^{K} x_k\, z_k,\ y \leq \sum_{k=1}^{K} y_k\, z_k,\ \sum_{k=1}^{K} z_k = 1,\, z_k \in \Lambda \right\},$$
$$\text{where } \Lambda \in \{NC, C\},$$
$$\text{with } (i)\ NC = \left\{z_k \in \mathbb{R}^K_+ : z_k \in \{0, 1\}\right\}, \text{and} \quad \text{(ii) } C = \left\{z_k \in \mathbb{R}^K_+ : z_k \geq 0\right\}, \tag{2}$$

where z is the activity vector. These technologies basically impose strong input and output disposability and variable returns to scale and differ only in the convexity assumption.

For an observation being evaluated, the radial measure of input technical efficiency $E_i(x,y)$ can be computed on non-convex non-parametric technology $L^{NC}(y)$ using the following closed-form expression:

$$E_i(x,y) = \min_{(x_k,y_k)\in B(x,y)} \left\{ \max_{n\in I(x_k)} \left(\frac{x_{kn}}{x_n} \right) \right\}, \tag{3}$$

where the better set $B(x, y)$ of the evaluated observation (x, y) is defined as follows:

$$B(x,y) = \left\{ (x_k, y_k) : x_k \leq x, y_k \geq y \right\}. \tag{4}$$

Its computation on a convex non-parametric technology $L^C(y)$ requires solving a linear program for each unit in the sample (see Färe, Grosskopf and Lovell (1994)):

$$\begin{aligned} E_i(x,y) &= \min_x \lambda \\ \text{subject to } \sum_{k=1}^{K} x_k\, z_k &\leq \lambda x, \\ \sum_{k=1}^{K} y_k\, z_k &\geq y \\ \sum_{k=1}^{K} z_k &= 1 \\ z_k \geq 0,\ x &\geq 0. \end{aligned} \tag{5}$$

The cost function designates the minimum outlays necessary to produce an output vector y given an input price vector $w \in \mathbb{R}^n{}_{++}$: $C(y,w) = \min\,\{wx \mid x \in L(y)\}$. For each observation being evaluated, the corresponding non-convex cost function $C^{NC}(w, y) = \min\,\{w \cdot x$: $x \in L^{NC}(y)\}$ has the following closed-form characterization:

$$C^{NC}(w,y) = \min_{y_k \geq y}\ w \cdot x_k. \tag{6}$$

Again, computing a cost function corresponding to convex non-parametric technology $C^C(w, y)$ requires solving a linear program for each unit observed (see Färe, Grosskopf and Lovell (1994)):

$$
\begin{aligned}
C^C(w, y) &= \min_x w \cdot x \\
\text{subject to } \sum_{k=1}^{K} x_k\, z_k &\leq x, \\
\sum_{k=1}^{K} y_k\, z_k &\geq y \\
\sum_{k=1}^{K} z_k &= 1 \\
z_k \geq\ 0,\ x &\geq 0.
\end{aligned}
\tag{7}
$$

The cost function estimated on a convex technology is always lower or equal to one estimated using a non-convex technology:

$$C^C(w, y) \leq C^{NC}(w, y). \tag{8}$$

The impact of convexity or not of production technology on the cost function has been known for a long time. Essentially, only the property of the cost function with respect to changes in outputs is at stake: while the cost function is non-decreasing in outputs in general, cost functions estimated on convex (non-convex) technologies are furthermore convex (non-convex) in the outputs.[4] Several authors (e.g., Lehmijoki (1984) or Färe and Lehmijoki (1987)) have also tried to relax the convexity assumption on technology to obtain a quasi-convex rather than a convex cost function.

Having briefly introduced the methodology necessary for estimating the cost function on both convex and non-convex specification of technology, we now turn to a description of the sample of Spanish electricity distributors employed in this study.

4 Indeed, Jacobsen (1970: proposition 5.2) has already pointed out explicitly that the convexity of the cost function in the outputs is linked to the assumption of convexity of the output sets.

