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Efficiency evaluation of hydroelectric power plants using data envelopment analysis

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Abstract. The purpose of this paper is to evaluate the efficiency of a network of hydroelectric power plants using the Data Envelopment Analysis approach. The network is modeled as a linear system with multiple inputs and outputs. As inputs one could consider, for instance, the age of a plant, the total number of hours that a plant is in operation during each year, etc. As outputs the model considers the electrical energy delivered per year, the number of hours that the plant is not in operation, etc. The proposed approach does not only evaluate each plant relative to the other ones, but it also 'produces' policy making scenarios that would enable plant managers to improve the plant's operational characteristics. Computational results based on real-world data are presented and discussed. Relationships between efficiency scores and various inputs/outputs are also investigated and some interesting trends are identified.

Keywords: efficiency evaluation; hydroelectric power plants; data envelopment analysis

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Introduction

The system under consideration in this work is the electricity generation system of Greece and in particular its hydroelectric power plants. Electricity generation in Greece, after World War II, had been based on conventional thermal lignite-fired power plants. This was mainly due to the fact that Greece has reasonably large lignite reserves and no oil resources. Trying also to achieve self-sufficiency in the energy/electricity sector, reliable fuel availability and cost control, as well as industrial development of economically retarded provincial areas with high unemployment, Greek governments had traditionally favored over the past four decades, therefore, the deployment of lignite-fired power plants (Papadias and Vournas, 1999).

Even today, half (about 55% in 2006) of the annual electricity production is carried out in lignite-fired power plants. The lignite power plants of the Greek electricity system are quite old and operate at low efficiencies. Considering also the high particulates emissions of these plants the adverse environmental effects are quite serious. In view of the continuously increasing pressure of the international community, the EU and environmental groups for "cleaner" and environmentally friendlier plants, with low or no CO_2, SO_2 and NO_x emissions and more rational energy/fossil fuel resources exploitation, the Greek electricity generation system has to abandon (better limit), its dependence on lignite, oil and other fossil fuels.

In its effort to achieve this target the Public Power Corporation (the equivalent of the Greek Electricity Generating Board) has planned to exploit renewable energy sources and in particular hydroelectric generation, to the highest possible degree. Integrating hydroelectric power plants in the electricity generating system of a country is beneficial not only from the environmental point of view but also from the technical one. Hydroelectric power plants

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achieve their rated power capacity very quickly and operate with high efficiency ratio (more than 80%). These characteristics and in particular their ability to respond to variable dynamic power demands very quickly, make them especially suitable for absorbing peak electricity demands. In most of the cases in Greece, hydroelectric power plants are utilized to meet peak electricity demands over the day and serve as power buffers to the thermal power plants, which are operated as base plants. Apart from this stabilizing effect to the electricity generating system and the profound favorable environmental consequences, hydroelectric power generation has also other serious economic and social implications. The dams required for the associated hydroelectric power plants water reservoirs do also serve as water management and river water-flow control 'tools' for irrigation and flood prevention purposes. Focusing on the electricity/power generation system there are currently 20 hydroelectric power plants-units in operation, with a total rated power capacity of 3.06 GW (for the year 2006) accounting for almost 12% of the total annual electricity production. To the authors' knowledge there is no other study analyzing or evaluating the efficiency of Greek hydroelectric power units. Such studies could obviously provide the management of the Public Power Corporation with useful information for operational 'corrections', modifications and improvements. The purpose of this work is, therefore, to carry out a systematic efficiency evaluation of the network of the hydroelectric power plants of the Greek electricity generating system.

The present evaluation has been carried out using the mathematical/linear programming tool of Data Envelopment Analysis (DEA). DEA is a well-established mature multi-criteria analytic tool/technique for evaluating the operational efficiency of systems that exhibit similar (operational) characteristics with several inputs and outputs. It has been used successfully for the evaluation of a vast variety of systems ranging from the retail services and education to industrial production (e.g. Sofianopoulou 2006), etc.

