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**THE EFFICIENCY OF EUROPEAN
TRANSMISSION SYSTEM OPERATORS:
AN APPLICATION OF DYNAMIC DEA**

Philipp von Geymueller

15 February 2007

Research Institute for Regulatory Economics
Vienna University for Economics and Business Administration

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“The efficiency of European Transmission System Operators: An application of dynamic DEA”

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Author's address:

Philipp von Geymueller
philipp.vongeymueller@wu-wien.ac.at
T.: +43 1 31336 5898

Editors:

Prof. Dr. Stefan Bogner
Prof. Dr. Heinrich Otruba

Editorial board:

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Prof. Dr. Christoph Weiss

Research Institute for Regulatory Economics
Vienna University of Economics and Business Administration
Library (Working Paper)
Augasse 2-6
1090 Wien
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1 Background and Motivation

When establishing an incentive based regulatory regime like the “RPI-X”-regime that has become the standard more or less throughout Europe it is one of the most important tasks of the regulator to assess the efficiency of the regulated enterprises as objectively and impartially as possible in order to be able to prescribe fair individual productivity gains that the enterprises have to achieve in the upcoming regulatory period.

To that end a few parametric and non-parametric methods have been employed. A very popular and instructive non-parametric approach is the Data Envelopment Analysis (DEA) as pioneered by Charnes, Cooper and Rhodes in 1979 (Charnes et al., 1979). The merit of DEA is that it specifies an efficient frontier without the need for the definition of a production function by laying a convex hull around the empirically available input-output combinations of the players in the sample. Following Farrell’s pioneering approach (Farrell, 1957) efficiency of the respective enterprise is then usually measured by the distance between the observation and the estimated ideal on the efficient frontier.

Regulation in liberalised electricity markets is primarily focused on the network (that is natural monopoly)-part of the regulated enterprises and this business is particularly characterized by “quasi-fixed” inputs like transformer stations and transmission cables/lines that cannot be adjusted to their optimal levels instantaneously such that decisions about the level of investment in one period have important implications not only for the efficiency in that period but also for that of subsequent ones. In other words: The characteristics of the liberalised electricity markets and especially those of the network part of it call for a dynamic perspective that captures the intertemporal aspects of investment in quasi-fixed inputs more accurately.

However, most adaptations of the original DEA-model that have been developed to capture the specifics of the various empirical situations have in common that they stay within a static framework and abstract from the intertemporal behaviour of the firm.

Amongst the first ones to realise this drawback were Jiro Nemoto and Mika Goto who therefore augmented the conventional DEA by treating quasi-fixed inputs at the end of one period as if they were outputs in that period and essential inputs in the subsequent one (Nemoto and Goto, 1999). In this setting the firm faces installation costs: the more resources are consumed in installing quasi-fixed inputs, the less there are left over for

producing outputs¹. On the other hand, more quasi-fixed inputs in the next period mean greater production possibilities and therefore profits in that and subsequent periods. This is the basic trade-off the firm faces: Either maximise output myopically in this period or invest in quasi-fixed inputs to increase output in subsequent ones.

Figure 1 is supposed to illustrate this concept. Variable inputs x_t and quasi-fixed inputs k_{t-1} at the beginning of period t are transformed by the production process P_t into regular outputs y_t and quasi-fixed inputs k_t at the end of that period. These quasi-fixed inputs k_t and the new variable inputs x_{t+1} are then inputs in the production process P_{t+1} of the subsequent period $t+1$.

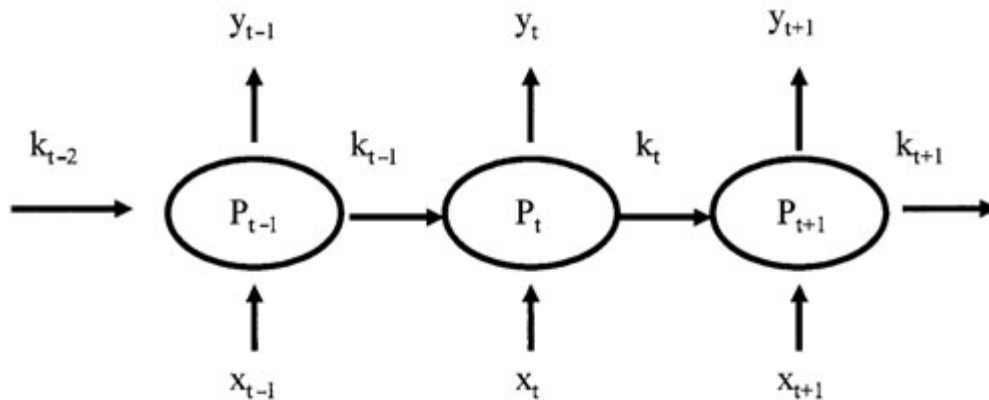


Figure 1: The technology of dynamic DEA
Source: Nemoto and Goto (2003)

