Energy Economics 70 (2018) 26–36

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Scale efficiency for multi-output cost minimizing producers: The case of the US electricity plants☆,☆☆

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ARTICLE INFO

Article history:
Received 20 July 2017
Received in revised form 6 December 2017
Accepted 12 December 2017
Available online 21 December 2017

JEL classification:
C61
D24
L94
Q29
Q39

Keywords:
Scale efficiency
Cost minimizing
Multi-output producers
Electricity generation

ABSTRACT

To know whether the optimal scale of production has been reached is valuable information for producers. To date, scale efficiency measurements have only been suggested for the entire production process. For multi-output producers, more detailed results are required. Hence, in this paper, we show how to provide such information at the output level. Attractively, our output-specific scale efficiency measurements are nonparametric in nature, they take the economic objective of the producers into account, they can be defined without observing the input prices, and they are easy to interpret and to use in practice. We apply our methodology to a sample of more than 3300 US electricity plants from 1998 to 2012, producing up to 10 types of electricity. We show that, while there is a scale improvement at the total electricity generation level, this is not the case for each of the 10 types of electricity. Also, we demonstrate that, in general, renewable electricity presents better scale of production than non-renewable electricity. Finally, we highlight the importance of multi-output plants in the US electricity sector, and show that this type of plant is preferable for the production of non-renewable electricity, while single-output plants are preferable for renewable electricity.

1. Introduction

Assessing the optimal scale of a production process is not a new topic in both the economic literature and the production theory. Indeed, the concept of scale efficiency could already be found in the works of Hanoch (1975), Panzar and Willig (1977), Forsund and Hjalmarsson (1979), Banker (1984), Banker et al. (1984), Färe and Grosskopf (1985), Banker and Thrall (1992), Forsund (1996), and Golany and Yu (1997). More recent works include those of Simar and Wilson (2002), Forsund and Hjalmarsson (2004), Krivonozhko et al. (2004), Zelenyuk (2006, 2016), Podinovski et al. (2009), and Peyrache (2013). These works have the investigating of scale efficiency of the entire production process in common. Or in other words, their methods indicate whether optimal scale is reached for the aggregate production level. In this paper, we suggest a technique that also provides scale efficiency results for individual output.

Our motivation to provide output-specific scale efficiency results is two-fold. On the one hand, by considering output-specific indicators, the realism and the discriminatory power of the model are naturally increased. The realism is increased since the links between the inputs and the outputs can be modelled by allocating the inputs to the output-specific production processes.[1] The discriminatory power is increased since output-specific optimization behaviours could be assumed. On the other hand, for multi-output producers, knowing whether the optimal scale is reached for each output separately is clearly additional relevant information; useful when choosing their strategy or when deciding how to allocate the inputs.

Our scale efficiency measurements are specially designed to take the economic objective of the producers into account. In particular,

☆ I thank the Editor-in-Chief Richard S.J. Tol, the Editor Perry Sadorsky, and the anonymous referees for their valuable comments that substantially improved the paper.
☆☆ This work was supported by the National Natural Science Foundation of China under Grant No. 71750110539.
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[1] For example, employees allocated to specific output production, machines used only to produce certain outputs. For more discussion on the allocation of inputs to outputs, refer, for example, to Färe and Grosskopf (2000), Salerian and Chan (2005), Despic et al. (2007), Färe et al. (2007), Tone and Tsutsui (2009), and Cherchye et al. (2015).

https://doi.org/10.1016/j.eneco.2017.12.017
0140-9883/

we assume that they are cost minimizers (the following is easily extended to profit or revenue maximizations). Cost minimization fits with many settings and applications, and is, by definition, a necessary condition for profit maximization. Our model is rooted in the nonparametric cost evaluation models initiated by Afriat (1972), Hanoch and Rothschild (1972), Diewert and Parkan (1983) and Varian (1984). That is, we impose very few structures on the production process and, therefore, only the following data are required: outputs, inputs, and input prices. The distinguishing feature of our methodology is that by modelling each output separately, we naturally give the option to assess scale efficiency at the output level. Finally, as the observation of the input prices is rather restrictive for some applications, we also provide alternative definitions of our scale efficiency concepts without this assumption.

We apply our methodology to the case of US electricity plants. The Environmental Protection Agency of the US developed a plant-level database for 1998 to 2012. For each plant, the coal, oil, gas, nuclear, other fossil, wind, solar, geothermal, hydro, and biomass electricity generations are specified. As such, by distinguishing between 10 different types of electricity generation, this database offers a unique opportunity to apply our methodology. In particular, the very detailed data allow us to evaluate scale efficiency of both the individual and aggregate electricity generation levels, and to make a distinction between multi- and single-output producers. Therefore, we can investigate whether multi- or single-output producers are preferable for each of the 10 types of electricity generation. This is valuable information for managers, regulators, and policy makers when deciding how to allocate the production of electricity and how to design the plants.