3 Spanish electricity distributors: data, specification issues, and empirical findings

3.1 Description of data and details on the ideal distribution network

Starting with a brief description of the data set already employed in GTL, we can highlight the following elements. There is in fact access to a pair of data sets. The first one describes the actual network as it existed in 1996. The other one describes the ideal engineering network as established by the consultants. The former database reflects the historical economic reality resulting from many years of managerial responses to changes in demand, network and market structure, and regulation based on economic incentives. The latter database reflects an ideal network design from scratch by engineers, in view of current technology as well as current and projected future demand. It needs no comment that these two databases differ substantially.[5]

Just to provide some more details, the Spanish reference or ideal distribution network connects all consumers with the electricity transportation grid around Spain. The relevant information about the consumers is given by (i) the geographic location; (ii) the demand for power; (iii) the kind of voltage (High, Medium and Low Voltages, denoted as HV, MV and LV); and (iv) the peak time demand of power. The model aims at minimizing investments and electricity losses (the difference between the amount of electricity entering the network and delivered to the consumers) as well as a level of quality. Thus, the model decides on the fixed assets, the operating cost and the electricity losses of the distribution network.

Given a geographical zone, the model decides the reference or 'ideal' network taking into account the characteristics of the zone: geographical location of the consumers, forecasted demand, environmental characteristics of the zone, location of the transportation grid, and the required level of quality. The spatial model identifies individual locations of HV consumers, but consumers of MV and LV are located by sets (i.e., groups of houses such as villages, towns and cities). The reference or 'ideal' network for Spain is divided by geographical zones (the provinces). For each province, the model decides on: (i) LV rural networks, (ii) MV and LV urban networks, (iii)

5 Section II in GTL offers some background on the regulation of electricity distribution in Spain.

networks associated with industrial estates, (iv) MV rural networks, and finally (v) networks of transportation and distribution. The latter networks provide electricity to HV/MV substations and to HV consumers. This network of HV lines is connected to the actual Spanish transportation grid system (see the Appendix for some more details).

Observe that the ideal network is exclusively based on local information and is very discrete in nature. Of course, the same observation applies to the historical network. Accordingly, it is difficult to see in the above described structure of these networks any mechanism that could imply convexity. This leads us to question the relevance of convexity when making benchmarking comparisons across networks.

In general, the engineering approach covers a wide range of methods that all have in common, that they employ at least partially hypothetical rather than observed input-output data (derived from blueprints, engineering theory, etc.) based upon direct technological information. This approach differs widely from simply conservatively estimating parameters and variables in a basic engineering production or cost model to extensive optimization and simulation modelling of an existing and/or ideal technology (*in casu*, an electricity distribution network) in all its technical details starting from the underlying processes (the latter requiring considerable effort and industrial expertise).[6] It is useful to recall that in the economics literature a similar approach has been initiated by the seminal article of Chenery (1949), but this research stream has remained rather marginal relative to mainstream production theory and applications (see Wibe (1984) for a survey). One way to state the main difference between economics and engineering is that economists use an aggregate approach (black box) while engineers perform a disaggregate modelling of the network structure.

3.2 Sample description

The actual data set describes the operations of nine distributors in the year 1996. Each distributor operates in one or more of the 47 Spanish provinces. By allocating operations per distributor to these provinces, they obtain a total of 68 distributor/province observations which form the basis of the analysis. Additionally, these observations can be allocated to each of the different Spanish distribution firms.

6 For references to the engineering literature: see the introduction and Ventosa et al. (2005).

The variables retained in the specification are five inputs ((i) LV, (ii) MV and (iii) HV lines, and substation transformer capacity from (iv) HV to MV and from (v) MV to LV) that yield five outputs ((i) LV and (ii) MV and HV electricity customers, (iii) service territory area, (iv) LV, MV and HV electricity distributed, and (v) service reliability). This specification of inputs and outputs is fairly conventional, although the inclusion of service territory area and service reliability among outputs and the disaggregation of line and transformer capacity as inputs make it more detailed than most other variable lists.

While outputs are identical for both networks, actual and ideal input prices and quantities are different between both networks. To economize space, for more details and for detailed descriptive statistics for outputs, input quantities and input prices the reader is referred to GTL (Section 3 and, in particular, Tables 1 to 3.)

3.3 Specification issues: decomposing the cost differential between both networks

Performance is measured in terms of the operating cost incurred in meeting electricity demand and the basic goal is to benchmark the actual performance of the existing distribution network against the potential performance of the ideal network designed by the consultancy. The cost differential between both networks is decomposed into three components to identify its sources: (i) a first component is a network design differential; (ii) a second component is an input price differential; and (iii) a third component is a cost efficiency differential. This benchmarking exercise comparing actual performance against ideal engineering standards established by an international consultancy, one would expect the first and second components to favour the consultancy's state of the art network, while there is no particular expectation for the third component.

