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STEAM-ELECTRIC SCALE ECONOMIES AND CONSTRUCTION LEAD TIMES

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ABSTRACT

There was a widespread belief in the 1970s that the construction of coal and nuclear generating units exhibited positive economies of scale. Recent empirical literature has confirmed this belief for coal plants. But these studies have not considered the relationships among cost, plant size, and the building period. This paper derives and estimates a model in which construction cost and lead time are jointly determined. Constant returns to scale are not rejected for nuclear units. While coal units may exhibit positive returns to scale, because larger plants take longer to build, these returns are lower than previously estimated.

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Geoffrey S. Rothwell**

Power plant construction costs and lead times rose quickly from 1968 to the mid-1980s, leading to plant cancellations and a financial crisis in the electric utility industry. During most of this period, there was a widely held belief that scale economies existed for both coal and nuclear generating units. The recent study of coal units by Joskow and Rose (1985a) identified a puzzle: If scale economies existed in the power plant construction, why did we see smaller plants being built after the mid-1970s? Joskow (1986) and Joskow and Schmalensee (1985) suggest that while there may have been scale economies in the construction of power plants, the decreased reliability of larger units reduced their attractiveness to utilities. But another explanation may be valid: larger plants required longer building periods, increasing financing costs and decreasing scale economies in construction.

I address this issue by developing a model where lead time and construction cost are jointly determined. I show that the optimal lead time depends on the discount rate and the elasticity of cost with respect to lead time. A translog cost function is proposed with three input prices: the wage of construction labor, the price of building materials, and the rental rate on construction equipment. From this function I am able to derive an expression for optimal lead time. The econometric form is similar to the estimation of a cost function with a non-linear factor demand equation. I estimate the system with data on the construction of coal and nuclear power plants. I find that the production function for generating capacity is homothetic in output and exhibits unitary elasticities of substitution among inputs, but that the building of coal plants is not homogeneous in output and neither technology is separable in lead time. Constant returns to scale are not rejected for nuclear units. While coal units may exhibit positive returns to scale, these returns are lower than previously estimated.

The first section reviews studies of coal and nuclear plant costs since 1974. Section 2 develops a model of construction cost and lead time based on the objective functions of two firms: the electric utility and the architect-engineer-constructor. I present the econometric form in Section 3. The last two sections discuss empirical results.

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1. A REVIEW OF CONSTRUCTION COST AND LEAD TIME STUDIES

Analyses of scale economies in steam-electric generation have given mixed results. Huettner (1974), examining 391 plants completed between 1923 and 1968, found economies of scale below 100 megawatts (Mw) of generating capacity at the plant level after 1940.[1] These conclusions were similar to the 12 earlier econometric and engineering studies he reviewed. However, later studies found positive economies of scale. Table 1 presents selected characteristics and parameter estimates from a dozen analyses of steam-electric construction costs and lead times published between 1974 and 1985. (Definitions of terms follow immediately after Table 1.) The form of the regression equation is identified in the second column. Columns 3-5 discuss each study's data: (col. 3) the adjustments to cost and the definition of lead time; (col. 4) the measurement of size and its range; and (col. 5) the fuel type, number of observations, and dates of unit completion. The last column lists (1) the estimated coefficient on size (or lead time in parentheses) in the cost equation, (2) the t-statistic in brackets, and (3) the page where the estimate can be found, after the colon. Interpretation of the coefficient on size depends on the functional form. Most authors use cost per kilowatt of capacity as the dependent variable. So, negative parameters imply positive scale economies: average cost decreases as size increases.

While all studies include size in the cost equation, only those in the Cobb-Douglas form lend themselves to an easy *ex post* calculation of the elasticity of cost with respect to size. Estimated scale economies for coal units are similar in Joskow and Rose (1985a) and Perl (1979). One would reject the hypothesis of constant returns to scale in both studies. Economies of scale for nuclear units are not well estimated. This is because of the small number of observations and the lack of variation in size. In two of the studies, Zimmerman (1982) and Paik and Schriver (1981), one cannot reject constant returns at a 95% confidence level. But Perl (1979) finds strong economies of scale. Although one would accept the hypothesis that estimates in all three papers are equal, it is difficult to explain Perl's finding.

But none of these studies explicitly examined the joint relationships among cost, size, and building lead time. Joskow and Rose (1985a, pp. 9-10) acknowledge that standard procedures for deflating cost will assign a higher real cost to plants that take longer to build. So construction times should be included in the study of power plant construction costs. The imposition of lead time separability (i.e., no interaction terms involving lead time), or the lack of a lead time variable, may have biased estimates of scale economies. I will propose a model in Section 3 to explore the influence of these restrictions. However, before doing so, I develop a simultaneous equations system where cost and lead time are jointly determined.

2. A MODEL OF CONSTRUCTION COST AND LEAD TIME

Although some electric utilities build their own power plants, the production of electric generating capacity usually involves two firms: the utility and the architect-engineer-constructor.

1. Huettner's 1974 study examined scale economies at the *plant* level. All analyses in Table 1 since Stewart (1979) have studied generating *units*. There are one or more units at a plant site. Although imprecise, I use the term "plant" generically to refer to generating "units."

The utility forecasts a time-path of exogenous demand and determines the optimal construction period as a function of demand, regulation, its discount rate, and the relationship of plant cost and construction time.[2] It then requests competitive bids from constructors to build a plant of a specific size to be completed by a given date.

I assume that, given a market-determined plant size, the objective functions are the following: (1) The electric utility attempts to maximize the net present value of a power plant by choosing an optimal lead time. (2) The constructor attempts to minimize the cost of the plant subject to exogenous plant size and lead time. In other words,

$$\max_{LT, X_i} \Pi(C(LT, Q(X_i), p_i, \tau), r, s, LT, T) \quad \text{s.t.: } Q = Q^* \ . \tag{1}$$

This can be shown to be equivalent to

$$\max_{LT} \Pi(C(LT, Q(X_i), p_i, \tau), r, s, LT, T) \quad \text{s.t.: } Q = Q^* \text{ and} \tag{2.1}$$

$$\min_{X_i} C(LT, Q(X_i), p_i, \tau) \quad \text{s.t.: } Q = Q^* \text{ and } LT = LT^* \ , \tag{2.2}$$

where Π is the net present value, C is the nominal cost of the plant exclusive of financing charges,[3] Q is the size of the plant in megawatts of generating capacity, LT is the lead time, the X_i are construction inputs (e.g., labor, materials, and equipment), the p_i are exogenous nominal prices of the inputs, τ (the date of plant completion) is a measure of regulatory and technical change,[4] r is the discount rate, s is the allowed rate of return, T is the lifetime of the plant, Q^* is the market demand for electricity generating capacity, and LT^* is the optimal lead time from equation (2.1).[5]

2. I do not consider the role of demand. Throughout the paper I assume that the size of the power plant is determined before optimal lead time or minimum cost.

3. To calculate real cost would mean deflating reported plant costs by the same indices I use as prices in estimating the cost function. See Section 3, below. Studies since Mooz (1979) have deflated costs by the Handy-Whitman index. However, this index assumes fixed ratios among inputs across all plants. It would be inappropriate to both deflate costs by the Handy-Whitman index and include components of this index as explanatory variables.

4. To obtain operating permits, power plants face stringent regulation before completion. Once the plant is finished, the imposition of new standards by regulators is more difficult. To measure regulatory changes over time, one option would be the introduction of a dummy variable for each year of plant completion, as in Joskow and Rose (1985a). However, I found that the rate of cost increase was nearly uniform over the sample period. To increase the degrees of freedom, I use the date of commercial operation for τ.

5. While it may be more realistic to consider the determination of an optimal lead time as a dynamic process occurring

While the present value of the plant is a function of the discount rate, it does not directly enter the cost function. Unless the utility negotiates a turnkey contract with the builder, the utility is responsible for project financing during the period of construction.[6] Although the constructor does not optimize with respect to r, it does optimize with respect to the rental price of construction equipment, a form of capital.[7]

The cost of capital to the utility is the opportunity cost of investing in construction inputs. The financing charge is a function of the discount rate, the length of the lead time, and the distribution of expenditures during the construction period. Under regulation, firms can recover financing costs in one of two ways. The first method is the Allowance for Funds Used During Construction (AFUDC), where the firm accumulates financing charges at a rate (the AFUDC rate) equal to a weighted average of the cost of debt and equity. (See Appendix B.) These charges are added to the rate base when the plant is completed. Table 1 shows that all authors, since Perl (1979), have subtracted AFUDC from the cost of the plant. The second method is Construction Work In Progress (CWIP). With CWIP, regulators add construction expenditures to the rate base at each rate hearing. Given that most utilities operated under AFUDC regulation at the time they ordered plants completed in the 1970s, I will not consider CWIP further.[8] (For a more complete discussion of AFUDC and CWIP, see Rothwell, 1985.)

