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Productivity and efficiency measurement of the Danish centralized biogas power sector

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A B S T R A C T

The widespread use of the renewable energy sources in the future's energy production is necessary, in order to avoid the predicted environmental, economic and social effects which can be derived from the overuse of fossil fuels. Denmark has announced to be fossil fuel independent with a renewable energy based heat and power source by 2050. Theoretically, the centralized biogas combined heat and power plants can play a determinant role in the subsequent Danish energy supply scheme, due to its feature to satisfy base load demand. The productivity and efficiency analysis of the currently operating Danish centralizes biogas CHP power plants is crucial in order to study whether there is a most efficient power plant which can be introduced as a “best practice” innovative technology for the future's Danish biogas power plants. In this paper we use the intertemporal Malmquist total factor productivity DEA method to analyze the change in the efficiency and productivity of the Danish centralized biogas power plants in the period 1992–2005.

1. Introduction

The development of the biogas power plants in Denmark has started after the first oil crisis. The purpose of the Danish energy policies at that time was to increase the share of the domestic resources against imported crude oil and to establish a more diversified energy supply scheme [28]. The environmental policies of the 1980s, intended to protect the water quality of the above- and belowground reservoirs, contributed to the wide spread of the Danish centralized biogas CHP plants [18]. However, the uncertainties caused by liberalization process of the energy market – replacing the fixed-price subsidy scheme with market determined price – resulted in no further expansion of the Danish centralized biogas sector [23,24].

In accordance with the current energy policy, Denmark announced to be fossil fuel independent with a renewable energy based heat and power source by 2050 [29]. Due to the predicted increased capacity of the intermittent sources, the based load power plants using renewable resources (e.g. biogas CHP plants) will play the key role in the new energy supply scheme. Before the further expansion of the Danish biogas sector, a productivity and efficiency analysis of the current biogas power plants is essential in order to possess benchmark for the future CHP plants. Therefore, in this paper the focus is on the productivity and efficiency measurement of the centralized Danish biogas power plants in the period 1992–2005, using intertemporal data envelopment analysis (DEA) method incorporates Malmquist index.

The paper is organized in the following way. In the next section the method is described including a literature review of applications to the energy and biogas sectors. In the subsequent section the DEA approach for dynamic productivity analysis is discussed. The case study is introduced in Section 4 while in Section 5 the results are presented. The paper ends with concluding the findings in Section 6.

2. Literature review

Efficiency and productivity measurement methods can be differentiated whether parametric econometric theory is used, or *a prior* assumptions regarding the correspondence between input and output have not been established (i.e. non-parametric methods). The previous group contains methods e.g. least square econometric models and stochastic frontier technique [2,21], while in the latter group the non-parametric data envelopment analysis (DEA) method is considered [8].

The non-parametric data envelopment analysis models (e.g. the

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radial CCR and BCC or the non-radial SBM) can be used to calculate technical efficiency of decision making units (DMUs). DMUs possess the highest output/input ratios of the sample frame the efficient frontier, with an assumed 100% efficient level. Those decision making units which are not lying on the frontier are considered to be inefficient. The previously mentioned basic DEA methods use static point of view, since the devised efficient frontier does not change over time.

However, when intertemporal productivity changes are studied, the technological innovation also has to be considered, besides the variations in the efficiency levels. Therefore, the expansion of the static DEA models is required, since in that dynamic environment the technological changes also contribute to the productivity changes of DMUs. The literature describes two methods which analyze changes of total factor productivity (TFP) based on Malmquist TFP index. Based on Nishimizu and Page [22]; Coelli et al. [8] introduce the Stochastic Frontier-like Methods, where the parametric stochastic production frontier theory is used in order to calculate technical change and efficiency. Total factor productivity can also be estimated by applying non-parametric DEA method to calculate the different distance functions of Malmquist TFP change indices. Once these indices are determined, technical change and technical efficiency results can be derived [8].

San Cristóbal [25] highlights the fact that the power sector related DEA literature is gathered from applications on electricity distribution and on power generation units. Zhou et al. [32] gives a detailed literature survey on DEA method used in energy and environmental related studies. As these papers show, despite the significantly increasing use of data envelopment analysis method in productivity and efficiency measurement in the power sector, the application of this theory on biogas power plant is still not widespread. Madlener et al. [20] investigates the performance (i.e. efficiency) of 41 Austrian biogas power using multi criteria (MCDA) and data envelopment analysis methods. This paper suggests the simultaneous usages of these two approaches as complementary techniques when managerial preferences are considered. While Djatkov et al. [13] uses DEA in order to analyze the efficiency of 10 biogas plants in Bavarian region, Germany, Djatkov and Effenberger [12] expands the methodology by applying the previously mentioned DEA method and the multi criteria technique to study the same plants, simultaneously. In the latter case, the conclusion is that the combined use of DEA and MCDA enables to analyze the efficiency of the biogas from all aspects, including technical, economic and environmental aspects. Djatkov et al. [14] develops a fuzzy sets theory based model in order to analyze the performance of 10 biogas power plants.