To be explicit, we designate the actual situation confronted by the distributors with the subscript 'a' (for actual) and the engineering benchmark designed by the consultants with superscript 'e' (for engineering). Now, we can define actual costs and the actual cost function ($w_a \cdot x_a \geq C_a^{\Lambda}\ (w_a,\ y)$) and engineering costs and the engineering cost function ($w_e \cdot x_e \geq C_e^{\Lambda}\ (w_e, y)$), whereby $C_a^{\Lambda}(w_a, y)$ and $C_e^{\Lambda}\ (w_e,\ y)$ embody the actual network and input prices respectively the consultant's ideal network and input prices. In addition to these two cost functions, we define two hypothetical cost functions to obtain the above decomposition. The first cost function $C_a^{\wedge}(w_e, y)$ describes minimal outlays with the actual network and the consultancy's ideal input prices. The second cost function $C_e^{\wedge}(w_a, y)$ describes minimal expenses with an ideally designed network and actual input prices. Recall that output demands are identical in both cases, which explains why we do not need any superscript to y in any cost function.

Returning to the observed cost differential between both networks $(w_a \cdot x_a - w_e \cdot x_e)$, the objective is to decompose it into three components to identify its underlying sources in an economically informative way. The cost differential $(w_a \cdot x_a - w_e \cdot x_e)$ can be decomposed as follows:

$$\begin{aligned}(w_a \cdot x_a - w_e \cdot x_e) = {} & 1/2\left\{\left[C_a^{\wedge}(w_a, y) - C_e^{\wedge}(w_a, y)\right] + \left[C_a^{\wedge}(w_e, y) - C_e^{\wedge}(w_e, y)\right]\right\} \\ & \text{network design differential} \\ & + 1/2\left\{\left[C_e^{\wedge}(w_a, y) - C_e^{\wedge}(w_e, y)\right] + \left[C_a^{\wedge}(w_a, y) - C_a^{\wedge}(w_e, y)\right]\right\} \\ & \text{input price differential} \\ & + \left\{\left[w_a \cdot x_a - C_a^{\wedge}(w_a, y)\right] - \left[w_e \cdot x_e - C_e^{\wedge}(w_e, y)\right]\right\} \\ & \text{cost} - \text{efficiency differential}\end{aligned}$$

It identifies three sources of cost differences: (i) the network design differential attributes part of the cost differential to differences in network design (averaged over actual and ideal input prices); (ii) the input price differential assigns a portion of the cost differential to input price differences (averaged over the ideal and the actual network's cost function); and (iii) the cost-efficiency differential attributes the remainder of the cost differential to cost efficiency differences.[7]

7 GTL define two options, indicated as Decompositions 1 and 2, and Decomposition 3 averaging both of these. Our empirical results focus on this third option since the other decompositions yield very similar results (very much as in GTL). In fact, the first two decompositions share a common cost-efficiency differential, but they have different network design and input price differentials. The latter phenomenon explains taking the arithmetic average (between curly brackets) of both components (which are themselves between square brackets). The first decomposition evaluates the (i) network design differential at actual input prices and (ii) the input price differential using the ideal network's cost function. The second decomposition evaluates the (i) network design differential at ideal input prices and (ii) the input price differential using the actual network's cost function. Since both hypothetical cost functions ($C_a^{\wedge}(w_e, y)$ and $C_e^{\wedge}(w_a, y)$) are unlikely to coincide in practice, these two first decompositions have been combined using an arithmetic mean form in Decomposition 3 (see text).

Estimation of the cost functions involved is straightforward using the methodology outlined in Section 2. In particular, for each of the 68 observations in the sample, one can apply the closed form expression (6) and solve the linear program (7) to obtain the non-convex respectively the convex cost functions.

3.4 Empirical findings

Table 1 reports the empirical findings on the decomposition of the cost differential. In contrast to GTL, we only report descriptive statistics at the sample level rather than results per distributor.[8] The first two columns of the upper part of Table 1 reveal that the actual network has an operating cost that is about 40% higher than that of the consultancy's ideal network yielding the cost differential in the third column. Thus, the consultancy's ideal network shows a substantial cost saving potential across the board and the decomposition defined above should ideally shed some light onto its constituent sources. The crucial question is now to what extent the convexity assumption drives any of these results.

