A DYNAMIC APPROACH TO ESTIMATE THE EFFICIENCY OF U.S. ELECTRIC UTILITIES

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Abstract

The static production efficiency model and the dynamic duality model of intertemporal decision making using a parametric approach have been continuously developed but in separate direction. The parametric approach takes statistical noise into account, which consequently provides accurate measures in a stochastic environment. In this study the static shadow cost approach and the dynamic duality model of intertemporal decision making are integrated to formulate theoretical and econometric models of dynamic efficiency with intertemporal cost minimizing firm behavior. The dynamic efficiency model is a dynamic measure of firms' inefficiency and it accounts for allocative and technical inefficiencies of net investment and of variable inputs.
The dynamic efficiency model is implemented by using the Generalized Method of Moment (GMM) estimation and empirically applied into a panel data set of 72 U.S. major investor-owned electric utilities using fossil-fuel fired steam electric power generation during the time period of 1986 to 1999. The major results of this study are that most electric utilities in this study underutilized fuel relative to the aggregated labor and maintenance input and they overutilized capital in production. The estimates of the input price elasticities present the substitution possibilities among the inputs. Finally, the results suggest evidence of increasing returns to scale in the production of the electricity industry.

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1. Introduction

Electricity deregulation and restructuring are now on the policy agenda in many states. The basis for historical regulation of the electricity industries has been to deal with natural monopoly issues in the production of electricity. The first main step toward deregulation was the Public Utility Regulatory Policies Act of 1978 (PURPA) passed by the Congress which allowed independent generators to sell their electricity to utilities at regulated rates[2]. Under regulation, electric utilities had a guaranteed profit for the generation of electricity. This led to strong incentives to overinvest in capital as well as operating at an inefficient level of production which is of broad interest for researchers and policymakers [e.g., Averch and Johnson (1962), Atkinson and Halvorson (1980), Crew and Kleindorfer (2002), Granderson and Linvill (2002)]. The level of inefficiency of electric utilities and the forces driving inefficient levels of production electricity are critical concerns. The 1992 Energy Policy Act, followed by the Federal Energy Regulatory Commission's (FERC's) Orders 888 and 889 in April of 1996, expanded PURPA's initiative by forcing utilities with transmission networks to deliver power to third parties at nondiscriminatory cost-based rates. These policy initiatives recognize that while electrical transmission and distribution remain natural monopolies, competition in generation is possible with new technology (e.g., gas turbines) that can achieve optimal size at modest scale and with open access to transportation networks. Policies to open markets led to new competitors in generation and marketing, with a restructuring of the industry away from the regulated, single-provider model. Deregulation in the electricity markets has been incomplete to date with

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[2] Smith (1996) presents an interpretive overview of the history and patterns of regulation in the electric industry and notes that regulations in early 1900s were not motivated by a consumerist response to monopoly pricing but rather served to protect the industry from the competitive pricing which dominated at that time.

continued regulation in some segments. Under partial regulation, electricity markets are not really deregulated but restructured. Vertical integration has diminished and some stages of electricity provision must compete in the market place. Deregulation of energy generation will provide important incentives for the efficient operation of electrical generators and it should provide firms the incentives to lower costs by improving technical and input allocative efficiency to maximize their profits. Understanding the cost structure of electric utilities in addition to other economically meaningful measurements such as technical and allocative efficiencies, economies of scale, and technology in the electricity industry, provides insightful information for policy makers in dealing with the issues related to restructuring the electricity industry.

2. Background

The estimation of the cost structure and scale economies of electric power generation in the U.S. has been extensively studied since the 1960s. The earlier studies defined various functional forms of cost functions and applied the estimation approach of the cost structure maintaining that all producers operate efficiently [Nerlove (1963), Christensen and Greene (1976), Considine (2000)]. The recent empirical applications of electric power generation relax this assumption to measure the inefficiency occurring in the production cost [Schmidt and Lovell (1979), Hiebert (2002)]. The stochastic cost frontier is applied to estimate the inefficiency level of each producer and assumes that an efficiently operating producer is represented by the estimated cost frontier. If a producer's observed costs are higher than the frontier, that deviation is attributed, in part, to inefficiency. A shortcoming of the stochastic frontier approach is the computational difficulties for decompositions of economic efficiency in the estimation. This shortcoming can be remedied by using stochastic estimation of the shadow cost approach. A shadow cost function is expressed in terms of shadow input prices and outputs, where shadow prices (internal to the firm) are defined as input prices forcing the technically efficient input vector to be the cost minimizing solution for producing a given output. Shadow prices will differ from market (actual) prices in the presence of inefficiency. However, these two approaches measuring inefficiency arising from production cost are developed under the static context are conditioned on some inputs, referred to as quasi-fixed inputs. The shortcomings of the static approaches include ignoring the explicit the role of time and how the adjustment of quasi-fixed inputs to the observed long-run level takes place. The analysis of the transition path of quasi-fixed factors toward their desired long-run levels can be remedied by explicitly incorporating costs of adjustment for the quasi-fixed factors. The underlying idea is that the adjustment process of quasi-fixed factors generates additional transition costs and the optimal intertemporal behavior of the firm can be solved by appealing to the notion of adjustment costs in solving the firm's optimization problem.

This study incorporates adjustment costs for the quasi-fixed factors into a model of firm behavior leading the firm's dynamic production decision problem. The static shadow cost approach is generalized using the dynamic duality model of intertemporal decision making to establish a dynamic efficiency model of the cost minimizing firm. The specific objectives of this study are to estimate and decompose cost inefficiency of the U.S. electric power generation, characterize the cost structure under dynamic adjustment and evaluate how different electric utilities will perform that are located within or outside of states with a restructuring plan.

The next section presents the theoretical background on the economics of efficiency and dynamic factor demands, followed by the development of the integrated theoretical and econometric models of a dynamic efficiency model. This is followed by a discussion of the primary sources of data used to construct the data set and key assumptions underlying the construction. The next section presents the estimation results of the dynamic efficiency model and then conclusions follow.

3. Theoretical Framework

3.1. Decomposition of Economic Efficiency and Shadow Cost Approach

Consider producers facing a strictly non-negative vector of input prices $w \in R^N_{++}$ seeking to minimize the cost $w'x$, given a non-negative vector of input quantities denoted $x \in R^N_+$, which they incur in producing a non-negative vector of outputs $y \in R^M_+$. The input-oriented measurement and decomposition of cost efficiency are illustrated in Figure 1. A producer uses input x^A, available at price w^A, to produce output y^A which is measured using Isoq $L(y^A)$. The measure of cost efficiency is given by the ratio of minimum cost $C(y^A, w^A) = w'^A x^E$ to actual cost $w'^A x^A$. The input-oriented technical efficiency of the producer can be defined as the ratio of expenditure at $w'^A \phi^A x^A$ to expenditure at $w'^A x^A$. A measure of input allocative efficiency is defined as the ratio of cost efficiency to input-oriented technical efficiency, $\left(w'^A x^E\right)/\left(w'^A \phi^A x^A\right)$. Figure 1 also illustrates how shadow prices, w^*, are input prices that make the technically efficient input vector $\phi^A x^A$ the minimum cost solution for producing a given output y^A. An input-oriented measure of the technical efficiency of the producer is provided by $\phi^A < 1$ since $y = f\left(\phi^A x^A\right)$. The producer is also allocatively inefficient since the marginal rate of substitution at $\phi^A x^A \in L\left(y^A\right)$ diverges from the actual input price w^A. However the producer is allocatively efficient relative to the shadow input price $w^* = \theta_{n1} w^A$ where θ_{n1} represents the values of allocative inefficiency of variable input demands. An estimate of allocative inefficiency of variable input demands greater (less) than one means that the ratio of the shadow price of the n^{th} variable input relative to the first variable input is considerably greater (less) than the corresponding ratio of actual prices. This implies that the firms are under- (over-) utilizing the n^{th} variable input relative to the first variable input. Following Kumbhakar and Lovell (2000) who generalize the early formulations of modeling inefficiency in dual function found in Toda (1976) and Atkinson and Halvorson (1980), a shadow cost function is expressed in terms of shadow input prices and outputs. Given a flexible functional form to specify the shadow cost function, the stochastic shadow cost system consisting of the producer's observed costs and observed input demand in terms of shadow input prices and outputs can be estimated after appending a linear disturbance into each equation.