To determine the optimal lead time (LT^*), I propose a functional form for the present value of a power plant and solve the first-order conditions. The present value is the sum of cash flows to the firm over the plant's life, discounted to time 0. I break cash flows into two periods: construction from $-LT$ to 0 and operation from 0 to T. If there is only one addition to the rate base at $t = 0$, then

$$\Pi = -\int_{-LT}^{0} CX_t \cdot e^{-rt}\, dt \;+\; \int_{0}^{T} CF_t \cdot e^{-rt}\, dt \;, \tag{3}$$

where CX_t are construction expenditures on the power plant, CF_t are the net cash flows during operation, and r is the expected discount rate.

Net cash flows from 0 to T are equal to revenues, RV_t, minus expenses, EX_t: $CF_t = RV_t - EX_t$. Under rate-of-return regulation, revenues equal the allowed rate of return on the rate base ($s \cdot RB_t$) plus depreciation (DB_t) plus expenses, where I assume that the utility uses a single value for the allowed rate of return over the plant's life. Substituting for RV_t, $CF_t = s \cdot RB_t + DB_t$. (This calculation assumes that rates are automatically adjusted for changes in EX_t.)

during the construction of the plant (e.g., the firm might reconsider the optimal lead time after the outcome of a stochastic process as in Cohen and Noll, 1983), it is doubtful that the solution to this dynamic problem would give an easily estimated econometric form.

6. Turnkey contracts were offered in the 1960s on some nuclear plants. Under them, a fixed price for a completed unit was negotiated. These plants are eliminated in the present study. On the development of the nuclear power industry under turnkey contracts, see Burness, Montgomery, and Quirk (1980).

7. Restricting the discount rate to the problem of maximizing present value allows identification of the lead time equation in Section 3. The correlation between cost and the discount rate is 3% in the coal sample and -12% in the nuclear sample.

8. Variables indicating states with full and partial CWIP regulation were not significant in any of the models considered in Sections 3 and 4.

In the first year of operation, the rate base is equal to the plant's cost, $C(LT)$, a function of lead time. One would expect that $(\partial C / \partial LT) < 0$: attempts to decrease the construction period will increase cost, e.g., speeding up construction requires more overtime, increasing the wage bill. This follows the analysis of Cohen and Noll (1983).

In each succeeding year, the rate base decreases with depreciation. I model depreciation with the straight-line method at a depreciation rate of d, equal to (1/T). Annual depreciation is uniform over the plant's life and is equal to $C(LT)/T$. So, $CF_t = [C(LT)/T] \cdot [s \cdot (T - t) + 1]$. Also, let $n(t)$ be the instantaneous rate of construction expenditure: $CX_t = C(LT) \cdot n(t)$. With these simplifications,

$$\Pi = -C(LT) \cdot \int_{-LT}^{0} n(t) \cdot e^{-rt}\, dt + [C(LT)/T] \cdot \int_{0}^{T} [s \cdot (T - t) + 1] \cdot e^{-rt}\, dt \,. \tag{4}$$

This must be modified slightly because of AFUDC regulation. The addition to the rate base at $t = 0$ is equal to $C \cdot (1{+}A)$, where

$$A = \int_{-LT}^{0} \int_{-LT}^{t} a \cdot n(x)\, dx\, dt \tag{5}$$

and a is the AFUDC rate. The expression for A implies that AFUDC is not compounded, following regulatory practices through most of the 1970s.[9] I simplify these expressions by assuming a uniform rate of spending: $n(t) = 1/LT$.[10] Under these assumptions, one can show that $A = (a \cdot LT/2)$. I assume that the AFUDC rate is equal to the discount rate and substitute $C(LT) \cdot [1 + (r \cdot LT/2)]$ for C(LT) in the last term of equation (4):[11]

$$\Pi = -[C(LT)/LT] \cdot \int_{-LT}^{0} e^{-rt}\, dt + [C(LT)/T] \cdot [1 + (r \cdot LT/2)] \cdot \int_{0}^{T} [s \cdot (T - t) + 1] \cdot e^{-rt}\, dt \,. \tag{6}$$

To find the optimal lead time, I differentiate equation (6) with respect to LT. In Appendix A, I show (assuming the allowed rate of return is equal to the discount rate) that the optimal lead time, LT^*, is equal to $2/r(\eta + 1)$, where η is the elasticity of cost with respect to lead time:

9. Although the Federal Power Commission changed its policy in its Order No. 561 (issued February 2, 1977) by allowing semi-annual compounding, during most of the 1970s, compounding was not allowed by federal regulators. Few state regulators allowed compounding before 1975. In the Pomerantz and Suelflow's survey of utilities (1975, p. 73), only four firms (out of 130) reported that they had compounded AFUDC.

10. While I assume a uniform expenditure rate to derive the optimal lead time, in calculating total AFUDC, I use construction expenditure rates that approximate industry spending patterns following Mooz (1979), based on U.S. AEC (1974). See discussion in Joskow and Rose (1985a, p. 25).

11. While the AFUDC rate might not have equaled the discount rate after 1977, during the 1960s and early 1970s, these two rates were similar. See Rothwell and Eastman (1986) on the difference between them from 1973 to 1982.

$(\partial \ln C/\partial \ln LT) = \eta$. This expression implies that η must be greater than -1 (for a positive lead time) and the optimal construction period (1) decreases with increases in the discount rate: $(\partial LT^*/\partial r) = -2/r^2 \cdot (1+\eta) < 0$, i.e., as the discount rate increases, so does the AFUDC penalty, and (2) decreases with increases in the elasticity of cost with respect to lead time: $(\partial LT^*/\partial \eta) = -2/r \cdot (1+\eta)^2 < 0$, i.e., as η increases, cost savings decrease from allowing the lead time to lengthen. Notice that $\ln LT = -\ln(r/2) - \ln(1+\eta)$. The first term on the right hand side arises from AFUDC regulation. The second term captures the relationship between lead time and the real cost of the plant. In the next section, I propose an expression for cost that readily yields an equation for η and lead time.

3. ECONOMETRIC SPECIFICATION

To derive econometric forms for power plant lead times and costs, I assume that the production function for generation capacity relates the factors of production (X_i) to a single output, Q, the size of the plant in megawatts: $Q = Q(X_i)$. The set of inputs that command the greatest attention of the engineering industry (see the *Engineering News Record*) are labor (L), materials (M), and equipment (K); where w, m, and k are the prices of each of these. Let $p_i = (w, m, k)$. The constructor minimizes the sum of the input costs: $\min(w \cdot L + m \cdot M + k \cdot K)$ subject to technical and contractual constraints, i.e., $Q = Q^*(L, M, K)$ and $LT = LT^*$.