As far as the evaluation of electricity/power generating systems, many researchers have applied DEA successfully. The works of Park and Lesourd (2000), Olaturi and Dismukes (2000) and Nag (2006) refer to the efficiency evaluation of power plants from the technical point of view, whilst the works of Korhonen and Luptacik (2004) and Sarkis and Cordeiro (2009) from the environmental point of view. On the other hand, the works of Athanassopoulos *et al*. (1999) and Vanisky (2006) examine the economical and enterprise politics aspects of the problem. Quite a few works have been also devoted to the efficiency evaluation of electricity distribution systems (Jamasb and Pollitt, 2002, Pahwa *et al*., 2002, von Hirschhausen and Kappeler, 2005, Chen *et al*., 2009). Finally, the works of Sarica and Or (2007) and Barros (2008) examine hydroelectric and renewable energy sources power plants.

The DEA technique is able to not only assess the efficiency of each one of the different units of a system relative to the other ones, but also 'suggest' corrective policies/measures, which could make the operationally inefficient units efficient. The basics of DEA as well as the particular model adopted in this work are briefly explained in the following section of the paper.

Brief overview of data envelopment analysis

In recent years DEA has been utilized in a great variety of applications for evaluating the performance of different systems. Through DEA it has been possible to gain new insight into systems that until then were extremely complicated to study because of the number and nature of parameters involved. DEA employs mathematical programming techniques to evaluate the efficiency of homogeneous decision making units (DMU), where DMUs can be, for instance, hospital units, retail stores, bank branches, manufacturing cells, etc. The efficiency is translated as the ratio of the weighted sum of outputs to the weighted sum of inputs.

In the present case study, the heart of the analysis lies in finding the best virtual power unit for each operating unit. If the virtual unit is better than the existing one in terms of making more output with the same input or using less input for the same output then the given operating unit is considered inefficient. The procedure of determining the best virtual DMU can be formulated as a linear program. Assessing the performance of n different DMUs involves the solution of n different linear programming problems.

Charnes, Cooper and Rhodes (1978) proposed one of the most basic DEA models, appropriately termed as the CCR model. Given that there are n DMUs and associated numerical data for each of the m inputs and s outputs for all DMUs, the fractional mathematical programming problem that is solved in order to obtain values for the input weight (v_i) ($i = 1,\ldots,m$) and the output weight (u_r) ($r = 1,\ldots,s$) variables is the following (Cooper *et al*. 1999):

$$\max \quad z \quad = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij_0}} \tag{1}$$

subject to

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad (j = 1,\ldots,n) \tag{2}$$

$$u_r \geq 0 , \quad (r = 1,\ldots, s) \tag{3}$$

$$v_i \geq 0 , \quad (i = 1,\ldots, m) \tag{4}$$

Where x_{ij} and y_{rj} correspond to the input and output parameter values for the j^{th} DMU respectively. Index j_0 refers to the DMU being evaluated. Objective function (1) maximizes the ratio of virtual output to virtual input of the DMU under evaluation by calculating the appropriate weights v_i and u_r. Constraints (2) ensure that this ratio does not exceed 1 for every DMU. This implies that the objective function value lies between 0.0 and 1.0; the latter value denoting that the DMU under examination is efficient. The above non-linear program is linearized and the solution of its linear equivalent produces the efficiency scores for all DMUs. In this work a particular extension of the CCR model, namely the output oriented variable returns to scale BCC model (Cooper *et al*. 1999, Banker *et al*. 1984) has been applied.

Input and output parameters

The present application of DEA has been carried out using real-world data for the input and output parameters that concern the operation of the 20 hydroelectric power plants-units of the Greek electricity system in the year 2006. Having carefully reviewed the relevant literature it was decided to use in the analysis the following parameters:

Input parameters

- Power capacity: It reflects the amount of electricity that can be potentially produced by each unit. It is expressed in MW.
- Commissioning date: It is directly related to the age of each unit (2006 being the reference year).
- Operation time: It reflects the (total) anual operation time of each unit and is expressed in hours.

