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Abstract

This paper provides up to date firm level analysis of the production technology and cost structures in the U.S. electric power generation industry. The paper applies an econometric approach into a dual restricted variable cost function within a "*temporal equilibrium*" framework. The Generalized Method of Moments (GMM) estimation is used to estimate the cost structures in the electric power generation industry. This paper is empirically implemented using a panel data (1986-1998) on 32 nuclear power generations for major investor owned utilities. The major result indicates that most of electric utilities in the nuclear electricity generation industry overutilized capital in production over time. Technological progress may have slowed over the sample period of this study. The results also show that electric utilities with small generation were operating at decreasing returns to scale whereas those with large generation were operating at increasing returns to scale in the production of the electricity industry in the sample data.

JEL Classification: D24

Keywords: Restricted Variable Cost Function, Generalized Leontief, GMM, U.S. Nuclear Power Generation, Temporal Equilibrium

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1. Introduction

The U.S. electricity industry comprises of four major segments; generation, transmission, distribution and marketing. Generation is the production of electricity from other energy sources such as burning of fossil fuel (i.e. coal, oil, and natural gas), nuclear fission, hydro, or geothermal. When the electricity is generated, transmission allows the electricity to be transported at high voltages and long distances from generation plants to local utility companies. Distribution is the process of moving electricity from the high-voltage transmission grid to lower voltages and the delivery of that power to users for heating, lighting, air conditioning, and other personal and commercial uses. Finally, the marketing section will involve the processes of advertising, selling, and billing for electricity uses.

The basis for historical regulation of the U.S. electricity industries has been to deal with natural monopoly issues in the production of electricity after the Public Utility Regulatory Policies Act (PURPA) of 1978 passed by the Congress had allowed independent generators to sell their electricity to utilities at regulated rates. These regulated rates were typically set equal to average cost instead of marginal cost of production. Traditionally, an electricity customer has paid one regulated price for electricity to a single vertically integrated utility responsible for generation, transmission, distribution, and marketing. The 1992 Energy Policy Act, followed by the Federal Energy Regulatory Commission's (FERC's) Orders 888 and 889, expanded PURPA's initiative by forcing utilities with transmission network 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 open access to transportation networks. Deregulation in the electricity markets has date been incomplete with continued regulation in some of its segments. Under partial regulation, electricity markets are not really deregulated but restructured. Brennan, Palmer, and Martinez (2002) provide a good review of the actions and roles of state and federal regulators to the U.S. electricity industry and issues surrounding its deregulation and restructuring.

Electricity is generated using a variety of different technologies and fuels. Fossil-fuel-fired boilers producing steam for turbine generators remain the dominant electricity generation technology in the United States. About 61.1 percent of all the electricity in 1999 supplied by the U.S. electric power industry comes from steam turbines fired by fossil fuel. Of this amount, coal-fired generation accounts for 84 percent, natural gas accounts for 12.7 percent, and petroleum comprises 3.3 percent (Energy Information Administration (EIA), 2000). Nuclear power generation is the second largest sector of the U.S. electricity industry and currently constitutes nearly 18.6 percent of total net generation technology. There are approximately 130 nuclear power generating units operated over the country in the recent year (Nuclear Energy Institute (NEI), 2000). However, technological and economic problems, including environmental factors, safety and waste disposal issues, may continue to limit growth prospects for nuclear power. No new nuclear plants have been constructed in the United States in recent years. The remaining power generation is from hydroelectric (8.7 percent), and nonutility (11.6 percent).

Buyers of electricity are typically classified as residential, commercial, and industrial customers. Each customer class purchases approximately one-third of the total power sold in the United States. Sellers of electricity are classified into the following categories: Investor-Owned Utilities (IOUs), publicly owned utilities, rural electric cooperatives, federally owned utilities, and Independent Power Producers (IPP). IOUs traditionally have been vertically integrated utilities generating, transmitting, and distributing the electricity that they sell to customers living in their exclusive territories. IOUs are the most important players in electricity markets. The EIA

(2000) report indicates that IOUs own 71 percent of the U.S. generating capacity owned by both utilities and nonutility generators in the United States and are responsible for 74 percent of all retail sales of electricity. Furthermore, publicly owned utilities account for about 14 percent of the U.S. generating capacity and 15 percent of electricity sales to final customers. The rural electric cooperatives, federally owned utilities, and IPP account for the remaining generating capacity and retail sales of electricity.

The recent studies of the U.S. electricity industry have used data on steam electric power generation for major IOUs to estimate cost structures and the possible savings in the production costs [e.g., Considine (2000), Atkinson and Primont (2002), Rungsuriyawiboon and Stefanou (2003)]. These studies used the data on the generation source which represents the dominant part of the U.S. electricity industry. The number of previously published studies on cost structures and scale economies for nuclear power generation is relatively small and outdated [e.g., Krautmann and Solow (1988), Marshall and Navarro (1991), Canterbery, Johnson, and Reading (1996)]. The purpose of this paper is to provide up to date information on cost structures of nuclear power generation. The paper is empirically implemented using panel data on 32 nuclear power generation for major IOUs over the time period of 1986-1998. Since the U.S. electric utility industry has been undergoing a restructuring, electricity deregulation and restructuring are now on the policy agenda in most states. The measures obtained in this paper in addition to those of the previous studies in this industry will provide useful information for regulators in designing suitable policies to promote the efficiency and productivity of electric utilities in the industry.