The reduced form solution to the constructor's optimization problem is the cost function: $C(LT^*, Q^*, p_i, \tau)$. This function can be represented by a number of forms related to the underlying technology. I use the translog form, proposed in Christensen, Jorgenson, and Lau (1973). The cost function is

$$\begin{aligned}
\ln C(LT^*, Q^*, p_i, \tau) = {} & \alpha_1 \ln LT^* + (1/2)\, \alpha_{10} (\ln LT^*)^2 + \alpha_{11} (\ln LT^*)(\ln Q^*) \\
& + \sum_{i=2}^{4} \alpha_{1i} (\ln LT^*)(\ln p_i) + \alpha_{15} (\ln LT^*)(\ln \tau) \\
& + \beta_0 + \beta_1 \ln Q^* + \sum_{i=2}^{4} \beta_i \ln p_i + (1/2)\, \beta_{11} (\ln Q^*)^2 \\
& + \sum_{i=2}^{4} \beta_{1i} (\ln Q^*)(\ln p_i) + (1/2) \sum_{i=2}^{4} \sum_{j=2}^{4} \beta_{ij} (\ln p_i)(\ln p_j) \\
& + \gamma_1 \ln \tau + (1/2)\, \gamma_{10} (\ln \tau)^2 + \gamma_{11} (\ln \tau)(\ln Q^*) + \sum_{i=2}^{4} \gamma_{1i} (\ln \tau)(\ln p_i) \ .
\end{aligned} \tag{7}$$

To insure that the cost function is homogeneous in prices, I impose the following conditions:

$$\sum_{i=2}^{4} \beta_i = 1\,, \ \sum_{i=2}^{4} \beta_{1i} = 0\,, \ \sum_{i=2}^{4} \alpha_{1i} = 0\,, \ \sum_{i=2}^{4} \gamma_{1i} = 0\,, \tag{8}$$

$$\text{and } \sum_{i=2}^{4} \beta_{ij} = 0 \text{ for } j = 2, 3, 4 \ .$$

Following many of the studies listed in Table 1, I add two control variables to equation (7). One, δ_1, indicates the first unit at a plant site. Generally, the cost of the first unit includes land and the cooling-water and electricity transmission systems. Given that these costs can be included in the rate base with the completion of the first unit, the firm has an incentive to add all plant-site costs to the cost of the first unit. If this influence is not controlled, changes in cost over time will not be properly estimated. The second variable, δ_2, distinguishes between power-production technologies. It indicates either coal plants with flue-gas desulfurization equipment, "scrubbers," or nuclear plants with boiling water reactor (BWR) technology. See Joskow and Rose (1985b) for a discussion of the cost effects of increased scrubbing efficiency.

Although factor-share information is not available on labor, materials, and equipment, with equation (7) one can calculate the elasticity of cost with respect to lead time.[12] This elasticity is $\eta = (\partial \ln C / \partial \ln LT^*)$:

$$\eta = \alpha_1 + \alpha_{10} \ln LT^* + \alpha_{11} \ln Q^* + \sum_{i=2}^{4} \alpha_{1i} \ln p_i + \alpha_{15} \ln \tau \,. \tag{9}$$

Substituting for η in the expression for optimal lead time, i.e., $2/r\,(\eta + 1)$, taking the logarithm of both sides, and approximating $\ln(1+\eta)$ with η (assuming $-1 < \eta < 1$):

$$\ln LT^* = \ln(\frac{2}{r}) - (\alpha_1 + \alpha_{10} \ln LT^* + \alpha_{11} \ln Q^* + \sum_{i=2}^{4} \alpha_{1i} \ln p_i + \alpha_{15} \ln \tau) \,. \tag{10}$$

To test the comparative statics result that $(\partial LT / \partial r) < 0$, I introduce α_0, a parameter on ln (2/r). Solving for $\ln LT^*$ yields

$$\ln LT^* = (\frac{1}{1+\alpha_{10}})(\alpha_0 \ln(\frac{2}{r}) - \alpha_1 - \alpha_{11} \ln Q^* - \sum_{i=2}^{4} \alpha_{1i} \ln p_i - \alpha_{15} \ln \tau) \,. \tag{11}$$

Here, $(\partial \ln LT / \partial \ln r) = -\alpha_0/(1 + \alpha_{10})$ should be less than zero according to the comparative statics results, e.g., if $\alpha_{10} > -1$, then $\alpha_0 > 0$. And $(\partial \eta / \partial LT^*)$ equal to α_{10} should be negative. Also, as size increases, one would expect that lead time would increase: $(\partial \ln LT / \partial \ln Q) = \zeta = -\alpha_{11}/(1 + \alpha_{10}) > 0$, e.g., if $\alpha_{10} > -1$, then $\alpha_{11} < 0$.

In estimating equations (7) and (11), one will measure LT^* with error v.[13] Let $\ln LT^* = \ln \hat{LT} + v$. Equation (7) becomes $\ln C(Q^*, p_i, LT^*, \tau) = \ln C(Q^*, p_i, \hat{LT}, \tau) + u$, where

$$u = v \cdot (\alpha_1 + \alpha_{10} \ln \hat{LT} + 0.5 \cdot \alpha_{10} \cdot v + \alpha_{11} \ln Q^* + \sum_{i=2}^{4} \alpha_{1i} \ln p_i + \alpha_{15} \ln \tau) \,. \tag{12}$$

The application of ordinary or generalized least squares to the cost equation leads to biased estimates, because the expectation of $(u \quad \ln \hat{LT})$ is not equal to zero. To avoid these problems, I use non-linear, instrumental-variable techniques to estimate cost and lead time simultaneously. Although the choice of instruments in non-linear estimation is not straight forward, I rely on the

12. Cost share information is available for structures, equipment, and land, but these do not correspond to the construction inputs.

13. Following Mooz (1979), I have measured the start of construction from the date of boiler or nuclear steam supply system (NSSS) order to the date of commercial operation. Although other start dates are available (see Table 1), they are all highly correlated with one another. For example, the mean NSSS order date is approximately three months before the the construction permit application date. The correlation between these two dates in my sample is 94%. The difference between the two dates is unrelated to any of the independent variables, e.g., the correlation between this difference and plant size is 6%.

standard practices employed in two and three stage least squares estimation (2SLS and 3SLS): I use all exogenous variables as instruments.[14] Further, while the method employed in Sections 2 and 3 has yielded a simple econometric form for lead time, equation (11) may be misspecified. This misspecification could arise from (1) the difference between *ex ante* and *ex post* lead times, (2) the non-uniformity of construction expenditures over time, or (3) the equating of the allowed rate of return and the discount rate with the AFUDC rate. Thus, 3SLS may be inconsistent when applied to joint estimation of equations (7) and (11). Tests for misspecification will be presented in the next section. The data for the estimation are discussed in Appendix B. Descriptive statistics are presented in Table 2. There are two samples: (1) coal plants larger than 100 megawatts completed between 1970 and 1980, and (2) non-turnkey nuclear plants finished between 1968 and 1980. (The only high-temperature gas-cooled reactor, the Fort St. Varian plant in Colorado, was deleted from the sample.)

To determine the structure of the cost function, and by duality, the characteristics of the production function, I follow Christensen and Greene (1976) and Evans and Heckman (1983). Let Model A refer to the system of equations (7) and (11) with the constraints in equations (8). A homothetic production function requires the separation of output and factor prices in the cost equation, i.e., β_{12}, β_{13}, $\beta_{14} = 0$ (Model B). Given homotheticity, if the elasticity of cost with respect to generating capacity is constant with respect to changes in size, the production structure is homogeneous in capacity: α_{11}, $\beta_{11} = 0$ (Model C1). Similarly, separability in lead time requires the elasticity of cost with respect to lead time to be constant: $\alpha_{1i} = 0$, $i = 0, \ldots, 5$ (Model C2, which is also homothetic in output).[15] Model C is homogeneous in output and separable in lead time. Unitary elasticities of substitution among factors imply that coefficients on the price interaction terms, $(\ln p_i)$ $(\ln p_j)$, are zero. Models D, E, F1, F2, and F correspond to Models A, B, C1, C2, and C with unitary elasticities. The primary difference between Model F and the Cobb-Douglas form in studies discussed in Table 1 is that in Model F lead time is treated as an endogenous variable.

The hypothesis of constant returns to scale can be tested by extending the definition of scale economies (SCE) in Christensen and Greene (1976):

$$SCE = 1 - \frac{d \ln C}{d \ln Q} = 1 - \left(\frac{\partial \ln C}{\partial \ln Q} + \frac{\partial \ln C}{\partial \ln LT} \cdot \frac{\partial \ln LT}{\partial \ln Q}\right) = 1 - \psi - \eta \cdot \zeta \ , \tag{13}$$

where

14. This raises the question of whether the size of the plant is exogenous. In one series of estimations I deleted Q from the list of instruments. Unfortunately, the parameter on size was not well estimated: the first stage R^2 was low. This lead to large standard errors for the parameters related to size. Given the importance of these parameters in testing the hypothesis of constant returns to scale, I returned size to the list of instruments. While power plant capacity may be endogenous to the electric utility's global profit-maximization strategy, because of the close connection between demand growth and lead time, in this analysis I will assume that size is a predetermined variable. This assumption is made in all studies reviewed in Table 1.