Under the traditional convexity hypothesis (upper part of the table), the largest potential cost saving is due to the fact that the consultancy's ideal network proposes lower input prices, and the second potential cost saving is attributable to the consultancy's ideal network being leaner. By contrast, the consultancy's ideal network is substantially less cost efficient than the actual network, which neutralizes a substantial part of the potential cost saving from the first two sources.

The two first findings are not surprising, since the consultancy's network was designed solely on the basis of current and projected future demand and without any weight of history. However, there are at least two plausible reasons to expect that the consultancy's ideal network is not as cost efficient as the actual network (see GTL). First, the consultancy's network has been designed by engineers in view of obtaining a superior network design, but with less concern for its cost efficiency. Second, since the standard cost parameters had not been adjusted for productivity changes since 1987 and standard cost reimbursement schemes allocate excess revenues to the firm, this provides distributor firms in the actual network with a powerful incentive to strive for cost efficiency.

8 To compare results, please contrast the last line in Table 4 of GTL with our sum results.

Table 1 – Cost differential decomposition in million Euros

		Actual cost	Ideal cost	Cost differential	Network design differential	Input price differential	Cost efficiency differential	Actual Cost efficiency	Ideal Cost efficiency
Convex	Mean	15.4	11.0	4.4	2.1	3.0	−0.8	1.5	2.3
	Trimmed Mean	14.6	10.8	3.8	1.9	2.7	−0.7	1.4	2.1
	St. Dev.	17.5	8.5	11.1	4.9	6.0	2.9	1.9	2.6
	Min	0.2	0.4	−5.0	−4.1	−3.3	−14.8	0.0	0.0
	Max	84.9	37.2	50.6	25.8	28.0	7.1	8.5	14.8
	Sum	1048.2	749.9	298.3	145.6	205.9	−53.2	102.7	155.9
Non-Convex	Mean				1.6	2.8	−0.1	0.1	0.1
	Trimmed Mean				1.5	2.5	−0.0	0.0	0.1
	St. Dev.				6.1	6.5	0.8	0.3	0.7
	Min				−13.4	−4.3	−4.7	0.0	0.0
	Max				25.8	27.8	1.6	1.7	4.8
	Sum				110.9	191.2	−3.9	5.0	8.8

Under the non-convexity assumption (lower part of the table), the two main potential sources of cost savings remain the same in relative importance, but their absolute amounts are reduced. The average network design differential and the input price differential reduce from 2.1 to 1.6 million and from 3.0 to 2.8 million euros. Furthermore, the cost disadvantage of the consultancy's ideal network remains, but it has become a very marginal not to say an almost negligible factor (with a reduction from −0.8 to −0.1 million euros on average). Also the aggregate results at the level of the country (see sum in last line) confirm that the sources of the observed cost differential are much smaller under non-convexity.

The explanation behind this last result is simple: whereas in the convex case only 20 and 15 distributors out of 68 are efficient in the actual and ideal network specifications, these numbers increase to 60 and 64 in the non-convex case. Just to elaborate a bit on the difference between both specifications, Figure 1 plots the kernel densities of cost efficiencies (=minimal costs/actual costs ≤ 1) for the actual network using convex and non-convex specifications. Clearly, the differences are very pronounced. Figures for the other cost functions involved in the decompositions look very similar (therefore, these are suppressed).

To formally test for this difference between both densities, the test–statistic of Li (1996) (see Fan and Ullah (1999) for refinements) is computed which is valid for dependent and independent variables alike. Under the null hypothesis that both distributions are identical and the alternative hypothesis that they are different, this test statistic asymptotically follows a standard normal-distribution (for small samples, a bootstrap approximation can be employed).[9] This test statistic for the cost functions on the actual and ideal networks amounts to 16.64 resp. 25.52 which surpasses the 1% significance level (critical value 2.33) widely. Similar results are obtained for the hypothetical cost functions (therefore, these are again suppressed). Thus, the null hypothesis can be rejected and it is safe to conclude that convex and non-convex estimates yield markedly different results.

The gist of this story is that for the Spanish regulation of electricity distribution via an engineering benchmarking grid model, the potential cost savings are mainly due to the fact that the consultancy's ideal network proposes lower input prices and that it is simply leaner in design. The initial important cost efficiency disadvantage of the ideal network largely disappears under non-convexity.