This paper applies an econometric model to estimate the structure of production for nuclear electricity generation. The paper adopts a dynamic factor demand approach developed by

Lau (1976) and McFadden (1978) using the dual restricted variable cost function. The restricted variable cost function reflects production or technological constraints facing the firm when output and certain input quantities referred as quasi-fixed inputs are fixed in the short-run. This framework of the firm's optimization problem is referred to as a "*temporal equilibrium or partial static equilibrium*". This model allows solving short-run demand equations for variable input and long-run demand equations for both variable and quasi-fixed inputs. The paper defines the functional form of the restricted variable cost function in a form of the Generalized Leontief (GL) functional form introduced by Diewert (1971). The system equation consisting of the restricted variable cost function and its input demand equations is implemented by using the Generalized Method of Moments (GMM) to estimate the parameters of the restricted variable cost function. Moreover, this paper obtains other economically meaningful measurements such as input demand elasticities, economies of scale, capacity utilization, and technological change in the nuclear electric power generation industry.

The outline of this paper is organized as follows. The next section presents a model specification of the short-run restricted variable cost function for electric power generation. This is followed by a discussion of the data set and variables. The next section provides the estimation procedures and the estimated results of cost structures for nuclear power generation and then conclusions follow.

2. Model Specification

The economic theory suggests that cost function for electric power generation will depend on the levels of outputs and the prices of inputs such as fuel, labor and maintenance, capital, and state of technology. Given exogeneity of output, input prices and state of technology, a cost function for the firm can be solved by

$$TC(P_i, Y, Z) = \arg\min \sum_i P_i X_i \, , \tag{1}$$

subject to $Y = f(X_i, Z)$,

where TC denotes total cost, P_i denotes the price of i-th input (i.e. fuel, labor and maintenance, and capital), X_i denotes the quantity of i-th input, Y denotes output and Z denotes technological level.

Since electricity utility firms have added very little new capacity in recent years, capacity inputs are not variable in the short run. In addition, nuclear power plants represent large, discrete pieces of equipment. Once they are built, there is likely to be little scope for adjusting the capital stock in order to change relative prices. The economic decision is to minimize cost with respect to variable inputs such as fuel, labor and maintenance conditional on output and capital constraints.

Then, there exists the following short-run restricted variable cost function for electric power generation.

$$VC = VC\left(P_1, P_2 \middle| K, Y, Z\right), \tag{2}$$

where VC is short-run variable costs depend upon two variable input prices: fuel P_1, and the aggregate of labor and maintenance P_2, contingent upon predetermined levels of capital stocks K, nuclear electric power generation Y, and the state of technology Z, represented with a time trend. VC is non-negative and non-decreasing in Y, homogenous of degree one, non-decreasing, and concave in the variable input prices P_i $(i = 1,2)$, and non-increasing and convex in the levels of quasi-fixed factors K.

To implement this model, the functional form of the restricted variable cost function will be presented in a form of the GL functional form[1]. The following GL short-run restricted variable cost function with non-constant returns to scale and with non-neutral technological change with symmetry and linear homogeneity in prices can be written as.

$$\begin{aligned} VC_t = {} & Y_t \left\{ \sum_{i=1}^{2} \left(\alpha_{it} + \sum_{f=1}^{f} \alpha_{if} D_{ft} \right) P_{it} + 2\alpha_{ij} \left(P_{it} P_{jt} \right)^{1/2} + \sum_{i=1}^{2} \delta_{iy} P_{it} Y_t^{1/2} + \sum_{i=1}^{2} \delta_{iz} P_{it} Z_t^{1/2} \right\} \\ & + \gamma_{kk} \sum_{i=1}^{2} P_{it} K_t + Y_t \sum_{i=1}^{2} P_{it} \left(\gamma_{yy} Y_t + 2\gamma_{yz} Y_t^{1/2} Z_t^{1/2} + \gamma_{zz} Z_t \right) \\ & + \left(K_t Y_t \right)^{1/2} \left\{ \sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it} \left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2} \right) \right\}, \end{aligned} \tag{3}$$

where t index of time periods; f index of firms; $i = 1$ and $j = 2$; α, δ, and γ are unknown parameters, and D_{ft} s are firm dummy variables for fixed firm effects. Morrison (1988) demonstrates that the GL functional form allows linear parameter restrictions for testing long-run constant returns to scale $\left(\delta_{iy} = \gamma_{yk} = \gamma_{yz} = \gamma_{yy} = 0 \right)$ and neutral technological change $\left(\delta_{iz} = \gamma_{yz} = \gamma_{zz} = \gamma_{zk} = 0 \right)$.

Given exogenous variable input prices $\left(P_i \right)$ and using Shepard's lemma by taking the partial differential of the short-run variable costs with respect to variable input prices, the input demand functions can be obtained by the following equation.

$$\begin{aligned} X_{it} = Y_t \Bigg[& \alpha_{ii} + \sum_{f=1}^{f} \alpha_{if} D_{ft} + \alpha_{ij} \left(\frac{P_{jt}}{P_{it}} \right)^{1/2} + \delta_{iy} Y_t^{1/2} + \delta_{iz} Z_t^{1/2} + \gamma_{yy} Y_t + 2\gamma_{yz} Y_t^{1/2} Z_t^{1/2} \\ & + \gamma_{zz} Z_t + \left(\frac{K_t}{Y_t} \right)^{1/2} \left(\delta_{ik} + \gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2} \right) + \gamma_{kk} \left(\frac{K_t}{Y_t} \right) \Bigg], \end{aligned} \tag{4}$$

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[1] The GL functional form is good approximation of technology with limited input substitution possibilities [Cave and Christensen (1980)] and it allows a closed-form solution for equilibrium levels for quasi-fixed inputs [Morrison (1988)].

for $i, j = 1$ and 2, respectively.