3.2. Dynamic Duality Theory of Intertemporal Decision Making

Consider the intertemporal model where the firm seeks to minimize the discounted sum of future production costs over an infinite horizon and the firm holds static expectations on the set of prices and the sequence of production targets[3]

$$J(w,c,K(t),y(t)) = \min_{I>0} \int_t^{\infty} e^{-rs}\left[w'x(s) + cK(s)\right]ds \tag{1}$$

subject to $\dot{K}(s) = I(s) - \delta K(s)$, $K(0) = K_0 > 0$, $K(s) > 0$, and $y(s) = F\left[x(s), K(s), \dot{K}(s)\right]$, for all $s \in [t, \infty)$,

where w is vector of variable input prices; x and K are vectors of variable inputs and quasi-fixed inputs, respectively; c is the vector of rental prices of quasi-fixed inputs; I and $\dot{K}$ are gross and net rates of investment, respectively; r is the constant discount rate ; δ is a constant depreciation

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[3] Price expectations are static in the sense that the decision maker expects the current real prices and technology to persist indefinitely in each base period (Epstein and Denny, 1983).

rate; $y(s)$ is a sequence of production targets over the planning horizon starting at time t and $F(x(s), K(s), \dot{K}(s))$ is the single output production function. The inclusion of net investment $\dot{K}$ in the production function reflects the internal cost associated with adjusting quasi-fixed factors in terms of foregone output.

The dynamic programming equation for the problem (1) can be expressed as

$$rJ(w, c, K, y) = \min_{x, I > 0} \{ w'x + cK + (I - \delta K) J_k + \gamma (y - F(x, K, \dot{K})) \}, \tag{2}$$

where $\gamma \geq 0$ is the Lagrangian multiplier associated with the production target and is defined as the short-run, instantaneous marginal cost (Stefanou, 1989).

Epstein (1981) demonstrates that a full dynamic duality can be solved by the appropriate static optimization problem as expressed in the dynamic programming equation. The result of intertemporal duality theory is that it provides readily implemental systems of dynamic factor demands. Differentiating the optimized version of the dynamic programming equation with respect to c and w yields optimal net investment demand and optimal variable input demand, respectively,

$$\dot{K}^* = J_{kc}^{-1}(rJ_c - K), \text{ and, } x^* = rJ_w - J_{kw}\dot{K}^* = rJ_w - J_{kw}\left(J_{kc}^{-1}(rJ_c - K)\right). \tag{3}$$

Empirical application of these dynamic factor demand specifications include Epstein and Denny (1983), Vasavada and Chambers (1986), Bernstein and Nadiri (1988), Fernandez-Cornejo et al (1992), and Luh and Stefanou (1991, 1996).

4. Specification of Dynamic Efficiency Model

4.1. Dynamic Efficiency Model Derivation

The static shadow cost model presented in Section 3.1 is generalized using the dynamic duality model of intertemporal decision making presented in Section 3.2. In the presence of allocative and technical inefficiencies in the production function, the behavioral value function of the dynamic programming equation for the firms' intertemporal cost minimization behavior in the presence of technical change that corresponds to the shadow prices and quantities can be expressed in the form of a behavioral Hamiton-Jacobi equation,

$$rJ^b\left(w^b_{nit}, c_{it}, K_{it}, y_{it}, t_{it}\right) = \left(w^b_{nit}\right)' x^b_{nit} + c'_{it} K_{it} + \dot{K}^{b'}_{it}\left(J^b_{k,it}\right) + \gamma^b_n\left(y_{it} - F\left(x^b_{nit}, K_{it}, \dot{K}^b_{it}, t_{it}\right)\right) + J^b_{t,it}, \tag{4}$$

where $J^b_{k,it} = \partial J^b_{it} / \partial K$ and $J^b_{t,it} = \partial J^b_{it} / \partial t$; $n = 1,...,N$ index of variable inputs; $i = 1,...,I$ index of firms; $t = 1,...,T$ index of time periods; c is the user cost of capital; K is a quasi-fixed input of capital stock; y is the output; t is time trend; $w^b = (\lambda_1 w_1,...,\lambda_N w_N)$ with $\lambda_n > 0$ representing the behavioral prices of variable inputs; λ_n is the allocative inefficiency parameters for n^{th} variable input; w_n is the observed n^{th} variable input price; $J^b_k = \mu J^a_k$ represents the marginal behavioral value of capital where J^a_k represents the observed marginal value of capital and μ is the allocative inefficiency parameter of net investment; $x^b = (1/\tau_x)x$ represents the behavioral variable inputs where $\tau_x \geq 1$ is the inverse of producer-specific scalars providing input-oriented measures of the technical efficiency in variable input use and x is the observed variable input use; $\dot{K}^b = (1/\tau_k)\dot{K}$ represents the behavioral net investment level where $\tau_k \geq 1$ is the inverse of producer-specific scalars providing input-oriented measures of the technical efficiency in net investment and $\dot{K} = dK/dt$ is the level of net investment; $\gamma^b \geq 0$ is the behavioral Lagrangian multiplier defined as the short-run, instantaneous marginal cost.

If the n^{th} variable input is allocatively efficient, λ_n = 1. The values of λ_n >1 (or <1) imply that the decision maker, *ceteris paribus*, allocates less (or more) of input n^{th} compared to the cost minimizing allocation. By specifying the first variable input price as the numeraire, the prices of variable inputs demands are redefined as $w_{nit}^b = (\lambda_n/\lambda_1)w_{nit} = \theta_{n1i}w_{nit}$, where $n = 1,..,N$ and $\theta_{11i} = 1$. The values of allocative efficiency of variable inputs demands, θ_{n1i}, represent price distortions of the n^{th} variable input relative to the first variable input. An estimate of allocative efficiency of variable inputs demands greater (less) than one means that the ratio of the shadow price of the n^{th} variable input relative to the first variable input is considerably greater (less) than the corresponding ratio of actual prices. This implies that the firms are under- (over-) utilizing the n^{th} variable input relative to the first variable input.

Without the notation of the indices of variable inputs, firms and time periods, the behavioral value function of the dynamic programming equation in (4) by using the basic idea underlying the input-oriented efficiency measurement approach can be rewritten in terms of $J^b(\lambda w, c, K, y, t)$ as

$$rJ^b(\lambda w, c, K, y, t) = (\lambda w)' x^b + c'K + \dot{K}^{b'} J_k^b(\cdot) + \gamma^b\left(y - F\left(x^b, K, \dot{K}^b, t\right)\right) + J_t^b(\cdot). \tag{5}$$

Differentiating (5) with respect to c and (λw), respectively, yields optimal investment demand

$rJ_c^b(\cdot) = K + \dot{K}^{b'} J_{kc}^b(\cdot) + J_{tc}^b(\cdot)$, or,

$$\dot{K}^b(\cdot) = \left(J_{kc}^b(\cdot)\right)^{-1}\left(rJ_c^b(\cdot) - K - J_{tc}^b(\cdot)\right), \tag{6}$$

and optimal variable input demand

$rJ_{(\lambda w)}^b(\cdot) = x^b + \dot{K}^{b'} J_{k(\lambda w)}^b(\cdot) + J_{t(\lambda w)}^b(\cdot)$, or,

$$x^b(\cdot) = (\lambda)^{-1}\left(rJ_w^b(\cdot) - \dot{K}^{b'}(\cdot) J_{kw}^b(\cdot) - J_{tw}^b(\cdot)\right). \tag{7}$$

In the presence of technical inefficiency of net investment and variable inputs, the corresponding observed investment and variable input demands using the input-oriented approach can be written in terms of the optimal investment and variable input demands as

$$\dot{K}^{o} = \tau_k \dot{K}^{b}(\cdot) = \tau_k \left(J_{kc}^{b}(\cdot)\right)^{-1}\left(rJ_{c}^{b}(\cdot) - K - J_{tc}^{b}(\cdot)\right), \tag{8}$$

$$x^{o} = \tau_x x^{b}(\cdot) = \tau_x (\lambda)^{-1}\left(rJ_{w}^{b}(\cdot) - \left(\dot{K}^{o\prime}/\tau_k\right)J_{kw}^{b}(\cdot) - J_{tw}^{b}(\cdot)\right). \tag{9}$$