15. With lead time separability, the lead time equation is reduced to $\ln LT = \alpha_0 \cdot (2/r) - \alpha_1$, where α_1 restricted to its estimated value from the cost equation. The lead time equation could not be estimated as such. I choose to include $\alpha_{15} \cdot \ln \tau$ in Models C2, C, F2, and F. Given that a model without $\alpha_{15} \cdot \ln \tau$ is nested within a model that includes it, if lead time separability is rejected with a high degree of confidence when $\alpha_{15} \cdot \ln \tau$ is included, then the model would also be rejected if α_{15} were restricted to zero.

$$\psi = \alpha_{11} \ln LT + \beta_1 + \beta_{11} \ln Q^* + \sum_{i=2}^{4} \beta_{1i} \ln p_i + \gamma_{11} \ln \tau \ ,$$

$$\zeta = -\alpha_{11}/(1 + \alpha_{10}) \ ,$$

and $\ln Q^*$, $\ln p_i$, $\ln LT$, and $\ln \tau$ are evaluated at their means. However, if the cost function is not homogeneous in output (as in Models A, B, C2, D, E, and F2), SCE will change with the size of the plant:

$$\frac{\partial SCE}{\partial \ln Q} = \theta = -(\beta_{11} + 2 \cdot \alpha_{11} \cdot \zeta + \alpha_{10} \cdot \zeta^2) \ . \tag{14}$$

While I have some expectations regarding the signs of the parameters in equation (14), without knowing the magnitudes of α_{10}, α_{11}, $\beta_{11,}$ and ζ, I cannot determine the sign of θ. According to the results of Heuttner (1974), one would expect that scale economies decrease as size increases. This will depend on the structure of the production function. If it is separable in lead time, then $\zeta = 0$ and $\theta = -\beta_{11}$, as in Models C2 and F2. If it is separable in lead time and output, *SCE* is a constant.

To summarize the discussion, I present a list of hypotheses that will be tested in the next section:

Hypothesis 1: Production function is Cobb-Douglas.
Hypotheses concerning parameters:
- Hypothesis 2.1: $\alpha_{10} < 0$,
- Hypothesis 2.2: $\alpha_0 > 0$ if $\alpha_{10} > -1$ or $\alpha_0 < 0$ if $\alpha_{10} < -1$,
- Hypothesis 2.3: $\alpha_{11} < 0$ if $\alpha_{10} > -1$ or $\alpha_{11} > 0$ if $\alpha_{10} < -1$.

Hypotheses concerning elasticities:
- Hypothesis 3.1: $-1 < \eta < 1$,
- Hypothesis 3.2: $\psi > 0$.

Hypothesis 4: SCE > 0 for coal plants, SCE = 0 for nuclear plants.
Hypothesis 5: $\theta < 0$.

The first and fourth hypotheses follow from the recent literature as presented in Table 1. Hypothesis 1 will be examined by comparing Models A, B, C1, C2, C, D, E, F1, F2, and F. To test Hypothesis 4, I impose constant returns to scale in each of these models. Hypotheses 2.1 and 2.2 are the comparative statics results regarding optimal lead time. Hypotheses 2.3 and 3.2 follow from the intuition that both lead time and cost should increase with larger plant size. If $\alpha_{10} > -1$ and $\alpha_{11} < 0$, then ζ, the elasticity of lead time with respect to size, is positive. Hypothesis 3.1 follows from the requirement that lead time be positive and is necessary to approximate $\ln(1 + \eta)$ with η. Hypothesis 5 is suggested by the results of Huettner (1974). If Hypothesis 1 is correct, then $\theta = 0$, and Hypothesis 5 will be rejected. If Hypothesis 1 is incorrect, Hypothesis 4 may be valid only at the mean value of plant size.

4. RESULTS

Before presenting my findings on returns to scale in the construction of steam-electric power plants, I examine the possibility of specification error in the joint estimation of equations (7) and (11) with non-linear, three stage least squares (NL3SLS). Using the test proposed in Hausman (1978), I compare estimates from non-linear, two stage least squares (NL2SLS) and NL3SLS. Also, I test the significance of imposing cross-equation parameter restrictions using a statistic proposed in Gallant and Jorgensen (1979).

The use of 3SLS in a situation where a structural equation is misspecified leads to inconsistent estimates. See Hausman (1978, p. 1264). While 2SLS is not as efficient as 3SLS, the misspecification of one equation will not give inconsistent 2SLS estimates of other equations in a system. One test of specification error relies on a comparison of 2SLS and 3SLS estimates of parameters and the covariance matrix:

$$m = (\Theta_{3SLS} - \Theta_{2SLS})' \; V(\Theta_{3SLS} - \Theta_{2SLS})^{-1} \; (\Theta_{3SLS} - \Theta_{2SLS}) \; ,$$

where Θ is a vector of estimated parameters and V is the difference in the covariance matrices of 2SLS and 3SLS parameter estimates. The statistic is distributed as a χ^2 with degrees of freedom equal to the number of parameters. If neither equation is misspecified, this statistic should be small.[16] Model A was estimated for both coal and nuclear power plant sub-samples. Tables 3A and 3B present OLS estimates for equation (11), 2SLS estimates for equation (7), and NL2SLS and NL3SLS estimates for the system of equations (7) and (11). The m statistic was 28.68 for coal plants with 24 degrees of freedom (cumulative $\chi^2 = 0.77$) and 0.84 for nuclear plants ($\chi^2 = 0.00$). The hypothesis that the NL2SLS and NL3SLS estimates are equivalent cannot be rejected. If one assumes that the cost equation is correctly specified, then this evidence supports the conclusion that the lead time equation is not misspecified.

If the NL3SLS estimator is consistent, one can test the equivalence of a model with and without cross-equation restrictions. With nested linear models the likelihood ratio (LR) test is convenient and is asymptotically equivalent to a number of other test statistics. See Breusch and Pagan (1980). However, the LR test is inappropriate for non-linear models. An analogous test is proposed in Gallant and Jorgenson (1979): a "quasi-likelihood ratio" (QLR) test. (A generalization of this test appears in Ruud, 1986.) Their statistic, T^0, is equal to the difference of the minimum distance criterion (labeled Objective in Table 3) for the general and restricted models (multiplied by the number of observations). It is asymptotically distributed as a χ^2 with degrees of freedom equal to the number of parameter restrictions. The test is more restrictive than the LR test in that the estimate of the error covariance matrix must be held constant across the unrestricted and restricted models. So it is not possible to compare models without reestimation.[18] The imposition of cross-equation

16. While it is possible to discuss the power of the Hausman test in the linear case, it is beyond the scope of this paper to calculate the power of the test when applied to non-linear estimation.

17. The parameter α_{10} appears in the lead time equation as a term multiplying all other variables, i.e., $1/(1 + \alpha_{10})$. It is not identified unless restricted to α_{10} from the cost equation. Thus, it could not be estimated with OLS. Also, it was not possible to test the cross-equation restriction for α_{10}.

18. For example, in Tables 3A and 3B the differences between the minimum distance criterion for models A and E are 4.85 and 4.24. But the covariance matrix has not been constrainted in estimating Model E. Thus, these differences are not the same as those listed in Table 4B.

restrictions in Model A does not significantly alter parameter estimates: $T^0 = 7.63$ for coal plants and $T^0 = 3.41$ for nuclear plants with five degrees of freedom ($\chi^2 = 0.82$ or 0.36, respectively). Encouraged by this examination of model specification, I discuss tests of Hypotheses 1 through 5.

The first issue is whether the Cobb-Douglas form adequately describes the relationship between plant cost, lead time, and construction inputs. Table 1 shows that many of the previous authors have used this functional form and relied on the estimates of scale economies from it. Again, using the QLR test, Table 4A presents the comparison of all models with Model F (homogeneous in output, separable in lead time, and unitary elasticities of substitution). The null hypothesis is that each model is equivalent to Model F. Equivalence is rejected at the 94% confidence level in all models except F2, implying that β_{11}, the parameter associated with $(ln\ Q)^2$, is insignificant in the more restricted models. This may explain why $(\ln Q)^2$ is included in only one of the models in Table 1. So, the Cobb-Douglas production function may not be an appropriate description of power-plant construction.

What are the characteristics of the production function for this technology? This can be answered by comparing each model with Model A (translog). For both coal and nuclear samples, Model A is equivalent to Models B, D, and E, implying homotheticity in size and unitary elasticities of substitution. Also, for nuclear units Model A is equivalent to Models C1 and F1, implying output homogeneity. Thus, the production function is not homogeneous in size for the coal plant sample and is not separable in lead time for either sample. These results on functional form indicate that earlier models of power plant cost might have been misspecified.