DEA methods are also used to compare the efficiency of several other types of renewable energy (RE) technologies [25] and [19]. San Cristóbal [25] considers 13 different RE technologies and compares their performance by applying multi criteria data envelopment analysis (MCDEA). On the other hand Lo Sorro & Ferruzzi [19] studies the efficiency of 21 technologies (both conventional and renewable), using DEA methods. Surprisingly, it is the large-scale wind turbine, a RE technology, which has been found to be the most efficient among the other technologies.

Based on Zhou et al. [32] several articles exist which study the intertemporal productivity of electricity generating units, using non-parametric Malmquist TFP index method. Yunos and Hawdon [31] analyzes the productivity changes of the Malaysia's National Electricity Board, considering the performance of transmission system operator of 26 other countries and 15 year timescale. Färe et al. [16] uses Malmquist input based TFP index in order to examine the productivity of 19 electricity generating utilities, between 1975 and 1981. Similarly, Chitkara [6] applies the same Malmquist TFP method to calculate the productivity changes of Indian power plants considering a five year period, and Agrell and Bogetoft [1] does a time series study of Danish district heating and cogeneration system units, in order to assess their environmental and economic efficiencies. Contrary to the previously mentioned articles, Sueyoshi and Goto [27] uses slack-adjusted data envelopment analysis (SA-DEA) method to intertemporal productivity change measurement. Applying the SA-DEA model, the efficiency and productivity of the ten electric power company is calculated on a 10 year timescale, by comparing the efficiency results to the fixed base (first) year. At the same time, Goto and Tsutsui [17] makes a bilateral comparison between Japanese and US electrical facilities, calculating with Intertemporal Efficiency Index (IEI).

For further explanation of the different (parametric and non-parametric) efficiency and productivity measurement methods see Coelli et al. [8]. Cooper et al. [10] and Cooper et al. [11] give introduction to data envelopment analysis method, while Seiford [26] and Cook and Seiford [9] make historical summary on DEA and publish a wide range of reference of literature on this field. In the next section, we will briefly introduce DEA and the Malmquist approach.

3. DEA approach for dynamic productivity analysis

The DEA method involves mathematical programming in order to determine the (in)efficiency of those DMUs, which do not belong to the efficient frontier (i.e. the border of the production possibility set, which indicate the efficient production). DEA is called non-parametric method, since it does not use fixed (pre-determined) weights for the inputs and outputs of all DMUs', but it derives variable weights from the given data. Moreover, DEA does not require the functional forms to be pre-assumed, contrary to the statistical regression (parametric) approach [10].

One basic DEA model, the CCR model [4] was based on the previous work of Farrell [15]. This model uses linear programming in order to maximize the output and input ratio of all DMUs, deriving the optimal weights of the inputs and outputs (also called multipliers) form the data set [11]. The CCR model assumes constant returns-to-scale, and it is applicable with both input- and output-orientations, severally. Banker et al. [33] published the BCC model, as an extension of the CCR model which assumes variable returns-to-scale. Both CCR and BCC models[1] are called "radial measure" model and used to calculate technical efficiency (purely technical and scale efficiencies).

Opposite the radial measure theory, non-radial DEA models combine both input- and output-orientations with focus on slack analysis (e.g. Additive model and Slacks-based measure of efficiency). These non-radial models differ from CCR and BCC theories by their translation invariance feature, since the additive [5] and slacks-based measure (SBM) models can handle semipositive input and output data [10]. The SBM model [30] has further advantages on additive model, since the previous has ability to measure efficiency with the property of unit invariance [9].

When the focus is on an intertemporal economic analysis of changes in DMU's efficiency and technology, the previously introduced DEA methods can be used to calculate the distance functions for Malmquist TFP index. Fig. 1 depicts an industry with three performers (DMUs) whose productivities are studied in two successive periods; the *b*th (base) and the current *t*th periods. Every decision making units use two inputs (x_1 and x_2) in order to produce a single output (y). On the axes the standardized inputs are illustrated, thus the points indicate the amounts of the two inputs

[1] CCR is named after Charnes, Cooper and Rhodes and BCC is named after Banker, Charnes and Cooper [33].