The dynamic programming equation for the firms' intertemporal cost minimization behavior corresponding to the actual prices and quantities can be expressed as

$$rJ^{a} = w'x + c'K + \dot{K}'J_{k}^{a} + \gamma^{a}\left(y - F\left(x^{b}, K, \dot{K}^{b}, t\right)\right) + J_{t}^{a}, \tag{10}$$

where input-oriented efficiency measurement is maintained. Considering the actual quantities as the optimal levels, optimized actual quantities are $\dot{K}^{o} = \tau_k \dot{K}^{b}(\cdot)$ and $x^{o} = \tau_x x^{b}(\cdot)$. The optimized actual dynamic programming equation can be expressed as

$$rJ^{a} = w'x^{o} + c'K + \dot{K}^{o\prime} J_{k}^{a} + J_{t}^{a}, \tag{11}$$

where $J_{k}^{a} = (1/\mu)J_{k}^{b}(\cdot)$ implying the marginal behavioral value of capital diverges from the marginal actual value of capital by μ, and assuming a shift in the behavioral value function is the same proportion as the actual value function so that $J_{t}^{a} = J_{t}^{b}(\cdot)$. The optimized actual value function can be rewritten in the terms of the behavioral value function as follows

$$rJ^{a} = w'(\tau_x/\lambda)\left(rJ_{w}^{b}(\cdot) - \dot{K}^{b\prime}(\cdot)J_{kw}^{b}(\cdot) - J_{tw}^{b}(\cdot)\right) + c'K + \left(\tau_k \dot{K}^{b}(\cdot)\right)\left(J_{k}^{b}(\cdot)/\mu\right) + J_{t}^{b}(\cdot). \tag{12}$$

Differentiating (11) with respect to *c* and *w*, respectively, optimized actual investment demand yields

$$rJ_c^a = K + \dot{K}^{o'} J_{kc}^a + J_{tc}^a \text{, or , } \quad \dot{K}^o = \left(J_{kc}^a\right)^{-1}\left(rJ_c^a - K - J_{tc}^a\right), \tag{13}$$

and optimized actual variable input demand yields

$$rJ_w^a = x^o + \dot{K}^{o'} J_{kw}^a + J_{tw}^a \text{, or , } \quad x^o = rJ_w^a - \dot{K}^{o'} J_{kw}^a - J_{tw}^a . \tag{14}$$

Differentiating (12) with respect to *c* and substituting into (13), the optimized actual investment demand in terms of the behavioral value function yields (up to second order terms)[4]

$$\left(\frac{2}{r} - \frac{2\tau_k}{r\mu} + \left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{cc}^b J_{kk}^b}{J_{ck}^b}\right) + \left(\frac{\tau_k}{\mu}\right) J_{ck}^b\right)\dot{K}^o = \left\{ \begin{array}{l} r\left(\frac{\tau_x}{\lambda}\right)\left(wJ_{wc}^b - \left(\frac{J_{kw}^b J_{cc}^b}{J_{ck}^b}\right)w\right) + r\left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{cc}^b J_k^b}{J_{ck}^b}\right) \\ -\left(2\frac{\tau_k}{\mu} - 1\right)J_{ct}^b - \left(\frac{\tau_k}{\mu}\right)\left(\left(\frac{J_{cc}^b J_{kt}^b}{J_{ck}^b}\right) + K - rJ_c^b\right). \end{array} \right\} \tag{15}$$

Differentiating (12) with respect to *w* and substituting into (14), the optimized actual variable input demand in terms of the behavioral value function yields (up to second order terms)

$$\begin{aligned} x^o = {} & r\left(\frac{\tau_x}{\lambda}\right)J_{ww}^b w - r\left(\frac{\tau_x}{\lambda}\right)\left(\frac{J_{kw}^b J_{cc}^b}{J_{kc}^b}\right)w + r\left(\frac{\tau_x}{\lambda}\right)J_w^b - r\left(\frac{\tau_x}{\lambda}\right)\left(\frac{J_{kw}^b J_c^b}{J_{kc}^b}\right) - \left(\frac{\tau_x}{\lambda}\right)J_{tw}^b + \left(\frac{\tau_x}{\lambda}\right)\left(\frac{J_{kw}^b J_{ct}^b}{J_{kc}^b}\right) \\ & + \left(\frac{\tau_x}{\lambda} - \frac{\tau_k}{\mu}\right)\left[\left(\frac{J_{kw}^b}{J_{kc}^b}\right)K + \left(\frac{J_{kw}^b J_{tc}^b}{J_{kc}^b}\right)\right] + r\left(\frac{\tau_k}{\mu}\right)\left[\left(\frac{J_{cw}^b J_k^b}{J_{kc}^b}\right) + \left(\frac{J_{kw}^b J_c^b}{J_{kc}^b}\right)\right] - \left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{cw}^b J_{kt}^b}{J_{kc}^b}\right) - \left(\frac{\tau_x}{\lambda}\right)J_{tw}^b \\ & - \dot{K}^o\left[\frac{2}{r}\left(\frac{\tau_x}{\lambda}\right)\left(\frac{J_{kw}^b}{J_{kc}^b}\right) + \left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{cw}^b J_{kk}^b}{J_{kc}^b}\right) + \left(\frac{\tau_k}{\mu}\right)J_{kw}^b - \frac{2}{r}\left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{kw}^b}{J_{kc}^b}\right)\right] + J_{tw}^b - \left(\frac{\tau_k}{\mu}\right)\left(\frac{J_{kw}^b J_{ct}^b}{J_{kc}^b}\right). \end{aligned} \tag{16}$$

The behavioral conditional demand for the numeraire variable input is derived by rearranging the behavioral optimized value function of the dynamic programming equation in equation (5) as

$$rJ^b = x_n^b + w^b x^b(\cdot) + cK + \dot{K}^b(\cdot)J_k^b + J_t^b, \tag{17}$$

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4 Third order terms involving the derivative of $J^b(\ )$ with respect to (w,c,k) and (w,c,t) are ignored. The econometric specification that follows is flexible up to second order terms.

where x_n^b is the behavioral demand for the numeraire variable input, and x^b is the behavioral demand for the other variable inputs, leading to the behavioral conditional demand for the numeraire variable input defined as

$$x_n^b(\cdot) = rJ^b - w^b x^b(\cdot) - cK - \dot{K}^b(\cdot)J_k^b - J_t^b. \tag{18}$$

The optimized actual demand for the numeraire variable input is

$$x_n^o = \tau_x x_n^b(\cdot) = \tau_x \left\{ rJ^b - w^b x^b(\cdot) - cK - \dot{K}^b(\cdot)J_k^b - J_t^b \right\}. \tag{19}$$

The optimal investment demand function for the single quasi-fixed factor case in (6) [Treadway (1971, 1974)] can be expressed as a univariate linear accelerator

$$\dot{K}_{it}^*\left(w^b, c, K, y, t\right) = \dot{K}_{it}^b(\cdot) = M\left(K_{it} - K_{it}^*\left(w^b, c, y, t\right)\right), \tag{20}$$

where M is the partial adjustment coefficient which indicates how quickly the current level of capital stock, K_{it}, will adjust to the optimal capital stock levels, K_{it}^*.

With two variable inputs and single quasi-fixed input of capital stock, the behavioral value function taking the quadratic functional form and assuming symmetry of the parameters where $A^{ij} = A^{ji}$ can be specified as

$$J^b = A^0 + P' \cdot \begin{pmatrix} A^{w_1} \\ A^{w_2} \\ A^c \\ A^k \\ A^y \\ A^t \end{pmatrix} + \frac{1}{2} P' \cdot \begin{bmatrix} A^{w_1 w_1} & A^{w_1 w_2} & A^{w_1 c} & A^{w_1 k} & A^{w_1 y} & A^{w_1 t} \\ A^{w_2 w_1} & A^{w_2 w_2} & A^{w_2 c} & A^{w_2 k} & A^{w_2 y} & A^{w_2 t} \\ A^{c w_1} & A^{c w_2} & A^{cc} & A^{ck} & A^{cy} & A^{ct} \\ A^{k w_1} & A^{k w_2} & A^{kc} & A^{kk} & A^{ky} & A^{kt} \\ A^{y w_1} & A^{y w_2} & A^{yc} & A^{yk} & A^{yy} & A^{yt} \\ A^{t w_1} & A^{t w_2} & A^{tc} & A^{tk} & A^{ty} & A^{tt} \end{bmatrix} \cdot P, \tag{21}$$

where $P' = \left(w_1^{b'} \quad w_2^{b'} \quad c' \quad K' \quad y' \quad t'\right)$.