What is the nature of the relationship between generating capacity, lead time, and cost? Table 5 presents estimated parameters and calculated elasticities related to Hypotheses 2 through 5. I use t-statistics to test whether $\alpha_{10} < 0$, $\alpha_0 > 0$, and $\alpha_{11} < 0$.[19] In every model $\alpha_{10} = (\partial\eta/\partial \ln LT)$ is greater than zero; it is significantly greater in most models. This contradicts the comparative static result that $(\partial LT/\partial\eta) < 0$ and indicates that there may be other influences, not adequately captured by the model, that dominate optimal behavior, such as changing regulatory requirements.

These influences do not seem to dominate the effect of the discount rate. Given that $\alpha_{10} > -1$, the sign of $(\partial \ln LT/\partial \ln r) = -\alpha_0 / (1 + \alpha_{10})$, should be negative, i.e., α_0 should be positive. This is true in all models. In the coal sample the parameter is stable across models and is significantly different from zero, see Table 3A. Although the estimated value of α_0 is similar in similar models for the nuclear sample, it is not well estimated.

Also, given that $\alpha_{10} > -1$, $\zeta = (\partial \ln LT/\partial \ln Q) = -\alpha_{11} / (1 + \alpha_{10})$ should be positive, because larger plants take longer to build. Thus, α_{11} should be negative. It is negative in all models that are not separable in lead time (separability implies that $\alpha_{11} = 0$). Calculated ζs are given in Table 5. They are approximately 17% for coal plants and about half as much for nuclear plants, i.e., a 10% increase in coal plant size induced a 1.7% increase in lead time. In sum, while lead times did

19. In Table 5 the significance of α_{11} and β_{11}, and by extension $\zeta = -\alpha_{11}/(1 + \alpha_{10})$, was tested by comparing models with and without these two parameters. α_{11} was extremely significant in all the coal models. In the nuclear plant sample it was significant at the 81% level in Models A and B and at the 91% level in Models D and E. β_{11} was significant at the 99% level in the coal sample and insignificant in the nuclear sample. Thus, it is not surprising to accept output homogeneity for the nuclear technology and to reject it for the coal technology.

respond to discount rates and size as expected, there was no empirical support for a decrease in lead time in response to a increase in the elasticity of cost with respect to lead time.

Further, the elasticity of cost with respect to size, ψ, is positive (and significantly different from 1 for coal plants) and the elasticity of cost with respect to lead time, η, is significantly different from zero in three models. Hypotheses 3.1 and 3.2 were tested by constraining $\eta = 0$ and $\psi = 1$. While η should be greater than -1 for positive lead times and less than 1 to allow the approximation of $\ln(1 + \eta)$, the testing of inequality constraints is more difficult than constraining η to zero. As indicated in Table 5, η is positive and significant at the 90% level in Models A (translog), B (homothetic in output), and C1 (homogeneous in output) with cumulative χ^2 equal to 0.94, 0.90, and 0.95, respectively. In many of the nuclear sample estimations η is negative. It is less than -1 (but insignificant) in Models C2 (separable in lead time) and C (homogeneous in output, separable in lead time). So, while there is some support for $\eta > 0$ in the coal sample, the relationship between the total cost of construction inputs and lead times is not well estimated in the nuclear plant sample. This relation might have been weakened by changes in the regulatory environment, i.e., as lead times rose, plants were subject to stricter health and safety codes, increasing the cost of the plant. These same influences may have effected scale economies.

For each model I have calculated the SCE as defined in equation (13). Given the difficulty in calculating the standard errors for SCE in non-linear models, I have imposed constant returns to scale (CRS) in each of the models. Using the quasi-likelihood ratio statistic, I test the equivalence of models without and with the CRS restriction. See Table 4C. First, notice that CRS would be accepted for every model estimated with the nuclear sample at any reasonable confidence level. Second, CRS would be rejected for all the coal sample estimates with the imposition of either homogeneity in output or separability in lead time. But this degree of confidence is much lower for Models A, B, D, and E. While one would reject CRS at the 95% level in each of these more general models, one would not reject it at the 97.5% level. (This is unlike Joskow and Rose, 1985a, where CRS is rejected at the 99% level.) This lower level of significance arises from the specification of these models. In them, as size increases, lead time increases, increasing cost and decreasing scale economies. However, the values for SCE in C1, C2, C, F1, F2, and F for coal plants are similar to those in Joskow and Rose (1985a) and Perl (1979). For nuclear plants, the SCE in Models C1, C2, C, F1, F2, and F are similar to Zimmerman's (1982) first model, and the SCE in Models A, B, D, and E are similar to Zimmerman's second model. But the tests of CRS in Table 4C, as well as in Table 1, are made at the mean value of plant size. Do returns to scale change as generating capacity increases?

The fifth hypothesis concerns the derivative of SCE with respect to plant size. It is a function of α_{10}, α_{11}, and β_{11}. Table 5 shows that all these parameters are significant in the coal sample. But when β_{11} is constrained to $-(2 \cdot \alpha_{11} \cdot \zeta + \alpha_{10} \cdot \zeta^2)$, one would not reject the hypothesis that $\theta = 0$. Calculated values for θ are almost always negative. For example, considering Model A with the coal sample, one can calculate the predicted scale economies for various plant sizes: at 114 Mw (the smallest plant) $S\hat{C}E = 0.29$, at 576 Mw (the median plant) $S\hat{C}E = 0.11$, and at 1300 Mw (the largest plant) $S\hat{C}E = 0.02$. While I reject homogeneity in output and separability in lead time for coal plants and I find that scale economies decrease with size for both coal and nuclear technologies, these declines are not significant for either sample.[20]

20. The difference in scale economies for small and large coal plants is difficult to determine. While $S\hat{C}E$ is closer to zero

Finally, control variables, δ_0 and δ_1, are significant, except where δ_1 represents boiling water reactors. For both technologies, additions to the rate base for the first unit are approximately 25% greater than later units at the same plant site. This results are similar to Joskow and Rose (1985a) and Zimmerman (1982). Also, the value of the parameter representing scrubbers is not significantly different from that in Joskow and Rose (1985a) and (1985b). In the nuclear sample, there appears to be no difference in cost between pressurized and boiling water reactors.

5. SUMMARY

As coal and nuclear power plant size grew in the 1970s, building costs rose with increased lead times. The production function for the construction of power generating facilities during the 1970s exhibited unitary elasticities of substitution among labor, materials, and construction equipment. It was homothetic in size, but it was not separable in lead time. While the derivation of a econometric form for lead time was done under a number of restrictive assumptions, it did not appear to be misspecified. The elasticity of lead time with respect to size was positive for both coal and nuclear units, and significantly so in the construction of coal plants. While the elasticity of cost with respect to lead time was positive in the coal sample, it was an insignificant factor in the building of nuclear reactors. I suspect that as lead times grew, changes in environmental regulation increased the number and complexity of plant sub-systems and changes in health and safety regulation, related to the construction industry, increased the cost of construction inputs.

The increase in lead times for larger plants and the apparent positive correlation between cost and lead time decreased estimates of scale economies for coal plants. The building of nuclear plants, contrary to electric utility expectations during the 1970s, did not result in positive returns to scale. While the issue of scale economies at the level of electricity generation is left to future research, the present paper questions a traditional rationale for protecting the monopoly status of those building electricity generating facilities, i.e, the belief that the construction of power plants exhibits increasing returns to scale.

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for large plants, those above 576 megawatts, than for smaller plants, the reduction in degrees of freedom and in the variation of size across the sample leads to the acceptance of CRS for both large and small plants. The number of observations in the nuclear sample did not permit a similar analysis.