Drawing from this theoretic framework Nemoto and Goto later conducted an empirical study in which they investigated the dynamic efficiencies of 9 privately owned vertically integrated Japanese electric utilities under rate-of-return regulation between 1981-1995 (Nemoto and Goto 2003). In order to get a measure of efficiency for the respective firms, they basically compared the actual cost with the cost that would have arisen, had the inputs been used technically, allocatively and dynamically efficient. They find that the main source of inefficiency is the dynamically inefficient (too high) use of quasi-fixed inputs which could be seen as empirical evidence for the conjectured “Averch-Johnson”-effect.

In this paper I present a study that, inspired by Nemoto and Goto’s work, investigates the dynamic efficiency of European Transmission System Operators. As opposed to Nemoto

¹ Nemoto and Goto were also able to relate their approach seamlessly to the adjustment-cost theory of investment, so that it provides a nonparametric alternative to the econometric Euler equation approach (Nemoto and Goto 1999, Appendix)

and Goto's focus however, I was primarily interested in the network operations of the respective enterprises. The ensuing problems of determining accurate prices for typical inputs and outputs of the network business of such enterprises induced me to focus solely on the evolvement of technical efficiencies over time. This way I could dispense with prices and still gain interesting insights in how a transition from a static to a dynamic framework changes the perception of the state of the industry, which in turn might have consequences on how the regulator assesses the efficiency of the regulated enterprises.

The remaining paper is structured as follows: In section 2 I first provide the mathematical formulation of the static and dynamic DEA-models that will be employed in the remaining empirical part of the paper. In section 4 the data and its sources will be discussed. Section 5, the core of the paper, is devoted to the presentation of the main results and the discussion of its implications. Section 6 gives a short summary of the main points made.

2 The dynamic DEA-model²

2.1 The production possibility set

Let x_t denote a $l \times 1$ vector of variable inputs used in the period t , k_t a $m \times 1$ vector of quasi-fixed inputs at the end of period t , and y_t a $n \times 1$ vector of outputs produced in the period t . The firm (or “decision making unit” – DMU) puts x_t and k_{t-1} into both production processes and investment activities in order to supply y_t to the market and to hold k_t at the end of that period. All combinations of $(x_t, k_{t-1}) \in \mathfrak{R}_+^{l+m}$ and $(k_t, y_t) \in \mathfrak{R}_+^{m+n}$, where the latter is producible from the former, constitute the production possibility set in period t :

$$\Phi_t = \left\{ (x_t, k_{t-1}, k_t, y_t) \in \mathfrak{R}_+^{l+m} \times \mathfrak{R}_+^{m+n} \mid (x_t, k_{t-1}) \text{ can yield } (k_t, y_t) \right\} \quad (1)$$

It is required that Φ_t satisfies the regularity conditions:

- (i) if $(\tilde{x}_t, \tilde{k}_{t-1}, k_t, y_t) \in \Phi_t$ and $(\tilde{x}_t, \tilde{k}_{t-1}) \leq (k_t, y_t)$, then $(x_t, k_{t-1}, k_t, y_t) \in \Phi_t$;
- (ii) if $(x_t, k_{t-1}, \tilde{k}_t, \tilde{y}_t) \in \Phi_t$ and $(\tilde{x}_t, \tilde{k}_{t-1}) \geq (k_t, y_t)$, then $(x_t, k_{t-1}, k_t, y_t) \in \Phi_t$;
- (iii) Φ_t is closed and convex.

If the production technology is constant returns to scale, Φ_t becomes a convex cone:

- (iv) if $(x_t, k_{t-1}, k_t, y_t) \in \Phi_t$, then $(cx_t, ck_{t-1}, k_t, y_t) \in \Phi_t$ for any $c > 0$.

As we are ultimately interested in empirical results we want to find a more accurate description of Φ_t that satisfies the above conditions than what a mere arbitrary guess of a production function á la Cobb-Douglas can yield. DEA provides a solution to this problem by constructing a polyhedral convex hull enveloping (hence the name) the observed data:

Suppose we have N observations, i. e. firms, with variable inputs $X_t = (x_{t1}, x_{t2}, \dots, x_{tN})$ (each x_{ti} represents the input-vector of a firm), quasi-fixed inputs at the beginning of period t , $K_{t-1} = (k_{t-11}, k_{t-12}, \dots, k_{t-1N})$ and quasi-fixed inputs at the end of the period t . Assuming constant returns to scale, the smallest set comprising these observations and satisfying (i)-(iv) takes the form:

² The mathematical description of the production possibility set is taken from Nemoto and Goto (2003).

$$\hat{\Phi}_t = \left\{ (x_t, k_{t-1}, k_t, y_t) \in \mathfrak{R}_+^{l+m} \times \mathfrak{R}_+^{m+n} \mid X_t \lambda_t \leq x_t, K_{t-1} \lambda_t \leq k_{t-1}, K_t \lambda_t \geq k_t, Y_t \lambda_t \geq y_t, \lambda_t \geq 0 \right\} \quad (2)$$

where λ_t is a $N \times 1$ intensity vector whose j th element is denoted by λ_{tj} .