4.2. Estimation Approach

The producer and input specific estimates of technical and allocative efficiencies must be specified to implement the dynamic efficiency model in the panel data context. Following Cornwell, Schmidt, and Sickles (1990), the allocative and technical efficiencies of net investment and of variable inputs[5] are specified as producer specific and time-varying specific parameters. All coefficient parameters of the system of equations in (15) and (16) can be estimated after appending a linear disturbance vector with mean vector zero and variance-covariance matrix Σ into the system equation. Joint estimation of the system equation provides parameter estimates of the behavioral value function represented by equation (21). Appendix A presents the specification of (15) and (16) for the functional form in (21). Further, the net investment equation does conform to the linear accelerator in (20) where $\left[r - \left(A^{ck} \right)^{-1} \right]$ is the adjustment rate per annum.

The maintained model is recursive in the endogenous variable of net investment demand, serving as an explanatory variable in the variable input demand equations. The estimation can be accomplished in two stages. In the first stage, the net investment demand is estimated by using the maximum likelihood estimation (MLE). In the second stage, since the variable input demand equations are over-identified, the system of variable input demand equations is estimated by using the Generalized Method of Moment (GMM) estimation given all parameter values that were obtained in the first stage. All predetermined variables, which include exogenous and dummy variables of each equation in the variable input demand equations, are defined as the instrumental variables of the system equation in the second stage. One proposal of the GMM

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[5] The allocative and technical efficiencies of net investment and of variable inputs are guaranteed to be non-negative by using the exponential transformation.

estimation is to find instrumental variables, z, that are correlated with exogenous variables in the model but uncorrelated with the residual, ε, implying the orthogonality conditions, $E(z'\varepsilon)=0$. If the disturbances are heteroscedastic and serially correlated, the estimation in the presence of heteroscedasticity and autocorrelation can be corrected by applying a flexible approach developed by Newey and West (1987). The number of autocorrelation terms used in computing the covariance matrix of the orthogonality conditions can be determined by the procedure of Newey and West (1994). However, estimating all parameters from the system of equations in (15) and (16) leads to the singularity in estimation due to a high nonlinearity of both the net investment demand and the variable input demand equations and the inclusion of many dummy variables. An alternative estimation approach can be accomplished by estimating the system of equations in (8), (9) and (19) and then estimating the remaining parameters of the system of equations in (15) and (16).

5. Discussion of Data

Data on fossil-fuel fired steam electric power generation for major investor-owned utilities in the United States are used to construct a data set in this study because these are the dominant sectors of the U.S. electricity industry[6]. The primary sources of data are obtained from the Energy Information Administration (EIA Form 1, Form 423, Form 759, Form 860a), the Federal Energy Regulatory Commission (FERC Form 1) and the Bureau of Labor Statistics (BLS). Output variable is represented by net steam electric power generation in megawatt-hour which is defined as the amount of power produced using fossil-fuel fired boilers to produce

[6] Approximately 61 percent of all the electricity in 1999 supplied by the U.S. electric power industry comes from fossil fuel-fired steam turbines. Investor-Owned Utilities own 71 percent of the U.S. generating capacity owned by both utilities and nonutility generators and are responsible for 74 percent of all retail sales of electricity (EIA 2000).

steam for turbine generators during a given period of time. The price of fuel aggregate is an average price of fuels (i.e. coal, oil, gas) in dollars per British Thermal Units (BTU). The fuel quantities can be calculated by dividing the fuel expenses by the average price of fuels in dollars per BTU. The aggregate price of labor and maintenance is a cost-share weighted price for labor and maintenance. The price of labor is a company-wide average wage rate. The price of maintenance and other supplies is a price index of electrical supplies from the Bureau of Labor Statistics. The weight is calculated from the labor cost share of nonfuel variable costs for those utilities with entirely steam power production. Quantities of labor and maintenance equal the aggregate costs of labor and maintenance divided by a cost-share weighted price for labor and maintenance. The capital stock is measured by using estimates of capital costs as discussed in Considine (2000). The values of capital stocks are calculated by the valuation of base and peak load capacity at replacement cost to estimate capital stocks in a base year and then updating it in the subsequent years based upon the value of additions and retirements to steam power plant. The price of capital is the yield of the firm's latest issue of long term debt adjusted for appreciation and depreciation of the capital good using the Christensen and Jorgenson (1970) cost of capital formula.

Initially all these data sources were combined to construct a data set from the variables for 110 electric utilities with all variables defined for the time periods 1986-1999. Electric utilities which are subsidiaries of holding companies[7] are aggregated into one entity. Once the holding companies which have generating plants located in both states with and without the deregulation plan were excluded, the remaining 72 electric utilities comprised the panel used in this study. They are divided into two groups according to the status of state electric industry

[7] Christensen and Greene (1976) showed that failure to recognize holding companies results in underestimating scale economies.

restructuring activity. Electric utilities within "Group A" have all plants located in states which enacted enabling legislation or issued a regulatory order to implement retail access while utilities within "Group B" have all plants located in states without the deregulation plan. The final set of the panel data on 72 electric utilities over the time period of 1986 to 1999 is used in this study. Lists of the electric utilities are presented in Appendix B.

6. Empirical Results

The dynamic efficiency model accounts for four inefficiency parameters: technical and allocative inefficiencies in net investment and variable input demands. Estimation of the system equation is complicated the highly nonlinear net investment demand equation leading to the singularity of estimating the net investment demand in the first stage of the estimation. An additional assumption that firms are perfectly technical efficient in net investment demand is assumed to implement the estimation. While this assumption permits estimation of the system, it is also not as restrictive in this context as may first appear. Technical inefficiency of net investment, τ_k, is represented by the physical operation of generating plants. Thermal conversion efficiency is used to measure the performance of generating plants. The report of EIA showed that the standard deviation of an average plant efficiency of steam electric power generating plants measured by thermal conversion efficiency is very low for each plant.[8]

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[8] Further, a sensitivity analysis on the technical efficiency parameter of net investment was performed by varying the technical efficiency parameter of net investment between 0.60 and 1.00. The likelihood and R^2 for each estimated equation are quite stable within this range and suggest no statistically significant change between the model with $\tau_k = 1$ and τ_k equal to any other value less than unity. While τ_k is firm and time-invariant, it's value on average should signal an alert concerning the potential misspecification of perfect technical efficiency in net investment. This statistical result along with the report of EIA showing that the low standard deviation of an average plant efficiency of steam electric power generating plants measured by thermal conversion efficiency suggests the assumption that $\tau_k = 1$ is a tolerable one.

Assuming a constant real interest rate of 5 percent, the estimated coefficients, standard errors, and p-values for the structural parameters of the full model using GMM estimation are presented in Table 1[9]. A lag of two periods of autocorrelation terms is used to compute the covariance matrix of the orthogonality conditions for the GMM estimation. R^2 values of net investment demand, of fuel and the labor and maintenance aggregate are 0.025, 0.976, and 0.951, respectively. The test of overidentifying restrictions from GMM estimation using the Hansen (1982) J test is significant. The null hypothesis fails to reject implying that the additional instrumental variables are valid, given a subset of the instrument variables is valid and exactly identifies the coefficient.

Table 2 presents average firm allocative and technical efficiencies of net investment and of variable input demands by all electric utilities and the group of electric utilities affected by the deregulation plan. The technical efficiency parameter of net investment is assumed to be unity. The allocative efficiencies of net investment range from 0.200 by Pacific Gas & Electric Co. (CA) to 1.218 by Montana Power Co. (MT) with an average of 0.594. The estimated value of the allocative efficiency of net investment is less than one implying that firms are over-utilizing the net investment. The estimated technical efficiencies of variable inputs range from 0.241 by Texas Utility Electric Co. (TX) to 0.991 by Rochester Gas & Electric Corp. (NY) with an average of 0.767. By specifying the aggregate prices of labor and maintenance as the numeraire[10], the estimated allocative efficiencies of variable inputs range from 0.084 by Montana Power Co. (MT) to 6.464 by Gulf State Utilities Co. (TX) with an average of 3.105. The values

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[9] The full set of estimated coefficients including the dummy variables used to calculate the allocative inefficiency parameters of variable inputs and net investment demands and the technical inefficiency parameter of variable input demand are available upon request from the author.