The system equation consisting of the restricted variable cost function in equation (3) and its input demand equations in equation (4) will be used to estimate the parameters of the short-run variable costs. Caves, Christensen, and Swanson (1981) show that characteristics of long-run production can be derived from the restricted cost function. The long-run cost function TC at time period t can be calculated by the following equation.

$$TC_t = VC_t + P_{kt} K_t^*, \tag{5}$$

where P_{kt} is the ex ante user cost of capital and K_t^* is the optimal capital stock.

The optimal capital stock at time period t $\left(K_t^*\right)$ can be derived from the capital equilibrium under the necessary conditions for convexity of $\partial VC_t / \partial K_t^* < 0$ and $\partial^2 VC_t / \partial K_t^{*2} > 0$. Lau (1978) and Morrison (1985a) showed that the shadow value of capital $Z_{kt} = -\left(\partial VC_t / \partial K_t^*\right)$ must equal the user cost of capital P_{kt} in a long-run equilibrium.

$$Z_{kt} = -\frac{\partial VC_t}{\partial K_t^*} = -\frac{1}{2}\left(\frac{Y_t}{K_t^*}\right)^{1/2} \left\{\sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right)\right\} + \gamma_{kk} \sum_{i=1}^{2} P_{it} \equiv P_{kt}\,. \tag{6}$$

Therefore, the closed-form solution for optimal capital can be derived as follows:

$$K_t^* = \frac{1}{4} Y_t \left\{\frac{\sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right)}{P_{kt} + \gamma_{kk} \sum_{i=1}^{2} P_{it}}\right\}^2 . \tag{7}$$

The necessary conditions for convexity are as follows:

$$\frac{\partial VC_t}{\partial K_t^*} = -\frac{1}{2}\left(\frac{Y_t}{K_t^*}\right)^{1/2} \left\{\sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right)\right\} + \gamma_{kk} \sum_{i=1}^{2} P_{it} < 0\,, \tag{8}$$

$$\frac{\partial^2 VC_t}{\partial K_t^{*2}} = \frac{1}{4}\left(Y_t K_t^*\right)^{1/2}\left\{\sum_{i=1}^{2}\delta_{ik}P_{it} + \sum_{i=1}^{2}P_{it}\left(\gamma_{yk}Y_t^{1/2} + \gamma_{zk}Z_t^{1/2}\right)\right\} > 0\,. \tag{9}$$

A measure of scale economics, which are defined as the proportionate increase of cost with the increase in the level of output, can be associated with the size of generating units or with multiunit at the plant level. Nerlove (1963) and Christensen and Green (1976) defined short-run scale economies as unity minus the cost-output-elasticity.

$$SCE_t^{SR} = 1 - \left.\frac{\partial \ln VC_t}{\partial \ln Y_t}\right|_{\overline{K}} = 1 - \frac{\left(\partial VC_t / \partial Y_t\right)\big|_{\overline{K}}}{\left(VC_t / Y_t\right)} = 1 - \frac{SRMC_t}{SRAC_t}\,, \tag{10}$$

where the value of the SCE_t^{SR} greater than zero imply scale economies, while values less than zero implying scale diseconomies.

In order to measure long-run scale economy, the derivative terms in equation (10) must be evaluated at the long-run equilibrium for given input prices, output, and the state of technology. Long-run scale economy measures include the output-induced changes in capital stocks. In a long-run equilibrium, the shadow value of capital $Z_{kt} = -\left(\partial VC_t \,/\, \partial K_t^*\right) = P_{kt}$, implies that long-run marginal costs simply equal short-run marginal costs evaluated at optimal capital stocks. A long-run scale economy measure can be defined as unity minus the ratio of long-run marginal cost to long-run average cost. Mathematical derivations of short-run and long-run input demand elasticities with respect to input prices, output and technological change are presented in Appendix A.

3. Data

Data used in this paper consist of a pooled time-series and cross-section of plants generating electricity from nuclear power. The data on the nuclear power generation for major investor-owned utilities in the United States are obtained over the period 1986-1998. The primary sources of data are obtained from the Energy Information Administration, the Federal Energy Regulatory Commission and the Bureau of Labor Statistics.

The data set used in this paper contains the measurements of firm output and input prices for nuclear power production. Output variable is represented by net nuclear power generation in megawatt-hour (mwh). The price of fuel is the multilateral Tornqvist price index for uranium[2]. The prices of uranium are the weighted-average-uranium price received by U.S. utilities in Dollars per Pound U_3O_8 Equivalent. The quantities of fuel equal the nuclear power production fuel costs divided by the multilateral Tornqvist price index for fuels. The price of labor and maintenance aggregate is the multilateral Tornqvist 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[3]. The quantities of labor and maintenance are measured as the aggregate costs of labor and maintenance divided by a multilateral Tornqvist price index for labor and maintenance. The cost shares for labor are computed by weighting the labor costs of nonfuel variable costs with summation of total operation and labor expenses. The capital stock is measured by using estimates of the value of capital stocks known as a perpetual inventory approach mentioned in Considine (2000). This method involves estimating a benchmark capital stock based upon installed capacity in a base year valued at replacement cost and then updating this value each year using annual plant and equipment retirements and capital expenditures. 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.