2.2 Technical efficiency – the additive model

Technical efficiency in the DEA-context can be defined in several ways. In the original formulation of Charnes, Cooper and Rhodes (1979), referred to as *CCR*-model, it was defined either as to what extent the inputs of each DMU could be reduced proportionally while remaining on the same isoquant (input-orientation) or as by how much the outputs could be increased proportionally while holding inputs constant (output-orientation). In our dynamic context this leads to problems as the quasi-fixed inputs have the character of outputs in period t and that of inputs in period $t+1$ and therefore, when trying to determine the technical efficiency of a DMU, both an input- and an output-orientation is required.

The so-called *additive model* circumvents the above problem by combining both orientations. Here efficiency is somewhat defined the other way round: For each DMU, the maximal sum of all slacks, i. e. the distances to the efficient frontier in all inputs and outputs, is determined. A DMU is efficient, only if this sum is zero. Figure 2 is supposed to illustrate the differences of the 2 concepts.

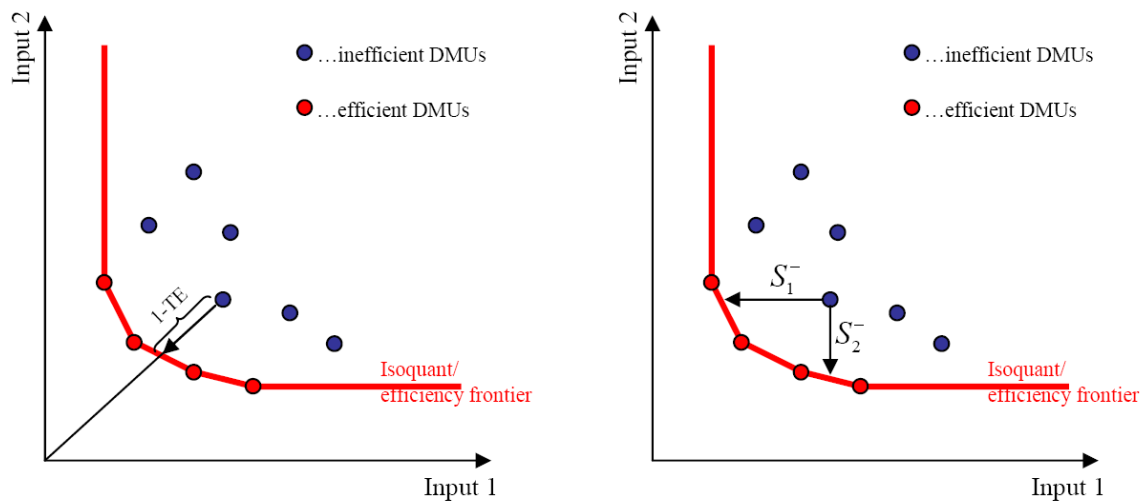


Figure 2: The CCR- (left) and the Additive model (right)

2.3 The intertemporal LP³-problem

Taking up the efficiency-concept from the additive model leads to the following intertemporal optimization problem: Maximise the sum of the slacks of all factors over

³ LP...“linear programming“

the entire time-horizon subject to the restrictions of the production possibility frontier as given by (2).

This problem is equivalent to the following linear program:

$$\begin{aligned}
& \max_{\{S_{k_0}, S_{x_t}, S_{y_t}, S_{k_t}^+, k_t, S_{k_t}^-, \lambda_t\}_{t=1}^T} \gamma S_{k_0} + \sum_{t=1}^T \gamma^t (S_{x_t} + S_{y_t} + S_{k_t}^+ + S_{k_t}^-) \\
& \text{s. t.} \quad k_{t-1} - K_{t-1} \lambda_t - S_{k_{t-1}} = 0 \quad t = 1 \\
& \quad \quad k_{t-1} - K_t \lambda_t - S_{k_{t-1}}^- = 0 \quad t = 2, \dots, T \\
& \quad \quad x_t - X_t \lambda_t - S_{x_t} = 0 \quad t = 1, 2, \dots, T \\
& \quad \quad Y_t \lambda_t - S_{y_t} - y_t = 0 \quad t = 1, 2, \dots, T \\
& \quad \quad K_t \lambda_t - S_{k_t}^+ - k_t = 0 \quad t = 1, 2, \dots, T-1 \\
& \quad \quad S_{k_0}, S_{x_t}, S_{y_t}, S_{k_t}^+, k_t, S_{k_t}^-, \lambda_t \geq 0 \quad t = 1, 2, \dots, T
\end{aligned} \tag{3}$$

where k_0 is the initial exogenous value of quasi-fixed inputs and γ is a discount factor.