[10] Choice of numeraire is arbitrarily selected in the empirical application. Factors used to decide the choice of numeraire are adjustment rate, the quality of estimation, convergence, and signs confirmation.

of allocative efficiency of variable input demands represent price distortions of fuel relative to the aggregate of labor and maintenance. An estimate of allocative efficiency of variable input demands greater than one means that the ratio of the shadow price of fuel relative to that of the labor and maintenance aggregate is considerably greater than the corresponding ratio of actual prices implying that the firms are under-utilizing fuel relative to the aggregate of labor and maintenance. The estimated results indicate that all electric utilities in this study except by two firms, Montana Power Co. (MT) and Southern Indiana Gas & Electric Co. (IN) under-utilized fuel relative to the aggregate of labor and maintenance. Moreover, all electric utilities in this study indicate over-utilization of net investment except by one firm, Montana Power Co. (MT). The results indicate that electric utilities located within states with the deregulation plan have average firm technical efficiency of variable inputs lower than electric utilities located outside of states with the deregulation plan. This result suggests that electric utilities with relatively high technical inefficiency in states adopting a deregulation plan improve the performance of their electric utilities. Furthermore, electric utilities located within states with a deregulation plan present average firm allocative efficiencies of variable inputs and of net investment lower than electric utilities located outside of states with the deregulation plan. These results imply that electric utilities located within states with the deregulation plan are under-utilizing fuel relative to the aggregate of labor and maintenance less than those located outside of states with a deregulation plan and over-utilizing net investment compared to those located outside of states with a deregulation plan. However, the magnitudes of the difference of allocative efficiencies of variable inputs and of net investment by the group of electric utilities affected by a deregulation plan are not dramatic.

The adjustment rate of capital, $\left\lfloor r-\left(A^{ck}\right)^{-1}\right\rfloor$, is 2.95 percent implying that the capital stock adjusts approximately 3 percent per annum to the long-run equilibrium levels. This sluggish adjustment of capital results from the non-storable characteristic of electricity and capital-specific nature of utility investments and magnitude of the investment. Most electric utilities will choose to buy power externally to meet additional demand in the short-run rather than build new generating plants since prices in wholesale market for electricity are usually not much higher than the marginal cost of generating electricity by the electric utilities in the short-run.

Weighted-average estimates of short-, intermediate-, and long-run input price elasticities evaluated at the long-run equilibrium level are reported in Table 3 for both the pre-deregulation (1986-1996) and the combined pre- and post-deregulation (1986-1999) periods.[11] All own-price elasticities have the expected negative sign. Overall, the estimated results of input demand elasticities between the two periods are similar and the number of elasticities does not change significantly in magnitude between the two periods. The magnitude of the short-run own price elasticity of demand for fuel indicates that it is price inelastic. The short-run own price elasticity of demand for the aggregate of labor and maintenance is larger in absolute magnitude than that for fuel. The cross-price elasticity estimates suggest that fuel, capital, and the aggregate of labor and maintenance are substitutes. The magnitude of the intermediate-run elasticity changes from the short-run elasticities is not significant because of the low adjustment rate of capital stock to its long-run equilibrium level. The long-run own price elasticities of demand for fuel and the aggregate of labor and maintenance are larger in absolute magnitude than the short-run own price elasticities. The magnitude of the long-run own price elasticity of capital indicates that it is significantly price elastic. The cross-price elasticity estimates suggest that fuel, capital and the

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11 Derivations of input demand elasticities are presented in Appendix C

aggregate of labor and maintenance are substitutes and the relatively large cross-price elasticities suggest the significant substitution possibilities among these inputs.

The estimated optimal capital stocks are calculated and compared to the actual capital stocks to account for the capacity utilization which provides some insight into the efficiency of capital use by a firm. Values of the ratio of optimal capital to actual capital stocks less than one imply that a firm is over-utilizing capital while values greater than one imply that a firm is under-utilizing capital. The distribution of the ratio of capital by firm is presented in Figure 2. There are 46 firms with values of the ratio of capital below the average. The estimated results indicate that all electric utilities in this study except by three firms, Kansas Gas & Electric Co. (KS), The Detroit Edison Co. (MI), and Texas Utilities Electric Co. (TX) are over-capitalized.

Table 4 presents weighted-average estimates of the short- and long-run marginal cost, average variable cost, average total cost, and scale elasticity for both the pre-deregulation (1986-1996) and the combined pre- and post-deregulation (1986-1999) periods[12]. The short-run scale elasticity is defined as the ratio of short-run average variable cost to short-run marginal cost while the long-run scale elasticity is defined as the ratio of long-run average variable cost to short-run marginal cost (Stefanou, 1989). Scale elasticity values less than one imply decreasing returns to scale while values greater than one imply increasing returns to scale. Overall, the estimates of the pre-deregulation period are consistent to the combined pre- and post-deregulation period. The estimates of short- and long-run marginal costs are 2.077 and 1.827 cents per kwh, respectively, for the pre-deregulation period. They decrease to 1.938 and 1.782 cents per kwh, respectively, for the combined pre- and post-deregulation period. In addition, the estimates of short- and long-run average total costs are 2.996 and 2.674 cents per

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12 Derivation of scale elasticity is presented in Appendix D

kwh, respectively, for the pre-deregulation period and 2.774 and 2.447 cents per kwh, respectively, for the combined pre- and post-deregulation period. These results support the hypothesis that the deregulation of energy generation can provide important incentives for the efficient operation of electrical generators by lowering costs to maximize profits. The estimate of scale elasticity measure indicates increasing returns to scale in the industry pre- and post-deregulation. However, the estimates for the pre-deregulation period indicate higher increasing returns to scale in the industry than those for the combined pre- and post-deregulation period.

7. Conclusions

This study addresses the evolution of the structure of electricity production as the industry faces deregulation using a structured economic model of dynamic production. The static shadow price approach and the dynamic duality model of intertemporal decision making are integrated to formalize the theoretical and econometric models of dynamic efficiency for cost minimizing firms. The results indicate most electric utilities in this study underutilized fuel relative to the aggregate of labor and maintenance and they overutilized net investment. The result suggests that electric utilities with relatively high technical inefficiency in production in states adopting a deregulation plan improve the performance of the utilities. The magnitudes of the difference of allocative efficiencies of variable inputs and of net investment by the group of electric utilities affected by the deregulation plan are not significant. The estimates of the short-, intermediate-, and long-run input price elasticities indicate the substitution possibilities among the inputs. Most electric utilities in this study had optimal capital below actual capital stocks implying that most electric utilities are over-capitalized in the production. The estimates of short- and long-run average (marginal) costs for the pre-deregulation period are higher than those for the combined pre- and post- deregulation period. These results suggest that the deregulation of energy generation will provide important incentives for the efficient operation of electrical generators and it presents firms with the incentives to lower costs to maximize their profits. The estimate of scale and elasticity measures indicates a supporting evidence of increasing returns to scale in the industry pre- and post- deregulation. However, the estimates for the pre-deregulation period suggest higher increasing returns to scale in the industry than those for the combined pre- and post- deregulation period.

References

Atkinson, S. E. and R. Halvorson. "A Test of Relative and Absolute Price Efficiency in Regulated Utilities." *Review of Economics and Statistics* 62(1980): 81-88.

Atkinson, S.E. and D. Primont. “Stochastic Estimation of Firm Technology, Inefficiency, and Productivity Growth Using Shadow Cost and Distance Functions.” *Journal of Econometrics* 108 (2002): 203-225.

Averch, H. and L. L. Johnson. “Behavior of the Firm under Regulatory Constraint.” *American Economic Review* 52 (1962): 1052-1069.

Bernstein, J.I. and M.I Nadiri. “Research and Development and Intra-Industry Spillovers: An Empirical Application of Dynamic duality.” *Review of Economic Studies* 56(1988): 249-69.

Bureau of Labor Statistics WebPages, *http://stats.bls.gov/blshome.htm*.