9 Further details on its application in a similar setting can be found in Kumar and Russell (2002).

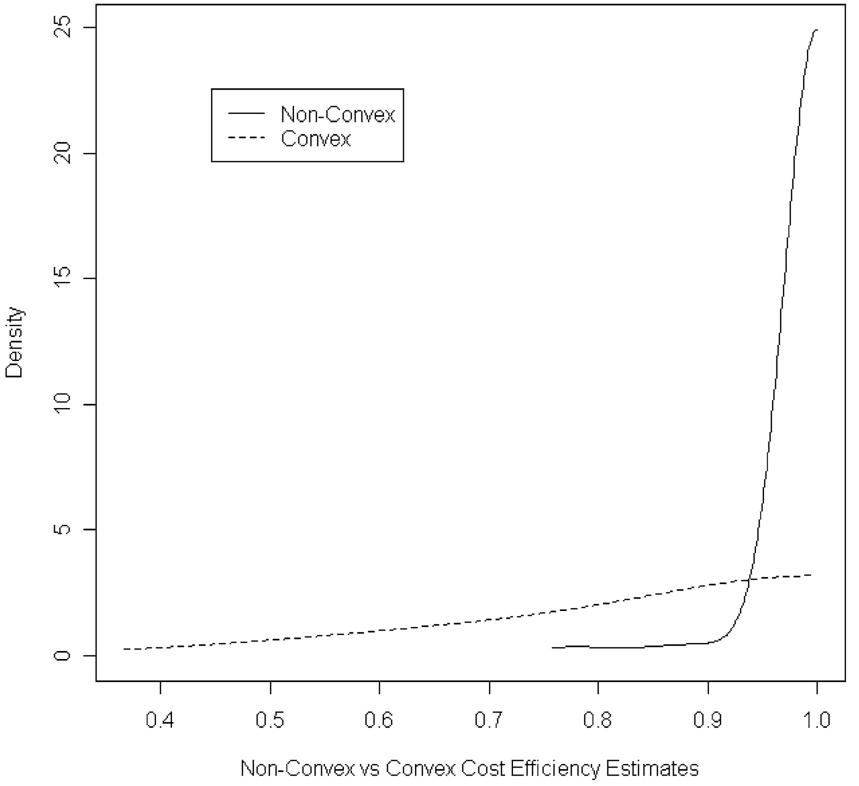

Figure 1 – Kernel densities (with boundary correction) of cost efficiency on convex and non-convex models for the actual network

Irrespective of the relative advantages of using either economic or engineering benchmarking models for regulatory purposes, the latter result increases the bite of this engineering benchmarking model.

Without over-interpreting the current result, we simply conjecture that convexity could play a major role in closing the gap between economic studies using an aggregate approach (black box) and engineering studies based on disaggregate modeling of the network structure. It could also play a role in at least partly settling the historical debate on the relative merits of economic and engineering approaches to production (e.g., see the debate between Wibe (1984, 1986) and Marsden and Pingry (1986) and Smith (1986)), since it may well bring both approaches closer in line.

4 Conclusions

Despite the fact that the impact of convexity of the technology on the cost function has been known for years (see Jacobsen 1970), very few if any empirical applications have documented this impact. This study has employed the recent models developed by BKVE to test for the impact of convexity in regulatory benchmarking in the electricity distribution sector. First, we have provided some evidence on the non-convex nature of electricity distribution through the description of the way that existing and 'ideal' electricity distribution networks are built. Second, we find that cost estimates differ significantly according to a non-parametric test statistic.

It is important that these empirical findings are corroborated by complementary research both in general production applications and in electricity distribution in particular, eventually employing other test approaches to evaluate the convexity axiom.[10] In the longer run, these results could eventually lead to a reconsideration of the convexity assumption in applied production analysis in general and in its use in regulatory practice in particular. In consequence, the regulation of other network industries (gas utilities, telecommunication companies, water distribution, etc.) should equally reconsider its choice of benchmarking model.