The program determines for each DMU the maximal slack-value for each input and output category for every point in time.

The intertemporal aspect in this program is represented by the constraints 2 and 5: The program tries to find the combination of $S_{k_t}^+, S_{k_t}^-$ and k_t for each period that maximises the total slack. In other words: Whereas the values of the variable inputs of each period are the exogenously given (but controllable by the firm) observed data, only the initial value for the quasi-fixed input is given exogenously and the subsequent optimal values are determined in the process of the optimization. This is where the basic trade-off of the firm is manifested: On the one hand it wants to close its gap to the efficient frontier concerning the outputs and thus also increase its amount of quasi-fixed inputs in this period but on the other hand such an increased amount of quasi-fixed inputs reduces its efficiency concerning the inputs in the following period. This shall be illustrated by Figure 3

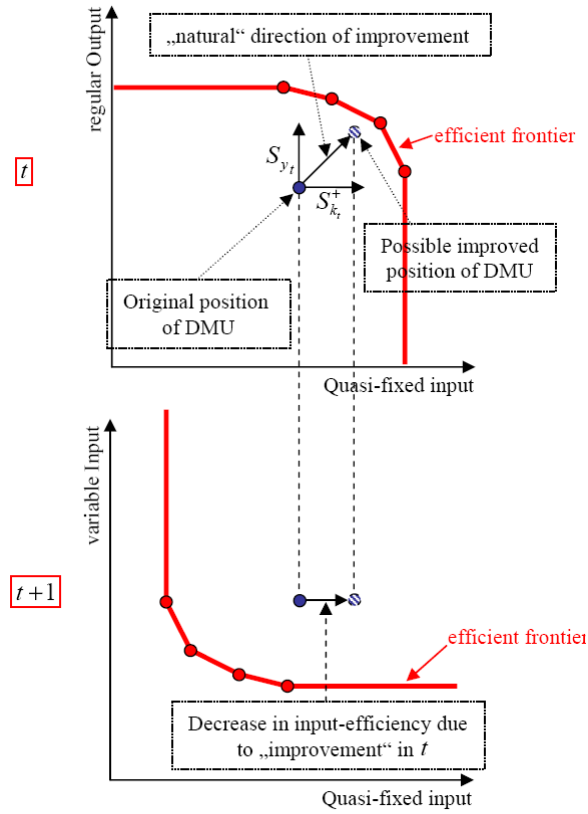


Figure 3: The trade-off between output improvement and input-efficiency deterioration

Since the slacks will be of different dimensions, the maximised objective value cannot be taken directly as a measure of efficiency.

Therefore firstly, the factor-efficiency (input, output or quasi-fixed input) of a DMU of a year is calculated by relating its efficient value (i. e. adding the maximised slack-values to the actual values) to the actual value:

$$ineff_i^t = \frac{F_i + S_{F_i}^*}{F_i}, \quad i \in (1, 2, \dots, m+n+l);$$

where F_i is the i th element of the vector of inputs, outputs and quasi-fixed inputs and $S_{F_i}^*$ is the slack that results from the above optimization for this factor.

Secondly, annual-efficiency per DMU is then the average of all eff_i :

$$Ineff^t = \frac{1}{m+n+l} \sum_{i=1}^{m+n+l} ineff_i^t.$$

Total efficiency is thirdly taken to be the average of each annual-efficiency:

$$INEFF = \frac{1}{T} \sum_{t=1}^T Ineff^t.$$

The respective efficiencies are then defined by $1 - ineff_i^t$, $1 - Ineff^t$ and $1 - INEFF$.

The relevance and importance of such a dynamic perspective becomes particularly evident when contrasting its empirical results with those of a more traditional static perspective. To that end, in the next section, the static setting will be specified.