APPENDIX A: DERIVATION OF THE LEAD TIME EQUATION

In this appendix I solve for the optimal lead time. First, I differentiate equation (6),

$$\Pi = -[C(LT)/LT] \cdot \int_{-LT}^{0} e^{-rt}\, dt$$

$$+ [C(LT)/T] \cdot [1 + (r \cdot LT/2)] \cdot \int_{0}^{T} [s \cdot (T - t) + 1] \cdot e^{-rt}\, dt \,, \qquad (6)$$

with respect to lead time. The derivative of the first term is

$$\frac{LT \cdot C' - C}{r \cdot LT^2} + e^{r \cdot LT} \cdot \frac{C \cdot (1 - r \cdot LT) - LT \cdot C'}{r \cdot LT^2} \,, \qquad (A.1)$$

where C' is the derivative of cost with respect to lead time. Similarly, if one assumes that the allowed rate of return is equal to the discount rate, one can show that the derivative of the second term is

$$C' \cdot (1 + r \cdot LT / 2) + r \cdot C / 2 \,. \qquad (A.2)$$

To determine the first-order conditions, the sum of these two expressions is set equal to zero. I multiply each term by $e^{-r \cdot LT} \cdot r \cdot LT^2$ and approximate $e^{-r \cdot LT}$ with $[1 - r \cdot LT + (r^2 \cdot LT^2 / 2)]$. After simplification the expression becomes

$$0 = -2 \cdot C + r \cdot LT \cdot C + r \cdot LT^2 \cdot C' \,. \qquad (A.3)$$

Next, let η be the elasticity of cost with respect to lead time: $\eta = (\partial C / \partial LT) \cdot (LT/C)$, or $(\eta / LT) = (C' / C)$. I substitute this into equation (A.3) and solve for LT^*:

$$LT^* = 2 / r\ (1 + \eta) \,. \qquad (A.4)$$

Second-order condition for present-value maximization was examined numerically with mean values for C and r. C' was set equal to $\eta \cdot C/LT$, where η is from Model A, estimated with data on coal plants, (see Table 5). The derivative of Π with respect to LT is negative for all values of LT, indicating that (A.4) represents a present-value maximum.

APPENDIX B: DATA

PLANT CHARACTERISTICS

Unit names and numbers, firms, and states are from the U.S. Department of Energy (DOE), *Generating Unit Reference File, 1900-1980* (GURF). This information was verified with the DOE, *Inventory of Power Plants in the United States, 1981 Annual.* Size, cost, and commercial operation date are from DOE, *Thermal Electric Plant Construction Cost and Annual Production Expenses,* 1979 and 1980, *Steam-Electric Plant Construction Cost and Annual Production Expenses,* 1975 through 1978, and Federal Power Commission, *Steam-Electric Plant Construction Cost and Annual Production Expenses,* 1964 through 1974. Unit cost was calculated by comparing the cumulative plant cost of the year when the unit was first reported with the previous year's cost. These costs include AFUDC. AFUDC was subtracted from total cost following the method described by Komanoff (1981, p. 316), based on Mooz (1979) and U.S. AEC (1974). The AFUDC rate is described below.

Construction start dates were collected from the GURF file as the "Date Ordered." Where this was not available, order date information is from either Komanoff (1981) or Mooz (1979). The construction permit issuance date was provided by Lewis Perl.

The dummy for a flue-gas desulfurization (FGD) system, or "scrubber," is equal to 1 if there was a FGD system in operation within the same calendar year as the unit's commercial on-line date. Data was taken from DOE, "FGD Capacity in Operation," *Cost and Quality of Fuels for Electric Utility Plants, 1980* and *1981.*

FACTOR PRICES

Construction wage rates are average union hourly wage rates in cents for all building trades by region as published in Bureau of Labor Statistics (BLS), *Union Wages and Hours: Building Trades,* July 1, 1960 through July 1, 1980, bulletin numbers 1290, 1355, 1397, 1432, 1487, 1547, 1590, 1621, 1668, 1709, 1747, 1807, 1841, 1907, 1972, 2012, 2038, and 2091.

The price of construction materials is the "Materials Cost Component Index" for 20 U.S. cities, published annually in *Engineering News Record* (*ENR*). The regional index is an average of city indices for those cities located in the regions defined for the construction wage data described above. Annual data from 1960 to 1971 were published in *ENR* (March 20, 1975). Quarterly data from 1972 to 1980 were published in *ENR* (March 18, 1982).

Equipment rental prices are the "Construction Machinery and Equipment" component of the BLS, Wholesale Price Index or Producer Price Index. Data for 1960 through 1974 was collected from *Wholesale Prices and Price Indexes.* Data for 1975 to 1980 was taken from DIALOG, *BLS Producer Price Index Database,* file 176.

AFUDC RATE

The AFUDC rate is a function of the cost of debt, the rate of return on common equity, and the equity-to-total-capitalization ratio:

$$a_i = i_i \cdot (1 - EC_i) + \frac{(z_{i,t-2} + z_{i,t-1} + z_{i,t})}{3} \, cdo \ t \ EC_i \ ,$$

where i is the rate on debt, EC is the equity-to-total-capitalization ratio, and z is the realized rate on common equity in period t. Bond ratings for each firm for 1960-75 are from "Securities Offered," *Moody's Public Utility Manual, 1955-75*. Ratings for 1976-80 are from *Moody's Corporate Credit Report* (November 9, 1983). These ratings were compared to "Moody's Bond Yields by Rating Groups," *Moody's Public Utility Manual, 1983,* to determine the rate on debt. The rate of return on common equity, z, for 1976-80 are from DOE, "Selected Financial Ratios," *Statistics of Privately Owned Utilities;* for 1971-75 from Federal Power Commission (FPC), "Rates of Return on Common Stock Equity," *Statistics of Privately Owned Utilities;* and for 1963-70 from FPC, *Performance Profiles: Private Electric Utilities in the United States* (April 1973). Equity-to-capitalization ratios for 1971-80 are from DOE, "Capitalization Ratio of Common Equity," *Statistics of Privately Owned Utilities;* for 1966-70 from FPC, "Capitalization Ratios," *Statistics of Privately Owned Electric Utilities, 1970;* and for 1965 from FPC, "Rate of Return on Common Stock Equity," *Statistics of Privately Owned Electric Utilities, 1966.*

TABLE 1: ESTIMATES OF SCALE ECONOMIES, 1974-1985

Citation	Estimated Form	Cost (Lead) Data	Size Data Range	Fuel: Obs. Dates	Scale (Lead Time) Coefficients [t-statistics]
Joskow & Rose (1985a)	Cobb-Douglas with Cost/Kw	$1980:w -AFUDC:v	Name 100-1300	Coal: 411 1960-80	-0.18 [5.72]:16
Zimmerman (1982)	Cobb-Douglas with Cost/Kw and ETIME	$1979:g -AFUDC:v (NR)	NR	Nuclear: 41 1968-78	-0.17 [1.33]:303 -0.26 [1.66]:306 (+1.01 [4.38]:303) (+0.97 [3.22]:306)
Komanoff (1981)	Cost/Kw on log(Mw)	$1979:w -AFUDC:v	Name 114-1300	Coal: 116 1972-77	Insignificant NR:220
	LT on log(Mw)	(On-line -Order)	"	Coal: 92 1972-77	+0.18 [5.53]:224
	Cost/Kw on log(Mw)	$1979:w -AFUDC:v	Design 457-1130	Nuclear: 46 1972-78	-0.27 [3.16]:207 -0.20 [2.54]:199
	LT on log(Mw)	(On-line -Permit)	"	Nuclear: 49 1972-78	+0.36 [3.48]:209
Paik & Schriver (1981)	Cobb-Douglas	$1975:w	Depend	Nuclear: 65 1971-79 p: 1980-81	+0.78 [5.21]:233 +0.92 [6.05]:233
Perl (1979)	Cobb-Douglas with Cost/Kw	$1977:w -AFUDC:NR	Name	Coal: 235 1965-78	-0.15 [4.99]:T12
	Cobb-Douglas with Cost/Kw and LT	" (On-line -Permit)	Design 450-1130	Nuclear: 50 1967-78	-0.44 [2.92]:T13 (-0.01 [2.37]:T13)
Mooz (1979)	log(Cost) on Mw	$1978:w +AFUDC	NetMw 457-1148	Nuclear: 54 12/1971-78 p: 1979-80	+1.04 [5.71]:31 +1.06 [5.91]:32
	LT on Mw	(On-line -Permit)	"	Nuclear: 62 12/1971-78 p: 7 units	+0.04 [4.17]:15
	LT/Kw on Mw	"	"	"	-6e-5 [5.63]:18

TABLE 1: ESTIMATES OF SCALE ECONOMIES, 1974-1985, CONT.