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2 For the formula how to construct the multilateral Tornqvist index, see Coelli, Rao and Battese (1998, Ch 4)
3 All indices used in this paper are obtained and calculated relative to the base period 1992.

The original panel of 56 firms is reduced to 32 because many companies are subsidizes of holding companies[4]. A list of electric utilities and a summary of the sample which reports average annual production and average total observed cost for each firm from 1986-1998 are summarized in Table 1. Average production over the period ranges from a low of 0.5 million mwh by Eastern Utilities Associates to 61.8 million mwh by Commonwealth Edison Co. Average production across all firms is 11.2 million mwh with a standard deviation of 12.4 million mwh. There are 20 firms with generation below the sample mean, and one firm that is nearly five times larger than the average firm. Average total observed cost is the ratio of the sum of variable cost and capital charges to generation. Average total observed cost over the period ranges from the lowest costs of 2.1 cents per kwh by Virginia Electric and Power Co. to 15.2 cents per kwh by Public Service to NM. Average total observed cost across all firms is 4.7 cents per kwh with a standard deviation of 5.5 cents per kwh. Table 2 presents a summary of the data used in this study. The mean of fuel price is 1.407 with a standard deviation of 0.480, and of labor and maintenance is 0.969 with a standard deviation of 0.170. The mean user cost of capital is 0.099 with a standard deviation of 0.023. The mean of fuel quantity is 0.567 million dollars with a standard deviation of 0.684 million dollars, and of labor and maintenance is 1.708 million dollars with a standard deviation of 1.747 million dollars. The mean value of capital stock is 12.526 million dollars with a standard deviation of 17.398 million dollars.

4. Estimation Procedures

The system equation consisting of the short-run restricted variable cost function in equation (3) and the two input demand equation in equation (4) can be estimated after appending

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

a linear disturbance vector with mean vector zero and variance-covariance matrix Σ into the system equation. The system of equations is first estimated with the minimum distance estimator developed by Berndt, Hall and Hausman (1974) using White's (1980) heterscedastic-consistent estimator for the standard errors. If the errors in the system equation are normally distributed, these estimates are equivalent to maximum likelihood (ML). Then, the estimated results from the ML estimation will be compared to the Generalized Method of Moment (GMM) estimation. One proposal of the GMM estimation is to find instrumental variables (z) so that they are correlated with exogenous variables in the model but uncorrelated with residuals (ε). That implies a set of orthogonality conditions that $E(z'\varepsilon) = 0$. If the disturbances are heteroscedastic and serially correlated, the estimation from the presence of heteroscedasticity and autocorrelation can be corrected by applying a flexible approach developed by Newey and West (1987). They estimated a variance-covariance matrix using weighted inner products of the residuals and instrument variables.

In this paper, the GMM estimation will be implemented by defining the right-hand side variables of each equation in the system equation as instruments. 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). GMM estimators are asymptotically efficient in a large class but are rarely efficient in finite samples. In addition, GMM estimation requires stationary data of variables in the model. The unit root tests for panel data developed by Im, Pesaran and Shin (1998) are employed to test the stationary of each variable. These unit root tests allow individual effects and different patterns of residual serial correlation. They involve estimation conventional unit root regressions for each panel, averaging the unit root statistics, and performing a test using the critical values computed by Im, Pesaran, and Shin (1998).

5. Empirical Results

The analysis begins with testing the stationary of each variable. The unit root tests are performed with and without a linear trend. The results from the unit root tests are summarized in Appendix B. The 20 variables consisting of three endogenous variables (i.e. average cost in equation (3) and the two input-output ratios in equation (4)) and 17 predetermined variables defined from combinations of input prices, output and capital are tested by following the studies of Im, Pesaran, and Shin (1998). The unit root tests have shown that there are 2 unit roots of variables without trend and 6 unit roots with trend. The tests reveal that the optimal lag structure in the augmented Dickey-Fuller regressions is two periods for all variables tested. Thus, two autocorrelation terms are defined in computing the covariance matrix of the orthogonality conditions for the GMM estimate.

Then, a number of hypothesis tests regarding the presences of constant returns to scale and neutral technological change were conducted using likelihood ratio tests. The null hypothesis of long-run constant return to scale was rejected because the chi-squared test statistics of 285.81 is higher than the critical value of 11.1 at the 5 percent level of significance. Moreover, the null hypothesis of neutral technological change was rejected because the chi-squared test statistic of 147.21 is higher than the critical value of 11.1 at the 5 percent level of significant. Thus, the hypothesis tests suggest that the GL short-run restricted variable cost function in equation (3) with non-constant returns to scale and with non-neutral technological change is an appropriate form for the analysis.

The estimated parameters of both models, ML and GMM estimations are reported in Table 3. The overall results from both models are very similar and have the same sign for all estimated parameters except the estimated parameter χ_{yz}. Compared with the ML estimation, the

GMM estimation has strong assumption which allows for the correction of autocorrelation problem in the model. As a result, it provides more reliable and accurate estimated results. The following empirical results are discussed upon the GMM estimates. The positive and significant α_{12} indicates that there are substitutions between energy and the labor and maintenance aggregate. 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. The parameter estimates of the GMM estimation are used to calculate other economically meaningful measurements such as input demand elasticities, economies of scale, capacity utilization, and technological change.