3 The static DEA-model

Broadly speaking, in the static setting the optimization problem remains the same as before except for the intertemporal aspects, that is, the quasi-fixed inputs in each period are taken to be exogenously given (but controllable by the firm) and therefore have the character of “normal” variable inputs. The corresponding LP-program looks as follows:

$$\begin{aligned}
 & \max_{\{S_{k_{t-1}}, S_{x_t}, S_{y_t}, \lambda_t\}_{t=1}^T} \sum_{t=1}^T \gamma^t (S_{k_{t-1}} + S_{x_t} + S_{y_t}) \\
 \text{s. t.} \quad & k_{t-1} - K_{t-1} \lambda_t - S_{k_{t-1}} = 0 \quad t = 1, 2, \dots, T \\
 & x_t - X_t \lambda_t - S_{x_t} = 0 \quad t = 1, 2, \dots, T \\
 & Y_t \lambda_t - S_{y_t} - y_t = 0 \quad t = 1, 2, \dots, T \\
 & S_{k_{t-1}}, S_{x_t}, S_{y_t}, \lambda_t \geq 0 \quad t = 1, 2, \dots, T
 \end{aligned} \tag{4}$$

The efficiency measures are calculated exactly as in the dynamic model.

4 The Data

The data for the empirical investigation stems from 7 European TSOs⁴ during the years 1999-2005. Even though the focus was originally laid on the network operations of the respective enterprises, the necessary sole reliance on company-reports and –websites and the fact these enterprises are still mostly vertically integrated, the pragmatic concession had to be made to take the whole enterprise into account. The list of interesting and relatively simple to gather factors comprised the following:

Inputs: Expenditures in manufacturing and other operating expenditures (TEUR), salaries and wages (TEUR) and employees.

Quasi-fixed inputs: Circuit length (km) and installed transformer capacity (MVA)

Outputs: Amount of energy transported over network (GWh)

In order to alleviate the known problem of DEA (when the sample size is not significantly larger than the amount of factors under consideration) to possibly deem DMUs efficient just because of them having extreme values in one or the other dimension, the following smallest possible set of interesting factors was chosen:

⁴ The TSOs are: REN (Portugal), FINGRID (Finland), RED (Spain), ELIA (Belgium), SVENSKA KRAFTNÄT (SWEDEN), STATNETT (Norway) and APG – AUSTRIAN POWER GRID (Austria).

Input: Employees⁵

Quasi-fixed input: Installed transformer capacity (MVA)⁶

Output: Domestic demand (TWh)⁷

The output-figure, domestic demand, was taken as a proxy for the amount of energy transported over the network because objective actual data was not obtainable. This seemed to be justifiable since we are dealing with the sole TSOs of the respective countries and the domestic demand and the amount of energy transported over a TSO-network are undisputedly highly correlated.

As a discount factor γ , $\left(\frac{1}{1+0.06}\right)$ was chosen.

5 Results

5.1 Total efficiency

Application of the static DEA-model led to the following total efficiency-results:

TSO	Total Efficiency
A	0.55
B	0.97
C	0.97
D	0.59
E	1.00
F	0.87
G	0.63

Table 1: Static total efficiency

As can be seen, TSO E is the only efficient TSO in the sample, followed by B, C and F. The least efficient TSO in the sample is TSO A.

⁵ Source: company reports.

⁶ Source: company reports.

⁷ Source: UCTE (www.ucte.org) and NORDEL (www.nordel.org).

In the dynamic setting the following figures result:

TSO	Total Efficiency
A	0.77
B	0.97
C	0.98
D	0.75
E	1.00
F	0.95
G	0.81

Table 2: Dynamic total efficiency

Again, TSO E is the only efficient enterprise and the ranking remains the same.

What distinguishes these results from the results above, however, is the fact, that all players, especially those with a particularly poor record from the static perspective, could improve their score significantly. The importance of this result will be illustrated at a later point.

In order to get better insights as to why a DMU is more efficient than another it is instructive to first look at how the efficiencies of the DMUs have evolved over time and then what where the specific sources of inefficiencies (i. e. variable inputs, quasi-fixed inputs or outputs).

5.2 *Evolution of efficiency over time*

When applying the static model, the following efficiency-development-path of the respective enterprises results:

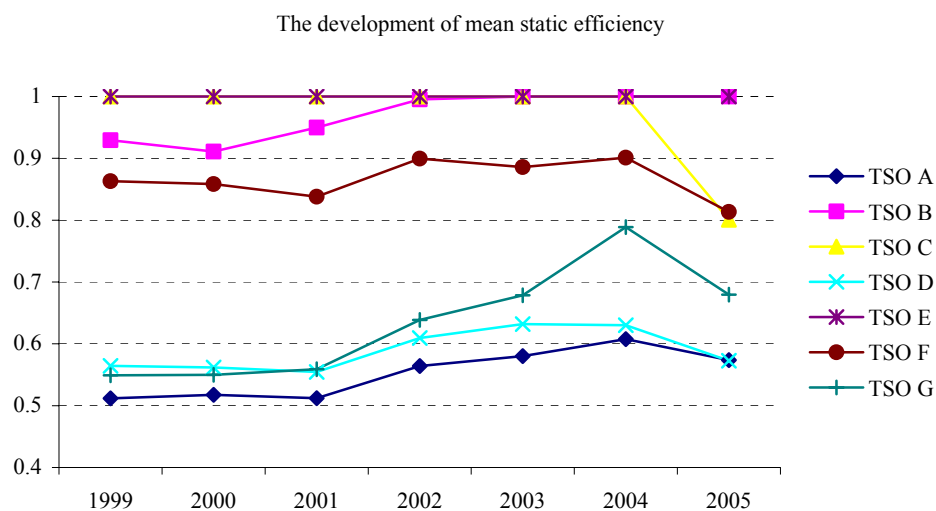


Figure 4: Development of mean static efficiency

It can be seen that all enterprises could increase their efficiency between 1999 and 2004 (e. g. TSO G: +43.7%) but in 2005 their (except TSO B and TSO E) efficiency

deteriorated. In order to identify the reasons for such a development we decompose the mean yearly inefficiency of the entire sample:

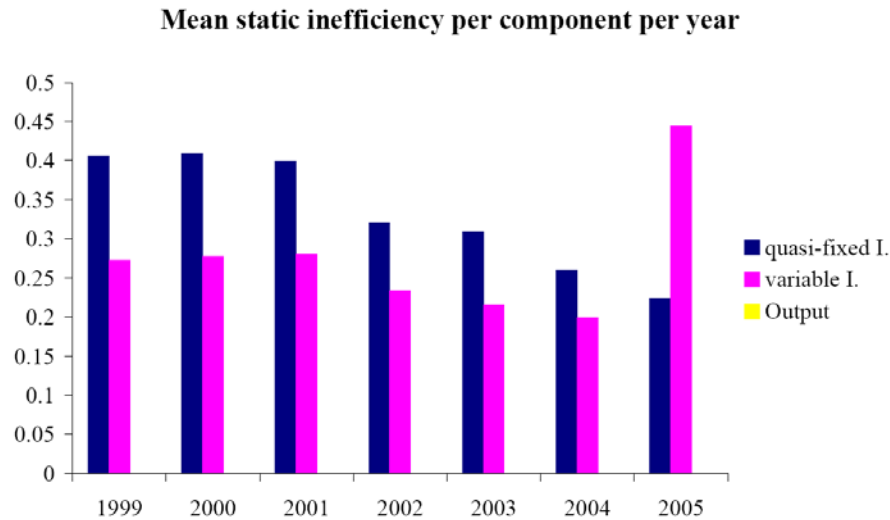


Figure 5: Static inefficiency by component per year

The static perspective seems to suggest that the observed pattern is due to significant efficiency improvements in variable- and quasi-fixed-inputs from 1999-2004⁸, where enterprises seem to have put an emphasis on the latter, and a sudden efficiency-deterioration of variable inputs (i. e. employees) in 2005. When analysing the behaviour of the firm from a static perspective it therefore seems that the respective regulatory regime induced the enterprises to put the emphasis on increasing the efficiency of their quasi-fixed inputs, thereby accepting a later deterioration of the efficiency of their variable inputs.

Applying the dynamic model leads to the following efficiency-development-paths:

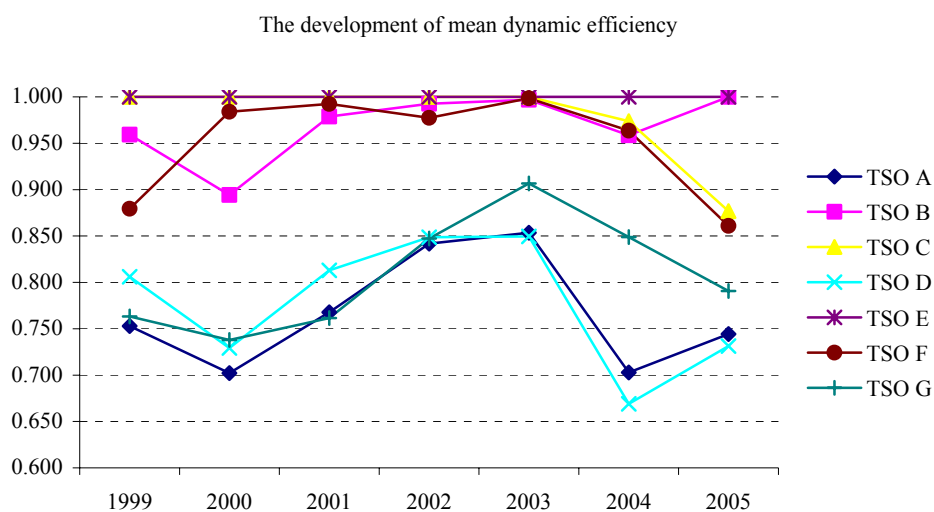


Figure 6: Development of mean dynamic efficiency

⁸ All TSOs were efficient in their outputs.