Output parameters

- Electricity delivered: It reflects the total amount of electricity produced by a single unit within a year (i.e. in 2006). It is expressed in MWh.
- Availability: It is the percentage of time within a year that the unit can be safely used for power generation.
- Scheduled operation interruptions: It is the percentage of time within a year that the unit is unavailable for electricity generation due to, say, scheduled maintenance.
- Unexpected operation interruptions: It is the percentage of time within a year that the unit is unavailable for electricity generation due to unexpected reasons, say, technical failures or breakdown.

Different scenarios investigated

It is well known that the reliability of DEA results increases as the number of independent units of the system evaluated gets larger. In the system under consideration in this work the number of independent hydroelectric power plants-units is just 20, which is rather low. In the DEA literature, however, there is an expression which relates the number of units evaluated to the number of input and output parameters considered. This expression reads:

$$n \geq \max \{ m\, s\, ,\, 3\,(m + s) \} \qquad (5)$$

where n is the number of units evaluated and m, s is the relevant number of input and output parameters respectively. Taking into account that in the particular instance of the problem investigated in the present work n is set to 20, reliable efficiency evaluation can be made with m and s set, say, to 2.

The efficiency evaluation of the units involved has been carried out with three different scenarios, focusing on the technological characteristics of the system. Different combinations of input and output parameters were considered. These combinations are summarized in Table 1.

Table 1. Efficiency evaluation scenarios

Scenario	*Input Parameters*	*Output Parameters*
1	Commissioning date Operation time	Electricity delivered Availability
2	Power capacity Operation time	Electricity delivered Availability
3	Commissioning date Operation time	Scheduled operation interruptions Unexpected operation interruptions

Results and discussion

The DEA software employed in this work is an in-house code developed at the Department of Industrial Management and Technology of the University of Piraeus (Greece) and runs in a Microsoft Excel environment. This code is used extensively in our department for both educational and research purposes. The results reported here have been obtained with DEA being carried out “in terms of the outputs”, i.e. trying to maximize favorable/‘positive’ outputs (scenarios 1 and 2) or to minimize unfavorable/‘negative’ outputs (scenario 3) with given/constant inputs.

Results concerning each one of the different scenarios considered are summarized as following: The relatively newer units should decrease operation time in order to become efficient. Older units, on the other hand, should increase both their annual electricity delivered and their availability in order to achieve better efficiency scores. Units with either low or high power capacity cannot improve efficiency by solely decreasing operation time. It seems that in order to improve efficiency both the annual electricity delivered and the availability should be increased. Interesting enough, neither maintenance interruptions nor operation interruptions due to technical failures affect dramatically the efficiency scores. Units evaluated as efficient may quite happily have either low or high operation interruptions (either scheduled or not scheduled). In general, inefficient units should achieve an unrealistically high reduction in operation interruptions in order to be efficient. In the case of some very old units operation time reduction may lead to efficiency.

The histogram in Fig. 1 presents the number of times (frequency) that each one of the different units is evaluated as efficient in the scenarios investigated. It is observed that units 2, 13, 16, 17, and 20 have been evaluated as efficient in all the cases tried (it is noted that efficient units are considered to be the ones achieving in the DEA software a score higher than 97%), whilst units 3, 8, 9, 12 and 15 are inefficient in all combinations tackled. Units 13, 16 and 17 are located in western mainland Greece in an area with very favorable hydrological conditions with quite high figures of annual precipitation. Unit 2, on the other hand, is located in western Macedonia close to an area, which does not only exhibit high rainfalls but also has high electricity demand. There is no need, therefore, of transmitting electric power to long distances.