Following the estimation, the tests for the regularity properties (i.e. monotonicity and curvature conditions) were checked at each data point in the sample of 416 observations. The tests showed that the monotonicity conditions for output and all inputs were satisfied at more than 97 percent of all observations. The concavity condition in the variable input prices and the convexity condition in the levels of quasi-fixed factors were satisfied at more than 95 percent of all observations.

Table 4 reports the estimated results of short and long-run elasticities evaluated at sample means. In the short-run, the own-price elasticity of demand for fuels is –0.507. The result is not much different with the –0.690 estimated by Krautmann and Solow (1988). The short-run output elasticity of fuel demand is 0.912 which reflects the close correspondence between fuel consumption and nuclear power production. In the short-run, the demand for labor and maintenance is price inelastic. In the long run, the own-price elasticities of demand for fuel and labor and maintenance are –0.503 and –0.185, respectively. There are very slight adjustment between short-run and long-run of own-price and cross-price elasticities of demand for fuels, labor and maintenance. The negative labor maintenance elasticity of capital demand indicates that capital and labor are complements, but the result indicates insignificant due to large standard error of the estimate. These results are consistent with the previous study by Krautmann and Solow (1988). The estimate for the own-price elasticity of capital is -2.102, also considerably very close to their estimate of -2.334. The short-run and long-run technological change elasticities of fuels, labor and maintenance in Table 4 provide insightful information for policy makers in designing policies to achieve a high growth rate in the production of electricity. The results indicate the technological change is biased toward the aggregate labor and maintenance, while it is biased against fuel in the short run. These results imply that the direction of technological change is fuel-saving and the capital-using in the short run. The long-run results indicate the technological change is biased toward capital, while it is biased against fuel and the aggregate labor and maintenance. These results imply that the direction of technological change is fuel- and the aggregate of labor and maintenance-saving and the capital-using in the long run.

Table 5 indicates that short-run marginal cost is 0.386 cents per kwh at the sample mean and increases to 0.493 cents per kwh in the long-run. Long-run average cost is 2.199 cents per kwh which it is approximately half of actual total average cost. The short and long run technological changes are negative. The estimates of technological change suggest that technological progress also shifts the cost function down over time. The magnitudes of the technological change are relatively small, but significant. These results suggest that technological progress in nuclear power generation may have slowed over the sample period of this study. The estimated result of short-run scale economies is 0.895 at the sample mean and decreases to 0.776 in the long-run. The estimated results suggest evidence of scale economies in the production of the electricity industry in this sample data. The average shadow value of capital reported in Table 5 is approximately 4.2 percent, which is considerably below the average user cost of capital of about 10 percent. The estimated optimal capital stocks as defined in equation (7) are calculated and compared to the actual capital stocks to account for the capacity utilization which provide some insight into the efficiency of capital use by an electric utility. Values of the ratio of optimal capital to actual capital stocks less than one imply that an electric utility is over-utilizing capital while values greater than one imply that an electric utility is under-utilizing capital. Table 5 reports that the average estimated optimal capital stock as a percentage of observed capital is about 60 percent. This result suggests that, on an average, electric utilities in the nuclear electricity generation industry had used current capital stocks at the disequilibrium level and they overutilized capital in production over time.

Figure 1 plots the estimates of short- and long-run scale economies for different output levels. Negative numbers indicate scale diseconomies and positive number with greater (less) than 1 implies increasing (decreasing) returns to scale. The estimates indicate scale economies in nuclear power generation. Figure 1 implies decreasing returns to scale at smaller outputs, with increasing returns to scale prevailing at larger outputs, or in other words, the downward sloping of short-long run average total cost curve.

6. Conclusions

The purpose of this paper is to provide up to date the firm level analysis of the production technology and cost structures in the U.S. electric power generation industry. Unlike the recent studies using data on steam electric power generation, this paper is empirically implemented using panel data on 32 nuclear power generation for major investor owned utilities over the time period of 1986-1998. This generation source is the second largest sector of the U.S. electricity industry. The number of previously published studies on this generation source is relatively small and outdated. Since the U.S. electric utility industry is undergoing a restructuring, electricity deregulation and restructuring are now on the policy agenda in most states. The measures obtained in this study in addition to those of the previous studies using data on steam electric power generation will provide useful information for regulators in designing suitable policies to promote the efficiency and productivity of electric utilities in the industry.

This paper applies an econometric approach into a dual restricted variable cost function to estimate input demand and scale elasticities, capacity utilization, and technological change within a "*temporal equilibrium*" framework. The Generalized Method of Moments (GMM) estimation is used to estimate the cost structures in the nuclear electric power generation industry. The major result indicates that most of electric utilities in the nuclear electricity generation industry overutilized capital in production over time. Technological progress may have slowed over the sample period of this study. The results also indicate decreasing returns to scale at smaller outputs, with increasing returns to scale prevailing at larger outputs,

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Appendix A: Derivations of Short- and Long-Run Elasticities

The short-run own-price and cross-price elasticities of input demand can be derived by taking partial derivative of the input demand in equation (4) with respect to input prices.