Broadly speaking it can be stated that efficiency of all inefficient enterprises except TSO F deteriorated between 1999 and 2000, improved between 2000 and 2003 and then deteriorated again. Again, we want to identify the reasons for such a development and therefore decompose the mean yearly inefficiency of the entire sample:

Mean dynamic inefficiency per component per year

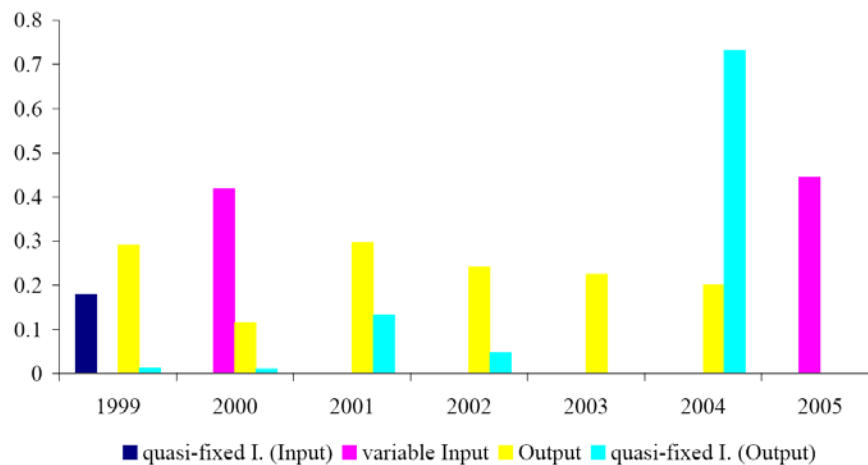


Figure 7: Dynamic inefficiency by component per year

Obviously the dynamic perspective suggests rather different reasons for the efficiency development than the static perspective: First of all, a significant contribution to inefficiencies stems from the output, which was entirely absent in the static model. Secondly, the pattern of inefficiency sources is somehow reversed compared to that of the static perspective: The increase in inefficiency in 2000 is entirely due to variable inputs and the increase at the end (2004, 2005) is to a great extent due to an increase in the inefficiency of quasi-fixed inputs.

When trying to find reasons for these differences it is important to remember that with the dynamic model the level of quasi-fixed inputs is endogenous. Apparently, the behaviour of the firm reflects the resulting trade-off (as stated in section 2.3) in that it chooses to have greater output-slacks (quasi-fixed input as output and “normal” Output) in this period in order to have smaller input-slacks in the next period (albeit at a decreasing rate). This way also the pronounced increase of quasi-fixed-input-slacks in 2004 and that of input-slacks in 2005 can easily be explained as a feature of the model in that the above trade-off vanishes in the last period (cf. equation (3)).

The relevance of these results lies not so much in the particular figures and the ranking itself but rather in the nearly diametrically opposed conclusions about the efficiency of the respective enterprises that could be drawn (by the regulator for instance) and the consequences this has on future income and incentives of the firms. The dramatic effects

of a potential wrong reliance on the static model shall be illustrated in the following section.

5.3 The optimal level of quasi-fixed inputs in the course of time

As already mentioned above, the main difference between the static and the dynamic model arises by the fact that the static model assumes the level of quasi-fixed inputs as exogenously given (but controllable by the firm) in each period whereas the dynamic model merely takes the initial value as given and determines subsequent ones endogenously. This of course has significant consequences on the amount of quasi-fixed inputs that is deemed optimal in each period in that the static model myopically seeks to minimize the amount of inputs for the respective period only but the dynamic model also takes into account that the level of quasi-fixed inputs in this period also has consequences on their amount in subsequent ones and thus on the efficiency in those periods. To illustrate this phenomenon, in what follows, the optimal paths of quasi-fixed inputs as prescribed by the static and by the dynamic model are depicted for 4 representative TSOs from the sample.