Citation	Estimated Form	Cost (Lead) Data	Size Data Range	Fuel: Obs. Dates	Scale (Lead Time) Coefficients
Stewart (1979)	Cost/Kw on log(Kw) and log(Kw)**2	Nominal	Name 20-800	Fossil: 19 Turbine: 39 1970-71	Elasticity calculated -0.18:559
Wills (1978)	Hedonic OLS with Cost/Kw	Nominal	Plant Name 5-1.9G	Fossil: 121 1947-70	Elasticity calculated +0.93:506
Joskow & Mishkin (1977)	Cobb-Douglas with Cost/Kw	$NR:NR	NR 200+	Fossil: 63 1952-65	-0.08 [1.79]:726
Bupp et al. (1974)	Cost/Kw on Mw	$1973:w +AFUDC	NR 457+	Nuclear: 36 1971-72 p: 1973-75	-0.27 [3.80]:I-6
	Cost/Kw on Mw	"	NR	Coal: 47 1969-72 p: 1973-75	Insignificant NR:I-10
Huettner (1974)	Cost/Kw on Mw	Nominal	Plant NetMw 5-1.9G	Fossil: 391 1923-68	Finds economies of scale after 1940 for plants below 100 Mw

TABLE 1: DEFINITIONS

AFUDC	Allowance for Funds Used During Construction
Depend	Net dependable electric generating capacity
Design	Designed electrical rating as reported to the NRC
ETIME	Log of difference between originally anticipated announcement and operation, Zimmerman (1982), p. 300
g	GNP implicit price deflator
G	Gigawatts: 1,000 megawatts, 1,000,000 kilowatts
Kw	Kilowatts of electric generating capacity
LT	Lead time of Construction
Mw	Megawatts of electric generating capacity
Name	Name plate rating of the generator
NetMw	Name plate rating minus in-house service
NR	Not Reported
On-line	Date of commercial operation
Order	Date of boiler or NSSS order
p	Indicates projected data
Permit	Date of construction permit issue
v	Average AFUDC rate from "Statistics of Privately Owned..."
w	Handy Whitman index

TABLE 2: COAL AND NUCLEAR COST, LEAD TIME, AND PRICE DATA

VARIABLE	N	MEAN	STD DEV	SUM	MINIMUM	MAXIMUM
COAL						
LNCT	193	11.48070	0.6137292	2215.775	9.652242	12.82195
LNLT	193	1.51821	0.1774039	293.014	0.980829	1.98100
LNSZ	193	6.28521	0.4687192	1213.045	4.736198	7.17012
LNAR	193	3.34045	0.1008444	644.707	3.086629	3.65236
LNWG	193	6.51475	0.2273370	1257.346	6.030685	6.92658
LNMT	193	7.44288	0.2336875	1436.477	7.015712	7.96311
LNEQ	193	7.61204	0.2119941	1469.123	7.343426	8.10742
LNTAU	193	4.31175	0.0389103	832.168	4.248495	4.38098
NUCLEAR						
LNCT	58	12.14748	0.6202145	704.5538	11.03609	13.39720
LNLT	58	2.00573	0.2211892	116.3321	1.56854	2.46830
LNSZ	58	6.70280	0.2618706	388.7625	6.10925	7.10332
LNAR	58	3.39146	0.0703912	196.7049	3.29621	3.54693
LNWG	58	1.87121	0.1479021	108.5302	1.56444	2.15756
LNMT	58	2.76116	0.1662762	160.1473	2.38876	3.14113
LNEQ	58	2.91554	0.1119481	169.1013	2.67346	3.28952
LNTAU	58	5.15324	0.1878520	298.8880	4.57434	5.52772

Definitions (all variables expressed in logarithms):

LNCT	Nominal plant cost excluding AFUDC
LNLT	Difference between boiler (or NSSS) order date and commercial operation date
LNSZ	Name plate rating in megawatts
LNAR	(2/r), where r is the AFUDC rate
LNWG*	Union construction wages
LNMT*	Price index of construction materials
LNEQ*	Price index of construction equipment rental rates
LNTAU	Commercial operation date

*Weighted sum of prices during construction, weighted by percent of expenditure during period.

NOTE: Because of extreme collinearity among the independent variables in the nuclear sample, lead time is expressed in months and prices are divided by 100 before taking logarithms.

TABLE 3A: PARAMETER ESTIMATES FOR COAL PLANTS

Endogenous Variables:
Log of Construction Cost and
Log of Construction Lead Time
(Standard Errors in Parentheses)

MODEL ESTIMATOR	OLS	A 2SLS	A NL2SLS	A NL3SLS	E NL3SLS
COST R^2		0.827	0.822	0.840	0.805
LEAD R^2	0.481		0.451	0.477	0.471
OBJECTIVE				146.830	151.680
α_0	0.028 (0.094)		0.480 (0.076)**	0.574 (0.069)**	0.522 (0.075)**
α_1	8.334 (1.206)**	30.180 (50.650)	78.950 (30.030)**	84.690 (34.097)*	109.730 (33.769)**
α_{10}		11.990 (4.852)*	13.570 (4.486)**	10.420 (4.394)*	14.644 (4.040)**
α_{11}	-0.183 (0.020)**	-1.748 (0.985)+	-2.335 (0.759)**	-2.017 (0.794)*	-2.688 (0.736)**
α_{12}	-0.198 (0.080)*	-2.719 (2.524)	-2.773 (1.339)*	-2.243 (1.197)+	-2.929 (1.186)*
α_{13}	0.047 (0.152)	-8.427 (4.000)*	-5.197 (2.475)*	-1.055 (1.705)	-3.392 (1.830)+
α_{15}	-2.045 (0.257)**	-9.698 (12.370)	-20.570 (7.663)**	-20.890 (8.527)*	-27.512 (8.369)**
β_0		406.39 (671.550)	817.510 (529.740)	765.480 (543.490)	1162.170 (520.260)*
β_1		-4.286 (11.750)	-14.710 (7.941)+	-17.040 (8.508)*	-19.029 (8.840)*
β_2		-27.360 (36.550)	-28.850 (30.630)	-25.699 (29.962)	-50.812 (25.500)*
β_3		90.000 (70.869)	125.360 (60.200)*	173.330 (55.880)**	91.460 (45.137)*

+ = Significant at 90% level * = Significant at 95% level ** = Significant at 99% level

TABLE 3A: PARAMETER ESTIMATES FOR COAL PLANTS, CONTINUED

MODEL ESTIMATOR	OLS	A 2SLS	A NL2SLS	A NL3SLS	E NL3SLS
β_{11}		0.405 (0.299)	0.535 (0.216)	0.466 (0.217)*	0.624 (0.214)**
β_{12}		0.154 (0.562)	0.215 (0.429)	0.303 (0.413)	
β_{13}		0.393 (1.158)	-0.075 (0.960)	-0.983 (0.851)	
β_{22}		0.616 (3.495)	0.282 (3.473)	-0.659 (3.430)	
β_{23}		5.619 (4.075)	5.195 (3.979)	5.701 (3.953)	
β_{33}		10.140 (9.451)	13.040 (8.924)	16.550 (8.711)+	
γ_{1}		-200.290 (318.630)	-391.440 (250.200)	-362.580 (256.270)	-562.440 (242.890)*
γ_{10}		50.340 (75.990)	94.550 (59.435)	86.317 (60.730)	136.760 (56.988)*
γ_{11}		1.283 (2.688)	3.710 (1.855)*	4.209 (2.000)*	4.647 (2.080)*
γ_{12}		7.685 (8.709)	7.870 (7.153)	6.558 (6.971)	13.102 (6.079)*
γ_{13}		-16.992 (16.095)	-25.599 (13.578)+	-36.571 (12.630)**	-20.265 (10.634)+
δ_{0}		0.287 (0.050)**	0.283 (0.048)**	0.260 (0.046)**	0.284 (0.047)**
δ_{1}		0.149 (0.069)*	0.153 (0.068)*	0.150 (0.068)*	0.180 (0.069)**

+ = Significant at 90% level * = Significant at 95% level ** = Significant at 99% level

TABLE 3B: PARAMETER ESTIMATES FOR NUCLEAR PLANTS

Endogenous Variables:
Log of Construction Cost and
Log of Construction Lead Time
(Standard Errors in Parentheses)