Some of the consequences of this specification issue for regulatory benchmarking are rather straightforward to anticipate. On the one hand, the demands on benchmarking in terms of sample sizes become more difficult when opting for non-convex approaches, since larger sample sizes are needed to estimate monotone rather than convex hull boundaries (see BKVE).[11] On the other hand, it may well become more difficult to manipulate frontier-based regulatory schemes since the impact of each single observation on the frontier is smaller in the non-convex case. Whether opting for non-convex benchmark strategies would have a mitigating impact on the gaming of the regulator remains to be seen. Jamasb, Nillesen and Pollitt (2003) offer a survey among regulators on these vulnerability issues in yardstick

10 Eventually, by extension similar studies in electricity generation may be needed as well.

11 An obvious solution is the development of international databases and/or the increase in the frequency of observations (e.g., quarterly versus annual observations) in an effort to increase the bite of regulation. Jamasb and Pollitt (2003) review the possibilities and potential pitfalls related to international benchmarking in the electricity sector.

competition and Jamasb, Nillesen and Pollitt (2004) provide some examples of manipulating benchmarking models in regulatory practice.

We hope the empirical results are of some interest to economists and engineers alike. It is unclear which of these groups knows less about the other. It is hoped that both fields can benefit from a mutual interest in one another's approaches and outcomes. Solely within the activity analysis tradition, that is at the basis of the non-parametric approach, there may well be a variety of inroads to close the apparent gap between economists and engineers.[12] One can mention, among others, the use of networks in non-parametric models (see, e.g., Färe and Grosskopf (2000)) where the representation of the product flow is consistent with the industrial engineering literature on multi-stage systems (see Golany, Hackman and Passy (2006)), the use of Petri nets in modelling production (e.g., Bonanno (1995)), etc. A recent attempt to bridge the gap between both fields is the book by Hackman (2008).

REFERENCES

ANANDALINGAM G., DAY R.W. and RAGHAVAN S., 2005, 'The landscape of electronic market design', *Management Science*, 51, 3, 316–327.

ARROYO J.M. and CONEJO A.J., 2000, Optimal Response of a Thermal Unit to an Electricity Spot Market, *IEEE Transactions on Power Systems*, 15, 3, 1098–1104.

BOGETOFT P., 2000, 'DEA and activity planning under asymmetric information', *Journal of Productivity Analysis*, 13, 1, 7–48.

BONANNO G., 1995, 'Modelling production with Petri nets', *Economic Notes*, 24, 2, 263–292.

BRIEC W., KERSTENS K and VANDEN EECKAUT P., 2004, 'Non-convex technologies and cost functions: definitions, duality and nonparametric tests of convexity', *Journal of Economics*, 81, 2, 155–192.

BRUNEKREEFT G., NEUHOFF K. and NEWBERY D., 2005, 'Electricity transmission: an overview of the current debate', *Utilities Policy*, 13, 1, 73–93.

CHENERY H.B., 1949, 'Engineering production functions', *Quarterly Journal of Economics*, 63, 4, 507–531.

12 Notice that there is also a wide variety of engineering applications using efficiency analysis (see Triantis 2004).

COELLI T.J., ESTACHE A., PERELMAN S. and TRUJILLO L., 2003, *A Primer on Efficiency Measurement for Utilities and Transport Regulators*, Washington, World Bank Publications.

CRONIN F.J. and MOTLUK S.A., 2007, 'Flawed competition policies: designing "markets" with biased costs and efficiency benchmarks', *Review of Industrial Organization*, 31, 1, 43–67.

ELMAGHRABY W., O'NEILL R., ROTHKOPF M. and STEWART W., 2004, 'Pricing and efficiency in "lumpy" energy markets', *Electricity Journal*, 17, 5, 54–64.

FAN, Y. and ULLAH A., 1999, 'On goodness-of-fit tests for weakly dependent processes using kernel method', *Journal of Nonparametric Statistics*, 11, 1–3, 337–360.

FÄRE R. and GROSSKOPF S., 2000, 'Network DEA', *Socio-Economic Planning Sciences*, 34, 1, 35–49.

FÄRE R., GROSSKOPF S. and LOVELL C.A.K., 1994, *Productions Frontiers*, Cambridge, Cambridge University Press.

FÄRE R. and LEHMIJOKI U., 1987, 'On quasi-convexity of the cost function', *Scandinavian Journal of Economics*, 89, 1, 115–118.

FARSI M., FILIPPINI M. and GREENE W., 2006, 'Application of panel data models in benchmarking analysis of the electricity distribution sector', *Annals of Public and Cooperative Economics*, 77, 3, 271–290.

FUSS M., MCFADDEN D. and MUNDLAK Y., 1978, 'A survey of functional forms in the economic analysis of production', in M. Fuss and D. McFadden, eds, *Production Economics: a Dual Approach to Theory and Applications*, vol. 1, Amsterdam, North-Holland, 219–268.