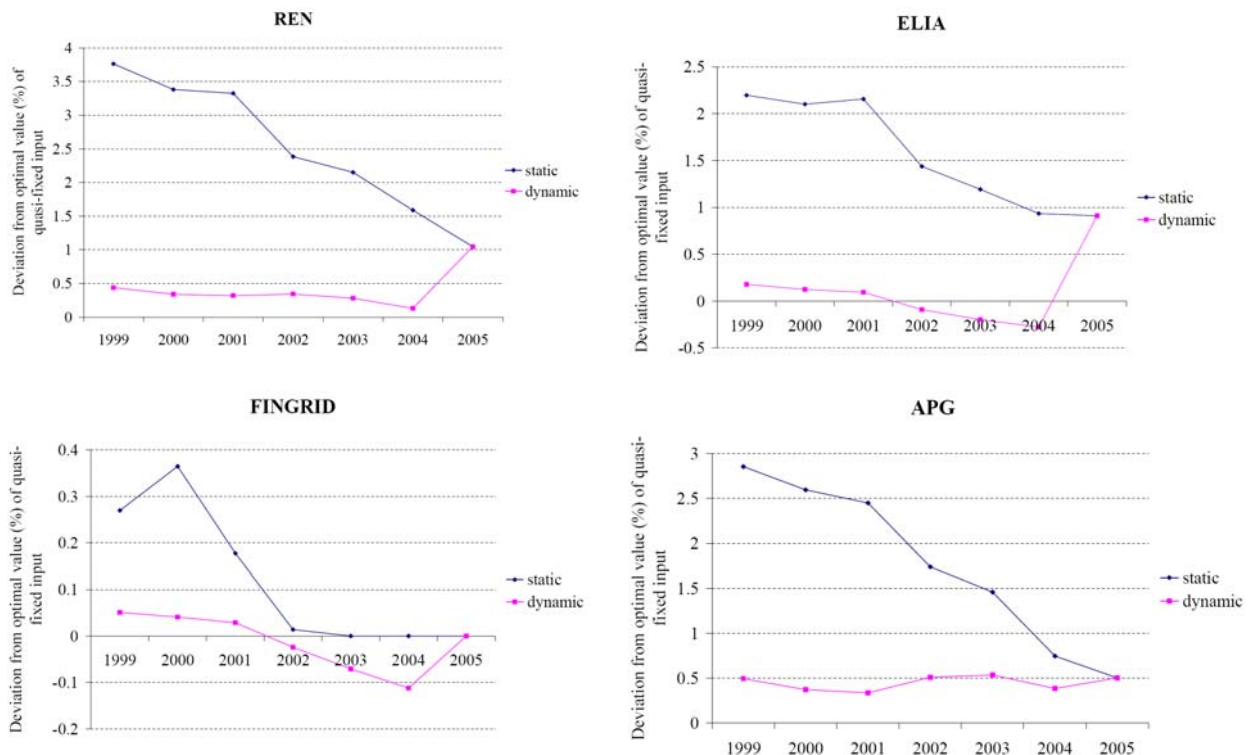


Figure 8: Dynamic and static optimal path of quasi-fixed input for 4 TSOs

Figure 8 shows for each of the 4 TSOs for each year the deviation (%) of the actual level of the quasi-fixed input from the optimal level as prescribed by the static model and by the dynamic model. It can be seen that for each TSO and for each year, the static model

detects a significantly higher deviation than the dynamic model. In other words, the static model identifies a much more dramatic oversupply of installed transformer capacity than the dynamic model. In some cases even (such as FINGRID 2002-2005 and ELIA 2002-2004⁹) the static model would imply a reduction in installed transformer capacity whereas the dynamic model would imply an increase.

⁹ ELIA in 2004 is a particularly drastic case where the static model would suggest a cut of installed transformer capacity by approximately 50% whereas the dynamic model would suggest an increase of about 3%.

6 Conclusion

The main purpose of this paper was to provide further evidence that the efficiency assessment of industries with large capital inputs that have a quasi-fixed character demands a dynamic perspective. I therefore formulated a DEA-model that, inspired by Nemoto and Goto's seminal paper (Nemoto and Goto, 1999), accounts for this necessity and applied it to 7 European transmission system operators.

The main findings can be summarized as follows:

Compared to the dynamic model, the static model

- generally underestimates the efficiency of the enterprises,
- identifies less plausible (wrong?) reasons for inefficiency and, most importantly,
- by ignoring the short term fixity and long term beneficial effects of quasi-fixed inputs prescribes much more severe reductions in those.

These results show that a sole reliance on the static model can lead to misleading conclusions about the actual efficiency of enterprises in industries where quasi-fixed inputs play an important role in that it might induce a myopic reduction in quasi-fixed inputs where in fact an increase is due.

Bearing in mind that especially the such defined quasi-fixed inputs constitute the backbone of a high-quality supply of electricity it becomes clear that such a reliance on a static viewpoint and the ensuing drive to increase efficiency by cutting down on quasi-fixed inputs can have very unpleasant consequences.

Putting it together, the present investigation shows again that especially regulators who are interested in whether the enterprises under scrutiny employ efficient amounts of capital inputs should definitely have a look at dynamic efficiencies and not rely on a static efficiency analysis only.

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