Moreover, our methodology offers two extra advantages in this context. On the one hand, it gives the option to allocate the inputs to each electricity generation type. In particular, renewable electricity is not produced by the use of fuel, while non-renewable electricity generation requires this production factor. As such, our methodology, which recognizes the links between production factors and electricity generation, is particularly useful as it increases the realism of the modelling of the plant production process. On the other hand, while the data for the production factors and electricity generation are available for the plant level, the input prices are only available at the state level. Thus, our methodology that works with partial/without input price data is also very attractive for that reason.

The rest of this paper unfolds as follows. Section 2 presents the methodology. In Section 3, we apply the methodology to the case of the US electricity plants from 1998 to 2012. Section 4 provides conclusions.

2. Methodology

We consider that we observe producers that are cost minimizers. In particular, we assume that they use P inputs, $\mathbf{x} \in \mathbb{R}^P_+$, to produce Q outputs, $\mathbf{y} \in \mathbb{R}^Q_+$. We denote the input price vector by $\mathbf{w} \in \mathbb{R}^P_+$. Firstly, we assume that we observe these input prices. This will be relaxed afterwards.

2.1. Output-specific framework

The distinguishing feature of our scale efficiency measurements is that we make a clear distinction between aggregate and individual outputs.[2] In particular, let us denote the q-th entry of $\mathbf{y}$ by y^q. As such, we will define scale efficiency measurements for both $\mathbf{y}$ and y^q. To achieve this goal, we model each output separately by its own production process, captured by input requirement set defined as follows for output q:

$$I^q\left(y^q\right) = \left\{\mathbf{x}^q \in \mathbb{R}^P_+ \,|\, \mathbf{x}^q \text{ can produce } y^q\right\}. \tag{1}$$

Cost evaluation does not require us to make strong assumptions about those sets. In fact, we follow Varian (1984) and only assume that those sets are nested: producing less outputs cannot lead to using more inputs.[3] In this context, $\mathbf{x}^q \in \mathbb{R}^P_+$ denote the inputs used to produce the output q. In fact, those inputs are connected to the aggregate inputs (in $\mathbf{x}$). Some inputs could be used to produce certain outputs (for example, employees, machines). That is, these inputs are allocated to specific output production processes. Next, some inputs could be used to produce all the outputs (for example, infrastructure, capital), i.e. these inputs are not allocated to specific output production processes. Formally, we have

$$(\mathbf{x})_p = (\mathbf{x}^1)_p + \ldots, (\mathbf{x}^Q)_p, \text{ if input } p \text{ is allocated,} \tag{2}$$

$$(\mathbf{x})_p = (\mathbf{x}^q)_p, \text{ if input } p \text{ is not allocated.} \tag{3}$$

Attractively, the distinction between allocated and non-allocated inputs provides a unifying framework that is consistent not only with production models integrating information on the internal production structure, but also with more standard production models (i.e. models that do not consider allocated inputs). As a final remark, note that the non-allocated inputs could also be interpreted as public good (they are non-rival and non-exclusive to the output production processes), and, therefore, they give rise to economies of scope in the production process (see Panzar and Willig, 1981;Nehring and Puppe, 2004).

As the output-specific inputs $\mathbf{x}^q$ could be different from the inputs $\mathbf{x}$, nothing guarantees that their price should be the same. As such, let us denote the prices of the output-specific inputs by $\mathbf{w}^q \in \mathbb{R}^P_+$. Note that, in general, while the input prices could be observed, the output-specific input prices are not. The relationships between the inputs and the output-specific inputs also imply specific relationships between their prices. These prices coincide with the aggregate prices for allocated inputs. Next, for non-allocated inputs these prices must add up to the aggregate prices. As explained previously non-allocated inputs could be interpreted as public good. As such, the output-specific prices have a similar interpretation as Lindahl prices that, by definition, sum up to the aggregate prices. In that case, the output-specific input prices capture the economies of scope of the production processes. Taking together, we obtain

$$(\mathbf{w}^q)_p = (\mathbf{w})_p, \text{ if input } p \text{ is allocated,} \tag{4}$$

$$\sum_{q=1}^{Q} (\mathbf{w}^q)_p = (\mathbf{w})_p, \text{ if input } p \text{ is not allocated.} \tag{5}$$

As a final remark, note that the actual cost of the producers could be rewritten exclusively by output-specific counterparts: $\mathbf{w}'\mathbf{x} = \sum_{q=1}^{Q} \mathbf{w}^{q\prime}\mathbf{x}^q$, where $\mathbf{w}^{q\prime}\mathbf{x}^q$ represents the cost of output q.

[2] For more discussion about efficiency analysis in output-specific frameworks, refer to Cherchye et al. (2013) for the cost setting, and Cherchye et al. (2016) for the profit setting.

[3] $I^q(y^q)$ is nested if $y^q \geq y^{q'} \implies I^q\left(y^q\right) \subseteq I^q\left(y^{q'}\right)$.