GOLANY B., HACKMAN S.T. and PASSY U., 2006, 'An efficiency measurement framework for multi-stage production systems', *Annals of Operations Research*, 145, 1, 51–68.

GRIFELL-TATJÉ E. and LOVELL C.A.K., 2003, 'The managers versus the consultants', *Scandinavian Journal of Economics*, 105, 1, 119–138.

HACKMAN S.T., 2008, *Production Economics: Integrating the Microeconomic and Engineering Perspectives*, Berlin, Springer.

JACOBSEN S.E., 1970, 'Production correspondences', *Econometrica*, 38(5), 754–771.

JAMASB T. and POLLITT M., 2001, 'Benchmarking and regulation: international electricity experience', *Utilities Policy*, 9(3), 107–130.

JAMASB T. and POLLITT M., 2003, 'International benchmarking and regulation: an application to European electricity distribution utilities', *Energy Policy*, 31(15), 1609–1622.

JAMASB T., NILLESEN P. and POLLITT M., 2003, 'Gaming the regulator: a survey', *Electricity Journal*, 16, 10, 68–80.

JAMASB T., NILLESEN P. and POLLITT M., 2004, 'Strategic behaviour under regulatory benchmarking', *Energy Economics*, 26, 5, 825–843.

JOSKOW P.L., 2006, 'Introduction to electricity sector liberalization: lessons learned from cross-country studies', in: F.P. Sioshansi and W. Pfaffenberger, eds, *Electricity Market Reform: An International Perspective*, Elsevier, 1–32.

KUMAR S. and RUSSELL R.R., 2002, 'Technological change, technological catch-up, and capital deepening: relative contributions to growth and convergence', *American Economic Review*, 92, 3, 527–548.

LEHMIJOKI U., 1984, 'Notes on quasi-convexity of the cost function', *Scandinavian Journal of Economics*, 86, 3, 385–389.

LI Q., 1996, 'Nonparametric testing of closeness between two unknown distribution functions', *Econometric Reviews*, 15, 3, 261–274.

MAKKONEN S. and LAHDELMA R., 2006, 'Non-convex power plant modelling in energy optimisation', *European Journal of Operational Research*, 171, 3, 1113–1126.

MARSDEN J.R. and PINGRY D.E., 1986, 'Engineering production functions and the testing of quantitative economic hypotheses', *Economica*, 53, 212, 533–534.

O'NEILL R.P., SOTKIEWICZ P.M., HOBBS B.F., ROTHKOPF M.H., STEWART W.R., Jr., 2005a, 'Efficient market-clearing prices in markets with nonconvexities', *European Journal of Operational Research*, 164, 1, 269–285.

O'NEILL R.P., BALDICK R., HELMAN U., ROTHKOPF M.H. and STEWART, W. Jr., 2005b, 'Dispatchable transmission in RTO markets', *IEEE Transactions on Power Systems*, 20, 1, 171–179.

PARK B.U., SIMAR L. and WEINER C., 2000, 'The FDH estimator for productivity efficiency scores', *Econometric Theory*, 16, 6, 855–877.

SCARF H.E., 1986, 'Testing for optimality in the absence of convexity', in: W.P. Heller, R.M. Starr and S.A. Starrett, eds, *Social Choice and Public Decision Making: Essays in Honor of Kenneth J. Arrow*, Volume I, Cambridge, Cambridge University Press, pp. 117–134.

SCARF H.E., 1994, 'The allocation of resources in the presence of indivisibilities', *Journal of Economic Perspectives*, 8, 4, 111–128.

SCHLEIFER A., 1985, 'A theory of yardstick competition', *Rand Journal of Economics*, 16, 3, 319–327.

SHUTTLEWORTH G., 2005, 'Benchmarking of electricity networks: practical problems with its use for regulation', *Utilities Policy*, 13, 4, 310–317.

SIMAR L. and WILSON P.W., 2000, 'Statistical inference in nonparametric frontier models: the state of the art', *Journal of Productivity Analysis*, 13, 1, 49–78.

SMITH V.K., 1986, 'Another view of the state of engineering production functions', *Economica*, 53, 212, 529–532.

TONE K. and SAHOO B.K., 2003, 'Scale, indivisibilities and production function in data envelopment analysis', *International Journal of Production Economics*, 84, 2, 165–192.