$$\left.\frac{\partial \ln X_{it}}{\partial \ln P_{it}}\right|_{\overline{K}_t} = -\frac{1}{2}\alpha_{12}\left(\frac{P_{jt}}{P_{it}}\right)^{1/2}\left(\frac{Y_t}{X_{it}}\right),\ \forall i, \tag{A1}$$

$$\left.\frac{\partial \ln X_{it}}{\partial \ln P_{jt}}\right|_{\overline{K}_t} = \frac{1}{2}\alpha_{12}\left(\frac{P_{jt}}{P_{it}}\right)^{1/2}\left(\frac{Y_t}{X_{it}}\right),\ i \neq j. \tag{A2}$$

The short–run input demand elasticities with respect to output and technological changes are:

$$\begin{aligned}\left.\frac{\partial \ln X_{it}}{\partial \ln Y_t}\right|_{\overline{K}_t} = \frac{Y_t}{X_{it}}\Bigg[&\alpha_{ii} + \sum_{f=1}^{f}\alpha_{if}D_{ft} + \alpha_{ij}\left(\frac{P_{jt}}{P_{it}}\right)^{1/2} + \frac{3}{2}\delta_{iy}Y_t^{1/2} + \delta_{iz}Z_t^{1/2} \\ &+ 2\gamma_{yy}Y + 3\gamma_{yz}Y_t^{1/2}Z_t^{1/2} + \gamma_{zz}Z_t + \frac{1}{2}\left(\frac{K_t}{Y_t}\right)^{1/2}\left(\delta_{ik} + 2\gamma_{yk}Y_t^{1/2} + \gamma_{zk}Z_t^{1/2}\right)\Bigg],\end{aligned} \tag{A3}$$

$$\left.\frac{\partial \ln X_{it}}{\partial Z_t}\right|_{\overline{K}_t} = \frac{Y_t}{X_{it}}\left[\frac{\delta_{iz}}{2Z_t^{1/2}} + \gamma_{zz} + \gamma_{yz}\left(\frac{Y_t}{Z_t}\right)^{1/2} + \frac{1}{2}\gamma_{zk}\left(\frac{K_t}{Z_tY_t}\right)^{1/2}\right],\ \forall i. \tag{A4}$$

The long-run own-price and cross-price elasticities of input demand with respect to input price can be defined as:

$$\frac{\partial \ln X_{it}}{\partial \ln P_{jt}} = \left.\frac{\partial \ln X_{it}}{\partial \ln P_{jt}}\right|_{\overline{K}_t} + \left[\frac{\partial \ln X_{it}}{\partial \ln K_t^*}\right]\frac{\partial \ln K_t^*}{\partial \ln P_{jt}},\ \forall i, j. \tag{A5}$$

The long-run input demand elasticities of capital, output and technological change are as follows:

$$\frac{\partial \ln X_{it}}{\partial \ln P_k} = \left[\frac{\partial \ln X_{it}}{\partial \ln K_t^*}\right]\frac{\partial \ln K_t^*}{\partial \ln P_k}, \tag{A6}$$

$$\frac{\partial \ln X_{it}}{\partial \ln Y} = \left.\frac{\partial \ln X_{it}}{\partial \ln Y}\right|_{\overline{K}_t} + \left[\frac{\partial \ln X_{it}}{\partial \ln K_t^*}\right]\frac{\partial \ln K_t^*}{\partial \ln Y}, \tag{A7}$$

$$\frac{\partial \ln X_{it}}{\partial Z} = \left.\frac{\partial \ln X_{it}}{\partial Z}\right|_{\bar{K}_t} + \left[\frac{\partial \ln X_{it}}{\partial \ln K_t^*}\right]\frac{\partial \ln K_t^*}{\partial Z} \; . \tag{A8}$$

Define the numerator and denominator of the optimal capital in equation (9) as

$$N_t = \sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right), \tag{A9}$$

$$D_t = P_{kt} + \gamma_{kk} \sum_{i=1}^{2} P_{it} \; , \tag{A10}$$

where

$$\frac{\partial \ln X_{it}}{\partial K_t^*} = \frac{1}{4}\left(\frac{Y_t N_t}{X_{it} D_t}\right)\left(\delta_{ik} + \gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2} + \gamma_{kk}\frac{N_t}{D_t}\right), \tag{A11}$$

$$\frac{\partial \ln K_t^*}{\partial \ln P_{it}} = 2P_{it}\left(\frac{\delta_{ik} + \gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}}{N_t} - \frac{\gamma_{kk}}{D_t}\right), \tag{A12}$$

$$\frac{\partial \ln K_t^*}{\partial \ln P_k} = -\frac{2P_{kt}}{D_t} \; , \tag{A13}$$

$$\frac{\partial \ln K_t^*}{\partial \ln Y_t} = 1 + \frac{\gamma_{yk} \sum_{i=1}^{2} P_{it} Y_t}{2 N_t K_t^*} \; , \tag{A14}$$

$$\frac{\partial \ln K_t^*}{\partial Z_t} = \frac{\gamma_{zk} \sum_{i=1}^{2} P_{it}}{\left(\sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right)\right) Z_t^{1/2}} \; . \tag{A15}$$