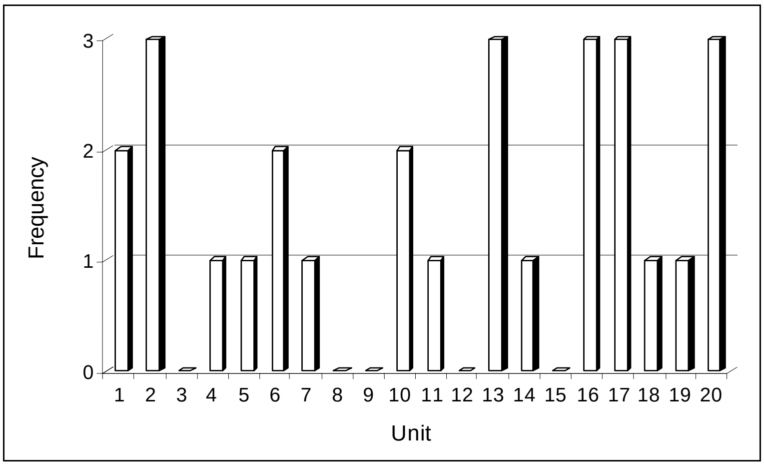

Fig. 1. DEA evaluated units' efficiency frequencies

The correlation of calculated efficiency scores with the age and the generating power capacity of the unit is shown in Fig. 2 and 3 respectively. Power function regression indicates that the curves best fitting these results are respectively: $y = 1.0088\, x^{-0.0783}$ and $y = 0.7122\, x^{0.0267}$.

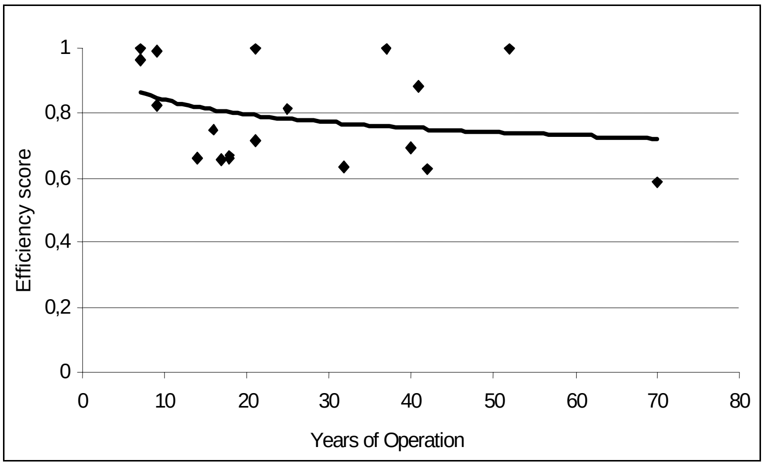

Fig. 2. Efficiency score versus years of operation

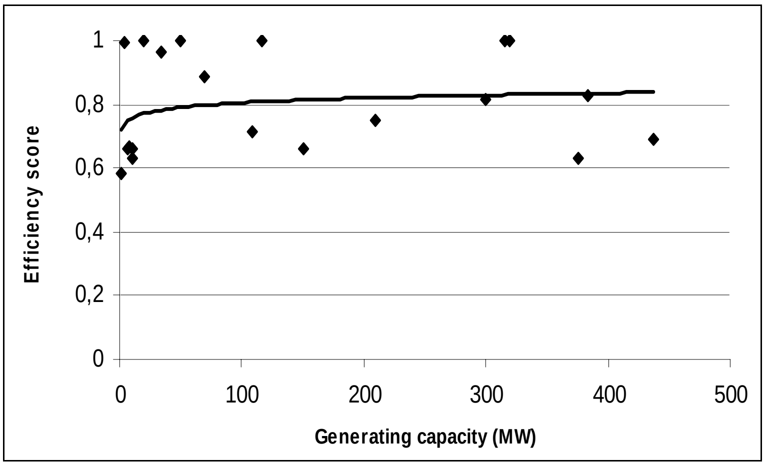

Fig. 3. Efficiency score versus generating power capacity

As expected, these relations indicate that the efficiency of the power plant-unit increases as the site of the plant gets bigger and decreases as the plant gets older.

Concluding remarks

In this work DEA technique was applied in order to evaluate the efficiency of hydroelectric power units of the Greek electricity generation system. Different scenarios focusing on the technological aspects of this problem were considered. Relationships between efficiency scores and various input and output parameters were examined and identified. Results of this study indicate that inefficient plants with less than 10 years of operation should decrease the annual operation time in order to become more efficient, whilst relatively older plants with more than 10 years of operation should increase both the electricity delivered and their availability in order to reach higher efficiency scores. The latter is also true irrespective of the power capacity of the plant.

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