Christensen, L. R. and W. H. Greene. “Economies of Scale in U.S. electric power generation.” *Journal of Political Economy* 84 (1976): 655-676.

Coelli, T.J., D. S. P. Rao, and G. E. Battese. “*An Introduction to Efficiency and Productivity Analysis*.” Kluwer Academic Publishers, 1998.

Considine, T. J. “Cost Structures for Fossil Fuel-Fired Electric Power Generation.” *The Energy Journal*, 21(2) (2000): 83-104.

Cornwell, C., P. Schmidt, and R. C. Sickles. “Production Frontiers with Cross-Sectional and Time-Series Variation in Efficiency Levels.” *Journal of Econometrics* 46(1/2) (October 1990): 185-200.

Crew M. A., and P. R. Kleindorfer. “Regulatory Economics: Twenty Years of Progress?” *Journal of Regulatory Economics* 21(1) (2002): 5-22.

Energy Information Administration WebPages, http://www/eia.doe.gov/index.html.

Esptein, L. G. "Duality Theory and Functional Forms for Dynamic Factor Demands." *Review of Economic Studies* 48 (1981): 81-95.

Epstein, L.G. and M. G. S. Denny. "The Multivariate Flexible Accelerator Model: Its Empirical Restrictions and an Application to U.S. Manufacturing." *Econometrica* 51 (1983): 647-674.

Federal Energy Regulatory Commission WebPages, http://www.ferc.fed.us.

Fernandez-Cornejo, J., C. Gempesaw, J.Elterich and S.E. Stefanou. "Dynamic Measures of Scope and Scale Economies: An Application to German Agriculture." *American Journal of Agricultural Economics* 74(1992): 283-99.

Granderson G. and C. Linvill. "Regulation, Efficiency, and Granger Causality." *International Journal Of Industrial Organization* 20(9) (2002): 1225-1245.

Hansen, L. "Large Sample Properties of Generalized Method of Moments Estimators." *Econometrica* 50 (1982): 1029-1054.

Hiebert, L. D. "The Determinants of the Cost Efficiency of Electric Generating Plants: A Stochastic Frontier Approach." *Southern Economic Journal* 68(4) (2002): 935-946.

Kumbhakar, S. C. and C. A. K. Lovell. "*Stochastic Frontier Analysis*." New York, New York: Cambridge University Press, 2000.

Luh, Y.-H. and S. E. Stefanou. "Productivity Growth in U.S. Agriculture under Dynamic Adjustment." *American Journal of Agricultural Economics* 73(4): 1116-25.

Luh, Y.-H. and S. E. Stefanou. "Learning-By-Doing and The Sources of Productivity Growth: A Dynamic Model with Application to U.S. Agriculture. " *Journal of Productivity Analysis* 4 (1993): 353-70.

Luh,Y.H. and S.E. Stefanou. "Estimating Dynamic dual Models under Nonstatic Expectation," *American Journal of Agricultural Economics* 78(4): 991-1003.

McLaren, K. R. and R. J. Cooper. "Intertemporal Duality: Application to the Theory of the Firm." *Econometrica* 48 (1980): 1755-1762.

Nerlove, M. "Returns to Scale in Electricity Supply," in *Measurements in Economics Studies in Mathematical Economics and Econometrics in Memory of Yehuda Grunfeld*, edited by C. F. Christ, Stanford University Press, 1963.

Newey, W. and K. West. "A Simple Positive Semi-definite, Heteroscedasticity and Autocorrelation Consistent Covariance Matrix." *Econometrica* 55(1987): 703-708.

Newey, W. and K. West. "Automatic Lag Selection in Covariance Matrix Estimation." *Review of Economic Studies* 61(1994): 703-708.

Schmidt, P. and C. A. K. Lovell. "Estimating Technical and Allocative Inefficiency Relative to Stochastic Production and Cost Functions." *Journal of Econometrics* 9(3) (February 1979): 343-366.

Smith, V. L. "Regulatory Reform in the Electric Power Industry." *Regulation* 19(1) (1996): 33-46.

Stefanou, S. E. "Returns to Scale in the Long Run: The Dynamic Theory of Cost." *Southern Economic Journal* 55 (1989): 570-579.

Toda, Y. "Estimation of a Cost Function When the Cost is not Mimimum: The Case of Soviet Manufacturing Industries, l958-l97l." *Review of Economics and Statistics* 58(l976):259-268.

Treadway, A. B. "The Rational Multivariate Flexible Accelerator." *Econometrica* 39 (1971): 845-855.

Treadway, A. B. “The Globally Optimal Flexible Accelerator.” *Journal of Economic Theory* 7 (1974): 17-39.

Vasavada, U. andR.G. Chambers. “Investment in U.S. Agricutlure.” *American Journal of Agricultural Economics* 68(1986): 950-60.

Appendix A

The system of equations (15) and (16) can be written in terms of the parameter estimates to yield the optimized actual investment demand equation

$$\left(\frac{2}{r}-\left(\frac{\tau_k}{\mu}\right)\left(\frac{2}{r}+\left(\frac{A^{cc}A^{kk}}{A^{ck}}\right)+A^{ck}\right)\right)\dot{K}^o$$
$$=r\tau_x\left[A^{wc}-\left(\frac{A^{wk}A^{cc}}{A^{ck}}\right)\right]w^b+A^{ct}-\left(\frac{\tau_k}{\mu}\right)K-2\left(\frac{\tau_k}{\mu}\right)A^{ct}-\left(\frac{\tau_k}{\mu}\right)\left(\frac{A^{cc}A^{kt}}{A^{ck}}\right) \qquad \text{(A1)}$$
$$+r\left(\frac{\tau_k}{\mu}\right)\left[\left(\frac{A^{cc}}{A^{ck}}\right)\left(\begin{array}{l}A^k+A^{wk}w^b+A^{ck}c\\+A^{kk}K+A^{kt}t+A^{ky}y\end{array}\right)\right]+r\left(\frac{\tau_k}{\mu}\right)\left[\begin{array}{l}A^c+A^{wc}w^b+A^{cc}c\\+A^{ck}K+A^{ct}t+A^{cy}y\end{array}\right],$$

and the optimized actual demand for variable inputs demands equation is

$$x^o=r\tau_x\left[\begin{array}{l}\left(A^{ww}-\left(\frac{A^{wk}A^{cc}}{A^{ck}}\right)\right)w^b+\left(\begin{array}{l}A^w+A^{ww}w^b+A^{wc}c\\+A^{wk}K+A^{wt}t+A^{wy}y\end{array}\right)\\-\left(\frac{A^{wk}}{A^{ck}}\right)\left(\begin{array}{l}A^c+A^{wc}w^b+A^{cc}c\\+A^{ck}K+A^{ct}t+A^{cy}y\end{array}\right)-\frac{1}{r}\left(A^{wt}-\left(\frac{A^{wk}A^{ct}}{A^{ck}}\right)\right)\\+\frac{1}{r}\left(\frac{A^{wk}}{A^{ck}}\right)+\frac{1}{r}\left(\frac{A^{wk}A^{ct}}{A^{ck}}\right)-\left(\frac{A^{wt}}{r}\right)-\frac{2}{r^2}\left(\frac{A^{wk}}{A^{ck}}\right)\dot{K}^o\end{array}\right]$$
$$\text{(A2)}$$
$$-\left(\frac{\tau_k}{\mu}\right)\left[\begin{array}{l}\left(\frac{A^{wk}}{A^{ck}}\right)K-r\left(\frac{A^{wc}}{A^{ck}}\right)\left(\begin{array}{l}A^k+A^{wk}w^b+A^{ck}c\\+A^{kk}K+A^{kt}t+A^{ky}y\end{array}\right)+\left(\frac{A^{wc}A^{kt}}{A^{ck}}\right)\\-\left(\frac{A^{wk}}{A^{ck}}\right)\left(\begin{array}{l}A^c+A^{wc}w^b+A^{cc}c\\+A^{ck}K+A^{ct}t+A^{cy}y\end{array}\right)+\left(\frac{A^{wk}A^{ct}}{A^{ck}}\right)+\left(\frac{A^{wk}A^{ct}}{A^{ck}}\right)\\+\left(\left(\frac{A^{wc}A^{kk}}{A^{ck}}\right)+A^{wk}-\frac{2}{r}\left(\frac{A^{wk}}{A^{ck}}\right)\right)\dot{K}^o\end{array}\right]+A^{wt}.$$