The short-run elasticity of cost with respect to technological change is

$$\frac{\partial \ln X_{it}}{\partial Z_t} = \frac{1}{VC_t}\left(\frac{Y_t}{Z_t}\right)^{1/2}\left[\frac{1}{2}\sum_{i=1}^{2} \delta_{iz} P_{it} + \gamma_{yz} \sum_{i=1}^{2} P_{it} Y_t + \frac{1}{2}\gamma_{zk} \sum_{i=1}^{2} P_{it} K_t^{1/2}\right] + \gamma_{zz}\left(\frac{Y_t}{VC_t}\right)\sum_{i=1}^{2} P_{it} \; . \tag{A16}$$

The long-run elasticity of cost with respect to technological change is

$$\frac{\partial \ln TC_t}{\partial Z_t} = \frac{1}{TC_t}\left(\frac{\partial VC_t^*}{\partial Z_t} + \frac{\partial VC_t^*}{\partial K_t^*} + P_{kt}\left(\frac{\partial K_t^*}{\partial Z_t}\right)\right), \tag{A17}$$

where

$$\frac{\partial K_t^*}{\partial Z_t} = \frac{\gamma_{zk} K_t^* \sum_{i=1}^{2} P_{it}}{\left(\sum_{i=1}^{2} \delta_{ik} P_{it} + \sum_{i=1}^{2} P_{it}\left(\gamma_{yk} Y_t^{1/2} + \gamma_{zk} Z_t^{1/2}\right)\right) Z_t^{1/2}}. \tag{A18}$$

Appendix B: Unit Root Tests

	Without Trend		With Trend	
	Test Statistic	**Two-tailed Area**	**Test Statistic**	**Two-tailed Area**
VC/Y	-11.436	0.000	-8.168	0.000
X_1/Y	-1.973	0.048	3.164	0.002
X_2/Y	-12.545	0.000	-12.391	0.000
P_1	-8.475	0.000	-3.903	0.000
P_2	7.954	0.000	0.491	0.623*
$\sqrt{P_1 P_2}$	-3.092	0.002	-0.371	0.710*
$P_1\sqrt{Y}$	-6.228	0.000	-6.201	0.000
$P_2\sqrt{Y}$	2.057	0.040	-2.833	0.004
$(P_1 + P_2)Y$	-0.275	0.783*	-0.960	0.336*
$P_1\sqrt{K/Y}$	-7.613	0.000	0.353	0.724*
$P_2\sqrt{K/Y}$	1.773	0.076*	-2.600	0.009
$(P_1 + P_2)\sqrt{K}$	-3.399	0.001	-11.308	0.000
$(P_1 + P_2)K/Y$	-7.644	0.000	-3.993	0.000
$\sqrt{P_2/P_1}$	-5.379	0.000	11.170	0.000
$\sqrt{Y}$	-5.056	0.000	-9.064	0.000
Y	-3.930	0.000	-5.871	0.000
$\sqrt{K/Y}$	-5.578	0.000	-5.811	0.000
$\sqrt{K}$	2.891	0.004	0.153	0.878*
K/Y	-9.008	0.000	-7.809	0.000
$\sqrt{P_1/P_2}$	-9.206	0.000	0.252	0.801*

* Not significant at the 0.05 level

Table 1: Nuclear electric power generation and average total cost, firm means, 1986–1998

Company Name	Gen (10^6 mwh)	Avg cost (¢/kwh)	Company Name	Gen (10^6 mwh)	Avg cost (¢/kwh)
The Southern Company	24.4	3.7	Madison Gas & Electric	0.7	2.7
Arizona Public Service	6.7	7.9	Eastern Utilities Associates	0.5	13.4
Entergy Corporation	19.0	2.7	Niagara Mohawk Power	5.7	6.3
Baltimore Gas & Electric	10.0	4.2	Ohio Edison	7.0	8.3
Carolina Power & Light	16.9	4.6	Pacific Gas & Electric	15.7	3.8
Centerior Energy Corp	11.6	6.9	Pennsylvania Power & Light	13.6	2.4
Commonwealth Edison	61.8	3.1	Public Service Co of NM	2.1	15.2
Consolidated Edison Co-NY	5.4	4.8	Public Service Electric & Gas	16.2	4.4
Consumers Energy	4.6	3.7	San Diego Gas & Electric	3.3	3.9
Delmarva Power & Light	1.6	4.0	Southern California Edison	15.9	4.0
Duke Power	34.9	2.3	Union Electric	7.3	2.5
El Paso Electric	3.6	4.1	United Illuminating	2.4	12.2
Florida Power & Light	19.3	3.1	Virginia Electric & Power	21.7	2.1
General Public utilities Corp	10.2	5.1	Wisconsin Electric Power	6.7	2.7
Kansas City Power & Light	3.9	3.5	Wisconsin Power & Light	1.5	2.7
Kansas Gas & Electric	4.2	2.3	Wisconsin Public Service	1.5	2.4
			Overall mean	11.2	4.7
			Standard deviation	12.4	5.5

Table 2: Data summary for 32 electric utilities over the periods of 1986 to 1998

Variable	Units	Mean	S. D.	Minimum	Maximum
Output	($\times 10^6$ *MWhr*)	11.190	12.391	0.024	70.403
Price Index of Fuel		1.407	0.480	0.627	2.098
Price Index of Labor and Maintenance		0.969	0.170	0.597	1.857
User Cost of Capital	(percent)	0.099	0.023	0.013	0.340
Fuel	($\times 10^6$ *dollars*)	0.567	0.684	0.004	4.689
Labor and Maintenance	($\times 10^6$ *dollars*)	1.708	1.747	0.010	13.890
Capital	($\times 10^6$ *dollars*)	12.526	17.398	0.209	94.749