MODEL ESTIMATOR	 OLS	A 2SLS	A NL2SLS	A NL3SLS	E NL3SLS
COST R^2		0.867	0.804	0.799	
LEAD R^2	0.822		0.847	0.862	
OBJECTIVE				47.14	51.38
α_0	0.149 (0.175)		0.914 (0.397)*	0.614 (0.378)	0.596 (0.388)
α_1	4.965 (0.878)**	292.390 (191.100)	333.310 (158.760)*	308.470 (180.430)+	387.320 (134.56)**
α_{10}		62.705 (47.662)	73.458 (37.402)+	69.994 (43.765)	87.776 (33.063)**
α_{11}	-0.111 (0.058)	1.965 (12.113)	-1.042 (4.025)	-4.941 (4.787)	-6.545 (4.035)
α_{12}	0.081 (0.116)	23.999 (14.965)	23.778 (11.789)*	12.870 (9.992)	16.502 (8.181)*
α_{13}	0.298 (0.240)	24.801 (18.074)	24.260 (15.167)	18.920 (14.309)	18.068 (12.952)
α_{15}	-1.084 (0.094)**	-77.860 (48.974)	-86.159 (41.827)*	-77.487 (46.402)	-96.925 (35.613)**
β_0		630.130 (402.230)	709.860 (318.730)*	641.000 (349.160)+	695.340 (231.030)**
β_1		17.279 (65.039)	5.385 (28.099)	-15.583 (25.748)	-11.387 (19.966)
β_2		133.570 (123.460)	144.150 (99.269)	84.698 (93.868)	96.011 (45.643)*
β_3		249.290 (154.280)	242.960 (134.590)+	188.090 (127.480)	46.600 (43.655)

+ = Significant at 90% level * = Significant at 95% level ** = Significant at 99% level

TABLE 3B: PARAMETER ESTIMATES FOR NUCLEAR PLANTS, CONTINUED

MODEL ESTIMATOR	OLS	A 2SLS	A NL2SLS	A NL3SLS	E NL3SLS
β_{11}		1.284 (2.813)	1.319 (2.530)	1.412 (2.517)	0.796 (2.116)
β_{12}		1.262 (5.194)	0.455 (3.237)	0.187 (3.293)	
β_{13}		-3.982 (6.561)	-4.356 (6.261)	-6.667 (6.053)	
β_{22}		-0.636 (21.094)	2.788 (16.171)	2.559 (16.792)	
β_{23}		19.109 (23.343)	18.496 (21.291)	9.649 (20.332)	
β_{33}		106.720 (70.016)	101.760 (59.848)+	78.357 (57.374)	
γ_{1}		-343.510 (189.690)+	-373.070 (172.310)*	-324.480 (184.870)+	-383.820 (132.970)**
γ_{10}		95.322 (54.792)+	100.090 (47.197)*	84.273 (49.082)+	101.950 (38.052)**
γ_{11}		-5.504 (14.650)	-2.249 (5.723)	3.082 (5.730)	3.870 (5.143)
γ_{12}		-36.256 (22.558)	-36.478 (19.791)+	-20.720 (17.463)	-24.872 (11.655)*
γ_{13}		-45.370 (31.012)	-43.745 (26.830)	-30.758 (24.886)	-16.040 (12.938)
δ_0		0.289 (0.122)*	0.293 (0.112)*	0.282 (0.111)*	0.256 (0.103)*
δ_1		-0.146 (0.189)	-0.102 (0.127)	-0.018 (0.130)	-0.016 (0.120)

+ = Significant at 90% level * = Significant at 95% level ** = Significant at 99% level

TABLE 4: COMPARISON OF MODELS

Table 4A: Equivalence with Model F (Cobb-Douglas)

Sample		Coal		Nuclear	
Model	df	T^0	Significance	T^0	Significance
A	10	126.58	0.000	18.21	0.052
B	8	124.67	0.000	15.80	0.045
C1	6	37.14	0.000	7.18	0.023
C2	4	10.40	0.034	14.68	0.005
C	3	10.35	0.016	7.10	0.069
D	7	116.51	0.000	15.71	0.028
E	5	118.35	0.000	14.98	0.010
F1	3	30.45	0.000	14.98	0.002
F2	1	0.23	0.632	0.25	0.617

Table 4B: Equivalence with Model A (Translog)

B	2	1.43	0.489	1.10	0.577
C1	4	83.78	0.000	2.85	0.583
C2	6	119.94	0.000	11.97	0.063
C	7	120.11	0.000	12.05	0.099
D	3	5.55	0.136	2.24	0.524
E	5	6.34	0.275	3.14	0.583
F1	7	89.03	0.000	6.45	0.488
F2	9	126.29	0.000	17.99	0.035
F	10	126.58	0.000	18.21	0.052

Table 4C: Constant Returns to Scale

Test of SCE = 1 at Mean Values of Independent Variables

A	1	4.60	0.032	1.03	0.310
B	1	4.00	0.046	0.74	0.390
C1	1	10.70	0.001	0.39	0.532
C2	1	10.03	0.002	0.37	0.543
C	1	18.43	0.000	0.21	0.647
D	1	3.90	0.048	0.03	0.862
E	1	3.97	0.046	0.80	0.371
F1	1	8.34	0.004	0.51	0.475
F2	1	12.94	0.000	0.42	0.517
F	1	19.12	0.000	0.80	0.371

NOTE: Test statistics based on Gallant and Jorgensen's (1979) T^0, distributed as a χ^2 with degrees of freedom (df) equal to the number of restricted parameters. Significance indicates the probability that the two models are equivalent.

TABLE 5: KEY PARAMETERS

Coal

Model	a_0	a_{10}	a_{11}	β_{11}	ζ	η	ψ	SCE	θ
A	0.57**	10.42*	-2.02*	0.47*	0.18**	0.40+	0.81**	0.12*	-0.08
B	0.55**	13.29**	-2.49**	0.56**	0.17**	0.33+	0.83*	0.11*	-0.10
C1	0.56**	6.66**	0	0	0	0.35+	0.82**	0.18**	0
C2	0.53**	0	0	0.03	0	0.26	0.81**	0.19**	-0.03
C	0.53**	0	0	0	0	0.26	0.80**	0.20**	0
D	0.52**	13.70**	-2.55**	0.60**	0.17**	0.23	0.84*	0.12*	-0.13
E	0.52**	14.64**	-2.69**	0.62**	0.17**	0.23	0.85*	0.11*	-0.13
F1	0.53**	8.33**	0	0	0	0.24	0.83**	0.17**	0
F2	0.51**	0	0	0.05	0	0.20	0.81**	0.19**	-0.05
F	0.52**	0	0	0	0	0.21	0.80**	0.20**	0

Nuclear

Model	a_0	a_{10}	a_{11}	β_{11}	ζ	η	ψ	SCE	θ
A	0.61	69.99	-4.94	1.41	0.07	0.07	0.69	0.31	-1.06
B	0.67	92.17*	-5.51	-0.02	0.06	0.27	0.75	0.24	0.34
C1	0.71	93.75*	0	0	0	0.39	0.85	0.15	0
C2	0.23	0	0	0.53	0	-1.23	0.89	0.11	-0.53
C	0.24	0	0	0	0	-1.20	0.86	0.14	
D	0.56	71.19	-6.26+	1.92	0.09	-0.12	0.69	0.32	-1.37
E	0.60	87.78**	-6.55+	0.80	0.07	0.00	0.76	0.24	-0.31
F1	0.57	82.57**	0	0	0	-0.08	0.83	0.17	0
F2	0.32	0	0	0.92	0	-0.93	0.84	0.16	-0.92
F	0.33	0	0	0	0	-0.90	0.80	0.20	0

+ = Significant at 90% level   * = Significant at 95% level   ** = Significant at 99% level

$$\zeta = \frac{\partial \ln LT}{\partial \ln Q} = -\alpha_{11}/(1+\alpha_{10})$$

$$\eta = \frac{\partial \ln C}{\partial \ln LT^*} = \alpha_1 + \alpha_{10} \ln LT^* + \alpha_{11} \ln Q^* + \sum_{i=2}^{4} \alpha_{1i} \ln p_i + \alpha_{15} \ln \tau$$

$$\psi = \frac{\partial \ln C}{\partial \ln Q} = \alpha_{11} \ln LT + \beta_1 + \beta_{11} \ln Q^* + \sum_{i=2}^{4} \beta_{1i} \ln p_i + \gamma_{11} \ln \tau$$

$$SCE = 1 - \frac{d \ln C}{d \ln Q} = 1 - \psi - \eta \cdot \zeta$$

$$\theta = \frac{\partial SCE}{\partial \ln Q} = -(\beta_{11} + 2 \cdot \alpha_{11} \cdot \zeta + \alpha_{10} \cdot \zeta^2)$$

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