The steady state capital stock presented in equation (20) can be written in terms of the parameter estimates as

$$K_{it}^*(\cdot)=-r\left(r\left(A^{ck}\right)^{-1}-I\right)^{-1}\left(A^c+A^{wc}w_{it}+A^{cc}c_{it}+A^{cy}y_{it}+A^{ct}\left(t_{it}-\frac{1}{r}\right)\right). \qquad \text{(A3)}$$

Appendix B

Lists of Electric Utilities in This Study

No.	Utility Name	State	Dum	No.	Utility Name	State	Dum
1	Cincinnati Gas & Electric	OH	1	37	Central Hudson Gas & Electric	NY	1
2	Montaup Electric	MA	1	38	Central Maine Power	ME	1
3	New England Power	MA	1	39	Consolidated Edison Co-NY	NY	1
4	PECO Energy	PA	1	40	Delmarva Power & Light	DE	1
5	Arizona Public Service	AZ	1	41	Duke Power	NC	0
6	Atlantic City Electric	NJ	1	42	El Paso Electric	TX	1
7	Niagara Mohawk Power	NY	1	43	The Empire District Electric	MO	0
8	Central Illinois Light	IL	1	44	Gulf States Utilities	TX	1
9	Central Illinois Pub Service	IL	1	45	Illinois Power	IL	1
10	Central Louisiana Electric	LA	0	46	Interstate Power	LA	0
11	Commonwealth Edison	IL	1	47	Kansas City Power & Light	MO	0
12	Consumers Power	MI	1	48	Kansas Gas & Electric	KS	0
13	The Dayton Power & Light	OH	1	49	Long Island Lighting	NY	1
14	Duquesne Light	PA	1	50	Madison Gas & Electric	WI	0
15	Florida Power & Light	FL	0	51	Minnesota Power & Light	MN	0
16	Florida Power Corp	FL	0	52	Montana Power	MT	1
17	Hawaiian Electric	HI	0	53	Nevada Power	NV	1
18	Houston Lighting & Power	TX	1	54	New York State Electric & Gas	NY	1
19	Indianapolis Power & Light	IN	0	55	Oklahoma Gas & Electric	OK	1
20	Kentucky Utilities	KY	0	56	Orange & Rockland Utilities	NY	1
21	Louisville Gas & Electric	KY	0	57	Otter Tail Power	MN	0
22	Northern Indiana Pub Service	IN	0	58	Pacific Gas & Electric	CA	1
23	Portland General Electric	OR	1	59	Pennsylvania Power & Light	PA	1
24	PSI Energy	IN	0	60	Potomac Electric Power	DC	1
25	Public Service Electric & Gas	NJ	1	61	Public Service Co of Colorado	CO	0
26	Sierra Pacific Power	NV	1	62	Public Service Co of NM	NM	1
27	South Carolina Electric & Gas	SC	0	63	Rochester Gas & Electric	NY	1
28	Southern California Edison	CA	1	64	San Diego Gas & Electric	CA	1
29	Tampa Electric	FL	0	65	Southern Indiana Gas & Electic	IN	0
30	Texas Utilities Electric	TX	1	66	Southwestern Public Service	TX	1
31	Virginia Electric & Power	VA	1	67	St Joseph Light & Power	MO	1
32	Wisconsin Electric Power	WI	0	68	The Detroit Edison	MI	1
33	Wisconsin Power & Light	WI	0	69	Union Electric	MO	0
34	Baltimore Gas & Electric	MD	1	70	United Illuminating	CT	1
35	Boston Edison	MA	1	71	UtiliCorp United I	MO	0
36	Carolina Power & Light	NC	0	72	Wisconsin Public Service	WI	0

* Dummy variable which "1" indicates electric utilities in "Group A" whereas "0" represents electric utilities in "Group B"

Appendix C

Derivation of input demand elasticities

Following Luh and Stefanou (1993), the short-, intermediate-, and long-run elasticities evaluated at the behavioral input prices are derived in the following. Defining the optimized actual variable input demands $x_n^{o*} = \tau_x x_n^{b*}$ (n = fuel and aggregate labor and maintenance) and the behavioral input prices as w_m^b (m = fuel, aggregate labor and maintenance, and capital).

Short-run variable input demand elasticity is

$$\varepsilon^{SR}_{x_n^o w_m^b} = \frac{w_m^b}{x_n^{b*}} \frac{\partial x_n^{b*}}{\partial w_m^b}\bigg|_{K=K(t),\dot{K}=0} = \frac{w_m^b}{x_n^{b*}}\left(rJ^b_{w_n^b w_m^b} \right), \tag{C1}$$

Intermediate-run variable input demand elasticity is

$$\varepsilon^{IR}_{x_n^o w_m^b} = \frac{w_m^b}{x_n^{b*}} \frac{\partial x_n^{b*}}{\partial w_m^b}\bigg|_{K=K(t)} = \frac{w_m^b}{x_n^{b*}}\left[rJ^b_{w_n^b w_m^b} - J^b_{kw_n^b} \frac{\partial \dot{K}^{b*}(\cdot)}{\partial w_m^b} \right], \tag{C2}$$

Since $\dot{K}_{it}^{b*}(\cdot) = M\left(K_{it} - K_{it}^*(\cdot)\right)$ and $M = \left(rI - \left(J^b_{ck}\right)^{-1} \right)$, $\partial \dot{K}^{b*}(\cdot)/\partial w_m^b = -M \partial K^*(\cdot)/\partial w_m^b$.

Therefore,

$$\varepsilon^{IR}_{x_n^o w_m^b} = \frac{r w_m^b J^b_{w_n^b w_m^b}}{x_n^{b*}} + \frac{J^b_{kw_n^b} w_m^b}{x_n^{b*}} \frac{\partial K^*(\cdot)}{\partial w_m^b} \cdot M = \varepsilon^{SR}_{x_n^b w_m^b} + \left(\frac{w_m^b}{x_n^{b*}} \right) J^b_{kw_n^b} \left(M \cdot \frac{\partial K^*(\cdot)}{\partial w_m^b} \right). \tag{C3}$$

Long-run variable input demand elasticity is

$$\varepsilon^{LR}_{x_n^o w_m^b} = \frac{w_m^b}{x_n^{b*}} \frac{\partial x_n^{b*}}{\partial w_m^b}\bigg|_{K=K^*,\dot{K}=0} = \frac{w_m^b}{x_n^{b*}}\left[rJ^b_{w_n^b w_m^b} - J^b_{kw_n^b} \frac{\partial \dot{K}^{*}(\cdot)}{\partial w_m^b} \right]. \tag{C4}$$

When the quasi-fixed factors adjust instantaneously $K = K^*(\cdot)$, $M = -I$. Hence, $\dot{K}^{b*}(\cdot) = -K^*(\cdot)$ and $\partial \dot{K}^{b*}(\cdot)/\partial w_m = -\partial K^*(\cdot)/\partial w_m$. Therefore,

$$\varepsilon^{LR}_{x_n^o w_m^b} = \frac{r w_m^b J^b_{w_n^b w_m^b}}{x_n^{b*}} + \frac{J^b_{kw_n^b} w_m^b}{x_n^{b*}} \frac{\partial K^*(\cdot)}{\partial w_m^b} = \varepsilon^{SR}_{x_n^b w_m^b} + \left(\frac{w_m^b}{x_n^{b*}} \right) J^b_{kw_n^b}. \tag{C5}$$

Defining the steady state capital stock as K^*, intermediate-run capital elasticity is

$$\varepsilon_{K,w_m^b}^{IR} = M \frac{w_m^b}{K^*} \frac{\partial K^*}{\partial w_m^b} . \tag{C6}$$

Long-run capital elasticity is

$$\varepsilon_{K,w_m^b}^{LR} = \frac{w_m^b}{K^*} \frac{\partial K^*}{\partial w_m^b} . \tag{C7}$$

Appendix D

Derivation of scale elasticity

The scale elasticity associated with the production technology is defined as the percentage change in output responds to a percentage change in all inputs. Following Stefanou (1989), the dynamic theory of cost allows for the selection of variable input demands and investment. The optimized actual dynamic programming equation in equation (5) can be viewed as the long-run cost function associated with the actual quantities. The short-run cost function associated with the actual quantities is defined as the summation of variable cost, wx^{o*}, and fixed cost, cK. The long-run average cost (*LRAC*) at time *t* is calculated by dividing the equation (5) with output, $y(t)$, while the short-run average cost (*SRAC*) at time *t* is calculated by dividing the short-run cost function with $y(t)$. The long-run marginal cost (*LRMC*) at time *t* is calculated by differentiating equation (5) with respect to $y(t)$ while the short-run marginal cost (*SRMC*) at time *t* is calculated by differentiating the short-run cost function with $y(t)$.