TRIANTIS K.P., 2004, 'Engineering applications of Data Envelopment Analysis: issues and opportunities', in: W.W. Cooper, L.M. Seiford and J. Zhu, eds, *Handbook on Data Envelopment Analysis*, Kluwer, Boston, pp. 401–441.

VENTOSA M., BÍLLO Á., RAMOS A. and RIVIER M., 2005, 'Electricity market modeling trends', *Energy Policy*, 33, 7, 897–913.

WIBE S., 1984, 'Engineering production functions: a survey', *Economica*, 51, 204, 401–411.

WIBE S., 1986, 'Observable and non-observable data: a reply', *Economica*, 53, 212, 535–536.

La régulation incitative et le rôle de la convexité dans le benchmarking des réseaux de distribution électriques: Economistes contre ingénieurs

Cet article illustre l'impact potentiel de la spécification d'une technologie de production convexe en établissant des coûts minimaux comparé à l'utilisation d'une technologie non-convexe comme benchmark des *réseaux de distribution d'électricité. Cette réflexion méthodologique est principalement motivée par la récente littérature d'ingénierie qui fournit des preuves de non-convexités dans les réseaux de distribution électriques. Une illustration empirique utilisant des spécifications non-paramétriques de la technologie expose ce point principal en utilisant l'échantillon des entreprises de distribution d'électricité espagnoles précédemment analysé dans Grifell-Tatjé et Lovell (2003).*

Anreizregulierung und die Rolle der Konvexität beim Benchmarking in der Elektrizitätsdistribution: Ökonomen versus Ingenieure

Dieser Beitrag illustriert die potenzielle Auswirkung der Spezifizierung einer konvexen Produktionstechnologie auf das Erreichen minimaler Kosten beim Benchmarking von Elektrizitätsdistributionsunternehmen im Vergleich zur Anwendung einer nicht-konvexen Technologie. Diese methodologische Betrachtung geht hauptsächlich zurück auf das aktuelle Schrifttum der Ingenieurswissenschaften, das den Nachweis für Non-Konvexitäten in der Elektrizitätsdistribution erbringt. Eine empirische Darstellung, die sich auf nicht-parametrische Technologie-Spezifikationen stützt, veranschaulicht diesen wichtigen Punkt, wobei eine Stichprobe spanischer Elektrizitätsdistributionsunternehmen verwendet wird, die früher schon in Grifell-Tatjé und Lovell (2003) analysiert wurde.

La regulación incitativa y el papel de la convexidad en el *benchmarking* de las redes de distribución eléctrica: economistas contra ingenieros

Este artículo muestra el impacto potencial de la especificación de una tecnología de producción convexa, que implica costes mínimos, comparada con la utilización de una tecnología no convexa como benchmark de las redes de distribución de electricidad. Esta reflexión metodológica está principalmente motivada por la reciente literatura de la ingeniería que proporciona pruebas de no convexidad en las redes de distribución eléctricas. La exposición de este punto central del trabajo se realiza a partir de una ilustración empírica que utiliza especificaciones no paramétricas de la tecnología, todo ello en una muestra de empresas de distribución eléctrica españolas previamente analizadas en Grifell-Tatjé y Lovell (2003).

Appendix: additional information on the ideal network

The 'ideal' engineering network is built by taking decisions per province about the following five kinds of installations:

(i) LV rural network:

Villages or towns with less of 350 houses only need one substation transforming MV to LV. A radial network in tree form connects them. This network is always aerial and in the towns and villages the lines are fixed on the facade.

(ii) MV and LV urban network:

For villages, towns and cities of more than 350 houses, the model calculates the number of HV/MV and MV/LV substations that are necessary. The lines could be aerial or underground depending on the characteristics of the town or city. The lines could be MV or LV.

(iii) Network associated to industrial estates:

The model calculates the necessary number of HV/MV and MV/LV substations. The lines could be aerial or underground depending on the characteristics of the industrial estate. Net and tree networks connect and deliver the electricity that could be MV or LV.

(iv) MV rural network:

This is the aerial network that connects all towns and villages with a demand for power of less than 10 MW and also MV consumers which are not located in industrial estates or inside towns, villages or cities. The model determines the number of HV/MV and MV/LV substations that are needed. These lines are MV.

(v) Network for Transportation of Distribution:

This network provides the electricity to HV/MV substations and HV consumers. This network is connected to the HV transportation grid system and is always aerial. The lines are HV.