Table 3: Parameter Estimates of ML and GMM Estimations

Parameter	ML Estimate	ML St. Error	ML P-Value	GMM Estimate	GMM St. Error	GMM P-Value
α_{12}	0.4263	0.1052	[.000]	0.6447	0.0744	[.000]
δ_{1y}	0.1806	0.0698	[.001]	0.0475	0.0451	[.293]
δ_{2y}	-1.2450	0.2882	[.000]	-0.9328	0.0977	[.000]
δ_{1z}	0.4012	0.1185	[.001]	0.6223	0.0747	[.000]
δ_{2z}	0.6154	0.1152	[.000]	0.7990	0.0680	[.000]
γ_{yy}	-0.0120	0.0054	[.026]	-0.0018	0.0035	[.611]
γ_{yz}	0.0084	0.0024	[.000]	-0.0067	0.0019	[.000]
γ_{zz}	-0.0135	0.0206	[.000]	-0.1255	0.0143	[.000]
δ_{1k}	0.0604	0.0571	[.289]	0.0502	0.0459	[.274]
δ_{2k}	0.0125	0.1397	[.929]	0.0158	0.0529	[.766]
γ_{yk}	-0.0123	0.0117	[.292]	-0.0114	0.0089	[.203]
γ_{zk}	0.0141	0.0098	[.154]	0.0043	0.0092	[.637]
γ_{kk}	-0.0048	0.0028	[.084]	-0.0312	0.0019	[.103]
Equation	R^2	DW		R^2	DW	
Cost	0.468	1.246		0.431	1.147	
Fuel	0.671	0.902		0.616	0.774	
L & M	0.476	1.300		0.472	1.220	
Log likelihood value			-107.728			
Test of overidentifying restrictions					89.7091	

Table 4: Short and Long–Run Elasticities Evaluated at Sample Means

Quantity	Prices: Fuel	Prices: Labor and Maintenance	Prices: Capital	Output	Technological change
Short-Run					
Fuel	–0.507 (0.058)	0.507 (0.006)		0.912 (0.159)	–0.225 (0.054)
Labor & Maintenance	0.186 (0.021)	–0.186 (0.021)		–0.135 (0.177)	0.059 (0.027)
Long-Run					
Fuel	–0.503 (0.057)	0.055 (0.059)	–0.003 (0.010)	0.907 (0.157)	–0.029 (0.007)
Labor & Maintenance	0.185 (0.022)	–0.185 (0.022)	0.001 (0.001)	–0.134 (0.176)	–0.008 (0.004)
Capital	3.245 (7.364)	–1.143 (7.397)	–2.102 (0.065)	–3.699 (12.27)	0.195 (0.552)

Notes: Standard errors are in parentheses.

Table 5: Estimates of Other Costs, Scale, Capital Stock Measures

Estimates	Unit	Short-Run	Long-Run
Marginal Cost	*¢/kwh*	0.386 (0.374)	0.493 (0.390)
Average Cost	*¢/kwh*		2.199 (0.220)
Technological Change	*%*	–0.100 (0.011)	–0.003 (0.002)
Scale Economies	*%*	0.895 (0.095)	0.776 (0.156)
Shadow Value	*%*	0.042 (0.024)	
Optimal to Actual Capital Stock	*%*	0.604 (0.024)	

Notes: Standard errors are in parentheses. Measures are evaluated at sample means.

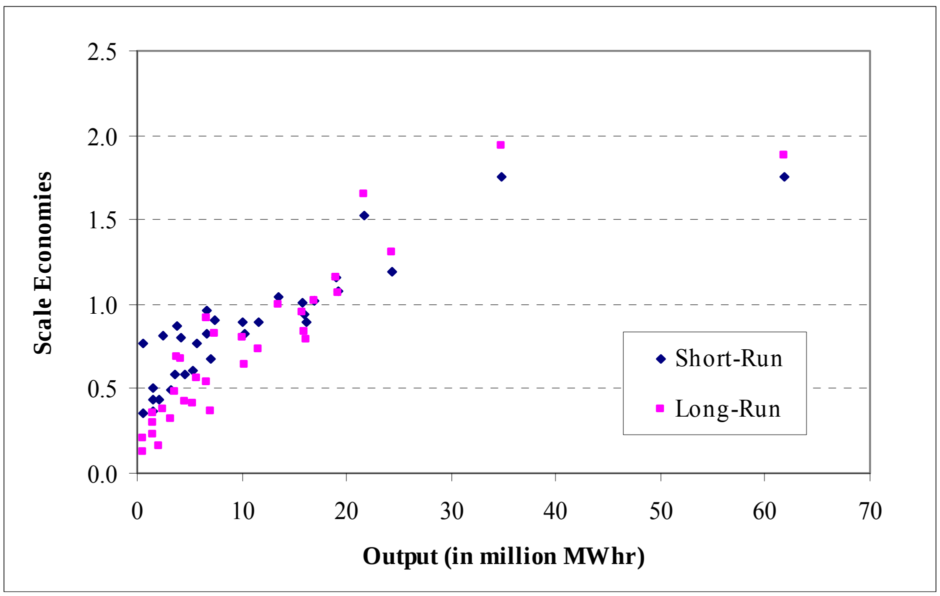

Figure 1: Short- and Long-Run Scale Economies