The short-run scale elasticity associated with the actual quantities yields

$$SE^{SR} = \frac{SRAVC}{SRMC} = \frac{wx^{o*}}{\gamma^{a*} y}, \tag{D-1}$$

where $\gamma^{a*} = \frac{d\left(wx^{o*} + cK\right)}{dy}$ is the short-run marginal cost (*SRMC*) at time *t*, and the long-run scale elasticity associated with the actual quantities yields

$$SE^{LR} = \frac{LRAVC}{SRMC} = \frac{wx^{o*} + J_k^a \dot{K}^{o*} + J_t^a}{\gamma^{a*} y}. \tag{D-2}$$

Table 1: Estimated Structural Coefficients, GMM Estimation Period 1986 to1999

Parameter	Estimate	Standard Error	P-value	Parameter	Estimate	Standard Error	P-value
$(A^{CK})^{-1}$	0.020	0.001	[.000]	A^{wk}	2.588	0.094	[.000]
A^{0}	-17.870	4.611	[.000]	A^{y}	0.459	0.567	[.418]
A^{c}	13.270	3.020	[.000]	A^{yy}	0.029	0.017	[.082]
A^{wc}	-1.582	0.202	[.000]	A^{yt}	-0.004	0.032	[.902]
A^{cc}	-32.110	4.241	[.000]	A^{t}	0.396	0.389	[.310]
A^{ct}	-0.682	0.223	[.002]	A^{tt}	0.007	0.042	[.870]
A^{cy}	0.176	0.086	[.042]	A^{k}	74.570	9.026	[.000]
A^{w}	0.637	0.200	[.001]	A^{yk}	-0.496	0.262	[.059]
A^{ww}	-0.931	0.115	[.000]	A^{kt}	-0.702	0.406	[.084]
A^{wt}	-0.084	0.014	[.000]	A^{kk}	7.576	4.990	[.129]
A^{wy}	0.126	0.007	[.000]				

Equation	R^2	DW
Investment	0.025	1.770
Fuel	0.976	1.606
Labor and Maintenance	0.951	1.035
Test of Overidentifying Restrictions	397.584	[.000]

Table 2: Average Firm Allocative and Technical Efficiencies of Net Investment and of Variable Input Demands, Given Firms are Perfectly Technical Inefficient in Net Investment

Electric Utilities	Allocative Inefficiency of net investment	Technical Inefficiency of variable input	Allocative Inefficiency of variable input
All Electric Utilities			
Minimum	0.200	0.241	0.084
Maximum	1.218	0.991	6.464
Average	0.594	0.767	3.105
Average Group A[1]	0.589	0.725	3.065
Average Group B[2]	0.611	0.809	3.151

[1] Electric utilities are located within of states with the deregulation plan

[2] Electric utilities are located outside of states with the deregulation plan

Table 3: Short-Run, Intermediate-Run, and Long-Run Elasticities for the periods of 1986-1999

Quantity	Prices		
	Fuel	Labor and Maintenance	Capital
Short-Run			
Fuel	-0.105 (-0.095)	0.105 (0.095)	0.196 (0.295)
Labor & Maintenance	0.733 (0.673)	-0.733 (-0.673)	0.605 (0.635)
Intermediate-Run			
Fuel	-0.112 (-0.121)	0.111 (0.119)	0.254 (0.344)
Labor & Maintenance	0.773 (0.690)	-0.776 (-0.695)	0.612 (0.643)
Capital	0.036 (0.042)	0.032 (0.030)	-0.051 (-0.050)
Long-Run			
Fuel	-0.325 (-0.304)	0.315 (0.295)	0.391 (0.491)
Labor & Maintenance	0.868 (0.974)	-0.876 (-0.985)	0.839 (0.869)
Capital	1.214 (1.399)	1.090 (1.002)	-1.712 (-1.652)

Note: Estimated values for the pre-deregulation periods of 1986-1996 in parenthesis

Table 4: Short-and Long-Run Scale and Cost Elasticities for the periods of 1986-1999

Marginal Cost	cents per kwh	Average Total Cost	cents per kwh
Short-Run	1.938 (2.077)	Short-Run	2.774 (2.996)
Long-Run	1.782 (1.827)	Long-Run	2.447 (2.674)
Average Variable Cost	cents per kwh	Scale Elasticity	Value
Short-Run	2.653 (2.851)	Short-Run	1.370 (1.373)
Long-Run	2.355 (2.550)	Long-Run	1.215 (1.228)

Note: Estimated values for the pre-deregulation periods of 1986-1996 in parenthesis

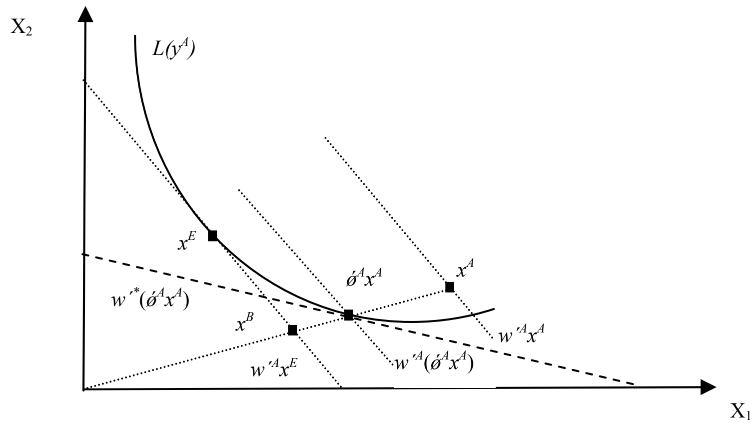

Figure : The Input-Oriented Measurement and Decomposition of Cost Efficiency

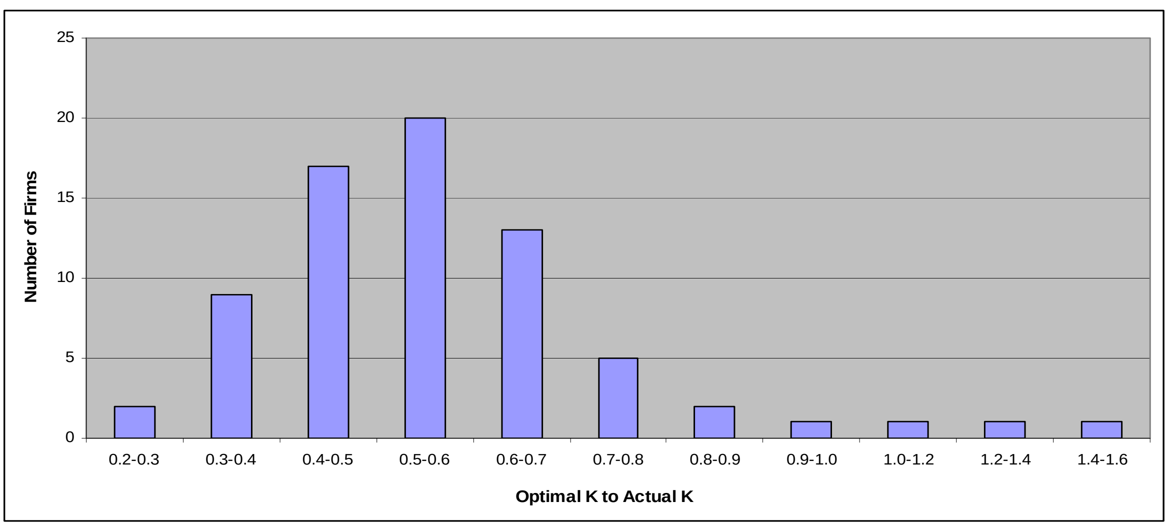

Figure 2: Distribution of the Ratio of Optimal Capital to Actual Capital